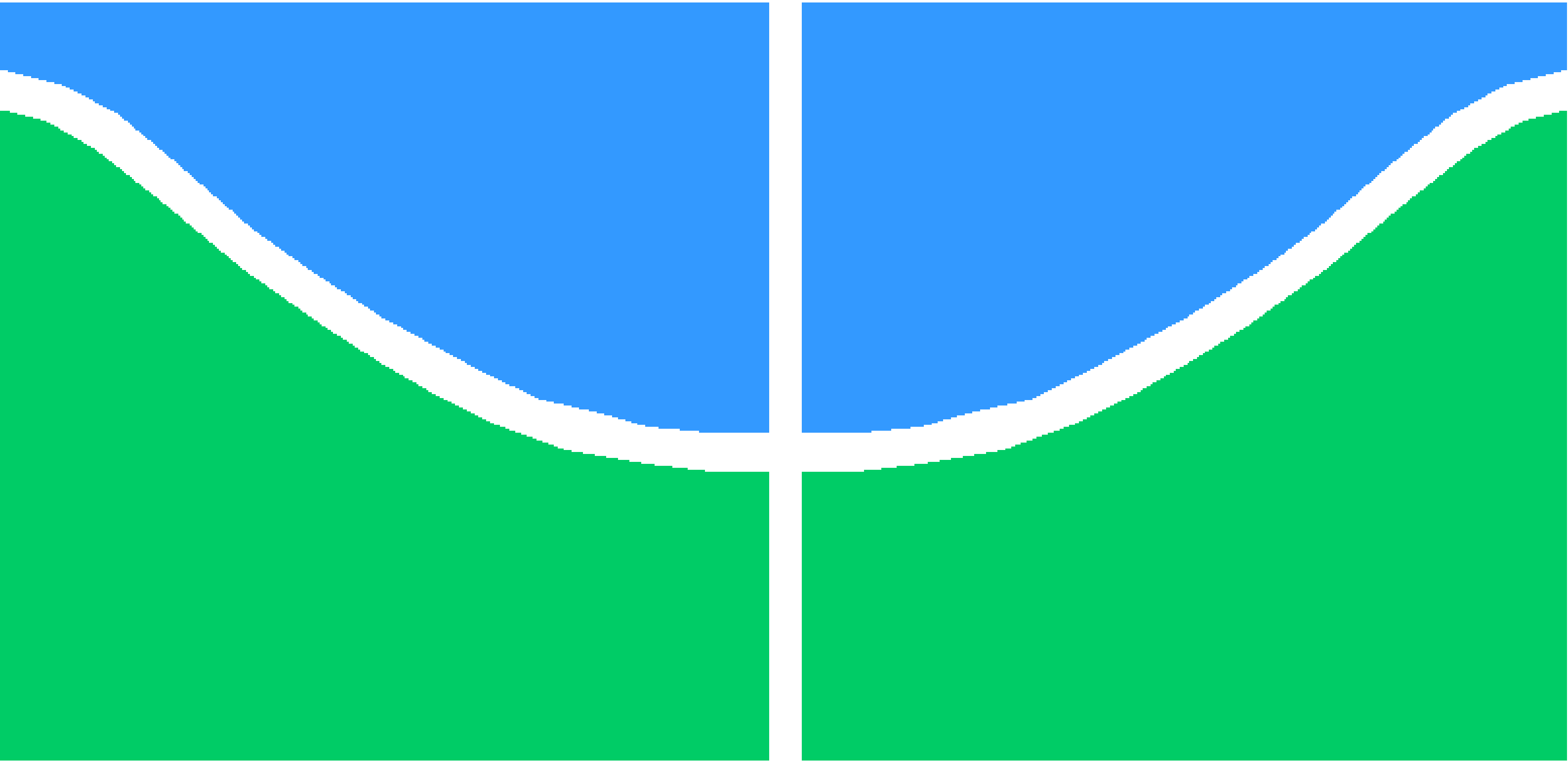


DISSERTAÇÃO DE MESTRADO

TÉCNICAS DE COMPARTILHAMENTO DE ESPECTRO BASEADAS EM TEORIA DOS JOGOS PARA ACESSO LOCAL EM SISTEMAS IMT-ADVANCED

Gustavo Wagner Oliveira da Costa

Brasília, Julho de 2008

UNIVERSIDADE DE BRASÍLIA

FACULDADE DE TECNOLOGIA

UNIVERSIDADE DE BRASÍLIA
FACULDADE DE TECNOLOGIA
DEPARTAMENTO DE ENGENHARIA ELÉTRICA

TÉCNICAS DE COMPARTILHAMENTO DE ESPECTRO BASEADAS EM TEORIA DOS JOGOS PARA ACESSO LOCAL EM SISTEMAS IMT-ADVANCED

GUSTAVO WAGNER OLIVEIRA DA COSTA

ORIENTADOR: PAULO HENRIQUE PORTELA DE CARVALHO

DISSERTAÇÃO DE MESTRADO EM
ENGENHARIA ELÉTRICA

PUBLICAÇÃO: DM - 346/2008

BRASÍLIA/DF: JULHO - 2008.

UNIVERSIDADE DE BRASÍLIA
FACULDADE DE TECNOLOGIA
DEPARTAMENTO DE ENGENHARIA ELÉTRICA

TÉCNICAS DE COMPARTILHAMENTO DE ESPECTRO BASEADAS EM TEORIA DOS JOGOS PARA ACESSO LOCAL EM SISTEMAS IMT-ADVANCED

GUSTAVO WAGNER OLIVEIRA DA COSTA

DISSERTAÇÃO DE MESTRADO SUBMETIDA AO DEPARTAMENTO DE ENGENHARIA ELÉTRICA DA FACULDADE DE TECNOLOGIA DA UNIVERSIDADE DE BRASÍLIA, COMO PARTE DOS REQUISITOS NECESSÁRIOS PARA A OBTENÇÃO DO GRAU DE MESTRE EM ENGENHARIA ELÉTRICA.

APROVADA POR:

Prof. Paulo Henrique Portela de Carvalho,Dr., ENE/UnB
(Orientador)

Prof. Leonardo Rodrigues Araújo Xavier de Menezes,Dr., ENE/UnB
(Examinador Interno)

Prof. Horácio Tertuliano Filho, Dr., UFPR
(Examinador Externo)

Robson Domingos Vieira, Dr., INdT
(Membro convidado)

BRASÍLIA/DF, 10 DE JULHO DE 2008.

FICHA CATALOGRÁFICA

COSTA, GUSTAVO WAGNER OLIVEIRA DA
Técnicas de Compartilhamento de Espectro Baseadas em Teoria dos Jogos para
Acesso Local em Sistemas IMT-Advanced [Distrito Federal] 2008.
xvi, 133p., 210 x 297 mm (ENE/FT/UnB, Mestre, Engenharia Elétrica, 2008). Dissertação de Mestrado - Universidade de Brasília. Faculdade de Tecnologia.
Departamento de Engenharia Elétrica.

1. Compartilhamento de Espectro	2. Teoria dos Jogos
3. IMT-Advanced	4. Quarta geração
I. ENE/FT/UnB	II. Título (série)

REFERÊNCIA BIBLIOGRÁFICA

COSTA, G. W. O. (2008). Técnicas de Compartilhamento de Espectro Baseadas em Teoria dos Jogos para Acesso Local em Sistemas IMT-Advanced. Dissertação de Mestrado em Engenharia Elétrica , Publicação 346/2008 , Departamento de Engenharia Elétrica, Universidade de Brasília, Brasília, DF, 133p.

CESSÃO DE DIREITOS

AUTOR: Gustavo Wagner Oliveira da Costa.

TÍTULO: Técnicas de Compartilhamento de Espectro Baseadas em Teoria dos Jogos para Acesso Local em Sistemas IMT-Advanced

GRAU: Mestre ANO: 2008

Gustavo Wagner Oliveira da Costa

QND 28 lote 20

72120-280 - Taguatinga - DF - Brasil

Dedicatória

A minha noiva Viviane.
Aos meus pais Bento e Maria de Lourdes.
Ao meu irmão Fábio.

Gustavo Wagner Oliveira da Costa

Agradecimentos

Agradeço ao Professor Paulo Henrique Portela de Carvalho pelos vários anos de orientação desde a graduação e por todo o esforço para o meu crescimento acadêmico e profissional.

Agradeço, também, a Nicola Marchetti e István Kovács, meus orientadores durante minha estadia como aluno visitante na Universidade de Aalborg, Dinamarca, onde grande parte deste trabalho foi desenvolvido. Agredeço a Nokia Siemens Networks, também em Aalborg,Dinamarca, pelo suporte financeiro sem o qual não seria possível completar este projeto.

Agradeço a minha família pelo suporte, mesmo nos momentos em que estive ausente.

E agradeço principalmente a Deus por ter me permitido grandes oportunidades na vida como, por exemplo, poder realizar este trabalho.

Gustavo Wagner Oliveira da Costa

RESUMO

A banda necessária para o provimento de serviços no acesso local será muito maior do que as utilizadas em sistemas 2G ou 3G, chegando a cerca de 100 MHz. Por causa disto, estes sistemas terão que trabalhar com espectro sem paridade e compartilhando um conjunto comum de recursos de espectro que será licenciado mas compartilhado entre operadoras. Neste trabalho é proposta uma solução inovadora, baseada em teoria dos jogos, que trata dos principais problemas em tal cenário: latência na alocação inicial de espectro, configuração autônoma, eficiência espectral e justiça na distribuição dos recursos. O protocolo proposto é dividido em duas partes para satisfazer todos estes requisitos, que são conflitantes. Os resultados obtidos mostram que o algoritmo proposto é capaz de prover eficiência espectral bem maior do que os casos mais simples de alocação fixa de espectro. No cenário estudado, o algoritmo proposto aproxima a eficiência espectral do planejamento de freqüências ótimo, sendo ao mesmo tempo capaz de redistribuir a capacidade de acordo com o tráfego e o número de estações rádio base ativas.

ABSTRACT

The required bandwidth for the envisioned services in IMT-Advanced local access is much larger than those usually allocated to 2G and 3G services, in the order of 100 MHz. For that reason, it is envisioned that such systems will have to work in an unpaired spectrum environment where the whole spectrum pool is licensed but shared amongst operators. A novel approach based on Game Theory is proposed, dealing with some of the main issues in such a scenario: latency for initial spectrum assignment, self organization, spectrum efficiency and fairness. In order to meet all those requirements, the proposed protocol has two special states. In the new entrant state the protocol makes an efficient initial spectrum assignment aiming at reduced latency. In the second protocol state, the game is repeated to track load variations, provide long term fairness and enhance the spectrum efficiency. The results show that the proposed framework is capable of providing spectrum efficiency considerably higher than simple approaches for uncoordinated deployment, such as full reuse or having separate spectrum pools. In fact, in the studied scenario, our approach approximates the spectral efficiency of the optimal spectrum planning for full load while tracking traffic variations and self adapting for the number of active base stations.

Prefácio

Este trabalho começou a ser desenvolvido na Universidade de Brasília no primeiro semestre de 2007. No segundo semestre de 2007 e primeiro semestre de 2008, o autor esteve na Universidade de Aalborg, na Dinamarca, como aluno visitante, realizando portanto mestrado sanduíche.

Durante esta estadia o trabalho foi financiado pela Nokia Siemens Networks e orientado por Nicola Marchetti, da Universidade de Aalborg, e István Kovács, da Nokia Siemens Networks.

Como pré-requisito para aprovação da estadia como aluno visitante, a dissertação foi primeiramente escrita em língua inglesa. Optou-se na tradução do texto pela tradução integral das partes principais do trabalho: o algoritmo proposto e os resultados atingidos. As partes consideradas como introdutórias foram apenas resumidas.

O texto original completo, em língua inglesa, foi incluso na forma de apêndices. Portanto, o leitor que não esteja familiarizado com teoria dos jogos e o problema de compartilhamento de espectro é remetido aos apêndices para uma introdução mais completa.

Diversas figuras foram mantidas, também, em língua inglesa.

SUMÁRIO

LISTA DE FIGURAS

LISTA DE TABELAS

LISTA DE SÍMBOLOS

Símbolos Latinos

U	Função utilidade	
B	Banda	[Hertz]
S	Potência do sinal	[Watts]
N	Potêcia do ruído	[Watts]
I	Potência da interferência	[Watts]

Símbolos Gregos

π	Função utilidade agregada com fator de desconto
δ	Fator de desconto

Siglas

2G	2^{nd} Generation
3G	3^{rd} Generation
3GPP	The Third Generation Partnership Project
4G	4^{th} Generation
AP	Access-Point
ARQ	Automatic Repeat reQuest
AS	Access Station
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BF	Beamforming
BS	Base Station
CCI	Co-channel interference
CR	Cognitive Radio
CSI	Channel State Information
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
DL	Downlink
dB	Decibels
DFCA	Dynamic Frequency and Channel Allocation
DoA	Direction of Arrival
DoD	Direction of Departure
DSA	Dynamic Spectrum Access
DSAN	Dynamic Spectrum Access Network
EA	Evolutionary Algorithm
EGT	Evolutionary Game Theory
ESS	Evolutionary Stable Strategy

FDD	Frequency Division Duplexing
FSU	Flexible Spectrum Usage
GA	Genetic Algorithm
GDSA	Game-based Distributed Spectrum Allocation
GPS	Global Positioning System
GSM	Global System for Mobile Communications
GT	Game Theory
H-ARQ	Hybrid ARQ
HAS	Home Access Station
HBS	Home Base Station
HRS	Home Relay Station
ICIC	Inter-cell Interference Coordination
IEEE	Institute of Electrical and Electronics Engineers
IMT	International Mobile Telecommunications
IMT-A	IMT-Advanced
IMT-2000	International Mobile Telecommunications-2000
ITU	International Telecommunications Union
LA	Link Adaptation
LAN	Local Area Network
LNA	Low Noise Amplifier
LOS	Line of Sight
LTE	3G Long Term Evolution
LTE-A	LTE Advanced
MA	Multiple Access
MAC	Medium Access Control
MANET	Mobile Ad-hoc Network

MCS	Modulation and Coding Scheme
MIMO	Multiple Input Multiple Output
MISO	Multiple Input Single Output
MS	Mobile Station
NBS	Nash Bargaining Solution
NE	Nash Equilibrium
NF	Noise Figure
NLOS	Non Line Of Sight
OFDD	Orthogonal Frequency Division Duplexing
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OTA	Over the Air
PC	Power Control
PHY	Physical Layer
PO	Pareto Optimal
PRB	Physical Resource Block
QoE	Quality of End user experience
QoS	Quality of Service
PS	Packet Switched
RAN	Radio Access Network
RF	Radio Frequency
RRM	Radio Resource Management
RS	Relay Station
Rx	Receiver
SB	Spectrum Broker
SC-FDMA	Single Carrier Frequency Division Multiple Access

SISO	Single Input Single Output
SINR	Signal to Interference plus Noise Ratio
SNR	Signal to Noise Ratio
SpS	Spectrum Sharing
SPRB	Shared Physical Resource Block
TCP	Transmission Control Protocol
TDD	Time Division Duplexing
TTI	Transmission Time Interval
Tx	Transmitter
UE	User Equipment
UL	Uplink
UMTS	Universal Mobile Telecommunications Systems
UTRA	Universal Terrestrial Radio Access
WLAN	Wireless Local Area Network
WRC	World Radiocommunication Conference
xG	Next Generation Networks

1 INTRODUÇÃO

Tradicionalmente, os sistemas de comunicação sem fio operam em bandas que estão licenciadas para uso por um único sistema em uma determinada área geográfica. Esta abordagem permite a cada sistema (tecnologia de rádio) ser otimizada de maneira independente das outras. Órgãos reguladores determinam os limites para emissão de potência e máscaras de espectro que devem ser obedecidas por estes sistemas licenciados. Desta maneira, as interações entre diferentes sistemas de comunicação ocorrem apenas nas freqüências de borda e podem ser minimizadas através do uso de bandas de guarda e planejamento adequado feito pelos órgãos reguladores.

No entanto, o modelo tradicional de licenciamento do espectro vem sendo pressionado pela crescente demanda. A evolução para maiores taxas de dados e a necessidade de provimento de qualidade do serviço (QoS) tem direcionado o desenvolvimento de novas tecnologias de rádio para utilização de bandas mais largas. Além disto, a tendência é pela utilização de transmissões de menor alcance, a fim de se maximizar a relação sinal interferência e, portanto, aumentar a taxa de dados além de se reduzir o consumo de energia em aparelhos móveis. Um exemplo desta tendência é a utilização de estações *relay* ou estações rádio base para prover acesso local de curto alcance a taxas de dados mais altas ou melhor cobertura que estações rádio base macro-celulares. Neste trabalho este tipo de estação para acesso local é referido de maneira genérica como HAS (do Inglês, *Home Access Station*) independentemente de ser uma estação *relay* ou rádio base.

O IMT-Advanced (IMT-A) vem sendo especificado pela *International Telecommunication Union* (ITU) e corresponde a quarta geração de telefonia celular. Os requisitos de taxa desejados são mostrados na figura 1.1

No acesso local, a banda necessária para se atingir os requisitos de 1 Gbps chega a ordem de 100 MHz. Este é um requisito de banda bastante alto e, por este motivo, esses sistemas terão de trabalhar em um ambiente de espectro compartilhado, pelo menos no acesso local, e novas técnicas terão de ser desenvolvidas para tornar a operação viável. Maiores detalhes sobre o IMT-A são apresentados no Apêndice I.1

No caso de diversas operadoras ou sistemas operarem no mesmo espectro, existe a competição pelos recursos de freqüência. Do ponto de vista analítico, uma das abordagens mais promissoras para a análise desse ambiente competitivo é a utilização de teoria dos jogos, que consiste em modelos matemáticos de conflito e cooperação entre tomadores de decisão racionais [4].

O objetivo deste trabalho é o desenvolvimento de um algoritmo para alocação distribuída e dinâmica de espectro com aplicabilidade no acesso local de sistemas IMT-A. Alguns dos trabalhos anteriores relacionados são descritos a seguir, representando o estado da arte na utilização de teoria dos jogos na solução do problema de compartilhamento de espectro.

Em [5], é utilizada uma abordagem cooperativa de teoria dos jogos. O compartilhamento de

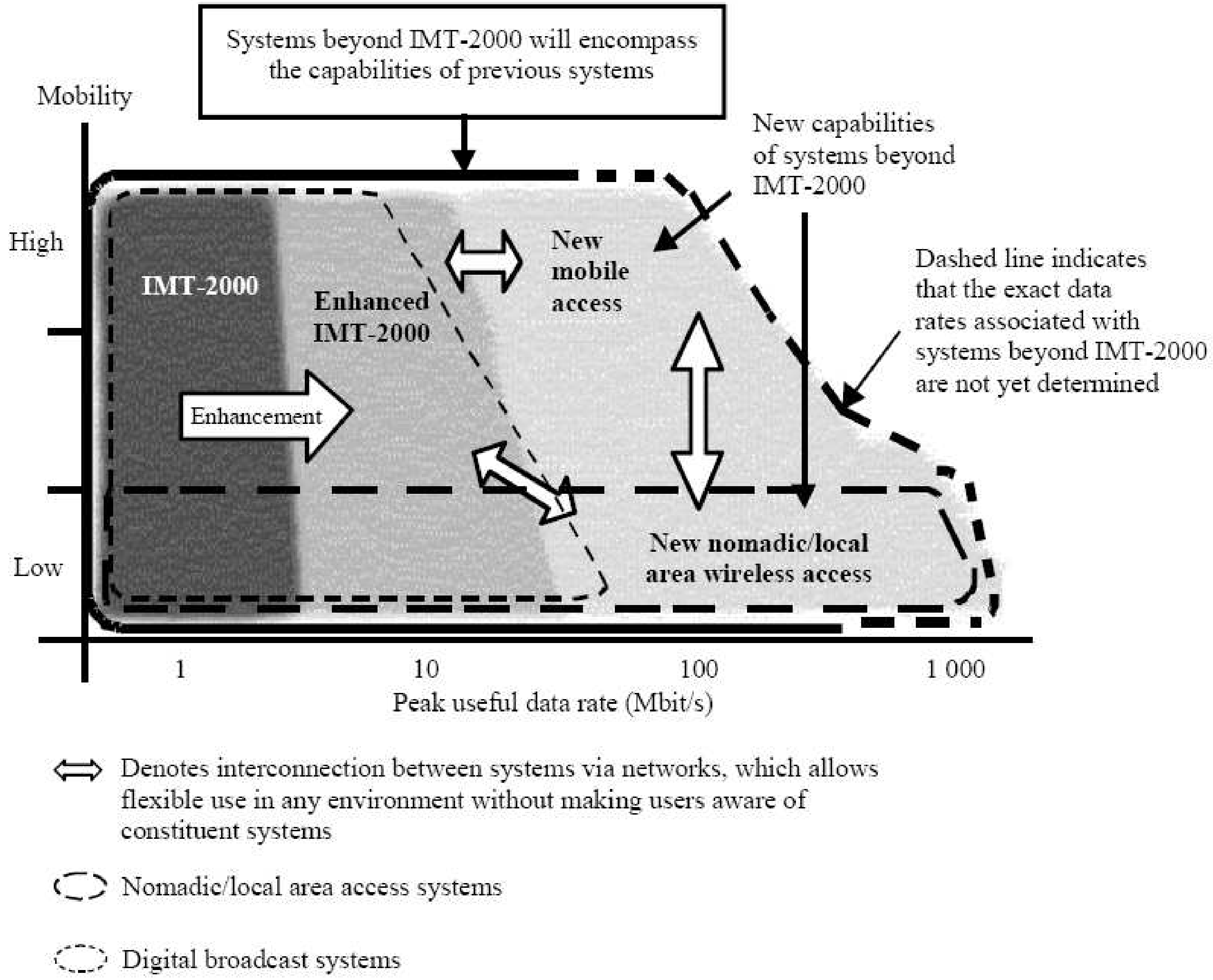


Figura 1.1: IMT-Advanced [1]

espectro é formulado como um jogo envolvendo N transmissores na rede. Estes N transmissores são os tomadores de decisão e, portanto, são os jogadores. Estão disponíveis K canais completamente ortogonais entre si e as estratégias possíveis são todas as possíveis alocações de potência de transmissão nos K canais. A função utilidade é dada pela capacidade de Shannon agregada ao longo dos K canais. A decisão dos N jogadores está acoplada pela razão sinal interferência (SINR) de cada canal, pois a capacidade de cada canal depende diretamente desse valor. Os autores mostram que o espaço de estratégias pode ser não convexo, o que dificulta a aplicação direta de técnicas de otimização, mas este espaço de estratégias aproxima-se de um espaço convexo quando o número de canais K é suficientemente aumentado. Em seguida, é proposto um algoritmo para otimizar localmente o produto de Nash e, assim, tentar aproximar localmente a otimização da solução global, chamada de solução de barganha de Nash. A solução proposta em [5] alcança um bom desempenho comparado a outras abordagens.

Em [6], um cenário de rede local sem fio (WLAN) é considerado. Duas funções utilidades são propostas com base na qualidade percebida do canal. Mais precisamente, as funções utilidades são baseadas no nível de interferência nos receptores. os dois casos considerados são: uma função utilidade egoísta que considera apenas o nível de interferência no receptor desejado e uma função utilidade cooperativa que considera também a interferência recebida nos receptores vizinhos. Para o segundo caso, é elaborado um protocolo para trocar a informação necessária em uma WLAN. Além disso, os autores mostraram que duas abordagens baseadas em teoria dos jogos, uma baseada em uma função potencial e outra baseada em aprendizagem sem remorso, têm a capacidade de conduzir a uma distribuição de SINR sensivelmente melhor do que alocações aleatórias de freqüência.

WLANs com suporte a QoS IEEE 802.11e são consideradas em [7]. O jogo é repetido, e o jogo base possui um único estágio mas é implementado em 3 fases: tomada de decisão, acesso competitivo e avaliação. A utilidade é uma função de três dimensões de QoS: taxa de dados, atraso e tempo de uso de canal solicitado. Os autores consideram um jogo repetido com horizonte infinito e mostram como diferentes estratégias se comportam em simulações.

Uma avaliação profunda do canal de interferência com dois transmissores e dois receptores é feita em [8]. Uma das principais conclusões é que a característica aleatória do tráfego ajuda a aliviar o acesso puramente competitivo. Portanto, o tráfego é uma importante dimensão a ser considerada no problema de compartilhamento de espectro. Além disto, a diferença de desempenho é bastante grande no caso em que há conhecimento de informações sobre a fila no outro transmissor comparado ao caso em que essa informação não está disponível.

As abordagens em [5], [6] e [7] mostram o potencial de se utilizar a teoria dos jogos na análise do problema e criação de soluções práticas para o compartilhamento de espectro. Porém, todas estas propostas envolvem algum tipo da sinalização explícita entre as entidades da rede. Este tipo de sinalização envolve complexidade e redundância adicionais que podem ser proibitivas no acesso local feito sem planejamento de rede. Por sua vez, [8] mostra que é importante considerar outros aspectos pouco abordados na literatura, como o tráfego e os casos em que a informação completa não é possível. Porém, nenhuma solução prática é proposta e apenas o caso com dois transmissores e receptores é analisado.

Neste trabalho, é proposta uma abordagem inovadora, baseada em teoria dos jogos, chamada Game-based Distributed Spectrum Allocation (GDSA). O GDSA é baseado unicamente em informações disponíveis localmente através do sensoriamento realizado nas HASs e nas estações terminais (UE). Não há nenhuma necessidade para sinalização explícita e troca de mensagens entre HASs. Através de simulações é demonstrado que o GDSA é capaz de prover uma maior eficiência espectral do que as alocações fixas de espectro mais simples, aproximando-se da alocação ótima. Além disto, o GDSA se adapta às variações do tráfego e fornece um grau razoável de equidade à longo prazo. A adaptação é feita sem conhecimento do tráfego ou mesmo infraestrutura das outras redes evitando, portanto, o compartilhamento de informações consideradas como estratégicas pelas operadoras. Na literatura, não foi encontrada pelo autor nenhuma outra abordagem que reúna tantas características favoráveis para a implementação prática.

A dissertação foi organizada da seguinte maneira. No capítulo 1 foi exposto o problema de compartilhamento de espectro no acesso local de redes IMT-Advanced. O capítulo 2 é uma breve introdução à teoria dos jogos com enfoque em jogos bayesianos, pois estes servem de base para o modelo adotado.

No capítulo 3, é apresentado o modelo adotado de compartilhamento de espectro e como ele interage com as funções de gerência de recursos de rádio comumente existentes em redes celulares. O capítulo 4 apresenta o desenvolvimento do algoritmo proposto, o GDSA.

No capítulo 5, são discutidos os resultados do GDSA obtidos através de simulação. O GDSA mostra-se superior a alocações fixas de espectro em pelo menos um aspecto: desempenho médio, desempenho mínimo ou menor complexidade. Finalmente, o capítulo 6 descreve as conclusões do trabalho e possíveis extensões.

Como descrito no prefácio, o texto foi originalmente escrito em língua inglesa. Optou-se por colocar todo o texto original em anexo. O texto original segue a mesma estrutura de capítulos aqui descrita.

2 TEORIA DOS JOGOS

Um jogo é qualquer situação em que os tomadores de decisões têm o resultado das suas próprias decisões afetadas pela decisão feita por outros tomadores de decisões.

Na terminologia de teoria dos jogos, a pessoa ou entidade que toma decisões é chamada de jogador. O objetivo de um jogador é o maximizar sua própria função utilidade. A função utilidade mede, portanto, o nível de satisfação de um jogador com o resultado do jogo.

Na figura 2.1, é mostrado um exemplo simples que demonstra o porque o gerenciamento distribuído de interferência é um jogo. Cada uma das HASs na figura 2.1 tem de decidir a sua potência de transmissão. Cada HAS pretende maximizar a capacidade de seu enlace, que é uma função da razão sinal ruído mais interferência (SINR). Assim, uma HAS pode decidir aumentar a potência de transmissão a fim de maximizar o nível de sinal recebido. Mas se, por exemplo, H1 aumentar a sua potência de transmissão irá aumentar, também, a interferência gerada para o outro enlace. O inverso também é verdadeiro: se H2 aumentar a sua potência de transmissão irá reduzir a SINR percebida pela UE 1, representada no lado esquerdo da figura 2.1. Portanto, as duas HASs têm de decidir as suas respectivas potências de transmissão, mas são mutuamente influenciadas pelas suas decisões. Por isso, o gerenciamento de interferência se caracteriza como uma situação de jogo.

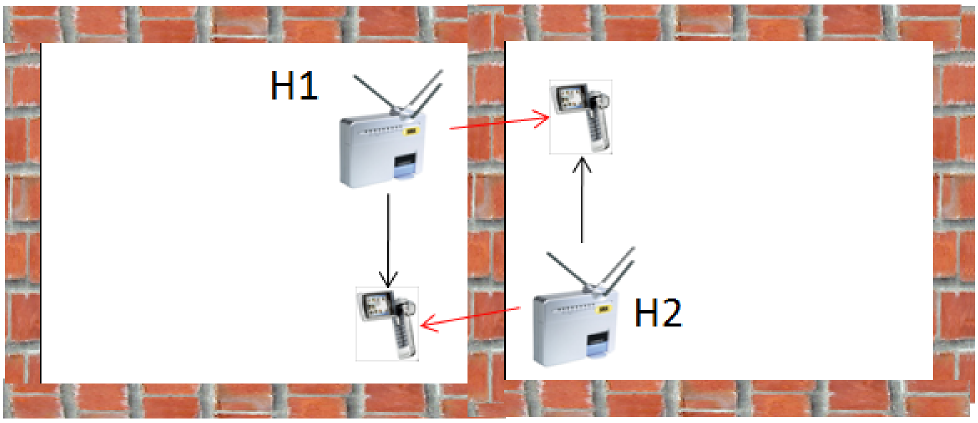


Figura 2.1: Exemplo de possível cenário de área local, onde a interferência pode ser da mesma ordem de magnitude do nível do sinal desejado.

Um dos conceitos-chave em teoria dos jogos é o conceito de Equilíbrio de Nash (NE). Um perfil de estratégias é um equilíbrio de Nash se ele satisfizer completamente a seguinte condição: cada estratégia no perfil é uma melhor resposta às estratégias dos outros jogadores. Isto pode ser interpretado da seguinte forma: em um equilíbrio de Nash, nenhum jogador tem incentivo para alterar a sua estratégia, dado que os outros jogadores também não alterem suas respectivas estratégias.

Em jogos em que existe um único NE, pode ser demonstrado que sob alguns pressupostos de racionalidade, o NE será sempre a solução do jogo [9], isto é, o equilíbrio de Nash será o perfil de estratégias efetivamente jogado quando o jogo for realizado.

É comum a modelagem do problema de compartilhamento de espectro como um jogo de informação completa. No entanto, esta é uma hipótese bastante restritiva se não existir nenhum mecanismo para a sinalização direta entre HASs. Por exemplo, se uma HAS precisa tomar uma decisão baseada somente em sensoriamento do espectro, então ela não poderá, em princípio, diferenciar diretamente quais são os seus interferidores. Sendo assim, uma HAS não sabe nem mesmo quantos outros jogadores estão envolvidos no compartilhamento do espectro.

Por esse motivo, neste trabalho são considerados jogos de informação incompleta, também chamado de jogos bayesianos [9]. Um jogo dinâmico de informação completa é definido através dos seguintes componentes:

- O conjunto de jogadores no jogo. Geralmente eles são denotados simplesmente por números $1, 2, ..., I$.
- O conjunto de possíveis estados do jogo, chamados nós de decisão, e a sua precedência.
- A definição dos conjuntos de informação. Um conjunto de informação é um conjunto de nós pertencentes ao mesmo jogador, e são indistinguíveis para esse jogador.
- Um conjunto de ações possíveis que o jogador correspondente pode tomar em cada conjunto de informação. Estas ações são chamadas de estratégias.
- Funções utilidade para cada jogador em cada nó terminal (um nó que encerra o jogo).

Além dos componentes previamente descritos, um jogo bayesiano possui os seguintes elementos:

- Os estados da natureza, modelando quaisquer processos aleatórios relevantes que não podem ser influenciados por nenhum jogador
- Uma função de mapeamento dos estados da natureza, ao tipo de cada jogador. O tipo é a informação privada relevante que um jogador possui.
- Cada um dos jogadores atribui uma distribuição de probabilidade aos estados de natureza. Isto representa a opinião um jogador tem sobre o tipo dos outros jogadores. O estado exato da natureza é desconhecido pelos jogadores.

Nesta modelagem, o jogo começa com o movimento da natureza. A natureza decide aleatoriamente o tipo de cada jogador e igualmente pode decidir sobre informações que não estão disponíveis para nenhum jogador. Em cada conjunto de informação, um jogador observa os resultados das decisões tomadas anteriormente e pode atualizar sua opinião sobre os tipos dos outros jogadores através da regra de Bayes [9]. Esta é uma propriedade muito importante que ajuda a aliviar a falta da informação e será explorada no desenvolvimento do protocolo proposto neste trabalho.

Para uma introdução mais completa à teoria dos jogos o leitor é referido ao Apêndice II.

3 MODELO DE COMPARTILHAMENTO DE ESPECTRO

Recentemente, têm sido dada bastante atenção na literatura às chamadas redes de acesso dinâmico ao espectro (DSAN) [10]. A diferença dessas redes com relação aos serviços tradicionais de comunicação sem fio é que elas são capazes de determinar dinamicamente qual é a porção do espectro que elas podem ou devem utilizar. Essa função é comumente chamada de compartilhamento de espectro.

O compartilhamento de espectro pode ser realizado em vários domínios tais como freqüência, tempo e espaço. O foco principal deste trabalho é o compartilhamento de espectro realizado no domínio da freqüência.

É considerado que na área geográfica relevante, como por exemplo um prédio, um ou mais sistemas IMT-A estarão compartilhando o mesmo conjunto de recursos de espectro para o acesso local.

A banda é licenciada para ser compartilhada apenas entre estes sistemas e portanto pode se assumir que não existe interferência de outras tecnologias de rádio.

Assume-se a utilização do *Orthogonal Frequency Division Multiple Access* (OFDMA) como técnica de múltiplo acesso e *Time Division Duplexing* (TDD) como técnica de duplexação.

O ponto de mudança do quadro de *uplink* para *downlink* é sincronizados e todos os sistemas, e, por conseguinte, as interferências de *uplink* e *downlink* são ortogonais entre si e podem ser consideradas separadamente.

O espectro disponível é dividido em blocos de subportadoras chamados *Shared Physical Resource Blocks* (SPRB) s. O SPRBs é a menor unidade de para o compartilhamento de espectro. Cada SPRB pode ser dividido em um número inteiro de *Physical Resource Blocks* (PRB)s, como mostrado na Figura 3.1.

A utilização dos PRBs é controlada pela gerência de recursos de rádio (RRM). Isto significa que dentro de um SPRB são aplicados, ainda, outros processos que afetam o padrão de interferência, como o escalonamento de usuários e o controle de potência. Decisões de RRM que não afetam outras redes ou as afetam positivamente podem ser tomadas a qualquer momento. Decisões de RRM que podem afetar negativamente outras redes devem ser feitas em conformidade com a estrutura considerada no algoritmo proposto de compartilhamento de espectro.

A interação entre o compartilhamento de espectro (SpS) e controle de potência (PC) é que o SpS estabelece qual é a potência máxima permitida por PRB e o controle de potência pode selecionar qualquer nível de potência que satisfaça esse limite. Isto porque a redução de potência irá sempre afetar outras redes de maneira positiva. Este conceito é ilustrado na Figura 3.2.

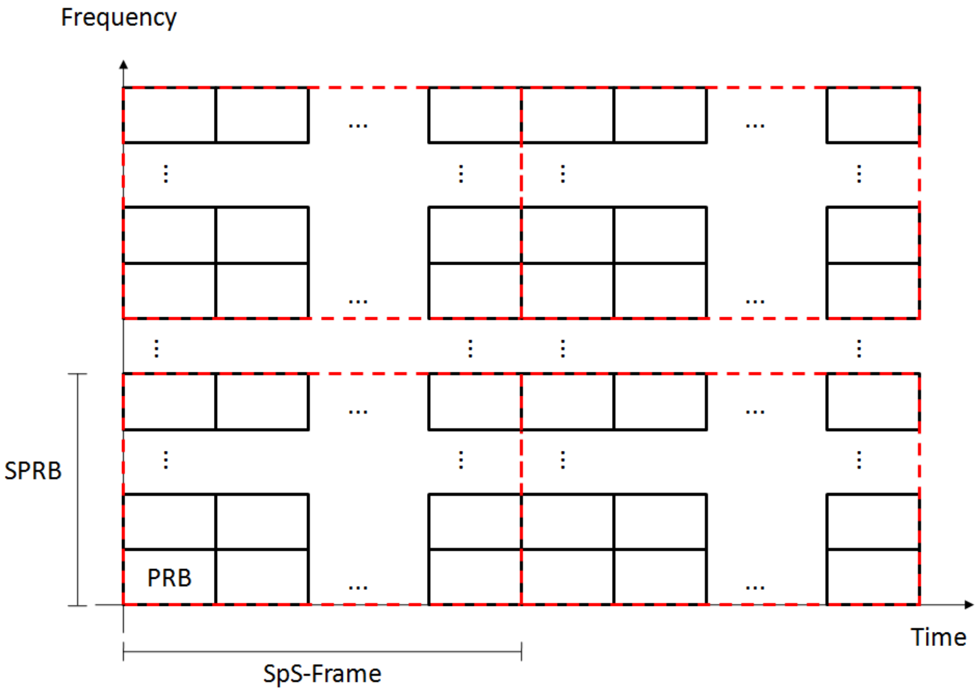


Figura 3.1: A granularidade utilizada nas funções de RRM é mantida mais fina do que a granularidade dos processos de compartilhamento de espectro, tanto no domínio da freqüência (SPRB vs PRB) e tempo (SPS-Frame vs Frame)

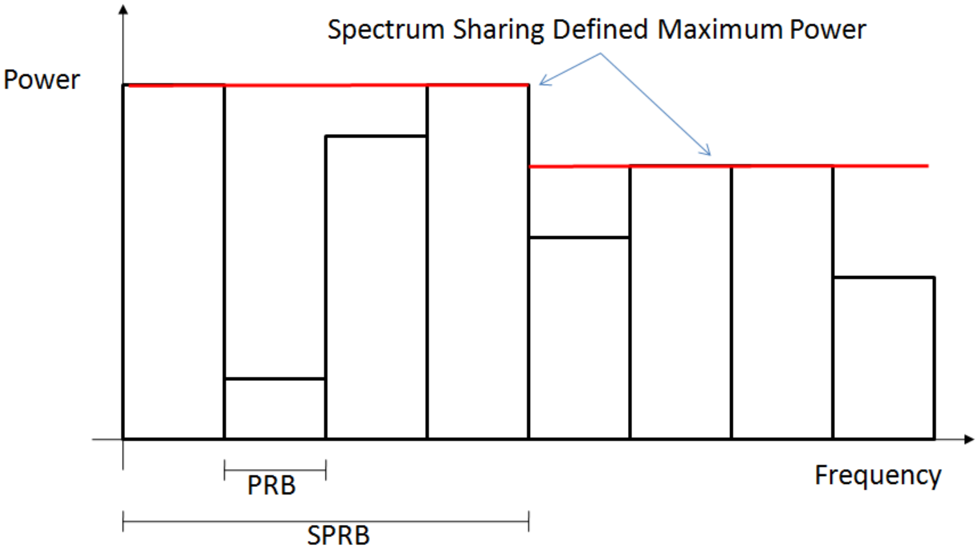


Figura 3.2: O algoritmo de compartilhamento de espectro estabelece a potência máxima por PRB. O controle de potência pode então selecionar a potência por PRB (ou usuário) de maneira independente, desde que o limite estabelecido pelo compartilhamento de espectro seja respeitado.

Assume-se que não exista nenhuma interface para a sinalização entre as diferentes HASs, mesmo aquelas que são da mesma operadora. Por isso, a sinalização é limitada ao sensoriamento do espectro e análise do ambiente de rádio-freqüência (RF). Assim sendo, os interferidores são tratados da mesma maneira, independentemente de fazerem parte da rede da mesma operadora ou não.

Outros aspectos relevantes para o compartilhamento de espectro são considerados no Apêndice III.

4 DESENVOLVIMENTO DO ALGORITMO PROPOSTO

4.1 INTRODUÇÃO

Neste capítulo, é proposto um algoritmo inovador para a solução distribuída do problema de compartilhamento de espectro. O algoritmo é baseado em teoria dos jogos, mas possui também alguns elementos heurísticos, o que é justificável pois existe relação entre teoria dos jogos evolucionária e algoritmos genéticos, como descrito no Apêndice II.7.

Alguns problemas típicos que aparecem em teoria dos jogos, como a implementação prática de um mecanismo de punição, são resolvidos através de algumas hipóteses e restrições, como por exemplo a hipótese de que todas as redes utilizam o mesmo algoritmo para definição das estratégias.

A organização do restante deste capítulo é a seguinte: na seção 4.2 o problema de compartilhamento de espectro no acesso local de redes IMT-Advanced é modelado como um jogo bayesiano. São identificados, então, três elementos que podem ser modificados e, portanto, utilizados como parâmetros de projeto.

Na seção 4.3 é desenvolvido o primeiro parâmetro de projeto, a saber, a estrutura do jogo. A função utilidade adotada é justificada com base na estratégia *Tit-for-Tat* e apresentada na seção 4.4. Na seção 4.5 são definidas as estratégias a serem utilizadas por todos os jogadores em cada um dos conjuntos de informação, finalizando assim os três parâmetros de projeto e completando a especificação do algoritmo proposto.

4.2 MODELO E PARÂMETROS DE PROJETO

Para o desenvolvimento de uma solução prática, o problema de compartilhamento de espectro é modelado como um jogo não-cooperativo, dinâmico e bayesiano com os seguintes elementos:

1. Os jogadores são as *Home Access Stations* (HAS). A partir deste ponto, os termos jogador e HAS são utilizados indiferentemente.

2. Os conjuntos de informação são os instantes de tempo em que uma HAS em particular está autorizada a modificar sua alocação de SPRBs.

3. As estratégias possíveis em cada conjunto de informação são todas as possíveis alocações de espectro.

4. A função utilidade deve ser formulada para maximizar a capacidade agregada de uma HAS.
5. A natureza determina aleatoriamente a posição geográfica das HASs e da UEs, bem como seus requisitos de tráfego.
6. O tipo de cada HAS é
    - requisitos de tráfego ;
    - medições efetuadas nas UEs e diretamente na HAS.

Potencialmente, cada jogador é afetado por um conjunto diferente de jogadores. Do ponto de vista de um jogador, os adversários são todos aqueles jogadores que têm zonas de exclusão sobrepostas a sua zona de exclusão. Uma zona de exclusão é definida como a área ao redor de um transmissor onde receptores de outros sistemas serão afetados consideravelmente caso estejam recebendo no mesmo espectro do referido transmissor. Em outras palavras, uma zona de exclusão define a região geográfica na qual um transmissor gera considerável interferência.

Considerando o modelo proposto de jogo, há três elementos que podem ser utilizadas como parâmetros para um projeto prático de um protocolo de compartilhamento de espectro:

- A estrutura do jogo (conjuntos de informação e sua precedência). Isto corresponde diretamente aos estados de protocolo permitidos.
- A função utilidade.
- Políticas limitando as estratégias disponíveis.

Nas seções seguintes são discutidas as escolhas de cada um destes parâmetros.

4.3 ESTRUTURA DO JOGO

Sabe-se que em jogos repetidos, podem existir equilíbrios de Nash mais eficientes do que no jogo base correspondente [9]. Por este motivo, supõe-se que a estrutura básica de jogo definida será constante, de conhecimento de todos os jogadores e indefinidamente repetida. Os objetivos a serem alcançados neste jogo repetido são:

- Taxas de dados de pico bastante elevadas, quando em condições favoráveis.
- Alta eficiência espectral, em quaisquer condições ou distribuição de tráfego.
- Capacidade de seguir as variações de tráfego.
- Equidade de longo prazo, em comparação com o planejamento ótimo de espectro para a plena carga.

Além destes aspectos a serem satisfeitos pelo jogo repetido, no longo prazo, existe um outro aspecto ainda não suficientemente explorado na literatura: no modelo de compartilhamento de espectro adotado todas as redes têm a mesma prioridade de acesso ao espectro. Caso se permita utilização plena dos recursos de espectro, pode ser que uma HAS, ao ser inicializada, encontre uma situação de utilização de espectro de tal maneira que simplesmente não haverá espectro disponível para sua alocação inicial. Em outras palavras, pode ser que não exista nenhuma lacuna no espectro. A inicialização do novo jogador poderá alterar drasticamente a situação de interferência levando a uma grande quantidade de reconfiguração de espectro. Além disso, se esta situação for tal que a nova HAS tenha que aguardar lentamente para começar a concorrer pelos recursos, então haverá uma grande latência na configuração inicial de uma HAS. Por esses motivos, esta situação de entrada de um novo jogador necessita de tratamento especial.

A estrutura do jogo base é definida, a seguir, considerando-se o problema do novo entrante descrito acima. A mesma solução é adaptada para o jogo repetido com pequenas modificações.

A estrutura do jogo base (protocolo) é definida em 3 fases

- **Fase de barganha**: o novo entrante é o único jogador a mover, decidindo a configuração inicial de espectro e iniciando as transmissões assim que esta configuração inicial for determinada.
- **Fase de resposta**: após determinar as mudanças no cenário de RF causadas, as HASs afetadas pelas transmissões iniciadas pelo novo entrante reconfiguram seu espectro para responder à ameaça do novo entrante.
- **Fase de ajuste**: o novo entrante faz novos ajustes na alocação de espectro, para se adaptar a resposta dada pelos outros jogadores e também para poder, neste momento, utilizar da informação de sensoriamento das UEs.

O número de estágios não é exatamente o número de fases. São definidos dois nós de decisão para o novo entrante, um no início e um ao final, e um nó de decisão para cada outro jogador afetado pela alocação de espectro do novo entrante.

A principal razão para a existência da fase de ajuste é que, na fase de barganha, o novo entrante dispõe apenas de medidas feitas na própria HAS, uma vez que nenhuma UE está sendo servida. Na última fase, o novo entrante pode usar medições das UEs e também se readaptar à nova configuração das outras HASs.

A figura 4.1 ilustra como o funcionamento deste protocolo está previsto em um caso simples com dois jogadores. Inicialmente, todo o espectro é utilizado pelas HAS que já está em atividade, nominalmente, HAS1. O novo entrante, a saber, HAS2, analisa o cenário de RF através de sensoriamento de espectro. A sua conclusão é que todo o espectro já está em uso. O novo entrante não sabe quantas HASs está enfrentando, nem qual a real alocação de potência delas. A HAS 2 sabe apenas que todo o espectro está em uso e qual é a potência detectada em cada SPRB. Neste exemplo, o novo entrante decide que o SPRB 4 está demasiadamente interferido e, por esse motivo, não vale a pena transmitir neste recurso de rádio. Assim, a HAS 2 decide que ele vai iniciar a transmissão nos SPRBs 1, 2 e 3. Uma vez que tenha sido determinada esta alocação de espectro

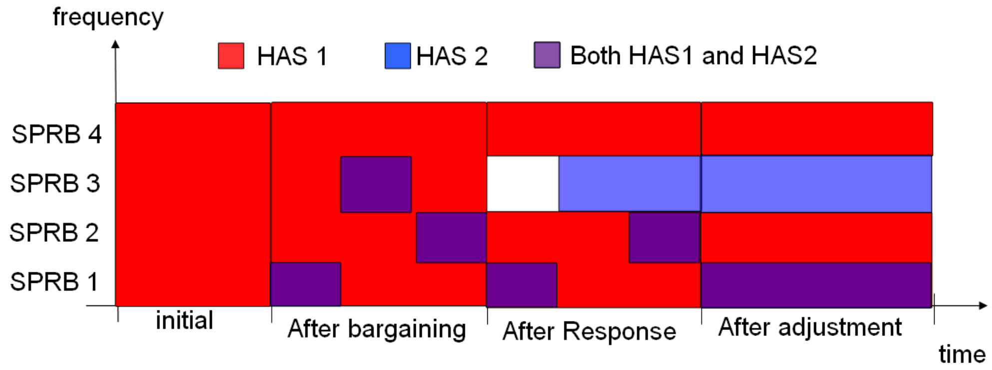


Figura 4.1: Exemplo do jogo de novo entrante com 2 HASs. O novo entrante, HAS 2, seleciona os SPRBs 1, 2 e 3 na negociação. A resposta dada pela jogador 1 é desistir do SPRB 3 e aumentar a potência nos blocos restantes. Na fase de ajuste o novo entrante desiste do SPRB 2. Ao final do algoritmo, o SPRB 1 ainda é compartilhado pelas duas HASs.

inicial, a HAS2 simplesmente inicia transmissão. No entanto, poderá haver diversas conexões em curso na HAS1. Estas conexões pré-existentes podem não se recuperar de um aumento súbito e prolongado da interferência, mesmo com a implementação de estratégias avançadas, como requisição de repetição automática híbrida, do Inglês *Hybrid ARQ* (H-ARQ). Para reduzir o impacto nas conexões pré-existentes, é proposto neste trabalho que nesta fase inicial seja utilizado um padrão de transmissão padrão esparso nos domínios da freqüência e do tempo. Um exemplo simples de tal padrão é só permitir a transmissão em apenas um SPRB por vez e trocar de SPRB a cada quadro de transmissão, de maneira pseudo-aleatória. Com esta abordagem, a interferência será randomizada no domínio da freqüência, permitindo que os processos de H-ARQ das conexões existentes sejam utilizados para se recuperar deste aumento súbito de interferência.

O padrão utilizado após a fase de barganha deve ser padronizado (conhecido por todos os jogadores) e facilitar o sensoriamento pelos jogadores afetados. Além disto, é desejável que este padrão seja claramente distinguível do desvanecimento observado no canal em questão. No entanto, projetar um padrão que satisfaça a todas essas características não faz parte do escopo deste trabalho.

Quando as transmissões iniciadas pelo novo entrante são detectadas pelas outras HASs, estas começam a fornecer a resposta. No exemplo da Figura 4.1, a HAS 1 decide renunciar o SPRB 3 uma vez que este se tornou fortemente interferido e decide também aumentar a potência nos SPRBs 1, 2 e 4. Quando a HAS2 determina que o SPRB 3 se tornou uma lacuna no espectro passa, então, a usá-lo plenamente.

Já quando a HAS2 inicia uma nova transmissão no SPRB 2 a qualidade percebida está severamente degradada. Isto é interpretado como um aumento de potência pelos adversários.

Considerando-se o conhecimento do novo entrante antes da fase de barganha e após a fase de resposta, pode-se inferir o seguinte: a opinião a priori sobre o SPRB 2 era que ele poderia potencialmente ser usado ao mesmo tempo por ambos os jogadores. A opinião a posteriori sobre SPRB 2 é que este SPRB é valioso para a HAS1 e de pouco valor para a HAS 2. Conseqüentemente, é melhor a HAS 1 não utilizar este SPRB.

Considerando que a opinião a priori sobre SPRB 1 era exatamente a mesma, a verificação a posteriori é o oposto: a qualidade no SPRB 1 ainda é boa (devido a uma alocação diferente de potência e ao desvanecimento independente do SPRB 2) e é interessante a transmissão neste SPRB.

Esta observação exemplifica porque esta estrutura dinâmica foi escolhida para este jogo bayesiano com saídas indiretamente observadas, uma vez que o algoritmo determina quais SPRBs podem ser compartilhados e quais não podem. Isto mostra, também, a importância de condicionar as decisões nas decisões feitas previamente por outros jogadores. O novo entrante não sabe quais são os recursos mais valiosos para os seus adversários, mas na fase de ajuste é capaz de condicionar indiretamente sua decisão nesta importância, pois ela se reflete na decisão de seus adversários tomada anteriormente durante a fase de resposta.

Como dito anteriormente, o jogo base é o mesmo independente de protocolo estar no estado normal de jogo repetido ou no estado de novo entrante. As diferenças nos dois estados são:

- No estado normal, qualquer HAS pode barganhar por mais espectro.
- As estratégias disponíveis são modificadas levemente (como mostrado na seção 4.5).
- A cada execução do jogo repetido (SpS-frame), a quantidade de SPRBs que podem ser alocados imediatamente é limitada. A única exceção é quando há um novo entrante.

Essa última restrição tem as seguintes motivações:

- Ajudar na convergência do algoritmo, quando repetido.
- Fornecer histerese em termos de atribuição dos recursos, pois há uma probabilidade elevada de que um nó que pare a transmissão começará a transmitir novamente depois de algum tempo.
- Reduzir o nível de interações indesejadas com RRM.

Em resumo, usando as estratégias apropriadas, espera-se que o protocolo GDSA seja capaz de determinar quais recursos de espectro podem ser compartilhados e quais não podem ser compartilhados usando somente sensoriamento de espectro e alocação de potência como forma de comunicação indireta. Não há necessidade de troca de mensagens entre as HASs.

4.4 FUNÇÃO UTILIDADE

A fim de motivar a definição de função utilidade adotado no GDSA, analisa-se aqui um jogo simplificado de compartilhamento de espectro simétrico, com informação completa.

A tabela 4.1 mostra a forma estratégica desse jogo simplificado. São dois jogadores. Para cada um deles, as estratégias possíveis são o número de SPRBs selecionados, que pode variar de 1 a 4. O primeiro número de cada entrada da tabela é a função utilidade do jogador selecionando entre uma das estratégias das linhas. De modo similar, o segundo número é a função utilidade do jogador que seleciona entre as colunas.

	1	2	3	4
1	3,3	3,6	3,9	1,10
2	6,3	6,6	4,7	2,8
3	9,3	7,4	5,5	3,6
4	10,1	8,2	6,3	4,4 NE

Tabela 4.1: Exemplo de jogo simétrico de compartilhamento de espectro baseado na capacidade agregada do número de SPRBs selecionados, levando-se em conta a adaptação de enlace. As estratégias disponíveis correspondem ao número de SPRBs selecionados.

O único equilíbrio de Nash é o ponto onde os dois jogadores selecionam todos os 4 blocos. Para compreender isto, basta observar que do ponto de vista de qualquer um dos jogadores, selecionar todos os quatro blocos irá sempre maximizar o resultado não importando o que o outro jogador faça. Em outras palavras, selecionar todos os blocos é sempre a melhor resposta a qualquer estratégia do adversário.

Recapitulando, um equilíbrio de Nash é um perfil de estratégias onde todas as estratégias são as melhores respostas para as estratégias dos adversários e, portanto, o fato de ambos os jogadores selecionarem todos os 4 blocos constitui um equilíbrio de Nash.

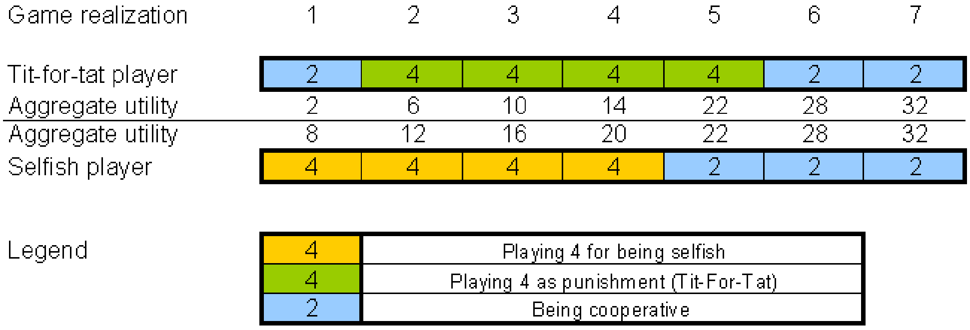
A solução cooperativa deste jogo seria que ambos os jogadores selecionassem dois blocos de forma a manter alocações de espectro ortogonais. Este perfil de estratégia dá um valor de função utilidade de 6 para cada um dos jogadores, enquanto o equilíbrio de Nash provê um valor de utilidade igual a 4. Este simples exemplo mostra que uma solução não-cooperativa pode levar a uma solução ineficiente.

Em um jogo repetido com saídas a cada fase observável, é possível copiar o comportamento do adversário para castigá-lo, quando não estiver cooperando. O medo da punição pode levar, então, os jogadores a assumirem uma postura cooperativa mesmo em um ambiente competitivo.

Permita-se, então, assumir que o jogo da tabela 4.1 seja repetido entre os mesmos jogadores com horizonte infinito, isto é, não havendo expectativa de que algum jogador pare de jogar em breve. Considere a seguinte estratégia baseada em uma estratégia conhecida na literatura de teoria dos jogos como *Tit-for-Tat* [9], que poderia se traduzir como olho por olho, dente por dente: na primeira rodada selecionar 2 SPRBs. Em cada uma das rodadas seguintes, repetir a estratégia adotada pelo adversário na rodada anterior.

Analisar-se-á, primeiro, o quão bom é o desempenho de um jogador que adote o *Tit-for-Tat* frente a um jogador que adote uma estratégia egoísta por tempo finito. Considere o exemplo da figura 4.2. Na quinta execução do jogo, o jogador egoísta desiste de alocar todos os SPRBs e a partir de então ambos os jogadores têm a mesma utilidade agregada. Com o *Tit-for-Tat* o jogador perdoa o jogador egoísta e volta à cooperação, quando o seu adversário resolver cooperar.

Ao se fazer uma análise semelhante no caso de ambos os jogadores adotarem o *Tit-for-Tat*, deduz-se que eles sempre irão cooperar, alcançando uma utilidade agregada maior do que no caso em que não há cooperação. Conclui-se portanto, que o *Tit-for-Tat* alcança um bom desempenho tanto contra jogadores cooperativos quanto contra jogadores não cooperativos.



Game realization	1	2	3	4	5	6	7
Tit-for-tat player	2	4	4	4	4	2	2
Aggregate utility	2	6	10	14	22	28	32
Aggregate utility	8	12	16	20	22	28	32
Selfish player	4	4	4	4	2	2	2

Legend

4	Playing 4 for being selfish
4	Playing 4 as punishment (Tit-For-Tat)
2	Being cooperative

Figura 4.2: Evolução da utilidade agregada quando um jogador usa *Tit-for-Tat* contra um outro que tenta ser egoísta por um tempo finito.

A fim de se realizar uma análise mais geral, mostrar-se-á que utilizar sempre todos os SPRBs **não** é a melhor resposta contra um jogador que utilize o *Tit-for-Tat* em um jogo repetido. Para isto será considerado um jogo com horizonte infinito. Em tais jogos, em geral é considerada uma função utilidade agregada com desconto. O sentido de se utilizar um desconto é que ganhos atuais devem ter um peso maior que ganhos futuros. Uma função utilidade agregada com desconto pode ser definida como (4.1):

$$\pi_i = \sum_{k=0}^{\infty} \delta^k U_{ki} \tag{4.1}$$

Onde a série é infinita por causa do hipótese de horizonte infinito, δ é um fator de desconto com $\delta \in (0, 1)$ e U_{ki} é a utilidade do jogador i na k-ésima repetição do jogo base. Suponha que o jogador 2 joga a estratégia *Tit-for-Tat* e o jogador 1 deseja encontrar a melhor resposta para ela. Em uma única repetição do jogo, a melhor resposta para qualquer estratégia é sempre a mesma: selecionar todos os 4 SPRBs. Sendo assim, faz sentido verificar se se esta também é uma melhor resposta à estratégia *Tit-for-Tat* no jogo repetido.

Na primeira execução do jogo, a adoção dessas estratégias dará ao jogador 1 uma utilidade no valor de 8 e a uma utilidade de 2 ao jogador 2. Em cada uma das execuções seguintes, ambos os jogadores terão uma utilidade de 4 por rodada, uma vez que o jogador 1 sempre seleciona 4 blocos e o jogador 2 sempre faz o que o jogador fez na rodada anterior. Sendo assim, pode-se escrever a utilidade agregada com desconto como percebida na primeira rodada como:

$$\pi_1 = 8 + \sum_{k=1}^{\infty} 4\delta^k \tag{4.2}$$

$$\pi_2 = 2 + \sum_{k=1}^{\infty} 4\delta^k \tag{4.3}$$

Os somatórios correspondem a séries geométricas a menos do termo de índice zero que é inexistente nos somatórios. Pode-se escrever os somatórios em termos de uma série geométrica como se segue:

$$\sum_{k=1}^{\infty} 4\delta^k = -4 + 4 + \sum_{k=1}^{\infty} 4\delta^k = -4 + \sum_{k=0}^{\infty} 4\delta^k \tag{4.4}$$

Substituindo-se esta soma nas equações precedentes e extraindo-se o valor constante 4 da soma:

$$\pi_1 = 4 + 4\sum_{k=0}^{\infty} \delta^k \tag{4.5}$$

$$\pi_2 = -2 + 4\sum_{k=0}^{\infty} \delta^k \tag{4.6}$$

Como o fator de desconto, δ, está confinado ao intervalo $\delta \in (0,1)$, a série geométrica converge para:

$$\sum_{k=0}^{\infty} \delta^k = \frac{1}{1-\delta} \tag{4.7}$$

E portanto, as utilidades agregadas de cada jogador correspondem a:

$$\pi_1 = 4 + \frac{4}{1-\delta} \tag{4.8}$$

$$\pi_2 = -2 + \frac{4}{1-\delta} \tag{4.9}$$

Considere agora o caso onde o jogador 1 também opta por utilizar a estratégia baseada no *Tit-for-Tat*. Ambos os jogadores irão sempre cooperar, jogando sempre a solução de barganha de Nash (NBS), e portanto a utilidade agregada de cada um é:

$$\pi_1 = \pi_2 = \sum_{k=0}^{\infty} 6\delta^k = \frac{6}{1-\delta} \tag{4.10}$$

Pode-se checar, como se segue, que se o valor de δ for apropriadamente escolhido, a utilidade agregada do jogador 1 será maior, caso ele escolha jogar também *Tit-for-Tat*, do que se ele for egoísta escolhendo sempre os quatro blocos:

$$\begin{aligned}\frac{6}{1-\delta} &> 4+\frac{4}{1-\delta}\\ \frac{2}{1-\delta} &> 4\\ 2 &> 4-4\delta\\ \delta &> \frac{1}{2}\end{aligned} \tag{4.11}$$

Portanto, com $\delta > 1/2$, escolher sempre os 4 blocos não é a melhor resposta à estratégia *Tit-for-Tat*, uma vez que é mais vantajoso para a HAS 1 utilizar também o *Tit-for-Tat*. Os mesmos cálculos podem ser feitos para comparar a estratégia *Tit-for-Tat* com todos as outras estratégias e mostrar que ela é uma melhor resposta contra si mesma e, por conseguinte, é um equilíbrio de Nash do jogo repetido.

Motivado pela eficiência da estratégia *Tit-for-Tat* desenvolver-se-á uma outra abordagem mais genérica, que pode ser adotada com qualquer número de blocos, e que é mais prática dada a natureza do problema de ser um jogo de informações incompletas.

Uma característica básica do *Tit-for-Tat* é que um jogador é capaz de copiar o comportamento do adversário na execução anterior do jogo para poder puni-lo e portanto utilizar isto contra ele.

Para decidir qual deve ser a banda de transmissão, será feita a seguinte hipótese: quando um jogador decidir a sua banda, ele irá provocar uma reação nos outros jogadores, e estes outros jogadores irão adotar como resposta selecionar a mesma largura de banda selecionada pelo primeiro jogador, o que em última instância irá afetar o mesmo.

Mais especificamente, deixe assumir que o conjunto de recursos de espectro que pode ser selecionado pelos jogadores possui uma largura de banda B. Deseja-se decidir qual deve ser a banda selecionada pelo jogador i para maximizar sua própria função utilidade.

Em um cenário limitado pelo ruído a predição baseada na capacidade de Shannon diz que sempre deverá ser utilizada a banda máxima possível, pois a capacidade é uma função crescente da banda:

$$C_i = B_i\, log_2(1+\frac{S}{N}) \tag{4.12}$$

Onde C_i é a capacidade de Shannon alcançada pelo jogador i, B_i é a banda selecionada pelo mesmo jogador, S é a potência do sinal recebido em watts e N é a potência do ruído, também em watts.

No entanto, em um cenário limitado por interferência, ao se assumir que a mesma quantidade de banda será utilizada pelos oponentes, a melhor decisão pode ser outra, pois selecionar mais banda irá causar uma reação dos adversários, que irão também selecionar mais banda. Este conceito é ilustrado na Figura 4.3

Seja B_i a banda escolhida pelo jogador i. No caso de dois jogadores, a parte da banda que

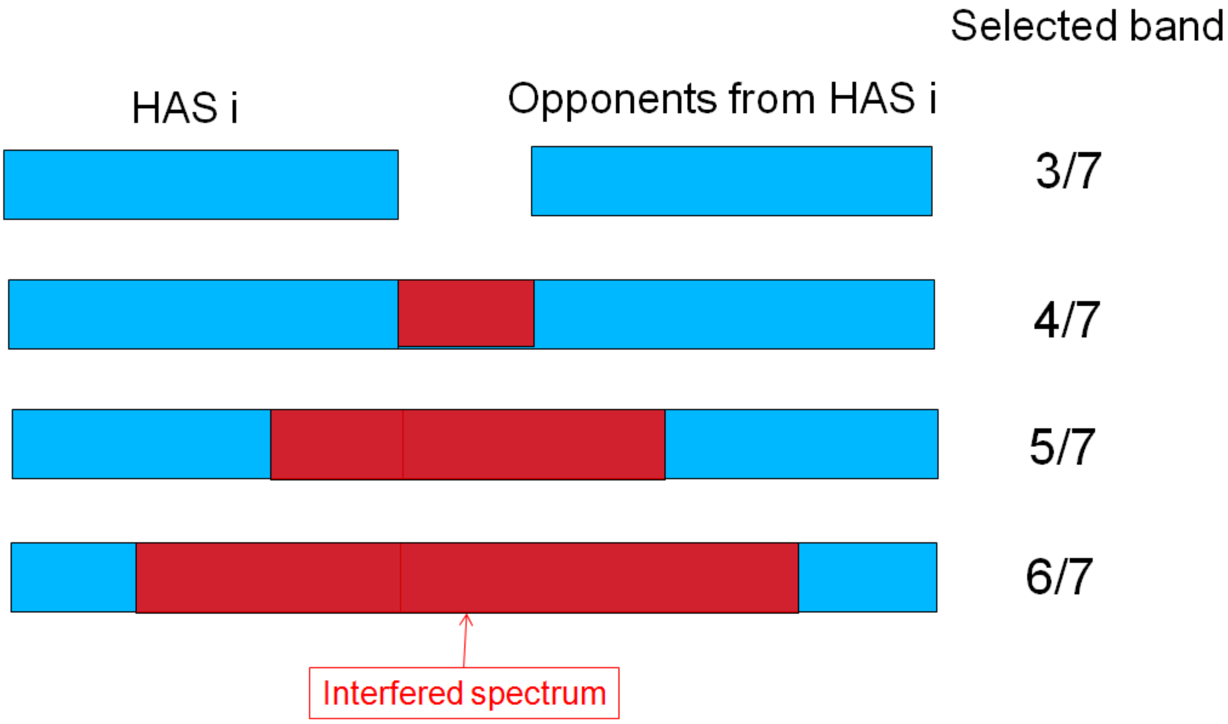


Figura 4.3: Um modelo simples, baseado na estratégia *Tit-for-Tat*, onde os oponentes de um jogador i irão selecionar a mesma quantidade de banda que o jogador i mantendo o máximo de ortogonalidade possível em relação à alocação do jogador i.

será compartilhada, B_{sh}, pode ser escrita como:

$$B_{sh} = \begin{cases} 0, & \text{if } B_i \leq B/2 \\ 2B_i - B, & \text{Caso contrário.} \end{cases} \tag{4.13}$$

De maneira similar, a parte da banda livre de interferência pode ser escrita como:

$$B_f = \begin{cases} B_i, & \text{if } B_i \leq B/2 \\ B - B_i, & \text{Caso contrário.} \end{cases} \tag{4.14}$$

Se a ortogonalidade entre a banda interferida e a banda não interferida puder ser mantida pelo receptor, então a capacidade total pode ser escrita como a soma das capacidades da banda livre de interferência B_f e da banda compartilhada, B_{sh}:

$$C_i = B_f\, log_2(1 + \frac{S_f}{N_f}) + B_{sh}\, log_2(1 + \frac{S_{sh}}{I_{sh} + N_{sh}}) \tag{4.15}$$

Onde S_f é o nível de sinal na banda livre de interferência, N_f é o nível do ruído sobre esta banda e S_{sh},I_{sh} e N_{sh} são respectivamente o nível de sinal, o nível de ruído e o nível de interferência ao longo da banda compartilhada. Usando o modelo Gaussiano para o ruído, o ruído total sobre cada uma das bandas é dado por:

$$N_{sh} = N_0\, B_{sh} \tag{4.16}$$

$$N_f = N_0\, B_f \tag{4.17}$$

No caso geral, o nível de sinal, S, irá variar ao longo da banda por causa de controle de potência no domínio da freqüência, escalonamento de diferentes usuários e seletividade em freqüência do canal. No entanto, para ilustrar o efeito do modelo baseado no *Tit-for-Tat*, serão assumidas as seguintes hipóteses:

- Desvanecimento **não**-seletivo na freqüência.
- Densidade espectral de potência de transmissão fixa ao longo de toda a banda.
- Transmissão de *downlink*.

Considerando-se essas hipóteses simplificadoras, os termos logarítmicos na equação (4.15) se tornam independente de B_i. A figura 4.4 ilustra o comportamento da capacidade total na equação (4.15) a luz destes pressupostos. Se a interferência é relativamente baixa quando comparada com nível de sinal recebido a capacidade ainda aumenta com o a seleção de mais banda. No entanto, se a interferência é maior ou está próxima do nível do sinal recebido a melhor opção é usar uma banda igual a metade da banda total, ou seja, $B/2$, que é o máximo da capacidade em relação a banda selecionada. O valor exato da banda que otimiza a capacidade irá depender do número de jogadores, suas posições e como eles jogam , porém este exemplo com suposições simplificadas ilustra conceito que adicionando mais largura de faixa está esperado realmente para reduzir a capacidade se a interferência é considerável.

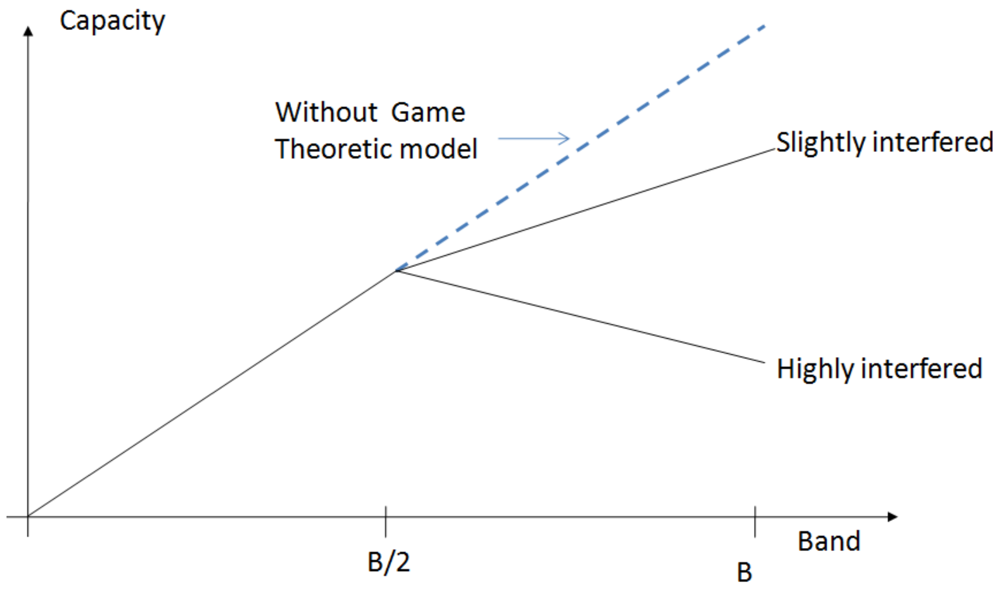


Figura 4.4: Considerando predições de teoria dos jogos, pode-se demonstrar que em situações com alta interferência uma seleção de uma maior largura de banda pode conduzir, de fato, a uma menor capacidade. Na primeira parte da banda os três gráficos coincidem. Na segunda parte, a linha tracejada mostra a capacidade que seria alcançada sem as considerações de teoria dos jogos. As linhas contínuas exemplificam casos em que a interferência é elevada ou baixa e os aspectos de teoria dos jogos são levados em consideração.

O modelo mostrado anteriormente tem uma série de restrições para aplicações práticas:

- Há incertezas em relação ao número de jogadores relevantes, bem como tráfego em cada um deles.
- Não leva em consideração a seletividade na freqüência nem alocação de potência no domínio da freqüência.
- O número de blocos é, na verdade, discreto.

Apesar dessas limitações, o importante desse modelo é entender que existe uma banda máxima a ser selecionada para se maximizar a capacidade em um jogo de compartilhamento de espectro. O reúso ideal irá depender da posição das HASs e do tráfego. Como uma aplicação mais prática do conceito mostrado pelo exemplo, foi definido um algoritmo para tentar estimar a utilidade de uma alocação de SPRBs.

O algoritmo é parametrizado para que possa ser ajustado ao reúso ideal de cada cenário. Há 2 parâmetros neste algoritmo. N_f é o número de SPRBs considerado ideal para cada jogador quando em plena carga e deve ser ajustado para cada cenário. I_{thr} é um limite usado para determinar se um bloco é considerado como altamente interferido. O sentido exato deste é que, se o bloco é interferido acima deste ponto de salvaguarda, acredita-se que uma transmissão neste bloco causará uma reação de outros jogadores que já que transmitem nesse bloco. Este é o algoritmo definido:

1. Conte o número de SPRBs na alocação, N_a, e o número total de blocos correspondentes a todos os recursos de espectro, N_T.
2. Para cada SPRB da alocação, calcule uma estimativa da capacidade. Atribua a soma de todas as capacidades estimadas à utilidade U.
3. Conte N_i, o número de blocos interferidos, isto é, o número de SPRBs nos quais $I > Ithr$.
4. Se $N_i + N_a > N_T$ e $N_a > N_f$, então aplicar uma penalidade a esta alocação através da atribuição $U = U/(1 + N_i)$.

Neste algoritmo, a adição de mais uma SPRB irá sempre aumentar a utilidade se o último SPRB adicionado não estiver bastante interferido. Quanto mais blocos estiverem interferidos, então maior será a penalidade, até o ponto em que a adição de um SPRB irá diminuir a utilidade. Quanto mais interferência um jogador gerar para os outros jogadores, mais agressivos serão seus oponentes em suas reações. Por essa razão, a penalidade é aumentada quando mais blocos interferidos são selecionados.

4.5 ESTRATÉGIAS

Finalmente, é apresentado o último parâmetro de projeto do protocolo GDSA: são escolhidas aqui as estratégias disponíveis em cada conjunto de informação.

Assume-se que as estratégias aqui definidas serão seguidas por todas as HASs. Estas estratégias são definidas através de algoritmos:

4.5.1 Fase de barganha

1. Selecione, um a um, o SPRB com o menor nível de interferência até que o tráfego desejado seja satisfeito.
2. Cada vez que for selecionado mais um SPRB, redistribua a potência disponível entre os SPRBs, isto é, atribua as potências máximas por SPRB (como exemplificado na Figura 3.2).
3. Cada vez que um SPRB for adicionado, recalcular a função utilidade. Se, ao adicionar um novo SPRB a utilidade for reduzida, deve-se parar com a seleção de SPRBs e utilizar os SPRBs selecionados exceto o último. A seleção deve parar mesmo quando os requisitos de tráfego não forem cumpridos (uma vez que novas adições de SPRBs irão apenas reduzir a taxa agregada).

4.5.2 Fase de resposta

1. Iniciar um temporizador de *backoff* proporcional à taxa de transmissão agregada atual (média móvel temporal ao longo de vários quadros).
2. Quando o temporizador expirar:
    - Se desistir do SPRB com maior nível de interferência aumentar a função utilidade estimada então este SPRB deve ser renunciado e a potência de transmissão deve ser redistribuída entre os SPRBs remanescentes. Deve-se então retornar à primeira etapa (reiniciando o temporizador)
    - Caso contrário, se a desistência do pior SPRB diminui a utilidade estimada, a HAS deve parar o processo e não modificar mais sua alocação até o próximo SpS-Frame.

O temporizador de *backoff* se destina a lidar com a situação em que há já existe mais de uma HAS compartilhando o mesmo SPRB. As HASs que possuem mais recursos irão abrir mão destes recursos primeiros e por isto, talvez, as outras HASs talvez não tenham que abrir mão de seus já escassos recursos por causa do novo entrante.

Este é um conceito dual em relação ao algoritmo de contenção no Carrier Sense Multiple Access with collision Avoidance (CSMA / CA). No CSMA / CA o temporizador de *backoff* é utilizado para decidir quando se irá tentar fazer um novo acesso ao espectro. Aqui o temporizador é utilizado para decidir quando deve se parar de utilizar o recurso de rádio. Isto é bastante semelhante à situação de jogos dinâmicos de temporização, tais como a versão dinâmica do jogo conhecido como chicken [9].

Na negociação, em vez de simplesmente selecionar os SPRBs segundo o ranking do nível de interferência, um elemento heurístico é adicionado: a seleção de SPRBs da lista ordenada é feita aleatoriamente, um a um, com uma probabilidade proporcional ao nível interferência. Isto pode conduzir a seleção de alguns SPRBs que são instantaneamente ruins, mas que podem se tornar bons por causa da desistência dos oponentes. Adicionar aleatoriedade em processos de seleção é comum em abordagens heurísticas. Em [11], um mecanismo semelhante ao descrito aqui é usado para selecionar quais serão os pais de uma nova cria em um algoritmo genético.

A variação máxima de potência na fase de resposta deve ser limitada através de uma política conhecida por todos os jogadores. O aumento do potência serve para advertir o novo entrante que este é um SPRB que será priorizado para utilização pela HAS fornecendo resposta. Porém, aumentos de potência irão influenciar também outros jogadores e, portanto, este aumento deve ser limitado.

4.5.3 Fase de ajuste

Na fase de ajuste o comportamento é bastante similar a fase de resposta, exceto pelo fato de que não há um temporizador de *backoff* e de que não se pode adicionar mais potência nos SPRBs remanescentes.

Para evitar aumentos desnecessários de potência sem quaisquer modificações de alocação, as HASs que aumentarem sua potência durante a fase de resposta, devem observar o comportamento do novo entrante na fase de ajuste. Caso o novo entrante desista de um SPRB, a potência neste SPRB deve ser reduzida para o nível anterior à entrada do novo jogador.

4.5.4 Estratégias para o jogo repetido

Como o jogo tem a mesma estrutura, seja no estado normal de jogo repetido ou no estado de novo entrante, é natural que as estratégias sejam bastante parecidas. De fato, há apenas algumas pequenas modificações. A seguir são enumerados os aspectos de estratégia que são diferentes no estado de jogo repetido em relação ao estado de novo entrante:

- No estado de novo entrante uma HAS pode em princípio alocar todo o espectro de uma só vez. Para melhorar a convergência e tornar as interações com RRM mais lentas, o número de SPRBs que pode ser alocado em cada iteração do jogo repetido é limitado e deve ser parte de uma política conhecida por todos os jogadores.

- No estado de novo entrante, apenas uma HAS irá tentar aumentar sua alocação, enquanto as outras irão apenas reagir a isto. No estado de jogo repetido, qualquer HAS pode tentar alocar recursos novos. De fato, o jogo repetido pode ser encarado como diversas versões reduzidas do jogo de novo entrante funcionando paralelamente.

4.6 CONCLUSÃO

Neste capítulo foi proposto um algoritmo para compartilhamento de espectro intra-sistema no domínio da freqüência. O algoritmo, chamado de GDSA, é composto principalmente de elementos baseados em teoria dos jogos, mas contém também alguns elementos heurísticos.

Foram identificados três parâmetros de projeto que foram analisados e especificados para obter o desempenho desejável.

A estrutura de protocolo e os estados foram propostos para aliviar a falta de informação sobre requisitos de tráfego e medidas de canal feitas por outras HASs, uma restrição gerada porque não é desejada qualquer tipo de sinalização direta entre as redes.

A função utilidade foi baseada na estratégia *Tit-for-Tat*, bastante conhecida em jogos repetidos.

As estratégias disponíveis em cada conjunto de informação foram restringidas, para melhorar o funcionamento do algoritmo.

5 RESULTADOS E DISCUSSÃO

5.1 INTRODUÇÃO

Este capítulo mostra os resultados obtidos para o GDSA em comparação com alocações fixas de espectro, o que mostra a potencialidade e a flexibilidade da utilização do algoritmo proposto. Os resultados tornam mais claras, também, o funcionamento interno das funcionalidades do protocolo apresentado no capítulo 4.

Este capítulo é organizado como se segue.

Na seção 5.2, o cenário de simulação é descrito, bem como algumas das hipóteses assumidas no ambiente de simulação. A seção 5.3 descreve os três casos de referência utilizados e porque é necessário mais de uma referência pra se comparar um algoritmo de alocação dinâmica de espectro com estratégias de alocação fixa do espectro.

Os resultados obtidos para se demonstrar a capacidade do protocolo GDSA no estado de novo entrante são mostrados na seção 5.4 e o estudo do estado de jogo repetido é feito na seção 5.5. Finalmente, a seção 5.6 mostra os resultados no estado de jogo repetido que são, em termos médios, bastante próximos da alocação ótima.

5.2 CENÁRIO DE SIMULAÇÃO

O desempenho do algoritmo proposto, GDSA, foi testada através de simulações sistêmicas. O cenário de simulação é mostrado na Figura 5.1 e é composto de quatro *Home Access Station*s (HAS). No caso de simulação cada HAS serve quatro *User Equipment*s (UE). As UEs tem capacidades de sensoriamento idealizadas, sendo capazes de determinar o nível de sinal, ruído e interferência em cada um dos blocos de recursos, isto é, em cada SPRB. As UEs também são capazes de informar esses valores de volta para a HAS que as serve, e o *overhead* para se realizar essa comunicação não é considerado nas simulações.

A capacidade é calculada diretamente pela fórmula Shannon para o caso de uma única antena em cada nó de comunicação. Isto é, apenas comunicação *Single Input Single Output* (SISO) é considerada.

O simulador utilizado distribui aleatoriamente as UEs e calcula as perdas de propagação de acordo com modelo adequado para o cenário de escritório mostrado na Figura 5.1. Não há modelo de mobilidade e portanto o simulador é estático. Em relação a tráfego a abordagem é semi-estática nas simulações de análise de desempenho do jogo repetido, como será explicado mais a frente.

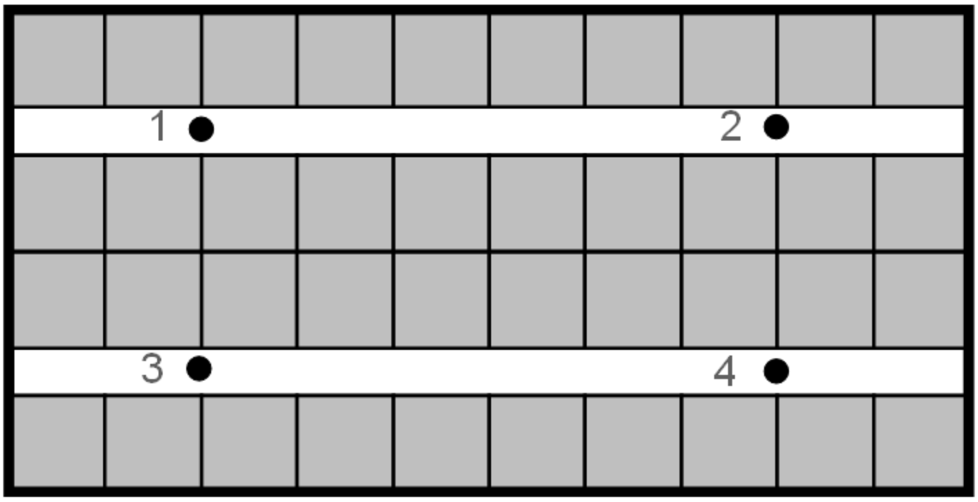


Figura 5.1: Cenário utilizado nas simulações. As HASs são numeradas de 1 a 4 e mostrada como pontos. As UEs são posicionadas aleatoriamente.

Em simulações sistêmicas, é comum se avaliar o desempenho com análise estatística em termos de capacidade média e da cauda distribuição. No caso de simulações estáticas o procedimento mais comum é realizar diversas execuções, cada uma correspondendo a uma potencial configuração instantânea da rede. No entanto, optou-se neste trabalho apresentar resultados correspondentes à uma única execução do simulador. O motivo é que se deseja demonstrar passo a passo o comportamento do algoritmo e, portanto, uma única execução deve ser acompanhada. A conseqüência, porém, é que para uma única execução não podem ser extraídas estatísticas suficientes para se estimar a cauda da distribuição do desempenho, uma vez que o número de UEs é bastante limitado (apenas 4 por HAS).

Dada essa limitação decidiu-se então analisar o desempenho através de duas figuras:

- Média da capacidade de Shannon das quatro UEs. Isto corresponde aproximadamente ao que acontece quando os usuários são agendados através de *round-robin*.
- Capacidade de Shannon da UE em pior condições (mais interferida). Isto corresponde ao que aconteceria caso as condições de tráfego fossem tais que apenas esta UE fosse escalonada, em todos os PRBs e em todos os frames.

Presume-se que cada uma das quatro HASs sejam de diferentes operadores e que não haja nenhum canal de comunicação definido para sinalização direta entre elas. A banda total disponível para as operadoras é uma banda contígua de 100 MHz com freqüência central de 3.5 GHz.

Apenas a comunicação das HASs para as UEs é considerada, ou seja, apenas o *downlink* é simulado. O modo é TDD, mas assume-se que todas as HASs são sincronizadas e têm o mesmo ponto de comutação de UL / DL. Por isto, não há interferência das transmissões de *uplink* nas transmissões de *downlink* e pode se simular o *downlink* separadamente. Os valores de capacidade mostrados correspondem à 100% do tempo alocado para o *downlink*.

O tráfego é *full-buffer*, ou seja, cada uma das comunicações de *downlink* possui um buffer infinito de pacotes pendentes para transmissão. Não foi utilizado controle de potência.

Como já foi mencionado, uma das principais características do algoritmo proposto que não foi ainda amplamente abordada na literatura é que o GDSA proporciona uma alocação inicial de espectro sob quaisquer condições.

Para testar esse aspecto,as HASs são ativadas uma a uma no cenário de simulação mostrado na Figura 5.1 . A ordem escolhida para o teste foi ativar a HAS 1 primeiro, seguido da HAS 4. A terceira HAS a ser ativada foi a HAS 2 e finalmente a HAS 3 é ativada. Esta ordem foi escolhida porque, ao ser ativada, a HAS 2 irá encontrar dois interferidores fortes já ativos. Isto cria uma maior dificuldade para o algoritmo encontrar uma alocação inicial, pois duas HASs terão que desistir de recursos para dar espaço ao novo entrante.

Cada vez que uma HAS é ativada o protocolo entra no estado de novo entrante. Isso fará com que seleção inicial de espectro seja realizada sequencialmente, o que irá produzir uma resposta diferente do caso da escolha do espectro ser simultânea.

A fim de verificar o comportamento quando o jogo é repetido diversas vezes, um modelo bem simples para variação do tráfego foi empregado na seção 5.5 A idéia básica do modelo aplicado é manter todas as HASs ativas durante um longo período, com demanda de tráfego variável, porém sempre elevado. A aplicação desse modelo de tráfego padrão é apresentada com mais detalhes seção 5.5.

5.3 CASOS DE REFERÊNCIA

Deseja-se mostrar com este trabalho que a alocação dinâmica de espectro é possível e benéfica mesmo se realizada com sinalização bastante limitada. Alocações fixas de espectro podem ser ótimas diante de um determinado cenário. Por exemplo, o reúso completo (reúso 1 de todos recursos de espectro) é o tipo de alocação ótima quando há pouca interferência, mas é uma estratégia ruim quando existe bastante interferência. Alocações de espectro ortogonais, por sua vez, são ótimas quando há bastante interferência mas são estratégias que não exploram completamente o canal quando há pouco tráfego (pouca interferência).

O verdadeiro potencial do compartilhamento dinâmico do espectro vem da possível adaptação à toda e qualquer situação de tráfego /interferência. Por este motivo, optou-se por comparar o GDSA com diversas estratégias de alocação de espectro fixa que representam alguns casos extremos.

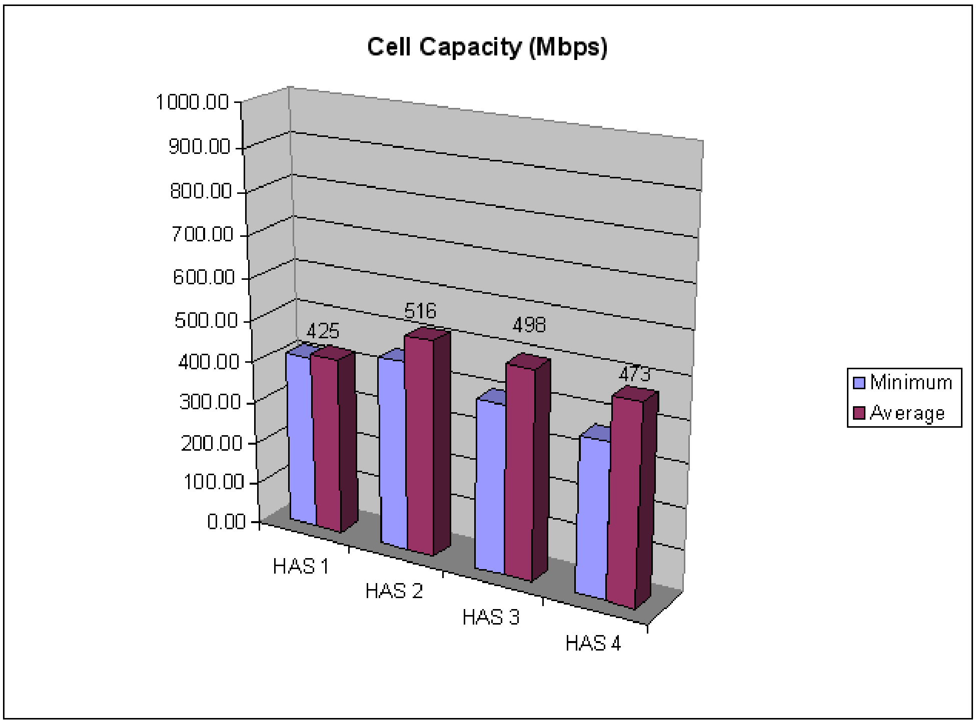


Figura 5.2: Capacidade média e mínima por célula para o reúso 4, quando todas as células estão ativas em plena carga.

5.3.1 Recursos Reservados de Espectro

A maneira tradicional de operação dos sistemas de comunicação é que cada sistema utilize sua própria banda de espectro alocada de maneira fixa pelo órgão regulador. Existem fatores políticos e econômicos para se manter esse tipo de abordagem. Por exemplo, as operadoras desejam realizar lucros sobre o licenciamento de espectro já realizado no passado. Portanto, o argumento técnico precisa ser bastante convincente para que as operadoras comecem a seguir na direção de compartilhamento dinâmico do espectro.

Ter um recurso reservado é também a maneira mais segura de operação em um ambiente competitivo. Cada operadora pode otimizar seu próprio espectro de maneira independente e sabe por força da lei que não haverá interferência de seus concorrentes no seu próprio espectro.

No cenário estudado, a reserva de recursos de espectro corresponde ao reúso 4, já que são 4 HASs, cada uma de uma operadora diferente. Quando todas as 4 HASs estão a plena carga, esta alocação é razoavelmente eficiente já que neste cenário ela provê comunicação livre de interferência. Como o cenário é limitado pelo ruído, a posição das UEs não tem grande influência sobre a capacidade de Shannon e, por isto a capacidade mínima é bem próxima da capacidade média. Esses resultados são mostrados na Figura 5.2

5.3.2 reúso Pleno

A maneira mais simples de se permitir utilização plena dos recursos sob pouca interferência é que todas as células tenham pleno acesso ao espectro o tempo todo. Esta abordagem é interessante principalmente em células isoladas, pois as taxas de dados de pico da tecnologia podem ser então alcançadas. Porém esta abordagem se torna problemática quando um número grande de células próximas.

A Figura 5.3 mostras as capacidades do reúso 1 com plena carga. Comparando-se o reúso 1 com o reúso 4, neste cenário, o reúso 1 atinge taxas médias maiores que o reúso 4 (Figura 5.2). Porém, a capacidade mínima provida pelo reúso 1 é bastante ruim comparada ao reúso 4. O motivo é que as UEs que estão em posições desfavoráveis irão sofre bastante interferência em todos os recursos de rádio. Assim é difícil manter a qualidade de serviço mínima para estas UEs, bem como manter a equidade na distribuição dos recursos quando o reúso 1 é utilizado.

Os resultados mostrados na Figura 5.3 justifica o temor das operadoras em relação ao uso de um conjunto comum de recursos de espectro. Sem maiores intervenções, o desempenho fica dependente do acaso (escolha pelo usuário das posições das UEs e HASs) e pode haver grandes perdas em relação a situação atual.

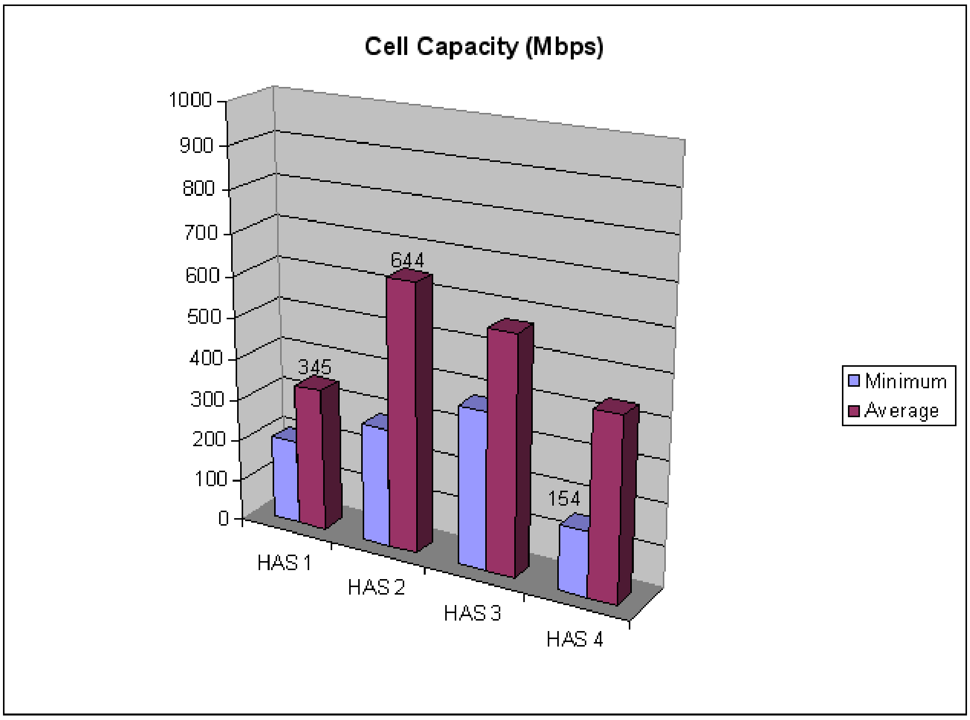


Figura 5.3: Capacidade média e mínima por célula para o reúso 1, quando todas as células estão ativas em plena carga.

5.3.3 Planejamento e Otimização de Rede

O melhor desempenho em ambiente macro-celular é alcançada através de planejamento e otimização de rede, técnicas que envolvem trabalho humano. A aplicação destas técnicas para ambientes internos seria bastante custosa se feita massivamente. Portanto, elas dificilmente serão aplicadas em cenários residenciais e também desejavelmente não serão aplicadas a ambientes empresariais.

No cenário de estudo proposto há um agravante: O espectro deve ser compartilhado de maneira ótima entre as 4 operadoras. Em um caso real isto envolveria coordenação entre planejadores das diversas operadoras, o que poderia levar ao vazamento de informações críticas, tais como a localização de usuários e tráfego gerado por eles.

Ainda assim, é interessante comparar o GDSA com a solução otimizada que poderia ser encontrada através de planejamento e otimização de rede. Neste caso foi feita a simulação extensiva de todas as possibilidades de alocação de espectro no cenário da Figura 5.1. Determinou-se através dessas simulações que a alocação ideal seria o reúso 2, aonde o espectro é reutilizado nas diagonais. Ou seja, a HAS 1 e 4 usarem 50% do espectro enquanto a HAS 2 e 3 utilizarem os outros 50%do espectro.

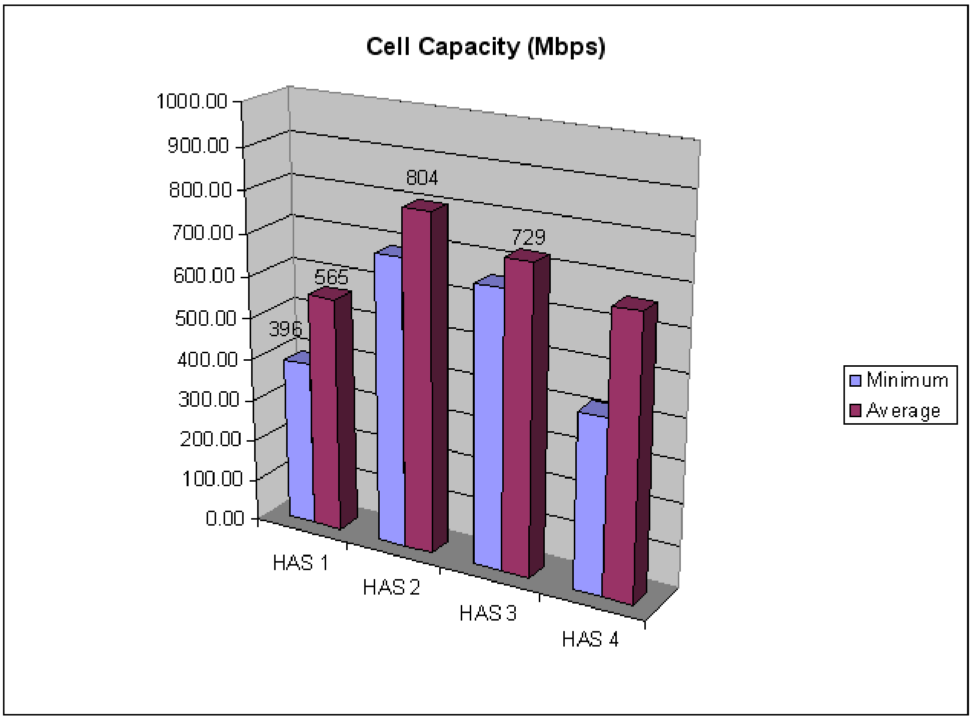


Figura 5.4: Capacidades ótimas quando todas as HASs estão ativas e em plena carga. Este reúso ótimo foi encontrado através de simulações extensivas.

Deve ser lembrando também que o planejamento de rede visa alguma situação específica de tráfego, geralmente o horário de maior movimento. Apesar de essa abordagem considerar o pior caso possível de interferência, não permite a plena adaptação as variações de tráfego existentes na realidade. Em redes celulares, algumas funções de RRM tratam das variações de tráfego, tais como controle de admissão e escalonamento. No entanto, no tipo de ambiente considerado, aonde não é possível a sinalização entre as células, esse tipo de função também não pode ser diretamente implementada de maneira distribuída.

Em princípio, seria possível implementar algoritmos de compartilhamento de espectro que encontrassem a alocação ótima de espectro em qualquer situação. No entanto, este tipo de otimização geralmente envolve centralização das decisões e sinalização pesada. Como salientado no capítulo 1algumas das propostas mais relevantes da literatura todas envolvem sinalização. O objetivo do GDSA é a aproximar a alocação ótima o máximo possível de maneira distribuída e sem a necessidade de sinalização entre as HASs.

5.4 NOVO ENTRANTE

Nas simulações desta seção, a banda de 100 MHz está dividida em 6 SPRBs para facilitar o entendimento da seqüência de decisões. Para o jogo repetido foram utilizados 10 SPRBs na banda de 100 MHz.

Mostra-se, nesta seção, como a utilização destes 6 SPRBs evolui ao longo do tempo por causa da ativação de novas HASs e como isso afeta as capacidades em cada 5.1 célula. É importante compreender a geometria do cenário (Figura 5.1) para analisar os resultados. Por causa da geometria e, portanto, das perdas de propagação, o sinal de interferência gerado pela HAS 1 tende a chegar mais fracamente nas UEs servidas pela HAS 4 do que nas UEs servidas pela HAS 2 ou 3. A relação exata depende da distribuição espacial das UEs, mas na média, a interferência gerada pela HAS 1 para as UEs servidas pela HAS 4 será pequena em comparação com as que são geradas pelas HAS 2 e 3.

Portanto, se a HAS 1 e HAS 4 decidem compartilhar o mesmo SPRB, haverá um pequeno impacto. Já se a HAS 1 optar por utilizar um SPRB que também será utilizado pela HAS 2 ou HAS 3, haverá um alto nível de interferência. De maneira geral, o impacto da utilização dos mesmos SPRBs em células adjacentes é bem maior do que o reúso em células que estão em diagonais opostas.

Os dois parâmetros para o algoritmo de cálculo da função utilidade descrito na seção 4.4 foram definidos da seguinte maneira.

- O número de blocos ideal para plena carga foi definido como metade da banda. Ou seja, o reúso alvo em plena carga é reúso 2. Uma vez que a banda está dividida em 6 SPRBs temos o parâmetro $Nf = 3$.
- O limiar de interferência I_{thr} usado para determinar se um bloco está sofrendo alta interferência, foi fixado em 25 dB acima do nível do ruído.

A primeira HAS a ser ativada, a HAS 1, e tem acesso pleno a todos os recursos de espectro. A capacidade alcançada é mostrada na Figura 5.5. Vale a pena lembrar que das abordagens de alocação de fixa de espectro, apenas o reúso 1 também irá prover o acesso completo ao espectro neste tipo de situação aonde há apenas uma célula isolada (apenas uma célula ativa).

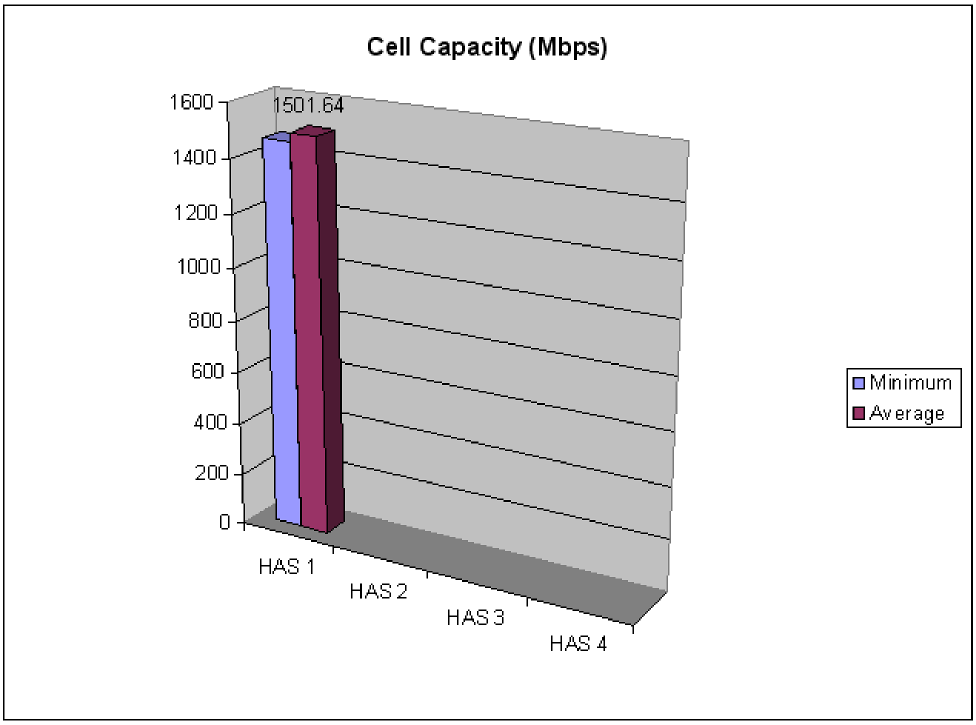


Figura 5.5: Capacidade da célula 1 quando é finalizado o processo de novo entrante.

A segunda HAS a ser ativada é a HAS 4. Uma vez que ela está na diagonal oposta a outra HAS ativa, o limiar de interferência I_{thr} não é alcançado em nenhum bloco e novamente o GDSA seleciona todos os blocos como a alocação inicial. A capacidade alcançada é apresentada na Figura 5.6. Embora se verifique uma diminuição substancial da capacidade de Shannon da HAS 1 após a ativação da HAS 4, a capacidade total é substancialmente aumentada devido ao reúso de espectro.

O próximo passo dessa simulação é o acionamento da HAS 2. Neste momento o cenário é realmente desafiador para que um algoritmo possa prover uma alocação inicial de espectro eficiente. O cenário de RF determinado através de sensoriamento feito na HAS 2 é o seguinte: Existem dois interferidores fortes e ambos estão utilizando completamente todos os recursos de espectro disponíveis. Em outras palavras, não existe qualquer lacuna no espectro. Ainda assim, o acesso ao espectro deve ser provido para a HAS 2 , uma vez que tem a mesma prioridade para acessar o espectro o que as outras HASs. Isso é bastante diferente do cenário geralmente considerado em rádio cognitivo [10].

Neste ponto é interessante mostrar os pormenores da evolução das decisões do algoritmo. A Figura 5.7 mostra como a alocação evolui. O novo entrante, a HAS 2, decide barganhar pelos SPRBs 1, 2 e 3. As duas HASs já existentes fornecem respostas, em diferentes instantes de

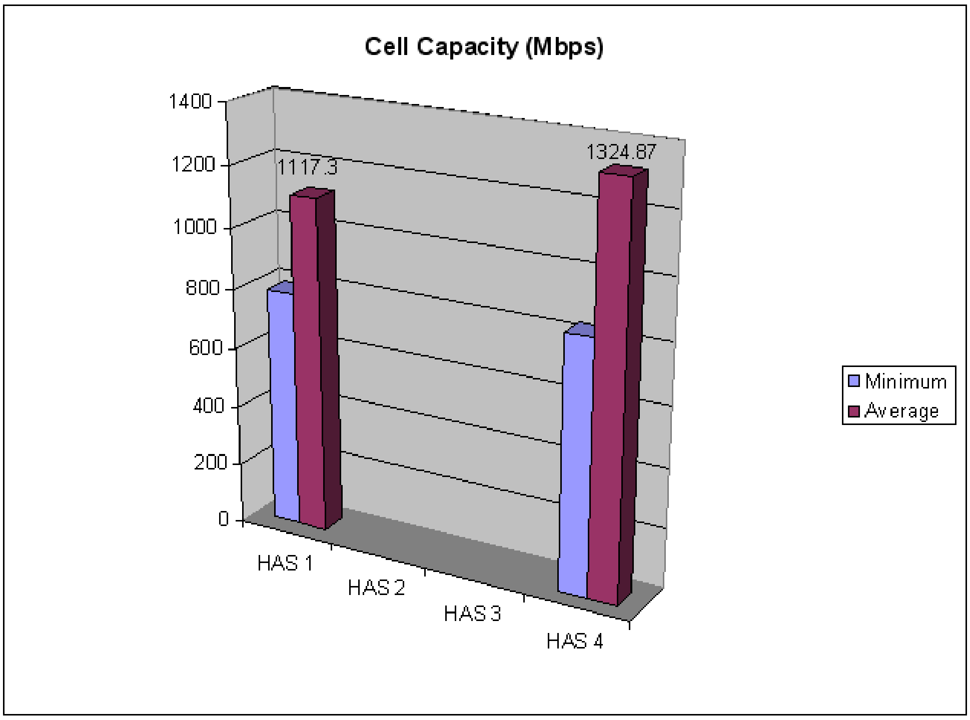


Figura 5.6: Capacidade média e mínima por célula depois que a segunda HAS (HAS 4) é ativada e finaliza o processo de novo entrante.

tempo, por causa do mecanismo de temporização descrito na seção 4.5. A primeira HAS a mover é a HAS 4 por possuir neste momento uma capacidade maior como mostrado na Figura 5.6. A HAS 4 desiste dos SPRBs 1 e 3. A HAS 1 por sua vez decide não utilizar mais os blocos 1 e 2. Essas desistências são suficientes para limpar bastante o espectro para a HAS 2. Note que a decisão da primeira HAS a mover pode ter influência na decisão da outro. Por esse motivo é importante a aplicação do temporizador.

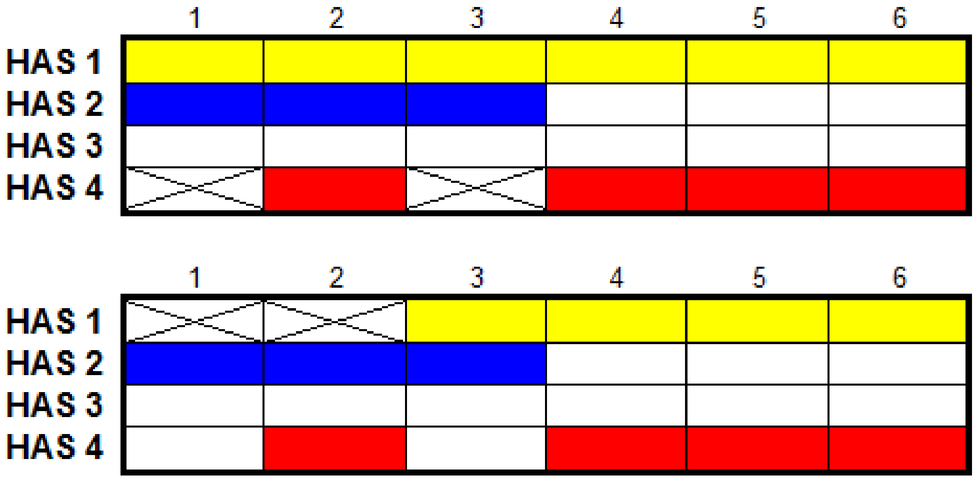
Na fase de ajuste, o novo entrante manterá a alocação dos 3 SPRBs. A capacidade de cada HAS após o processo ser finalizado é mostrada na Figura 5.8

A última tem de ser ativada, a HAS 3, simplesmente decide por alocar os mesmos SPRBs que a HAS 2, o que não causa nenhuma reconfiguração adicional, pois o espectro já foi limpo no passo anterior. Os resultados após a ativação de todas as 4 HASs são mostrados na Figura 5.9. Embora não haja equidade da distribuição dos recursos em termos médios, a capacidade mínima é bastante igualitária.

Os resultados mostrados até agora exemplificam o comportamento passo a passo do algoritmo quando as HASs são ativadas uma por vez. Os resultados a seguir comparam o GDSA com estratégias de alocação fixa de espectro utilizadas como referência.

Na Figura 5.10 são mostradas a média de capacidade das células, isto é, a média da capacidade de Shannon de todas as 16 UEs.

Quando apenas uma HAS está ativa o cenário limitado por ruído. Apenas o GDSA e o reúso



	1	2	3	4	5	6
HAS 1	🟨	🟨	🟨	🟨	🟨	🟨
HAS 2	🟦	🟦	🟦			
HAS 3						
HAS 4	☒	🟥	☒	🟥	🟥	🟥

	1	2	3	4	5	6
HAS 1	☒	☒	🟨	🟨	🟨	🟨
HAS 2	🟦	🟦	🟦			
HAS 3						
HAS 4		🟥		🟥	🟥	🟥

Figura 5.7: Seqüência de alocações de espectro quando a terceira HAS, HAS 2, entra em cena, causando grandes reconfigurações. Na fase de barganha, a HAS 2 aloca 3 SPRBs. A HAS 4 responde desistindo dos SPRBS 1 e 3 (figura ao topo). Na figura mais abaixo, é mostrado que a HAS 1 desiste dos SPRBs 1 e 2 levando à alocação de espectro final fornecida pelo estado de novo entrante do GDSA.

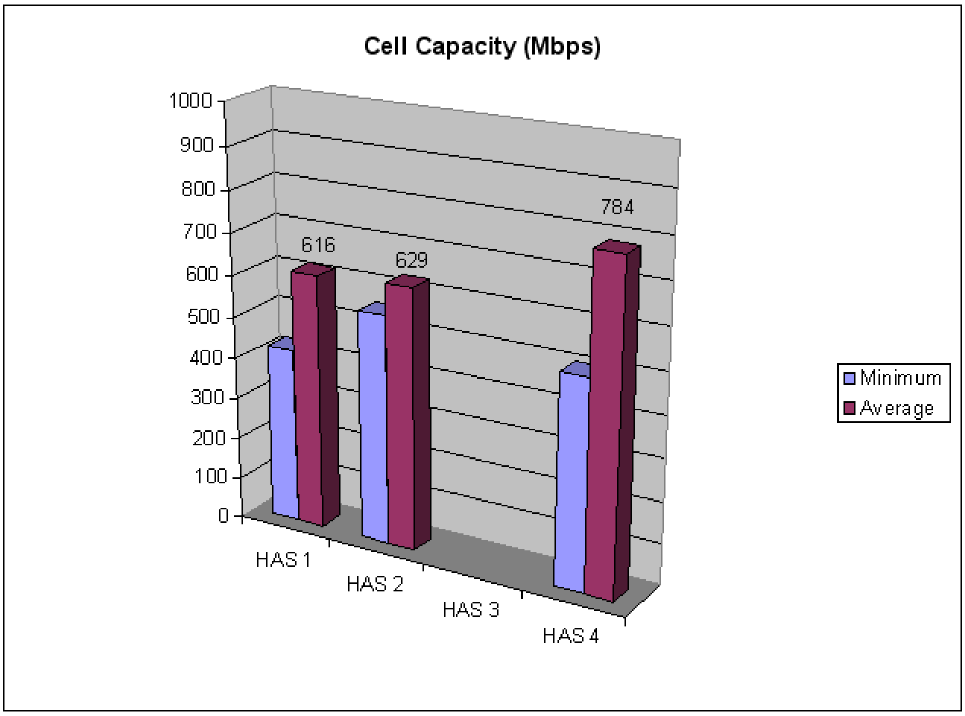


Figura 5.8: Capacidade média e mínima por célula depois que a terceira HAS (HAS 2) é ativada e finaliza o processo de novo entrante.

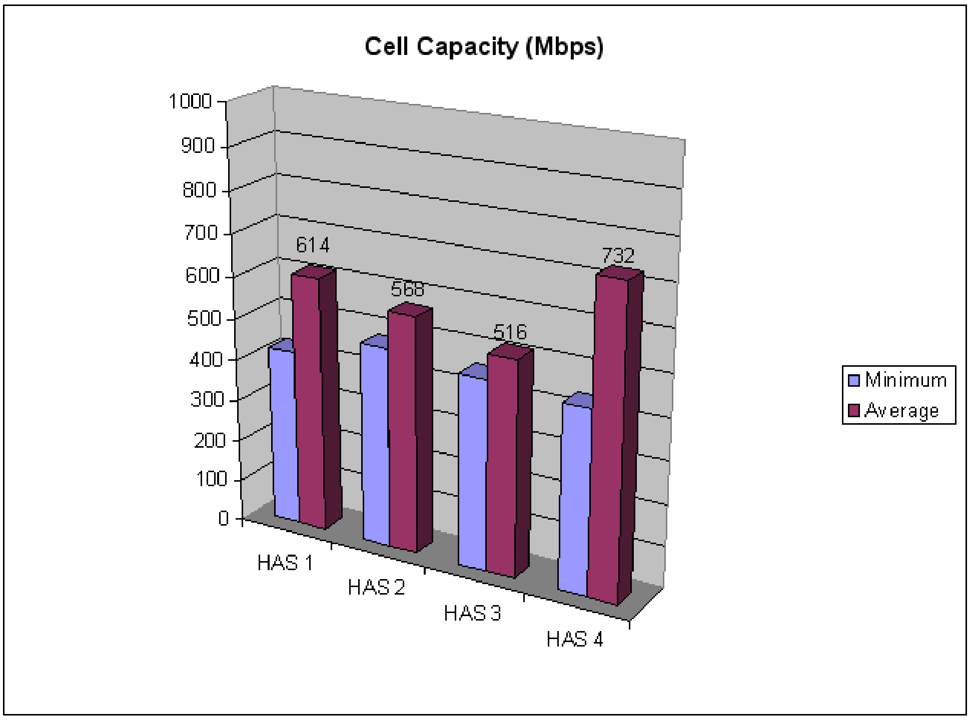


Figura 5.9: Capacidade média e mínima por célula depois que todas as células foram ativadas.

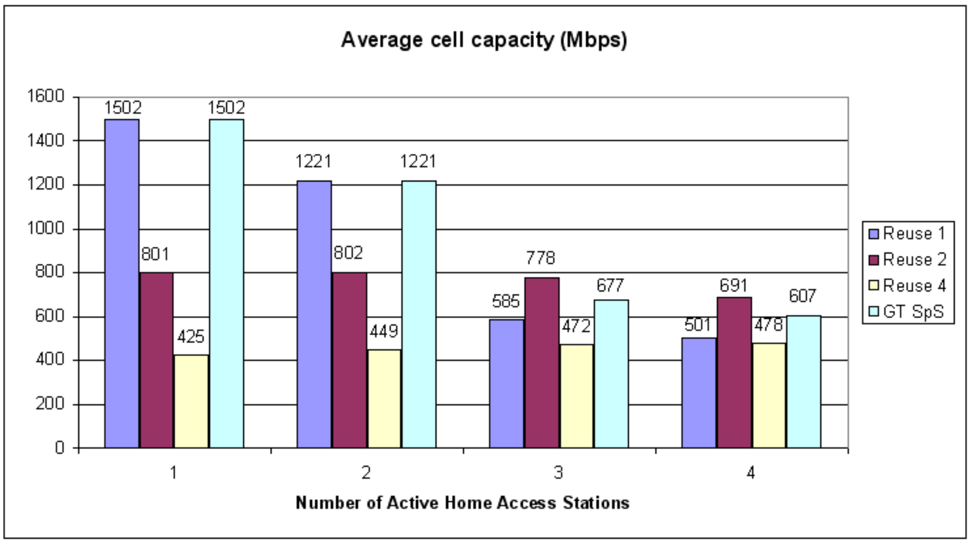


Figura 5.10: Comparação da capacidade média (média das 16 UEs) atingida nos quatro esquemas considerados, GDSA, reúso 1, reúso 2 e reúso 4.

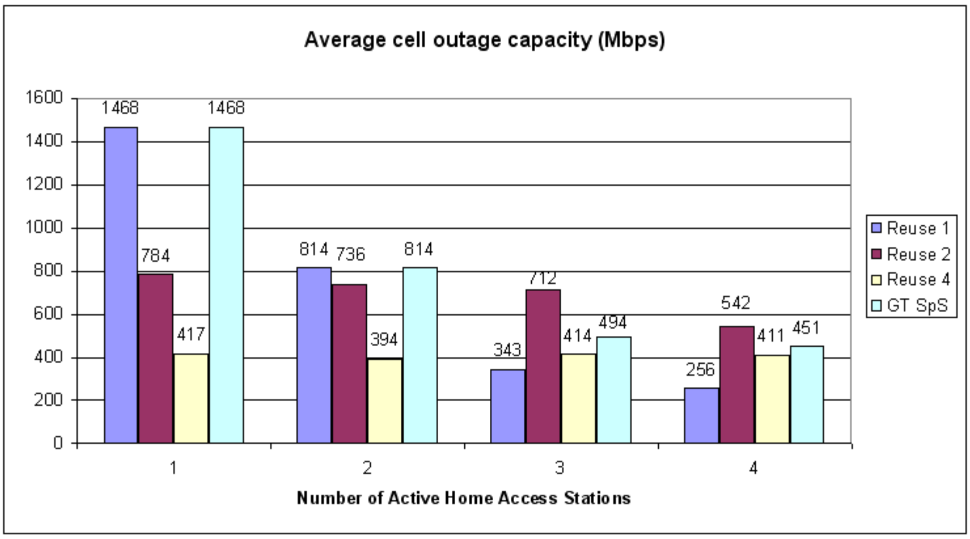


Figura 5.11: Comparação da capacidade mínima (média das 4 células) atingida nos quatro esquemas considerados, GDSA, reúso 1, reúso 2 e reúso 4.

1 fazem pleno uso do canal nesta situação, levando as maiores capacidades. O mesmo pode ser dito de quando há duas HASs ativas, em diagonais opostas. O cenário passa a ser limitado por interferência, mas esta é baixa suficiente para que ambos as HASs possam utilizar todos os recursos de espectro. Com acesso pleno ao espectro, estas abordagens permitem picos de taxa de dados muito mais altos quando em condições de canal favoráveis. Comparando a capacidade do GDSA a capacidade do reúso 4, que representa cada HAS com seu próprio espectro, o GDSA permite que uma capacidade de Shannon 3,75 vezes maior seja alcançada.

Vale ressaltar que, embora, o reúso 2 tenha sido determinado como a melhor abordagem para plena carga neste cenário, essa não é uma estratégia ótima quando há apenas uma ou duas HASs ativas. Isso mostra uma das maiores limitações de alocações fixas de espectro: elas só podem ser otimizadas para uma única condição (plena carga, neste caso). Ao contrário, o acesso dinâmico ao espectro permite a otimização para diversas condições e distribuições de tráfego.

Em seguida, é analisado o outro indicador de desempenho: a média, das 4 células, para a capacidade de Shannon mínima em cada uma das células. A Figura 5.11 mostra este indicador em função do número de células ativas para cada das 4 abordagens, isto é, GDSA e as três referências.

Ao se analisar conjuntamente a capacidade mínima e a capacidade média pode-se compreender que o reúso 1 e reúso 4 tem papéis opostos, mas complementares, neste cenário. Quando existe pouca ou nenhuma interferência o reúso 1 comporta-se bem permitindo o acesso completo ao espectro. Porém, o seu desempenho de capacidade mínima quando a carga está plena é inaceitável. Pode-se concluir que com o reúso 1 as taxas de pico desejadas são alcançadas, mas não é possível manter um mínimo de qualidade de serviço em condições ruins de interferência.

O reúso 4, que neste caso significa cada operadora com seu próprio espectro, é uma maneira bastante segura de se manter o mínimo de qualidade quando o tráfego é alto em todas as células.

Porém, a maior limitação aparece justamente nos cenários de pouca ou nenhuma interferência, aonde a taxa atingível é sensivelmente menor do que nos casos em que o espectro pode ser plenamente explorado.

O GDSA por sua vez, através da adaptação é capaz de juntar as melhores características dessas abordagens sendo melhor ou pelo menos igual a essas duas abordagens em todos os cenários mostrados nas Figuras 5.10 e 5.11.

O reúso 2 foi determinado através de simulação extensiva de todas as possíveis alocações como a alocação ótima quando todas as células estão com demanda de tráfego plena. Ainda assim, nos cenários de pouca ou nenhuma interferência o GDSA é capaz de atingir níveis mais altos de taxa. Apesar de o GDSA não atingir a mesma taxa do reúso 2 nos cenários com muita interferência, ele se aproxima mais desse reúso ótimo do que as outras estratégias.

Além disto, vale ressaltar que o GDSA determina a alocação sem qualquer tipo de overhead de sinalização entre as HASs ou necessidade de planejamento de freqüências. Sem considerar pelo menos uma destas possibilidades, dificilmente poderá se alcançar o reúso ótimo em qualquer cenário. O planejamento de freqüências é inviável em um cenário local porque o posicionamento das HASs é aleatório, escolhido pelo usuário. Mesmo nos casos em que a posição possa ser fixada e o planejamento realizado, como um escritório, é indesejável fazê-lo por causa do alto custo de realizá-lo em grandes escalas (talvez no futuro serão centenas de milhares de HASs em uma grande cidade.) Em princípio seria possível definir algoritmos inteligentes de alocação que consigam atingir a alocação ótima e, portanto, taxas brutas maiores que o GDSA. Porém, há de ser considerado que isso envolveria maior complexidade de protocolo e que o overhead deve ser determinado para que se possa averiguar se a taxa líquida seria realmente maior ou menor que o GDSA.

5.5 JOGO REPETIDO

Uma das principais motivações de que o jogo seja repetindo é que com a repetição possa se aumentar ainda mais a eficiência e a equidade da divisão dos recursos de espectro.

Outra motivação chave é, talvez, mais importante. O jogo será repetido para acompanhar as mudanças nas condições de carga, canal e decisões de RRM. Uma análise detalhada deste segundo aspecto seria mais bem avaliado em um simulador sistêmico dinâmico, onde processos dinâmicos como a mobilidade, tráfego e desvanecimento são detalhadamente considerados.

Uma vez que fui utilizado neste trabalho um simulador estático, decidiu-se verificar o potencial de longo prazo do GDSA através de um modelo semi-estático de variação de tráfego bastante simples. Neste modelo a carga fracional, isto é, o percentual de banda requisitado por cada célula, é variado lentamente e com isto pode se testar a capacidade GDSA de seguir os requisitos de tráfego.

O modelo é o seguinte: foram definidos passos de simulação que são realizados para uma mesma execução do simulador. A cada 8 passos, há uma chance de que alguma HAS não necessite mais de um SPRB e irá simplesmente encerrar a transmissão neste SPRB. De modo similar, a cada 5 passos uma HAS é selecionada para tentar adicionar mais SPRBs. Isto não significa que ela necessariamente conseguirá incrementar a alocação. Ela deve seguir a estrutura do protocolo e as estratégias definidas para o estado de jogo repetido. O exato padrão que foi aplicada nas simulações a seguir é mostrado na figura 5.12.

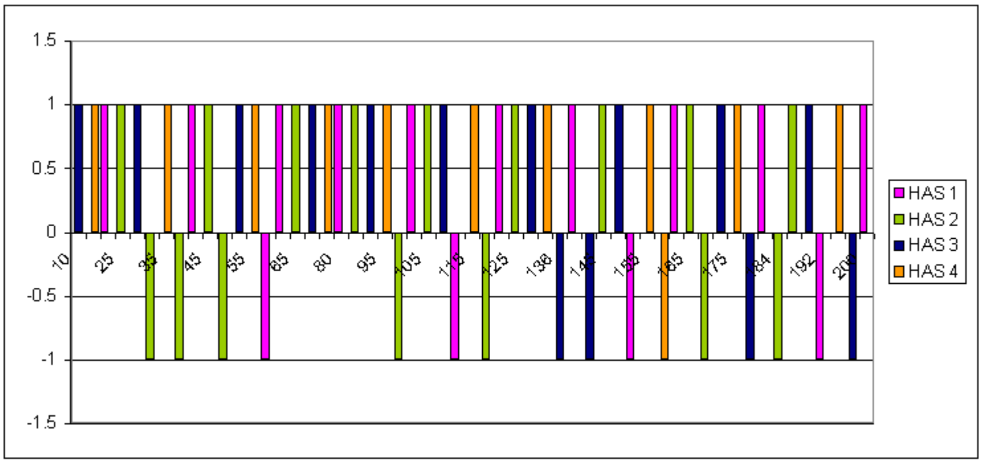


Figura 5.12: Modelo simples para criar variação na carga fracional de SPRBs. No eixo x é mostrado o passo de simulação. Escolhe-se aleatoriamente HASs para tentar alocar mais SPRBs (representados por +1 no eixo y) ou para desistir espontaneamente um SPRB (representado por -1 no eixo y).

Primeiramente é considerado o caso em que não há restrição alguma as alocações no estado de jogo repetido. Isto é, em princípio, quando uma HAS deseja aumentar o número de SPRBs alocados, poderá pleitear por todos os SPRBs de uma só vez. Este caso é mostrado na figura 5.13. Ao se comparar a Figura 5.12 e a Figura 5.13 percebe-se que não há mudança nas alocações até que alguma HAS pare de utilizar o espectro. Na Figura 5.13 percebe-se, entre os passos 100 a 150, que há bastante variação nas alocações de espectro e que o algoritmo tem problemas de convergência caso sempre possa se realocar o espectro completamente. Após essa região sem convergência, o algoritmo adquire uma nova configuração estável.

No entanto se for aplicada a política que restringe o número de blocos a ser realocado por SpS-Frame a convergência é bem mais rápida. Na figura 5.14 é mostrado o caso em que somente é possível alocar um SPRB por SpS-Frame. Verifica-se, neste caso, um comportamento muito melhor de convergência. Mas não é apenas isto. Ao se comparar o estado estável atingido no passo 200, percebe-se que a alocação menos atribulada gerada por esta política leva a uma melhor eficiência. Isto é mostrado na figura 5.15 aonde se compara o estado alcançado no passo 200 no caso de se aplicar a política ou não.

Na figura 5.14 não há uma clara tendência se, à longo prazo, o GDSA irá beneficiar mais um

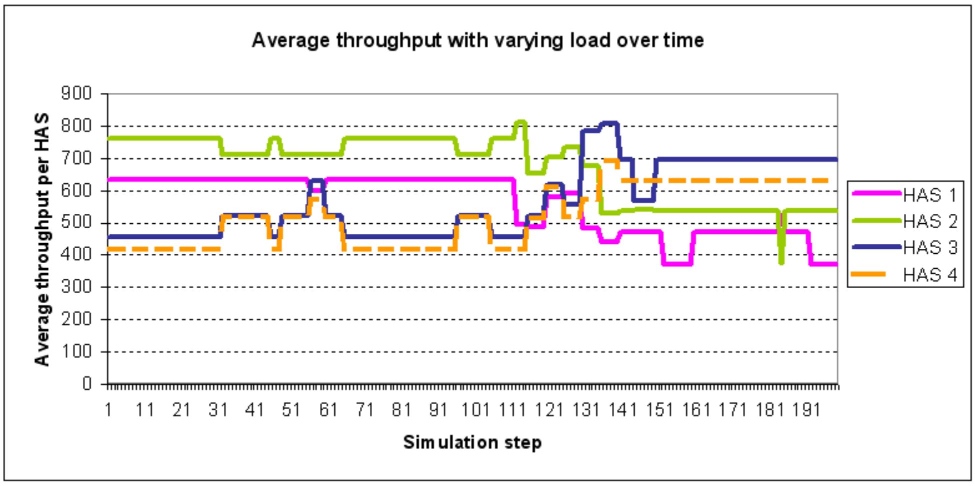


Figura 5.13: Evolução da capacidade média no caso de não haver nenhuma restrição limitando o número de SPRBs que podem ser adicionados a cada SpS-Frame.

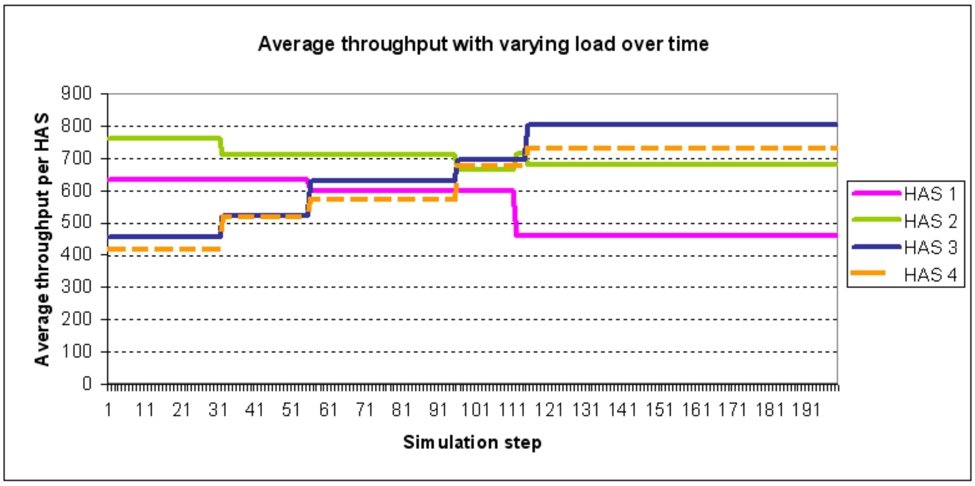


Figura 5.14: Evolução da capacidade média no caso de ser aplicada uma política limitando a um único SPRB o número de SPRBs que podem ser adicionados a cada SpS-Frame.

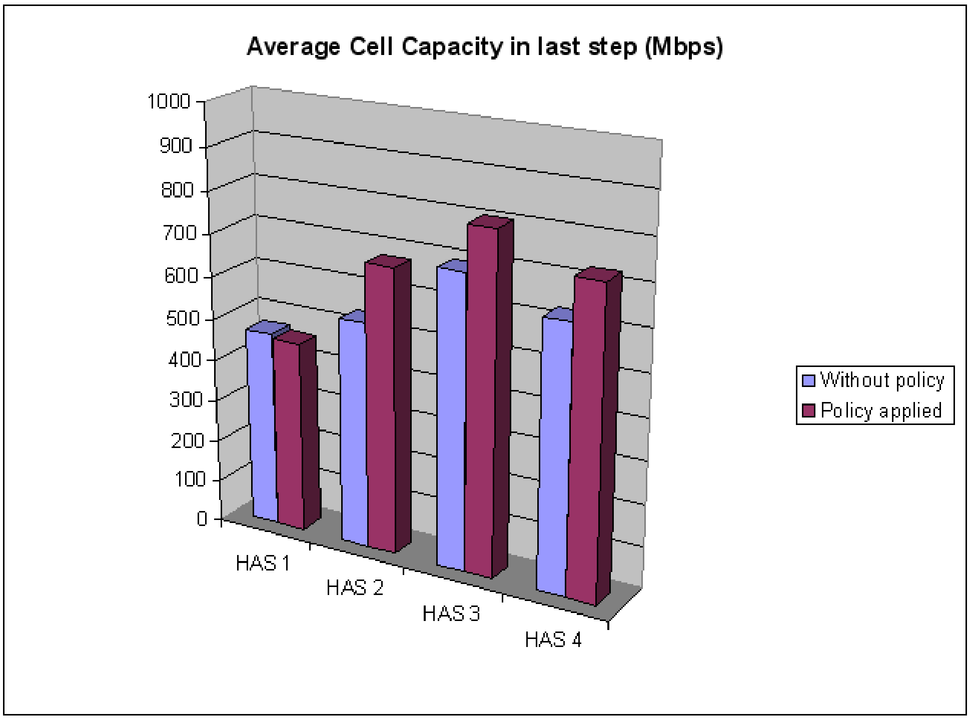


Figura 5.15: Comparação da capacidade média atingida no estado estável do passo 200, para os 2 casos: de aplicação ou não da política que restringe as alocações.

jogador do que outro nem que manterá a eficiência. Em outras palavras, não é claro se haverá equidade nos recursos e distribuição eficiente dos mesmos.

Para avaliar o comportamento de longo prazo do GDSA foram simulados 2000 passos e a média da capacidade de Shannon de cada célula foi avaliada ao longo dos 2000 passos. O resultado é mostrado na Figura 5.16, onde o GDSA é comparado com o resultado ótimo para plena carga. É importante entender que nesta comparação, a carga no reúso 2 é fixa, enquanto que no GDSA o tráfego foi variado espacialmente. Conclui-se através desta comparação que o GDSA é capaz de aproximar o comportamento ótimo na média.

5.6 CONCLUSÃO

Neste capítulo foi a avaliado o desempenho do Game-based Distributed Spectrum Allocation (GDSA), um *framework* para compartilhamento dinâmico de espectro entre redes que foi proposto no Capítulo 4. O GDSA foi avaliado através de simulações sistêmicas em um cenário de escritório. Neste cenário, o GDSA foi capaz de superar as estratégias mais simples de alocação fixa de espectro em todos os aspectos. O algoritmo proposto se mostrou capaz de prover auto-organização distribuída da alocação do espectro, sendo, portanto, bastante favorável para implementação no acesso local, onde se deseja evitar o planejamento das posições dos equipamentos.

O GDSA foi também capaz de seguir as variações de tráfego, acomodando distribuições espaciais assimétricas de tráfego e, ainda assim, aproximar a eficiência do reúso ótimo para carga plena.

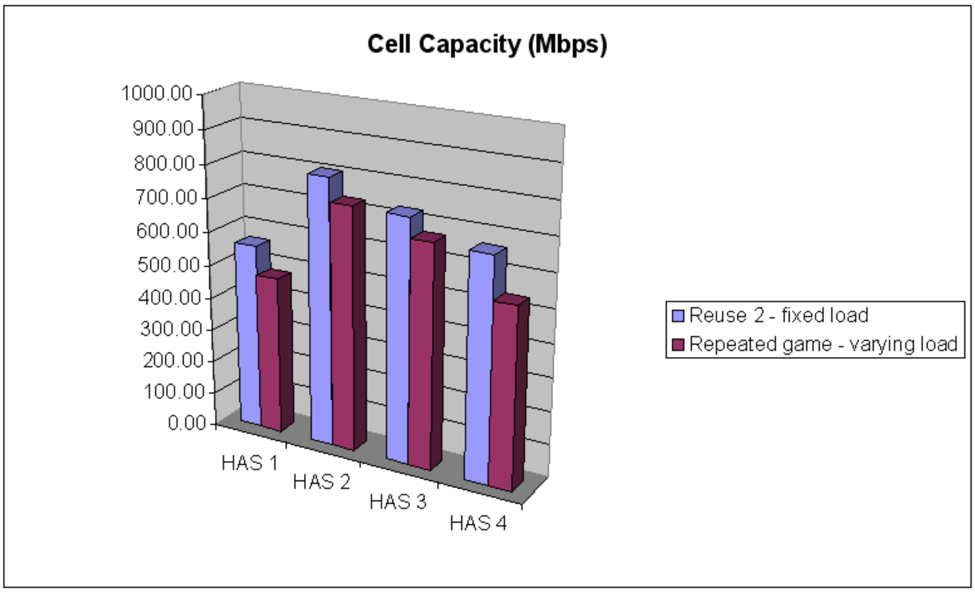


Figura 5.16: Comparação do GDSA, onde é aplicado um padrão de tráfego variável, com o reúso ótimo para carga plena, onde a carga é máxima e fixa. Percebe-se que o GDSA aproxima o comportamento ótimo no longo prazo.

6 CONCLUSÕES E TRABALHOS FUTUROS

6.1 CONCLUSÕES

Neste trabalho, foi proposta uma nova abordagem para o compartilhamento de espectro dinâmico entre diversas redes de uma mesma tecnologia de rádio. O algoritmo proposto traz inovações em relação aos algoritmos encontrados na literatura. As principais contribuições do algoritmo proposto, batizado de Game-Based Distributed Spectrum Allocation(GDSA), são as seguintes:

- Não há necessidade de sinalização direta. O protocolo funciona apenas com a informação disponível através de sensoriamento.
- A estrutura de protocolo proposta alivia a falta de informação, sobre requisitos de tráfego e medidas de canal, na tomada de decisões.
- A função utilidade proposta acelera a convergência para soluções eficientes.
- GDSA é capaz de fornecer alocações iniciais eficientes mesmo quando o espectro já estiver em plena utilização.
- O GDSA se adapta a diferentes cenários e distribuições espaciais de tráfego, permitindo auto-organização, em termos de alocação de espectro.

Em particular, podem ser feitas mais algumas observações no cenário estudado:

- O GDSA permite alcançar o maior pico de taxa de dados, ou seja, o pleno acesso a todos os recursos de rádio é permitido quando isto é viável.
- No caso estudado, o GDSA supera as estratégias mais simples de alocação fixa de espectro em todos os aspectos.
- Em termos de eficácia de longo prazo, o GDSA aproxima-se da eficiência do reúso otimizado para plena carga. Como vantagem em relação ao reúso otimizado, mas fixo, o GDSA consegue redistribuir a capacidade espacialmente de acordo com as variações de tráfego.

6.2 TRABALHOS FUTUROS

O compartilhamento dinâmico de espectro é ainda uma área bastante nova de pesquisa. Existem, portanto, diversas possibilidade de extensão deste trabalho:

1. **Solução compatível com o release 8 do LTE**: Apesar de as características principais do LTE-A terem sido consideradas no desenvolvimento do GDSA, foi considerado ao longo do trabalho que esta seria uma solução disruptiva em relação ao LTE release 8. No entanto, soluções compatíveis com tecnologias anteriores são sempre preferíveis, por causa dos equipamentos legados em funcionamento. Em princípio, o GDSA pode ser adaptado para ser compatível com terminais release 8. Para tanto, as estruturas de canais de controle comuns e dedicados deve ser cuidadosamente considerada.

2. **Sistema de votação para a definição do ponto de mudança UL/DL**: Para manter a ortogonalidade, todas as redes devem ter o mesmo ponto de mudança de UL/DL. Como é importante ter um único ponto de mudança e trocá-lo é uma operação que exige bastante sinalização por cada uma das redes, então também é bem importante a definição de um protocolo distribuído para determinação de qual deve ser este ponto.

3. **Otimização do compartilhamento de espectro em outros domínios**: Como descrito no ApêndiceIV.3 há diversas considerações a serem feitas para otimizar o compartilhamento de espectro em outros domínios, como espaço e potência.

4. **Extensão da solução para o TDD sem sincronismo entre redes**: Se os requisitos de sincronização, que são bastante restritivos, não forem alcançados, será importante a extensão da solução para redes TDD sem o sincronismo entre as redes. Como explicado no Apêndice III.5.2 o problema se torna mais complexo por haver interferência entre *uplink* e *downlink* e a distribuição espaço-temporal da interferência terá de ser considerada.

5. **H-ARQ específico para a fase de novo entrante**: Mesmo utilizando-se um padrão tempo-frequencial esparso, um novo entrante pode potencialmente causar bastante problema às conexões previamente existentes. A definição de estratégias de H-ARQ específicas para essa fase de novo entrante poderá ser bastante benéfica para se manter a qualidade de serviço durante esta fase.

6. **Otimização cross-layer da camada de transporte e compartilhamento de espectro**: Uma das principais características do TCP é lidar com congestionamento, geralmente no *core* de redes de comunicação TCP/IP. O compartilhamento de espectro, por sua vez, lida com um diferente tipo de congestionamento: congestionamento no acesso ao espectro. Por esse motivo, uma possível área de pesquisa é a otimização cross-layer de algoritmos da camada de transporte e compartilhamento de espectro.

7. **Controle de admissão compatível com compartilhamento de espectro**: A função de RRM que tenta evitar o congestionamento de espectro internamente em uma rede é o controle de admissão. Com o compartilhamente de espectro, essa funcionalidade deve também ser desenvolvida para atuar entre redes.

REFERÊNCIAS BIBLIOGRÁFICAS

[1] ITU-R Recommendation M.1645. Framework and overall objectives of the future development of IMT-2000 and systems beyond IMT-2000.

[2] AKYILDIZ, I. F. et al. Next generation dynamic spectrum access cognitive radio wireless networks: a survey. *Comput. Netw.*, Elsevier North-Holland, Inc., New York, NY, USA, v. 50, n. 13, p. 2127–2159, 2006. ISSN 1389-1286.

[3] SKLAR, B. Rayleigh fading channels in mobile digital communication systems, part i characterization. *Communications Magazine, IEEE*, v. 35, n. 7, p. 90–100, 1997.

[4] MYERSON, R. B. *Game Theory: Analysis of Conflict*. [S.l.]: Harvard University Press, 1991. Paperback. ISBN 0674341163.

[5] SURIS, J. E. et al. Cooperative game theory for distributed spectrum sharing. In: *Communications, 2007. ICC '07. IEEE International Conference on*. [S.l.: s.n.], 2007. p. 5282–5287.

[6] NIE, N.; COMANICIU, C. Adaptive channel allocation spectrum etiquette for cognitive radio networks. *Mob. Netw. Appl.*, Kluwer Academic Publishers, Hingham, MA, USA, v. 11, n. 6, p. 779–797, 2006. ISSN 1383-469X.

[7] BERLEMANN, L. et al. Radio resource sharing games enabling qos support in unlicensed bands. *IEEE Network, Special Issue "Wireless Local Area Networking: QoS Provision and Resource Management"*, p. 59–65, Jul 2005.

[8] SIMEONE, O.; BAR-NESS, Y. A game-theoretic view on the interference channel with random access. *IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks(DySPAN) 2007*, p. 13–21, April 2007.

[9] FUDENBERG; TIROLE. *Game theory*. [S.l.]: MIT Press, 1991.

[10] AKYILDIZ, I. F. et al. Next generation/dynamic spectrum access/cognitive radio wireless networks: a survey. *Comput. Networks*, Elsevier North-Holland, Inc., New York, NY, USA, v. 50, n. 13, p. 2127–2159, September 2006. ISSN 1389-1286.

[11] BRITO, L. da C. *Estratégias Evolucionárias Híbridas Dirigidas à Obtenção da Frente Ótima de Pareto no Projeto de Circuitos de Comunicação*. [S.l.]: Universidade de Brasília, 2003. Ph.D thesis.

[12] ITU-R Report M.2078. Estimated spectrum bandwidth requirements for the future development of IMT-2000 and IMT-Advanced.

[13] HAYKIN, S. Cognitive radio: brain-empowered wireless communications. *Selected Areas in Communications, IEEE Journal on*, v. 23, n. 2, p. 201–220, 2005.

[14] NOKIA AND NOKIA SIEMENS NETWORKS. Views for The LTE-Advanced Requirements. *3GPP RAN Workshop on IMT-Advanced*, abr. 2008.

[15] T-MOBILE INTL. Requirements on LTE-Advanced. *3GPP RAN Workshop on IMT-Advanced*, abr. 2008.

[16] CENTRE OF EXCELLENCE IN WIRELESS TECHNOLOGY. IMT Advanced Technical Requirements - An India Perspective. *3GPP RAN Workshop on IMT-Advanced*, abr. 2008.

[17] CORMEN, T. H. et al. *Introduction to Algorithms, Second Edition*. [S.l.]: McGraw-Hill Science/Engineering/Math, 2001. Hardcover. ISBN 0070131511.

[18] NIYATO, D.; HOSSAIN, E. A game-theoretic approach to competitive spectrum sharing in cognitive radio networks. *Wireless Communications and Networking Conference, 2007.WCNC 2007. IEEE*, p. 16–20, Mar 2007.

[19] NASH, J. Two-person cooperative games. *Econometrica*, v. 21, n. 1, p. 128–140, April 1953.

[20] WEIBULL, J. W. *Evolutionary Game Theory*. [S.l.]: Harvard University Press, 1997. Paperback.

[21] RIECHMANN, T. *Genetic Algorithms and Economic Evolution*. [S.l.], mar. 1999.

[22] MITOLA, J.; MAGUIRE, G. Cognitive radio: making software radios more personal. *Personal Communications, IEEE [see also IEEE Wireless Communications]*, v. 6, n. 4, p. 13–18, 1999.

[23] PARSONS, J. D. *The Mobile Radio Propagation Channel*. [S.l.]: Wiley, 2000. Hardcover. ISBN 047198857X.

[24] COMER, D. *Internetworking with TCP/IP: principles, protocols, and architecture. Volume 1 4th edition*. Upper Saddle River, NJ, USA: Prentice-Hall, Inc., 2000. ISBN 0-13-470154-2.

[25] PROAKIS, J. *Digital Communications*. [S.l.]: McGraw-Hill Science/Engineering/Math, 2000. Hardcover. ISBN 0072321113.

[26] SWOKOWSKI, E. W. *Cálculo com Geometria Analítica*. [S.l.]: Editora McGraw-Hill do Brasil, 1995.

APÊNDICES

I. INTRODUCTION

Traditionally, wireless communication systems operate on bands which are licensed to a single system. This approach allows for each system to be optimized indepedently of others. Regulations about power emissions and spectrum masks limit the undesired interactions amongst different communication systems to the borders of frequency bands, and, therefore, these kind of interactions can be avoided by the use of guard bands and adequate planning from regulatory bodies.

The spectrum licensing model is now being pushed by demand, and spectrum is considered to be a scarce resource. In [12], it is reported that by 2020 the spectrum needs for existing and upcoming cellular systems will sum a total of 1720 MHz, for a high user demand scenario. Such a huge bandwidth will unlikely be available in most countries.

The limited spectrum availability is more a consequence of the licensing model instead of real spectrum usage. Some reports show that the spectrum in some frequencies is largely unutilized over time [2]. For that reason, there has been an increasing interest in devoloping Dynamic Spectrum Access Network (DSAN)s, i.e., networks capable of dinamically accessing the free parts of the spectrum already used by other networks.

The functionalities of a DSAN are described by [2]:

- **Spectrum sensing**: Detecting the spectrum utilization of other networks in the same environment
- **Spectrum mobility**: Maintaining seamless communication during spectrum reconfigurations
- **Spectrum management**: Determining the best spectrum available to meet the requirements of the users
- **Spectrum sharing**: Determining how the networks in the same geographical area can achieve coexistence in the same spectrum pool and a fair share of spectrum allocation

Since DSANs share the same spectrum resource they may decide to compete for the resource or cooperatively share it in the most fair manner. Game Theory is a branch of mathmetics that study conflict and cooperation between rational decision makers and, therefore, it has been of increase interest to model and solve spectrum sharing issues.

There are some lessons from unlicensed bands that can be applied to DSANs. As a matter of fact, unlicensed bands provide examples of spectrum sharing. Except for a few rules about power emission levels, these bands can be used by any service/system. Indeed, they have been used for a pleathora of applications. However, the excessive freedom in the utilization of unlicensed bands proved to be a challenging scenario for system design. For instance, it is much harder to provide Quality of Service (QoS) or coverage guarantees than in licensed bands. Also, the scalability of existing solutions, such as Wireless Local Area Network (WLAN)s is relatively limited.

There are two main cases to be considered in DSANs:

- A DSAN opportunistically reuses the spectrum owned by a existing legacy network which is not aware the spectrum is actually shared
- Several DSANs share the spectrum amongst themselves in order to achieve higher spectral efficiency

Most of the research on DSANs conducted so far focus on the first concept, under a framework named cognitive radio. Here we use the definition by [13]: *"The cognitive radio, built on a software-defined radio, is defined as an intelligent wireless communication system that is aware of its environment and uses the methodology of understanding-by-building to learn from the environment and adapt to statistical variations in the input stimuli, with two primary objectives in mind:*

- *Highly reliable communication whenever and wherever needed;*
- *Efficient utilization of the radio spectrum."*

The second concept, of sharing spectrum only amongst DSANs, can also be built on cognitivity(learning) but that may not be desirable in terms of complexity. When considering DSANs of the same technology, i.e. intra-system spectrum sharing, one can make assumptions about things such as modulation, access scheme, power levels and duplexing. These assumptions together with standardized policies and protocols can lead to spectrum sharing concepts that do not need to build upon cognitivity.

The next section introduce a use-case for intra-system spectrum sharing in IMT-Advanced.

I.1 IMT-ADVANCED

International Mobile Telecommunications-2000 (IMT-2000) is the global standard for 3^{rd} Generation (3G) wireless communications. The 3G systems have been evolving during the past years and evolution will continue, but 3G technology will eventually reach its limits.

For the sake of evolution, International Telecommunications Union (ITU) recommendation ITU-R M.1645 [1] describes the user trends and needs for systems beyond IMT-2000. Later references for systems beyond IMT-2000 use the terminology IMT-Advanced (IMT-A). The minimum technical requirements of IMT-A are expected to be finalized in June 2008 [14].

As shown in figure I.1 considerably higher data rates are expected in IMT-A in comparison to IMT-2000. In special, nomadic/local area peak data rates need a substantial increase.

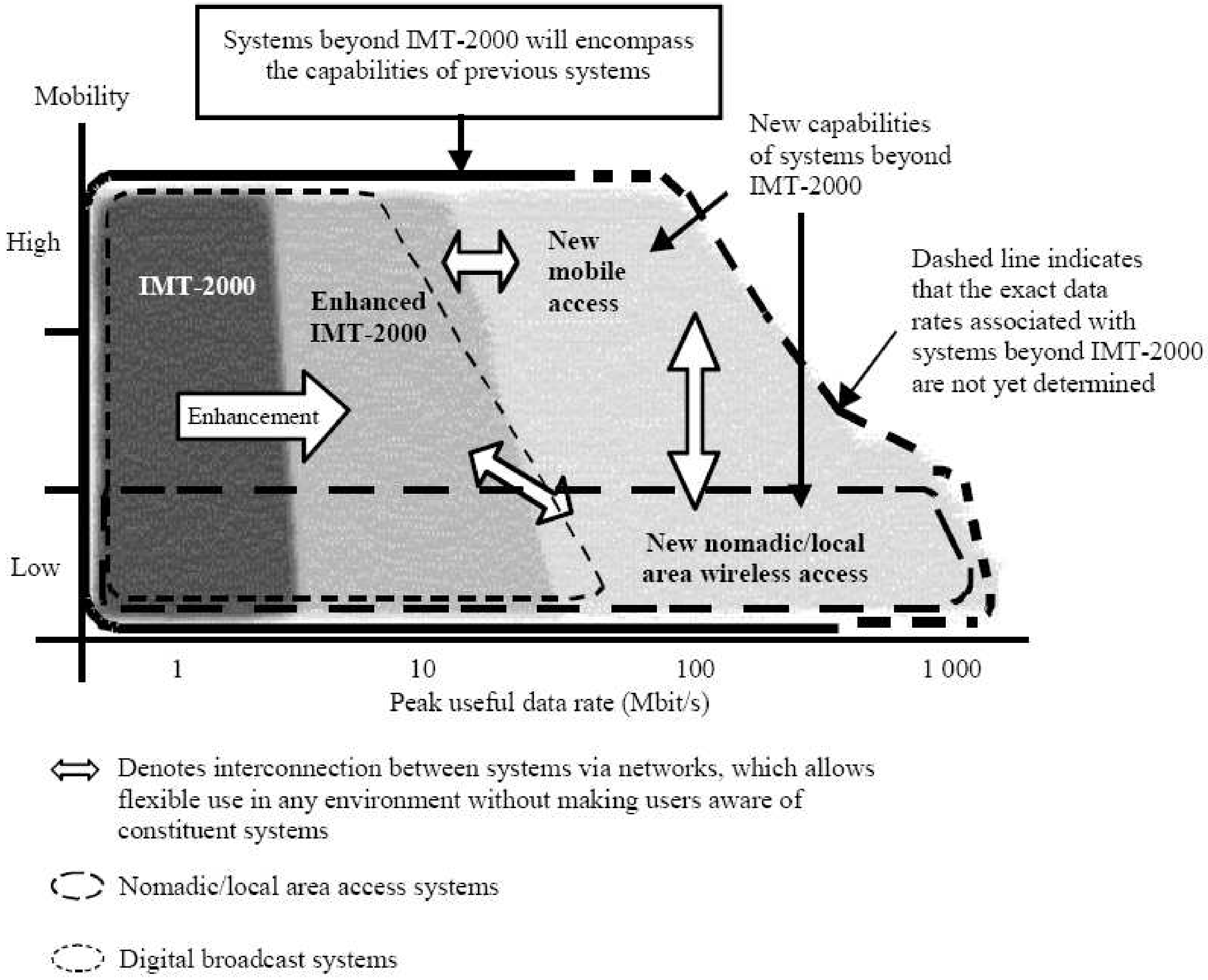


Figura I.1: IMT-Advanced [1]

IMT-Advanced is in the proccess of standardization. Therefore, these data rates are targets instead of specifications. The target data rates for local access will require a large bandwidth operating at high spectral efficiency.

ITU World Radiocommunication Conference (WRC) is realized every four years to agree in world spectrum regulation. WRC 07 identified the following new bands for use by IMT/IMT-Advanced [15]:

- 450-470 MHz band
- 698-862 MHz band
- 790-862 MHz band
- 2.3-2.4 GHz band

- 3.4-3.6 GHz band.

Not every band will be available in every country. Even the largest bands will not be enough to accomodate several operators operating at 100 MHz bandwidth. For example, in India 4-6 operators are expected to cohabit [16] in the same geographical area. If unpaired spectrum is considered, still every 2-3 operators will have to share the same bandwidth. Therefore, in order to achieve the desired peak data rates intra-system spectrum sharing can become a key component of IMT-A systems.

Inter-system spectrum sharing will also have to be considered, e.g., in the C-band of fixed satelite services (3.4-3.6 GHz band)

Next, we briefly discuss two candidate systems for IMT-Advanced.

I.2 LTE ADVANCED

3G Long Term Evolution (LTE) is the new The Third Generation Partnership Project (3GPP) air interface, which represents the next step in Universal Mobile Telecommunications Systems (UMTS) evolution. Standardization of LTE is well advanced. The downlink is based on Orthogonal Frequency Division Multiple Access (OFDMA) and uplink uses Single Carrier Frequency Division Multiple Access (SC-FDMA). The architecture is considerably simpler than UMTS in order to reduce latency. This means that more intelligence is moved towards the Base Station (BS) (eNodeB in LTE terminology). Advanced Multiple Input Multiple Output (MIMO) techiniques are supported. There is support for both Frequency Division Duplexing (FDD) and Time Division Duplexing (TDD).

LTE gives support for frequency domain packet scheduling, link adaptation and Hybrid ARQ (H-ARQ)

LTE Release-8 fulfills most of the wide area requirements for IMT-A. Future LTE releases will consider enhancements in order to fulfill all IMT-A requirements. The evolution of LTE in order to achieve these requirements is called LTE Advanced (LTE-A). LTE-A may encopass some targets over those of IMT-A requirements.

According to [14] 80-90% of traffic is generated in indoor or hotspot nomadic areas. Therefore, the overall user perception of the system will be highly affected by the local area deployment. That summed to the fact that LTE already will meet several of the IMT-A requirements, means that solutions for local area deployment are likely to be on spotlight in LTE-A development.

I.3 PROBLEM DEFINITION

Figure I.2 shows how the functions of a Dynamic Spectrum Access Network relate to the layers of current wireless communication systems. In the scope of this work only the interactions of spectrum sharing and management with physical and link layer are considered. Spectrum sensing is considered as one enabler technology to spectrum sharing, but it is not discussed in detail.

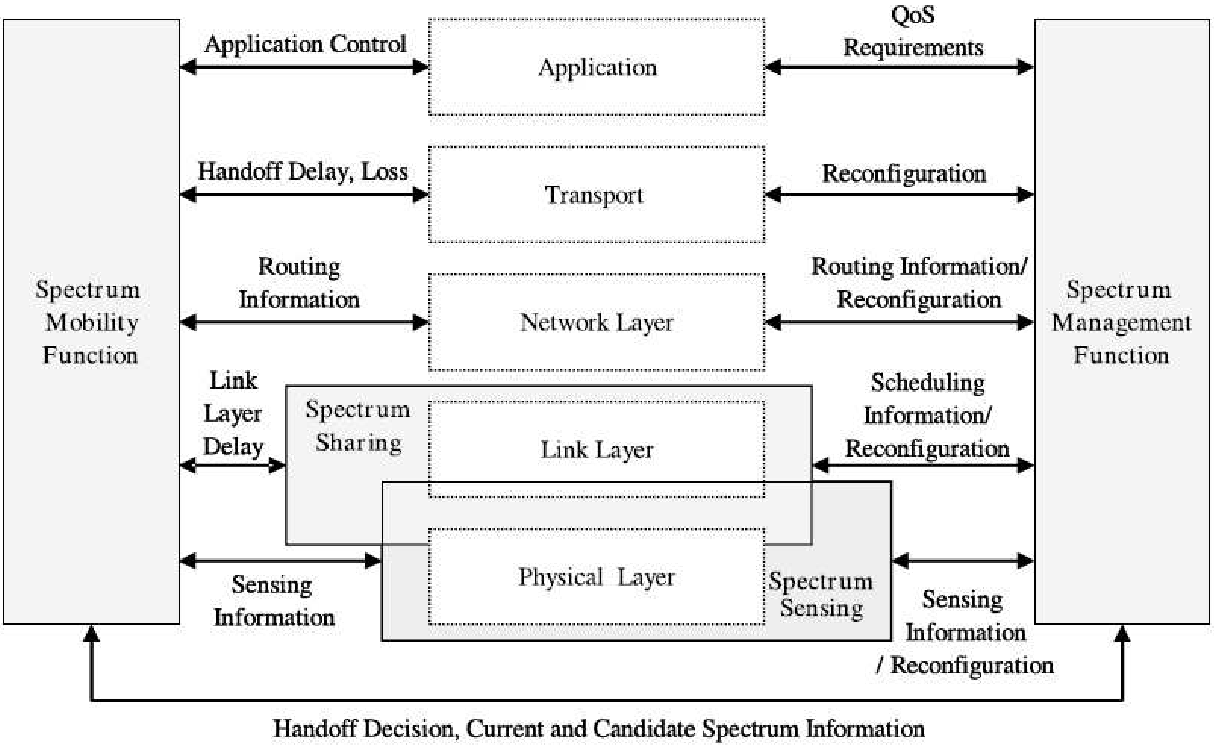


Figura I.2: Functionalities of a Dynamic Spectrum Access Network[2]

We consider intra-system spectrum sharing in a common spectrum pool focusing in local access scenario. This pool is licensed to a limited number of operators, which is determined by the regulator. Each of the operators have the same priority to access the spectrum.

Spectrum sharing can be accomplished in several domains such as frequency, time and space. The focus of this work is on spectrum sharing solutions on frequency domain. The spectrum is considered to be divided into smaller subchannels which do not interfere each other, meaning that only Co-channel interference (CCI) has to be taken into account for interference coordination amongst. One such example is an OFDMA system, with frequency synchronization. The case study is LTE-A, and those are the parameters used in simulations.

The local area deployment will be done by means of Home Access Station (HAS) which can be either Home Base Station (HBS) or Home Relay Station (HRS). The deployment of HASs is uncoordinated, and therefore the solution has to involve some degree of self organization. Independently of the existing Radio Frequency (RF) scene a HAS must be able to access spectrum and provide a service. A HAS shall be plug and play, i.e., installation should be simple enough to be done by any person avoiding the costly operations of network planning, commissioning and optimization.

There is no interface between HASs, even within the same operator. Therefore, all signaling is limited to spectrum sensing the RF environment. Also, interferers are treated the same way regardless of being from the same operator or not.

Control channels are not considered in the spectrum sharing solution. However, this is important to consider in a practical implementation.

II. GAME THEORY

II.1 INTRODUCTION

The main objective of this chapter is to give a brief introduction to game theory, providing the reader with the necessary concepts to the understanding of the text. Along with that, some relevant proposals of utilization of game theory to solve the spectrum sharing problem in order to illustrate more concretely the potential of game theory in spectrum sharing issues.

Definition 1 *Game Theory (GT) is defined as the study of mathematical models of conflict and cooperation between rational decision makers. [4]*

The name Game Theory resembles the fact that games are situations of conflict and cooperation. Nevertheless, the applications of GT go far beyond board or card games. Most noticeably, GT has been applied with great success in economics. More specifically, GT is well suited to study the relationships in oligopolies.

GT has also been used to explain behavior in social sciences and in the studies of populations (Biology). In the recent years, several applications to Game Theory have been developed in network engineering. A big deal of attention is being given to game theoretic approaches for spectrum sharing, which is the main interest here.

We start with the definition of a game:

Definition 2 *A game is any situation where decision makers have the outcome of their own decisions affected by other decision makers.*

In the following sections we will look at the following aspects of Game Theory:

- Static games of complete information - section II.2
- Dynamic games of complete information - section II.3
- Repeated games - section II.4
- Incomplete information - section II.5
- Cooperation - section II.6
- Evolutionary Game Theory - section II.7

Examples of application of these concepts in spectrum sharing are provided throughout this chapter. These concepts are heavily utilized in the derivation of utility function in Section IV.4.

II.2 STATIC GAMES OF COMPLETE INFORMATION

We start with one well known example of game. It is known in the literature as the stag hunt game. It was actually described first by Rousseau, in *Discourse on the Origin and Basis of Equality among Men*: "If a group of hunters set out to take a stag, they are fully aware that they would all have to remain faithfully at their posts in order to succeed. But if a hare happens to pass near one of them, there can be no doubt that he pursued it without qualm, and that once he had caught his prey, he cared very little whether or not he had made his companions miss theirs."

This story from Rousseau describes a situation where cooperation leads to the better welfare of all the hunters. Note, however, that if a hunter has any reason to believe that the others won't keep their positions, then his best shot is to find a hare himself. Why? Because he has a very small probability of catching the stag alone. Therefore each hunter can be tempted to break the social contract, when he sees the possibility of easily guaranteeing his own welfare.

Rousseau's description leaves some margin for interpretation. For instance, he does not define the number of hunters or what is the probability of catching a stag given the number of hunters that stick to the task. Also, it can be important to define how much is the value of a hare compared to the individual share of a successful hunt stag.

Game Theory deals with such kind of conflict/cooperation situation with mathematical formality. Once a game has been formalized there is no margin for interpretation, as in the Rousseau's example. In other words, a game has a precise mathematical definition. Having one example at hand, we can more formally define a game. A game in strategic form is defined as a set of 3 elements.

- The set of players in the game. Usually we simply denote them by numbers {1, 2, ..., I}
- The pure strategy space S_i for each player i. A combination of strategies, i.e. , a ordered vector $S = \{s_1, s_2, ..., s_I\}$ is named a strategy profile. The set of all strategy profiles is the Cartesian product of the strategy spaces.
- The payoff functions that give player i's utility $U_i(S)$, where S is a strategy profile.[1]

The strategies are called pure strategies, because one can also consider mixed strategy. A mixed strategy is a probability assignment over the pure strategy space. For example, if there are three pure strategies, a player with a mixed strategy $0.5, 0, 0.5$ will randomly play the first strategy 50% of time and the third strategy also 50% of time, but it will never play the second pure strategy. We can now define more formally the elements of the stag hunt game. The set of players is the set of hunters. Let us first model it by assuming we have 2 players (hunters).

---

[1] The assumption is that every player wants to maximize his own utility. In some games it is easier to model in terms of a cost function $C_i(S)$ which players want to minimize. In those cases one can define the utility function to be $U_i(S) = -C_i(S)$

The strategy space is defined for each player. We can assume that there are only 2 strategies: *hunt stag* or *hunt hare*. In these case both players have the same strategy space, but this is not necessarily true.

The are four strategy profiles. Namely, $S_{ss} = \{s_1 = stag, s_2 = stag\}$, $S_{sh} = \{s_1 = stag, s_2 = hare\}$ $S_{hs} = \{s_1 = hare, s_2 = stag\}$ and $S_{hh} = \{s_1 = hare, s_2 = hare\}$

Finally, let us assume the hunters have no preference about stag or hare meat. With that assumption one way to define the payoff function is to define it as the amount of meat available for each hunter. Let us assume a hare weights 2 kilograms and one stag weights 100 kilograms. If they catch a stag, they will divide it so the payoff will be 50 to each of them. We also assume that if the 2 hunters go for a stag, they have 100% probability of catching it, while if just one of them goes for the stag he has 0% probability of being successful. Catching one hare is 100% guaranteed if the player plays hare. Therefore, we have:

- $U_1(S_{ss}) = 50$ and $U_2(S_{ss}) = 50$, since they divide the stag in 2 equal parts.
- $U_1(S_{sh}) = 0$ and $U_2(S_{sh}) = 2$
- $U_1(S_{hs}) = 2$ and $U_2(S_{ss}) = 0$
- $U_1(S_{hh}) = 2$ and $U_2(S_{hh}) = 2$

Notice that the reward for each player depends not only in his action, but also the actions of the other players. It is important to highlight that this is what characterizes a situation being a game and not a decision to be taken independently by each player.

In games involving 2 players and a small number of strategies it is quite useful to show the game in a tabular form such as Table II.1 . We can condensate all important information in a simple and intuitive view. The player 1 plays rows. So, his strategic space is represented by the row labels. Similarly, the player 2 strategies are represented by the column labels. Within that representation, each of the table entries represents one strategy profile. The utilities associated with each strategy profile are presented directly on each entry. The first utility is for player 1 (rows) and the second utility is the one of player 2 (columns).

	hunt stag	hunt hare
hunt stag	50,50	0,2
hunt hare	2,0	2,2

Tabela II.1: Stag Hunt game with 2 players in strategic form

This simple view allows us to see more clearly what are the options (strategies) of each player and their consequences. It may now be clearer why this game formulation is called strategic form. However, the dimension of the table is equal to the number of elements in a strategy profile. For that reason, the table view is less intuitive for 3 players and hardly understandable with 4 or more players. As an example, consider the stag-hunt game with 3 players shown in Table II.2. It is easier to understand as 2 separate parts, shown in the left and right of Table II.2. As before, player 1 selects a row and player 2 selects a column within a table. Player 3 selects which of the tables (left/right) will actually be played.

	hunt stag			hunt hare	
	hunt stag	hunt hare		hunt stag	hunt hare
hunt stag	$100/3$,$100/3$,$100/3$	0 , 2, 0	hunt stag	0,0,2	0,2,2
hunt hare	2,0,0	2,2,0	hunt hare	2,0,2	2,2,2

Tabela II.2: Stag Hunt game with 3 players in strategic form

II.2.1 Nash Equilibrium

Definition 3 *A strategy profile is called a Nash equilibrium if it satisfies the following condition: every strategy in the profile is a best response to the strategies of the other players.*

This can be interpreted as follows: in a Nash equilibrium, no player has incentives to change his strategy, given that the other players also do not. NE is the fundamental concept in the prediction of the solution of a game. The solution is the set of actions that will be actually be taken by each player when the game is realized. In case of a unique Nash Equilibrium, it can be proved that if the following conditions hold, the NE is the solution of the game:

- The players want to maximize their own utilities
- The players do not make mistakes in the analysis or execution of the game
- All players are capable of deducing the NE solution
- All players know that every other player is capable of deducing NE solution. They also know that every other player knows that every other player is capable of deducing NE solution.
- In short, for any statement of the form: "every player (knows that every other player)^n is capable of deducing NE solution"is true for any n from 0 to number of players, where the term within parenthesis is repeated n times.

However, even if those conditions hold, a game can have several NE, in which case the solution is not clear. In order to find the solution for games with multiple NE, there exist some other concepts called Nash Equilibrium refinements. In static games, the most important refinement is Pareto optimality, defined next section. In the case of dynamic games subgame perfection is one important refinement and it is defined later.

In the space of pure strategies, NE may not exist. For that reason, it is also important to consider the space of mixed strategies. A mixed strategy is a vector of the same dimension of, assigning probabilities of playing each of the pure strategies. The pure strategy space is included in the mixed strategy space and it can be generated by using the canonical vectors as the probability assignment. For example, if there are four strategies, the probability assignment made by the 4-dimensional canonical vector e^3 corresponds to the third pure strategy.

II.2.2 Pareto Optimality

In a game, every player has its own utility function. The utility function represents the rationality of the player in terms of preferences and each player wants to maximize its own utility. However it is not straightforward how to consider utilities accross players. Consider the example in Table II.3.

	Strategy A	Strategy B
Strategy C	0.5 , 0.5	0 , 3
Strategy D	1.5 , 0	1 , 0.5

Tabela II.3: A game with 3 Pareto optimals: C,B ; D,A and B,D

One can be tempted to evaluate how good a solution is by summing the utilities of each player. However, one cannot say that the strategy profile C,B is better than strategy profile D,A because the numerical values of utility are only meaningful to the player itself. What can be affirmed is that the strategy profile C,B is the best for the column player and at the same it is the worst for row player. Similarly, the strategy profile D,A is the best for row player and the worst for column player.

In these kind of optimization problems, where the several dimensions cannot be reduced to a single value the concept of Pareto optimality becomes very important. Within GT context, Pareto optimality is defined as follows:

Definition 4 *A Pareto optimal strategy profile is a profile such that no player can increase its own utility unless at least one of the other players' utilities is decreased.*

Pareto Optimal (PO) solutions are not necessarily fair or unique. They just represent the maximum efficiency that can be achieved in 1 or more objective dimensions. In Table II.3 there are three POs. B,C is the most efficient profile in the dimension of row player utility. A,D is the most efficient profile in the dimension of row player utility. Finally, D,B is a strategy profile that is efficient in one direction that trades-off both players.

Pareto dominated strategy profiles are those which are not Pareto Optimal. In the example of Table II.3, the strategy profile A,C is Pareto dominated by the strategy B,D because no players lose by moving from A,C to B,D and at least one player benefits from that change.

The comparison of PO set with NE set is important in two-fold:

- If the PO set is disjoint from NE set, it means that every player would benefit from not playing a NE strategy profile. The price of anarchy is the rate between the best Pareto optimal and the worst NE.
- If in a multiple NE game only one of the NE is Pareto optimal, it is an efficient solution. This is an important NE refinement.

Both players playing hunt stag is Pareto optimal in Stag-Hunt game. Notice that the definition of the price of anarchy is loose, because one has first to define what is meant by the best PO and what is meant by the worst NE, when they are multiple.

II.2.3 Well known game examples

In this section we will introduce some other well-known examples from GT literature, that along with the Stag-Hunt game, form a very simple set of static games to which more complex games are usually compared.

II.2.3.1 Prisoner's dilemma

The prisoner's dilemma is perhaps the most famous game-theory example. Two suspects of a severe crime are arrested for another crime. For the minor crime they will get 6 months each. The police offer each prisoner the following: if you confess that you both made the major crime, defecting your partner, you will be free to go, relieved of both crimes, while your partner will have the full 10 years sentence. The prisoners know that if both of them confess they will spend 5 years in prison. Defining the cost function as the number of years they spend in prison, we have the formulation shown in Table II.4, where the utility is the negative of the cost function.

	Remain silent	Defect
Remain silent	-0.5 , -0.5	0 , -10
Defect	-10 , 0	-5 , -5

Tabela II.4: Prisoner's dilemma

The interesting fact about the Prisoner's dilemma is that the unique NE is to both players to defect, which is quite inefficient. Actually, all the other 3 strategy profiles are Pareto optimal. Therefore, in Pareto optimality sense the NE is the most inefficient outcome possible. In special, the outcome strategy profile where both of them remain silent is way better than the NE for both players and it is also the only fair Pareto optimal. Therefore, the price of anarchy in the prisonert's dilemma is very high: selfish behavior leads to the most inefficient possible outcome.

II.2.3.2 Chicken

The chicken game is probably one of the preferred by Hollywood movies. The game consists of 2 players driving their cars in high speed directly into route of collision. The toughest guy will keep straight to the win while the "chicken"will swerve to save both their lives. The worst possible outcome is that both players are tough enough to crash the car instead of swerving. In practice, chicken is best modeled as timing dynamic game, but we will take a static version here.

Table II.5 shows the static version of chicken game in strategic form.

	swerve	straight
swerve	tie,tie	lose,win
straight	win,lose	crash,crash

Tabela II.5: Chicken game in strategic form

The key aspect of this game is that crashing is way worse than losing the game. Mathematically: $win \succ tie \succ lose \succ\succ crash$. In GT, $\succ$ means strictly preferred. So, every rational player will eventually swerve if the opponent does not do it first, because losing is much more preferred than crashing. The game has 2 Nash equilibria: { swerve,straight } and {straight,swerve}. That is, the best response for swerving is keep heading straight while the best response for heading straight is swerving.

While the situation after which the game was named seems just a game of proud between youthful degenerates, this situation emerges in several applications. Bertrand Russell, a vigorous proponent of nuclear disarmament, compared the chicken game with the situation of nuclear brinkmanship. This is an aggressive kind of politics, where nuclear arsenal is used to threaten other countries forcing them to back down and fulfill own interests. Of course, if both countries keep threatening until effective use of the nuclear weapons, this would lead to total annihilation as showed in table II.6.

	back down	"use"nuclear weapons
back down	tie,tie	lose,win
"use"nuclear weapons	win,lose	annihilation,annihilation

Tabela II.6: Nuclear brinkmanship game. Note this is a chicken game.

This game is also remarkably similar to a situation where we have 2 strong interferers trying to share the wireless medium in table II.7. However we modify it because if you do not transmit anything you just do not care about what the opponent does. Even with the modification the game still have the same 2 Nash equilibria.

The Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol, can be justified by the game in table tab:InterferenceChickenGame. The transmitter first listens to the

	do not transmit	transmit
do not transmit	lose,lose	lose,win
transmit	win,lose	crash,crash

Tabela II.7: Interference game in strategic form

media before transmission, and a collision is such a bad condition that it only goes for transmission if it the channel is not occupied yet.

This approach is known as contention, where the transmitters are contending for the wireless medium. Strictly taking the meaning of the word contention, the term could be applied to any non-cooperative game theoretic approach. We will avoid the use of the term contention for non-cooperative approaches, because the term is well established as a reference to CSMA/CA systems.

II.3 DYNAMIC GAMES

Several practical games cannot be described accurately in terms of static games. For example, a company starting operation in a mature market does not have the same conditions as the ones already operating for a long time. The companies already there have some timing advantage over the new entrant. They make their decisions first (at some point in the past), while the new entrant will have to make its decisions on top of that. This situation leads to different equilibria compared to the situation where all players take their decisions simultaneously. Communication protocols are also more naturally modeled as dynamic games, because of the communication delays. In general, different network elements have different information, unless it is signaled. Still, signaling is neither instantaneous nor costless.

While thinking in terms of timing highlights the need for a dynamic model, the element that makes a dynamic game different from a static one is information. Players can take their decisions at different times, but if they do not know any information about the decisions of the other players the game is static. Consider, for instance the well known game rock-paper-scissors. The players hardly make their decisions exactly at the same time, but as they do not know about each other decision the game is static. On contrary, in a chess game at every move the players know the past moves and can make their decisions conditioned on the history of the game.

A game in extensive form is composed of the following elements:

- The players of the game
- A set of possible states of the game, called decision nodes, and their precedence
- The definition of the information sets of each player
- The definition of the actions that can be taken at each information set

- Utility functions for each player in every terminal node

A dynamic game is more naturally represented by a game in extensive form, which can be graphically depicted as a generalized decision tree. A tree is a directed acyclic graph [17]. A graph is composed of nodes and arcs. In a tree a special node is denominated the root. There is exactly one path between the root and any given node.

In dynamic games, the root is the state the game begins. Each node corresponds to a particular state the game can reach. In game-theory terminology a node is called a decision node. In each decision node, one of the players has a possible set of actions. A node cannot be shared by two players. Figure II.1 shows an example of dynamic game, where the root is represented in the top. Player 1 has the first move selecting amongst three possible actions. For that reason, the root is labeled with player 1. The nodes that follow the root are game states where player 2 selects actions and so on.

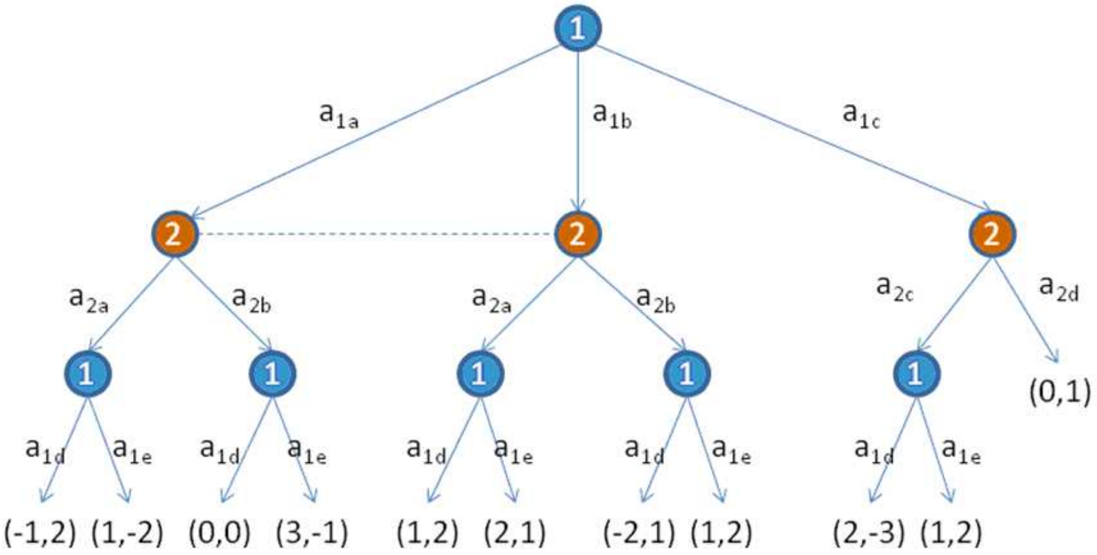


Figura II.1: Example of dynamic game

A key concept in dynamic games is the information set concept. An information set is a set of nodes which are indistinguishable for a player. For instance, in the example of Figure II.1 player 2 has the information whether player 1 selected a_{1c} or not, but it cannot distinguish between the actions a_{1a} and a_{1b}. This is represented by the dashed line connecting the nodes. Notice that all nodes of an information set necessarily have the same possible actions, otherwise it would be possible to distinguish them based on the actions available.

Each leaf node of the tree represents one of the possibilities on how the game ends, and therefore each of them is assigned with the players' utilities. Notice, also, that the number of actions before the game finishes is not necessarily equal for all paths. In Figure II.1 , if the path a_{1c} and a_{2d} is taken, the game end after two actions, while in the other possibilities it ends after three actions.

In fact, in real applications there may be such a large number of possible actions and decision nodes, that drawing a generalized decision tree is not viable. The important thing is to identify these elements of extensive form.

Static games are naturally represented in strategic form, but can also be represented in extensive form by defining that each player has just a single information set.

A dynamic game is usually represented in extensive form, but it can also be represented in strategic form. The interpretation in dynamic form, a player waits until a node is reached and then makes the decision. However, if each player makes a complete contingency plan, describing the actions to be taken in each information set, the corresponding game will be in strategic form. This result is important because it allows applying NE concept directly to dynamic games. One example is shown in next section.

II.3.1 Subgame perfection and backward induction

Although the concept of NE is directly applicable to dynamic games, some NE may be more credible than the others. This can be seen through an example. Consider the game presented in Figure II.2. It is a dynamic game composed of 3 stages and it has 2 NE.

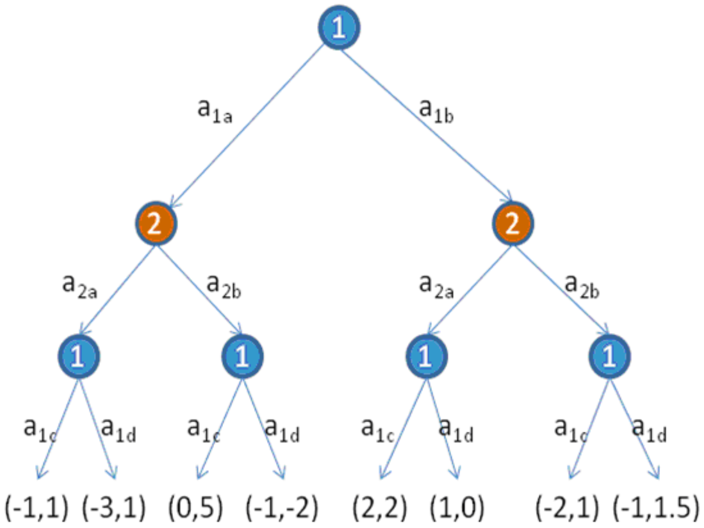


Figura II.2: A dynamic game with 2 Nash Equilibria.

The first step to identify the NE of the game in Figure II.2 is to write the equivalent game in strategic form. This is presented in Table II.8.

Aiming at maximizing its own utility, player 2 may try to induce the most favorable NE equilibrium to him by saying: "I will play a_{2b} no matter what."Should player 1 believe him and play a_{1a} in the first move? The answer is no. This is what is called an empty threat. Once the game is effectively played and player 1 has chosen action a_{1b}, player 2 will choose a_{2a} if he is rational and wants to maximize his own utility. This example shows that not all NE are likely to

	a_{2a}	a_{2b}
a_{1a} and later a_{1c}	1,-1	0,5 NE
a_{1a} and later a_{1d}	-3,1	-1,-2
a_{1b} and later a_{1c}	2,2 NE	-2,1
a_{1b} and later a_{1d}	1,0	-1,1.5

Tabela II.8: Game of Figure II.2 in strategic form. The Nash equilibria are denoted by NE.

happen when you consider the full dynamics of the game.

An important NE refinement in dynamic games is subgame perfection. A NE is subgame perfect if it is also a NE for all proper subgames of the game. A proper subgame is a subtree that does not partition any information sets. Intuitively, a player will look at smaller, parts, i.e., subgames to make its decisions and understand the game.

Backward induction is a recursive algorithm used to derive subgame perfect solutions. It consists of analyzing the terminal nodes and selecting the actions on each of them which will maximize the utility of the player that make decision on those nodes. Then the terminal nodes are eliminated and substituted with the utilities of the selected actions. The algorithm is then repeated until the actions to be taken at the root are selected. Figure II.3 shows the first step of backward induction to solve the game of Figure II.2. For example, the leftmost node of Figure II.2, was substituted by the utility of action a1c in that node, since a_{1c} provides more utility to player 1 than a_{1d} at that particular decision node.

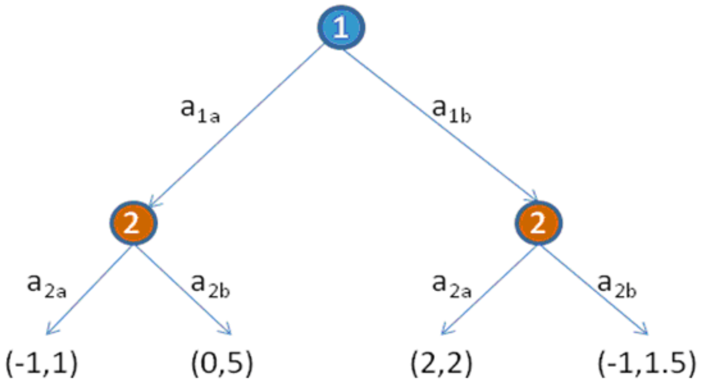


Figura II.3: First step to solve the game of Figure II.2 using backward induction.

Now, analyzing the game in Figure II.3, backward induction is repeated but now the terminal nodes belong to player 2. Therefore, we select the actions that maximize player 2 utilities: in the left node he should choose a_{2b} and in the right node the best option a_{2a}. The result is the game shown in Figure II.4. Finally, from Figure II.4 we see that the best option to player 1 is to start playing by a_{1b}, and we expect that the output of the game will be (2,2).

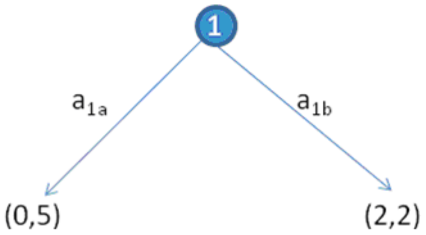


Figura II.4: Last step to solve the game of Figure II.2 using backward induction.

II.3.2 Application example

[18] considers a cognitive radio scenario where a primary user wants to share spectrum with a number of secondary users that will be charged for that. The revenue is the profit made on spectrum minus the cost of the spectrum. First, a static Cournout game [9] is formulated, but that is only useful if the secondary users can evaluate the profit of each other. A dynamic Cournout game is then presented, where the secondary users can make decisions based only on the price function given by the primary user. Stability analysis of this second approach is made.

II.4 REPEATED GAMES

A repeated game is a game where a base game is played more than once by the same players and each player wants to maximize the total utility accumulated through all repetitions. The base game can be either static or dynamic. The only requirement is that at each repetition the game must have the same structure and it is possible to define the utilities of the base game.

The utility of the repeated game is usually defined on top of the utility of the base game by using a discount factor δ, where it is typically assumed that $0 < \delta < 1$. This factor is included to give more weight to present rounds than future ones. If the utility in the k-esim repetition of the game is U_{ki}, the total utility in the repeated game is:

$$\pi_i = \sum_{k=0}^{N} \delta^k U_{ki} \tag{II.1}$$

Where, N is the number of repetitions of the game and can be infinite. In repeated games, it is possible to achieve some equilibrium states that are not possible for the base game. Consider the repeated prisonert's dilemma as described in Table II.4. If the discount factor is close to 1, a single round of double defection will incur a cost that is equal to 10 rounds of cooperation (both prisoners keeping silence).

One important class of strategies in repeated games is the class of trigger strategies. They consist of strategies where a new behavior starts as soon as a new condition is detected. Two examples of trigger strategies applied to repeated prisonert's dilemma are:

- Tit-for-tat: Start cooperating. After each round play what your opponent played last round.
- Grim: Start cooperating. After your opponent defect for one round, defect forever.

In Tit-for-tat, the punishment will keep as long as the opponent keeps defecting, but it will be forgiven as soon as he wants to go back into cooperation. In Grim, a single defection of the opponent will make punishment last forever. Grim kind of strategies are inefficient in the case the players do not have perfect execution. A defection made by mistake will lead to infinite defection. The fear of future punishment can lead to cooperative behavior even in games where non-cooperative behavior is mandatory in the base game.

In Section IV.4 we will go through a detailed example of repeated game in a spectrum sharing situation, and use the discounted utility function to design our practical utility function.

II.4.1 Application Example

WLANs with IEEE 802.11e QoS support are considered in [7]. It is assumed each of WLANs has a hybrid coordinator, which means that there is the possibility to allocate contention free period. The basic single stage game is considered to have 3 phases:

- Decision making
- Competitive access
- Evaluation

The first and third are the needed processing to make decisions and observe the output. Utility is a function of three QoS dimensions: throughput, delay and demanded period length. The authors consider a repeated game with infinite horizon and show how different strategies perform with respect to each other through simulations. However the considered strategies are well-known in game theoretic formulation of repeated games, and the analysis is limited to the case of two networks.

II.5 INCOMPLETE INFORMATION

In the developments discussed so far, complete information is assumed. This means that all the elements of the game are common knowledge to all players, such as, game structure, utility functions and past history(in multi-stage games such as repeated games). In several cases of practical interest information is not complete. Here are some examples:

- One player has some kind of private information which is not accessible to the other players.

- There is information that is not available for any player at all.
- Each player only has knowledge about his own utility function.
- The outputs after a game stage are not observable.
- Outputs are observable, but with some noise.

All these situations refer to the fact that at some point of the game there is information which is not common knowledge to all players. One example is a Poker game. As long as the deck is properly shuffled, the order of the cards is unknown by the players. In some variants all the information a player has is his own hand and has to make decisions based solely on that. Some Poker variants, such Texas Hold'Em, have some cards which are common knowledge to all players. This, in general, makes the game more interesting as a player can also infer his belief about the hands of other players based on the publicly available information. Good poker players understand the kind of oponent they have and adapt to it.

In next subsection we discuss how to model the situation where there is relevant game information which is not available to any player at all, and then we present the definition of a game of incomplete information.

II.5.1 Nature player

If someone is just presented Table II.1 and asked if one would play hunt stag or hunt hare, one would very likely answer it would play hunt stag. There the difference in the payoffs is very significant. So most people will think that the risk associated with hunting stag will be worth, i.e., the risk that the other players play hare. However, this is not the whole story about this game. What if, for instance, even if both players cooperate they have just 10% of chance of catching a stag? Then the options to each of the players look as following:

- If I play stag I need that *both* my opponent cooperates by playing stag and conditions are favorable, which will happen only 10% of times. But if both conditions hold I will get a huge prize.
- If I play hare, I will win a small prize despite of my opponent or chance.

Therefore, risk aversion would probably lead the players to play hare, even if on average the prize is still bigger for a stag. One way to properly represent this condition is adding a third player called Nature, which does not have utility functions. Nature plays stag is hard to catch 90% of times and stag is easy to catch 10% of times. This situation is represented in Table II.9

Notice that in the game represented Table II.9 neither player 1 nor 2 knows what is the actual move of nature when making their choice. They only know about the statistical behavior of nature. Also Nature player does not have any assigned utility

Stag is easy to catch (10% of times)			Stag is hard to catch (90% of times)		
	hunt stag	hunt hare		hunt stag	hunt hare
hunt stag	50 , 50	0 , 2	hunt stag	0,0	0,2
hunt hare	2,0	2,2	hunt hare	2,0	2,2

Tabela II.9: Stag Hunt game with 2 players and nature move in strategic form

II.5.2 Bayesian games

Games of incomplete information are also called Bayesian games, because of the inherent probabilistic model. In order to introduce the structure of a Bayesian game we need the following definition:

Definition 5 *The* type *of a player is any relevant information a player has that is not common knowledge.*

In addition to the game elements presented in the previous sections, a Bayesian Game has also the following elements:

- The states of Nature player
- A function mapping the states of Nature to the types of each player
- Each of the players assign a probability distribution to the states of Nature. This represents the belief a player has about the type of the other players. The exact state of Nature is unknown by players

In a dynamic game with observable outputs, players can update their beliefs about each other types based on Bayes' Rule [9]. This is a very important property that help to alleviate the lack of information and we will exploit it on the development of our protocols in chapter IV

II.5.3 Application Example

[8] provides a game-theoretical analysis of the interference channel with two transmitters and two receivers. The cases where the transmitters have full or partial knowledge about each other backlogged traffic are considered. The main conclusion is that the random packet arrival alleviates the drawbacks of purely competitive random access. Therefore, traffic is an important dimension to be accounted in spectrum sharing problem. Furthermore, the results in [8] show that for a static game, the performance is severely degraded in the case where the information about the demanded traffic is not complete. [8] is an example of why it is important to model spectrum sharing as incomplete information games.

II.6 COOPERATION

When the price of anarchy (section sec:ParetoOptimality) is high, there can be raise for questions such as: Would it not be better if all players simply agree on cooperating to reach a PO solution?

A solution where the players agree to cooperate in order to have an increased utility compared to the non-cooperative solution is called a bargaining solution. In such a solution, the agreements must be binding, i.e., no player can cheat by playing a different play than agreed. One of the views to find this cooperative solution is an axiomatic point of view, first provided by Nash [19]. Instead of focusing in the proccess, the axiomatic view focus on the characteristics that such a solution must have.

Definition 6 *A solution is called a Nash Bargaining Solution (NBS) if it has all the characteristics enumerated below.*

1. **Pareto optimality**: Why this is a necessary condition for a solution to be a NBS can be seen by absurd. If the solution is not PO than there exists another solution that is better for at least one player and is at least as good for the others. Therefore, that would be a better agreement point for bargaining, which contradicts the first one being a solution.

2. **Individual Rationality**: Utility increases or stay the same when moving to NBS. No player will accept a bargaining proccess if that means a loss to him (compared to the non-cooperative solution). In other words, the NBS must Pareto dominate the non-cooperative solution.

3. **Invariance to Affine Transformations**: If utility functions are scaled or offset, the NBS must still be the same strategy profile.

4. **Indepedence of Irrelevant Alternatives**: If the strategy space is reduced, but still containing the original NBS strategy profile, then this same profile must still be the NBS of the reduced game.

5. **Symmetry**: It must be indepedent of player label. It only depends on non-cooperative utility and feasible utilities. For instance, if both players have the same utility functions and the same non-cooperative utility, than in the NBS they also must have the same utility.

Let us denote the utility for player i at the non-cooperative solution to be u_i^0. Let the set $I = i \in 1, ..., N\ u_i > u_i^0$, be the set of players that can achieve a utility strictly greater than in non-cooperative solution. The Nash Product is defined as follows:

$$\prod_{i \in I} (u_i - u_i^0) \tag{II.2}$$

If the utility space is convex, it can be proven that the strategy profile that maximizes the Nash Product is the unique NBS [5]. This uniqueness is important because it is easier for the players to determine what should be the cooperative solution by a closed form

While, we used the price of anarchy nomenclature to motivate a NBS, one way to define the price of anarchy is as the rate between the NBS and the non-cooperative solution.

It is not necessary that all players agree on cooperation to achieve some degree of cooperation. Players can form coalitions and cooperate within the coalition. The objective of a coalition is to maximize the total utility of the coalition, against other coalitions or indepedent players. Of course, a player will only decide to be part of a coalition if it can do better by taking part on it than being indepedent. The coalition where all players cooperate is named grand coalition.

II.6.1 Application Examples

In [5], a cooperative approach for spectrum sharing is taken. The game formulation is to consider the players as the N transmitters in the network. There are K channels, and the possible strategies are the transmission powers allocated for each channel. The utility function is given by aggregate Shannon capacity, based on the Signal to Interference plus Noise Ratio (SINR) of each channel. The authors show that the strategy space can be non-convex, but it becomes near convex as the number of channels, K, increases. Then, the use of a NBS to find the solution of the games is proposed. While, the calculation of the exact NBS would involve information exchange involving all transmitters, the authors propose a distributed algorithm to optimize the NBS locally, up to two hops. They assume there is an underlying method to exchange the needed information to calculate the NBS within two hops. Their solution achieve second best average throughput, second best outage throughput and best fairness compared to other three algorithms: Maximization of sum throughput, Maximization of minimum throughput and a water-filling based approach.

In [6], a WLAN scenario is considered. The utility functions are defined based on the perceived channel quality, namely incoming interference. Two cases are considered: a selfish utility that considers only its own interference level and a cooperative utility where each receiver considers the incoming interference for itself and its neighbors. For the second case, the authors devised a protocol to exchange the needed information over a WLAN scenario. Also, they showed that two game-theoretic approaches, one based on potential game formulation and another based on no-regret learning, have the capacity to lead to SINR distribution better than random allocations. While utility functions are in principle given by the modeling of the problem, [6] uses the modified utility function to enhance the overall performance, achieving some degree of cooperation. This is one example that utility function can be used as a design parameter to achieve more efficient protocols. This is also explored in this work in section IV.4.

II.7 EVOLUTIONARY GAME THEORY

Evolutionary Game Theory (EGT) provides a different point of view in the analysis of games. Traditional GT focus on the aspects of equilibrium, which is by nature static. One of the key concepts of EGT is also about equilibrium considerations and can be view as a NE refinement. However, EGT is also dedicated to the analysis of game dynamics, in the sense of how the strategies evolve from an initial state to the equilibrium state or, in other cases, why no equilibrium is ever achieved.

An evolutionary process is characterized by the existence of a population. Three basic mechanisms act over the population to modify it over time:

- The *mutation* mechanism defines how new variants of the population appear.
- A *breeding* mechanism, which defines how the current population generates offsprings. *Replication* is when an offspring is an exact replication of its single parent. *Recombination* is when the characteristics of two parents are combined to generate an offspring.
- The third mechanism is *selection*. This is well-known in Biology as the survival of the fittest. Formally, each individual is assigned a fitness function. Developments are usually made considering that fitness function is an increasing fucntion of expected utility.

Figure II.5 shows one example of discrete time evolutionary process. The initial population, generation $G^{(0)}$, is modified by mutation and breeding. Finally, the selection mechanism will define which individuals will be part of the next generation. The process continue cyclically. In practice, generations can be overlapping and breeding and mutation applied continuously.

In EGT, instead of considering the interaction directly amongst players, the players are considered to be extracted randomly from a population. Figure II.6 illustrates the concept. The players are drawn from the respective populations and matched up in a game. The most successful (fittest) strategies will have more offsprings in the next generation than in current one. The least successful strategies will be diminished and potentially vanish in the future. Mixed strategies can either be directly available to players or interpreted as the percentages of the population programmed to play a particular pure strategy.

II.7.1 Evolutionary Stability

The concept of evolutionary stability provides an important NE refinement.

Consider a symmetric two-person game, i.e., games with the following characteristics:

- There are two player positions
- The strategies available in each of the positions are exactly the same

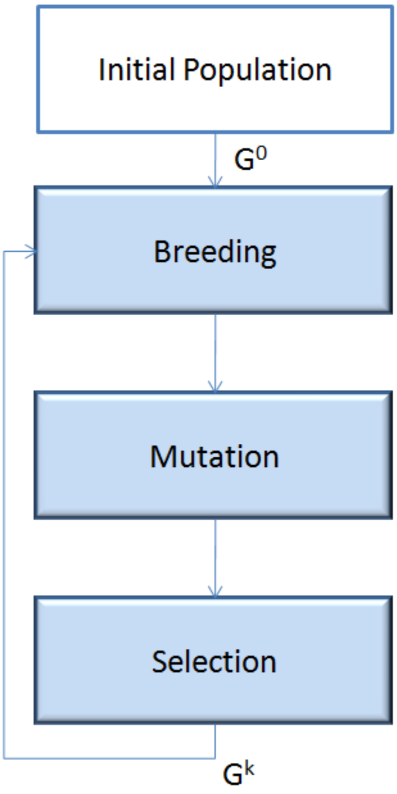


Figura II.5: One example of discrete evolutionary proccess. Selection mechanism defines a new generation.

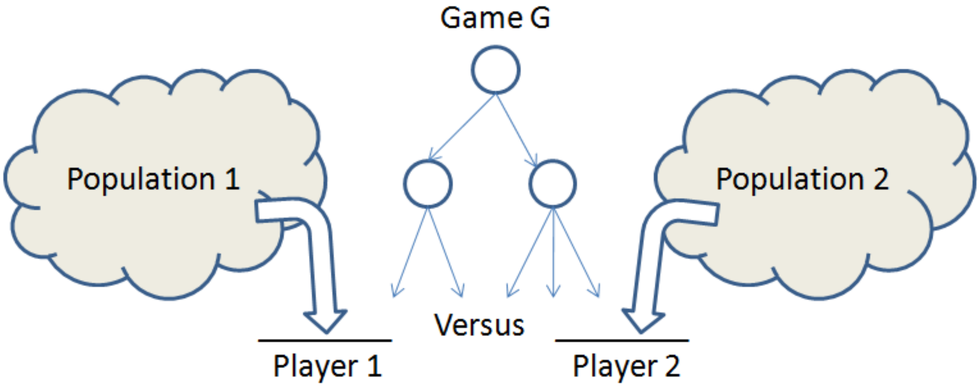


Figura II.6: Evolutionary view on a game. Players are randomly drawn from populations in order to effectively play a game realization.

- The utility is indepedent of position. It is only dependent on the selected strategy profile.

Most examples given in section II.2 are symmetric games. We assume that both players are drawn from the same population. Initially, the population is purely composed of the strategy x, which can be either pure or mixed. This strategy x, is called the *incumbent*. A small amount of mutants, all programmed to the same strategy y appear in the population. y can also be a mixed or pure strategy. Let us denote the share of mutants in the total population as ϵ. A player is expected to be placed against a x player with probability $(1-\epsilon)x$ and against a y player with probability ϵ. This is similar as facing a mixed strategy $\epsilon y + (1-\epsilon)x$. Denoting the utility of strategy s_1 versus strategy s_2 as $U[s_1, s_2]$ we have the following definition[20]:

Definition 7 *A strategy x is an Evolutionary Stable Strategy (ESS) if for every strategy $y \neq x$ there exists some positive $\bar{\epsilon}_y \in (0,1)$ such that inequality $U[x, \epsilon y + (1-\epsilon)x] > U[y, \epsilon y + (1-\epsilon)x]$ holds for all $\epsilon \in (0, \bar{\epsilon}_y)$*

In other words, a strategy is ESS if and only if it does better against the post invasion mixed strategy than any mutant does. Therefore, if mutation is a sparse event in time, evolutionary forces will restitute equilibrium to the ESS.

The name correlation of EGT and Evolutionary Algorithm (EA) is not occasional. Both consider evolutionary processes. EA are learning heuristics commonly applied in optimization problems. One special case of EA, the Genetic Algorithm (GA), is considered in [21]. The author shows that the learning process of GA results in a series of near NE, finally moving toward an ESS. This observation justifies the use of heuristical approaches to solve games. In particular, this is potentially applicable for solving spectrum sharing problem.

II.7.2 Replicator dynamics

As mentioned before, EGT also deals with dynamic aspects of game. This analysis using time-continuous replication as the breeding mechanism is called *replicator dynamics*.

We consider here a population of pure strategies. Let us assume that the utility function measures the fitness of individuals, directly affecting the number of offsprings that an individual has per time unit (the fittest the more offsprings). Let us also assume that replication occurs continuously over time and death rates are equal to all individuals. There can be also a background fitness which offsets all

With the assumptions above, it can be shown that for replicator dynamics the growth rate $\dot{x}_i/x_i$ of a strategy i is given by the difference between the fitness of this strategy and the average population fitness [20]

$$\frac{\dot{x}_i}{x_i} = [u_i(x,t) - \phi(x,t)] \tag{II.3}$$

Where, the average fitness at time t is given by:

$$\phi(x,t) = \sum_{n}^{i=1} x_i u_i(x,t) \tag{II.4}$$

As equation II.3 is specified for every pure strategy, it forms a set of differential equations.

In several cases, the replicator dynamics converge to the ESS as time goes to infinity, but this is not necessarily true.

II.8 CONCLUSION

In this chapter, the basic game theory concepts were presented. Several practical situations can be modeled as games. Games can be classified into static or dynamic games, as well as complete or incomplete information. Spectrum sharing protocols are more accurately represented by dynamic games of incomplete information. However, in order to have simpler models, static games and complete information may also be considered. Cooperative game-theoretic solutions can be quite efficient, but the involve the exchange of information before the game realization and this may not be feasible in an uncoordinated deployment scenario. Evolutionary game theory justifies the utilization of heuristic elements into the proposed framework in chapter IV.

III. SPECTRUM SHARING

III.1 INTRODUCTION

Terms such as Cognitive Radio[22], Next Generation Networks (xG)[10], Dynamic Spectrum Access (DSA)[10] and Spectrum Sharing (SpS) have been in use in the literature with similar meanings. Therefore, we start by attempting a precise definition for Spectrum Sharing. Dynamic Spectrum Access and Spectrum Sharing terms will be used interchangeably.

One of the most important results in telecommunication is that bandwidth limited signals modulated at different frequencies are orthogonal, as long as there is enough carrier separation. According to Fourier theory, no signal of limited time duration is bandwidth limited in the strict sense. However, if the power spectral density is low enough outside the band of interest, the signal can be considered bandwidth limited for practical purposes. The original signal can be filtered to enhance this characteristic.

Using that principle, several transmissions can use the same media at the same time. *Spectrum* is a term used to refer to a continuum of possible values, in this case the continuum of frequencies of interest. Throghout this text we use the term to refer to the spectrum available in the wireless media. In that sense, the spectrum is shared since the first time two wireless communication networks were deployed in the same geographical area. So what is new in Spectrum Sharing? The answer is on the dynamic nature of spectrum sharing. We use the following definition:

Definition 8 *Spectrum Sharing (SpS) is a mechanism for two or more wireless communication networks, within the relevant geographical area, to determine* **dinamically** *their spectrum allocation.*

From that definition, the term Dynamic Spectrum Access would probably be the more appropriate for the concept, but we will use Spectrum Sharing as most of the literature. The dynamic aspect is implicitily understood by the historical fact that in the past spectrum has been shared amongst networks with the use static spectrum allocations.

SpS is dealing with dynamic spectrum allocation amongst different networks. However, wireless networks can be formed of several entities, attempting to transmit several messages at the same time through the wireless medium. Therefore, spectrum is further divided within a network. In cellular networks the term Radio Resource Management (RRM) is commonly used to refer to the functions that control the spectrum usage and infrastructure utilization within a network. As the wireless media is the same, the problems of sharing spectrum within or amongst networks are coupled as discussed in section III.7.

Spectrum sharing deals mainly with the usage of the wireless medium. For that reason, it is important to have understanding of the mobile radio channel and the nature of interference. We show those aspects on the next sections.

III.2 THE MOBILE RADIO CHANNEL

Radio wave propagation is quite complex. Just to mention some of the involved phenomena:

- Specular reflection.
- Scattering.
- Refraction.
- Diffraction.

In a mobile radio environment, another dimension is added to this problem: mobility. Because of mobility, the spatial variation of the received signal is perceived in time. Due to the complexity of the problem, a statistical approach is commonly chosen to characterize the mobile radio channel. A classical approach, which has been used for several years in RF planning and simulations, is to divide the spatial variation of the received signal into three components:

- Median path loss.
- Large scale variation due to shadowing.
- Small scale variation due to multipath.

Using the link abstraction, one can *model* the behavior of propagation phenomena by superimposing these three aspects. We will first describe what is a link and then we will discuss about phenomena behind these three components.

III.2.1 Link abstraction

Wave propagation is broadcast by nature. As wave propagates, their power density becomes smaller and smaller, but at the same time the power is spread over a larger area. However, several applications of wireless deal with point-to-point communication and for that reason the link abstraction becomes important, because we want to characterize what happens between the points involved in the communication.

In Single Input Single Output (SISO) communication a link is usually defined as the RF channel between a transmitter node and a receiver node. We consider that the most straightforward and clear way of extending the concept for a MIMO case is to define a link as the RF channel between a transmitter antenna and a receiver antenna. Still, special treatment is needed for the links belonging to the same node since there may be correlation between the links.

One of the main characteristics of a link is how much the power is attenuated from the transmitter to the receiver. This attenuation is called *path loss*, L. A common statistical model of path loss is to estimate it by superimposing the median L_{median} and 2 random variables:

$$L = L_{median} + S + M \tag{III.1}$$

Where all the values are in Decibels (dB), where S is a lognormal distributed random variable representing shadowing and M is a Rayleigh distributed random variable representing multipath.

For instance, if one wants to know how likely is for a receiver to receive power above a threshold the link budget can be calculated considering the tail of each distribution as illustrated in Figure III.1[3].

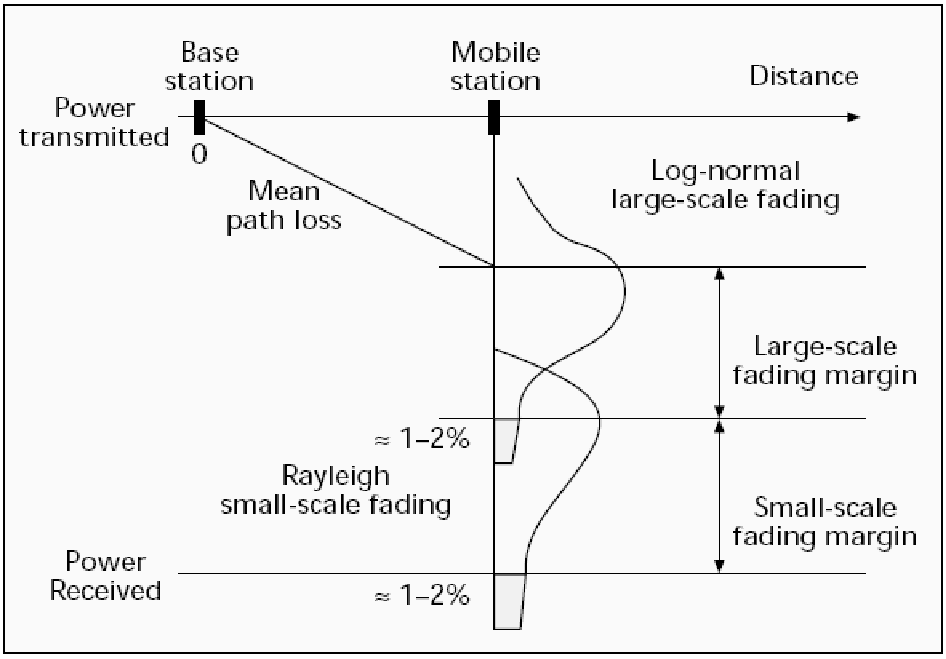


Figura III.1: Received power can be statistically characterized by superimposing 3 components. [3]

In some cases, it is needed to have the path loss in linear figures. We denote it by lowercase l and the conversion can be done by:

$$l = L^{\frac{L}{10}} \tag{III.2}$$

III.2.2 Median path loss

Free space propagation is deterministically dependent on frequency and distance between transmitter and receiver antennas. In near surface propagation, measurements show that there is correlation of median path loss with exactly the same components, frequency and distance, and other effects such as antenna heights, terrain and environment.

III.2.3 Shadow fading

The environment surrounding and in between a RF transmitter and a receiver influences directly the received signal. For instance, the path may be obstructed by buildings, bridges, vegetation and so on. There is also terrain variation. These obstructions are said to shadow the signal, from where the name shadow fading comes. Measurements show that shadow fading usually fits very well a log normal distribution. For that reason, shadow fading is also called log-normal fading.

III.2.4 Multipath fading

Because of reflection, scattering and diffraction, there are many paths from which an electromagnetic wave can propagate between a transmitter and a receiver. These wave fronts may arrive at different angles and phases. The exact way the signal is combined depends on the receiver and equalizer algorithm and implementation. Figure III.2 illustrates the multipath concept in Non Line Of Sight (NLOS) case.

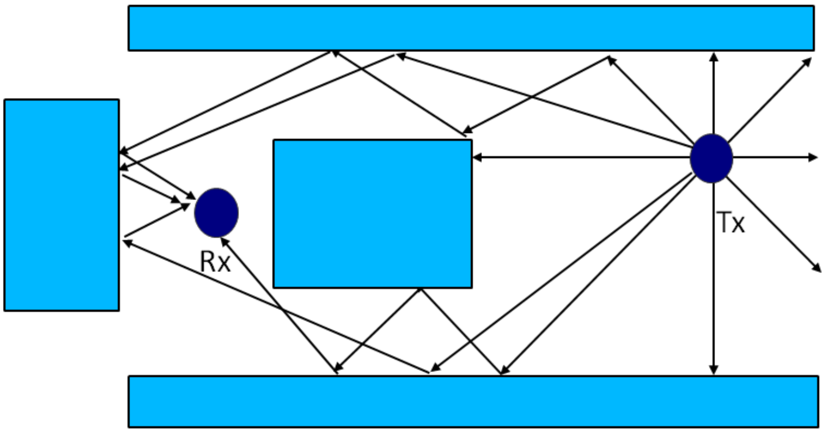


Figura III.2: The waves may go from the transmitter to the receiver through various paths.

Considering that the components of the signal arrive from all angles with a random phase uniformly distributed the sum of all components result in a Rayleigh distribution for the envelope of the received signal. This approximation is usually employed when there is NLOS condition. When there is Line of Sight (LOS) condition, all the multipath components of the signal are summed with a much stronger one that comes from only one direction, resulting in a Rician distribution, given the same assumptions.

One of the important implications of multipath is time dispersion/frequency selectivity. Every path has its own length, as shown in Figure III.2. As fast as wave propagation can be, it is not instantaneous and it is dependent on the total length the wave has traveled. For that reason, the signal as perceived by the receiver system is spread over time. The frequency domain description of time dispersion is frequency selectivity. This is exemplified in Figure III.3 for two different signals. The coherence bandwidth is a frequency range where the power spectral density has strong correlation, and it is a common way of characterizing frequency selectivity.

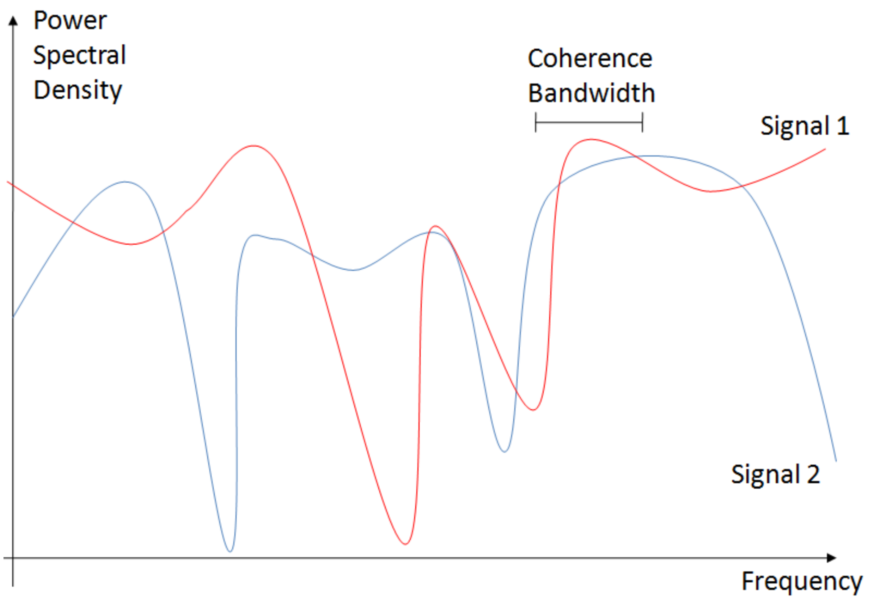


Figura III.3: Example of received signals coming through frequency selective channels.

There are many other statistical models for multipath fading presented in the literature. Some of them are presented in [23].

III.3 LINK CAPACITY

A link is a RF communication channel. Considering the Additive White Gaussian Noise (AWGN) model, the capacity is given by Shannon capacity formula:

$$C = BW\ log_2(1 + \frac{S}{N}) \qquad \text{(III.3)}$$

Where, C is the channel capacity measured in bits per second, BW is the bandwidth in hertz, S is the power of the intended signal and N is the noise power over the interest bandwidth. All the power values are given in Watts.

When interference is non-colored, i.e., constant over all the interest bandwidth, it is common to extend the AWGN formulation to interference. In order to be non-colored (white), transmission powers must be constant over the considered band and the bandwidth must be sufficiently smaller than the coherence bandwidth.

Assuming statistical indepedence of signals, and non-colored interference one can treat interference the same way as noise and the formula can be written as:

$$C = BW\ log_2(1 + \frac{S}{I + N}) \qquad \text{(III.4)}$$

Where I is the total interference power.

The Shannon capacity gives an upper bound, to capacity but that is actually approximated within a range by systems such as LTE. More accurate link capacity modeling involves complex link level simulations, that may include for instance colored and adjacent channel interference. However, it is commonplace in link models that capacity is directly dependent on the fraction Signal to Interference plus Noise Ratio (SINR):

$$SINR \equiv \frac{S}{I+N} \tag{III.5}$$

III.4 SIGNAL AND INTERFERENCE

As capacity is a function of SINR, it is important to understand how the components of this fraction relate to each other.

Noise is always present and can be determined by a characteristic of the receiver system named Noise Figure (NF). When noise dominates the sum I+N , the system is said noise-limited. Conversely, if this sum is dominated by interference, the system is interference-limited.

We next analyze the other components other than noise. For simplicity, let us assume SISO transmissions. We label all antennas present in the interest geographical area as $1, 2, ..., N_A$ where N_A is the total number of antennas. We analyze the link from antenna i (transmitter) to antenna j (receiver). The received signal is given by:

$$S = \frac{g_i \; g_j \; P_i}{l_{ij}} \tag{III.6}$$

Where g_i is the gain of antenna i as a linear value, g_j is the gain of antenna j, also as a linear value and l_{ij} is the path loss between the two antennas given by equation III.2. If the antennas are directional g_i and g_j depend, respectively, on the Direction of Arrival (DoA) and Direction of Departure (DoD) of the wave. In order to simplify the notation we will use the following term definition:

$$\hat{g}_{ij} = \frac{g_i \; g_j}{l_{ij}} \tag{III.7}$$

Then we can rewrite equation III.6 as:

$$S = \hat{g}_{ij} \; P_i \tag{III.8}$$

The interference, in its turn, is given by all the other relevant received signals. Statistical indepedence of signals allow us to write the total interference power directly as a sum of the power of each interference signal. Therefore, we can write the total interference power as:

$$I = \sum_{k \neq i} \hat{g}_{kj} \; P_k \tag{III.9}$$

Where k assumes all antenna values but i and j. In $\hat{g}_{kj}$, we used the same simplified notation given in equation III.8. P_k is only non-zero if the antenna is transmitting something.

Substituting the equations III.8 and III.9 in III.5, we can write the instantenous SINR for the link from i to j as:

$$SINR_{ij} = \frac{\hat{g}_{ij} \; P_i}{N + \sum_{k \neq i} \hat{g}_{kj} \; P_k} \tag{III.10}$$

Keeping equation III.10 on mind, we illustrate the nature of signal and interference with the example shown in Figure III.4, which shows two concurrent downlink transmissions using the same transmission band. The signal power is denoted by C , as in modulated signals the power is almost purely on the carrier.

Each of the base stations need to decide their transmission powers. As they want the maximum link capacity, which is a function of the SINR, they may want to increase the transmission power in order to increase the received signal power as given by equation III.8. But if, for instance, the base station on the left side increases its transmission power it will also increase the generated interference to the other link as given by equation III.9.

The converse is also true: if the base station on the right side increases its transmission power it will reduce the SINR perceived by the User Equipment (UE) 1, in the left side. So, the base stations have to decide their transmission powers, but they are influenced by each other decisions. Therefore, this is characterized as a game situation.

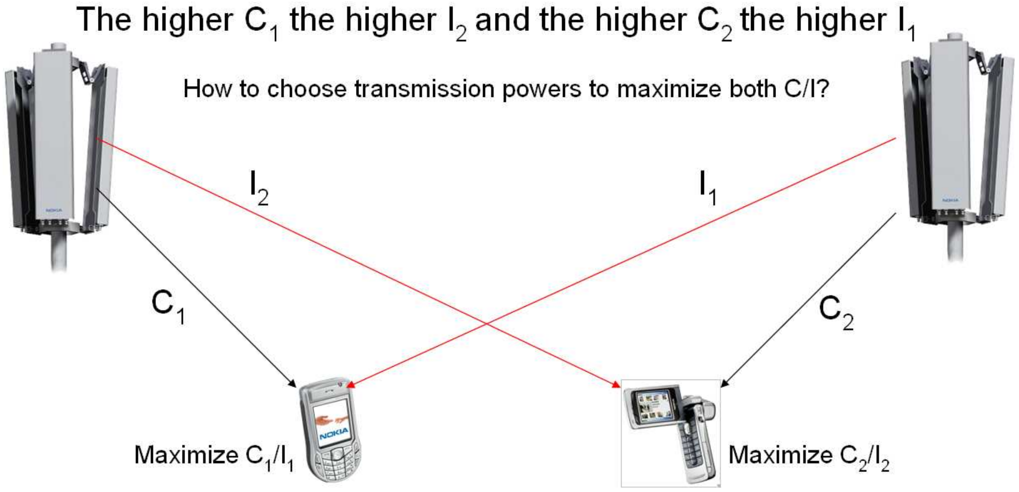


Figura III.4: SINR game. Two base stations have to decide their transmission powers but they influence each other because of interference.

The problem illustrated in Figure III.4 is the classical Power Control (PC) problem. While, PC has indeed been analyzed by Game Theory in the past, other solutions are more common. These

PC solutions are usually cooperative in nature. The reason is that with the classical spectrum licensing model, all interference comes from within the same network, given that the regulator did a proper spectrum assignment and separation. Since a network wants to maximize its system capacity, PC usually has the target to reduce the transmission power as much as possible, for a mantaining a minimum time average of SINR.

However, in a shared spectrum environment a greedy network could exploit a gentle one, by simply using maximum transmission powers all the time, which would ultimately lead for the best performance for the greedy network and the worst performance for the gentle one. This raises the following question: Why would you care about the performance of the other network which can be even from a competitor? In fact, in SpS competitiviness is more likely than co-operation. For that reason, non-cooperative Game Theory deserves extra attention in Spectrum Sharing compared to traditional PC issues.

The complexity of signal and interference considerations escalates very quickly with the number of transmitter nodes, as Figure III.5 shows.

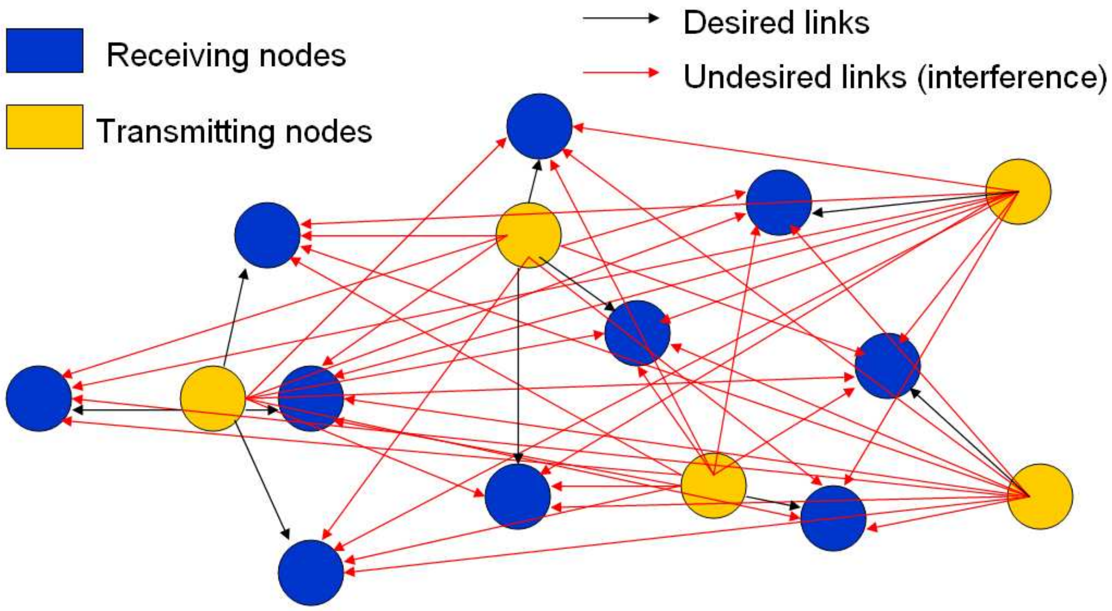


Figura III.5: With only 5 transmitter nodes and 10 receiver nodes there are already 50 path losses to be considered in SINR optimization

As the problem escalates it becomes more important to have a macro view on interference behavior, instead of focusing on one to one interference interactions. For that reason we discuss the large scale spatial signature of interference in next section.

III.5 SPATIAL CHARACTERIZATION OF INTERFERENCE

From a receiver point of view, the aim is to estimate and minimize the incoming interference. From a transmitter point of view, the problem can be inverted: How much interference is being generated to others? Figure III.6 shows the concept of exclusion zones. An exclusion zone is the area around a transmitter where receivers from other links will experience considerable interference. In the example of Figure III.6, the frequency bands in red and blue can be reused by the outer cells because there is no overlapping between their exclusion zones. The cells in the middle need exclusive frequencies and the isolated cell in the lower left can use all frequencies.

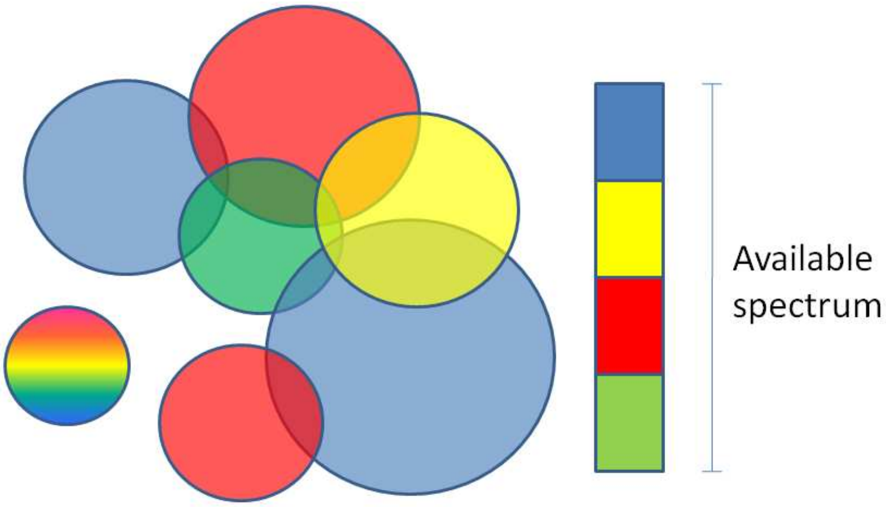


Figura III.6: Frequency can be reused if there is no overlapping of exclusion zones.

The exact shape of the exclusion zone depends on channel, antenna and receiver system characteristics. Conceptually, the size of exclusion zones can be modified if a simple policy, where some of the channels are used only for low power transmission and other part is used only for high power transmissions. This concept is illustrated in Figure III.7. Now the frequencies used in the outer cells can be reused more often. This benefit can be even brought to the other cells, depending on the way the spectrum is shared.

While this works fine for the ideal circular format of the cells, the varying propagation conditions may limit the usage of this approach in practice.

III.5.1 Antennas and Beamforming

Antennas play an important role in the shaping of exclusion zones. Directional antennas change the spatial signature of the signal or interference. In fact, in point-to-point fixed radio communication the antennas are choosen to be as directional as feasible in order to maximize the received SINR.

When the position of one or more nodes is unknown it is not possible to use full directivity for antennas. In cellular networks it is commonplace to use a technique named sectorization in order

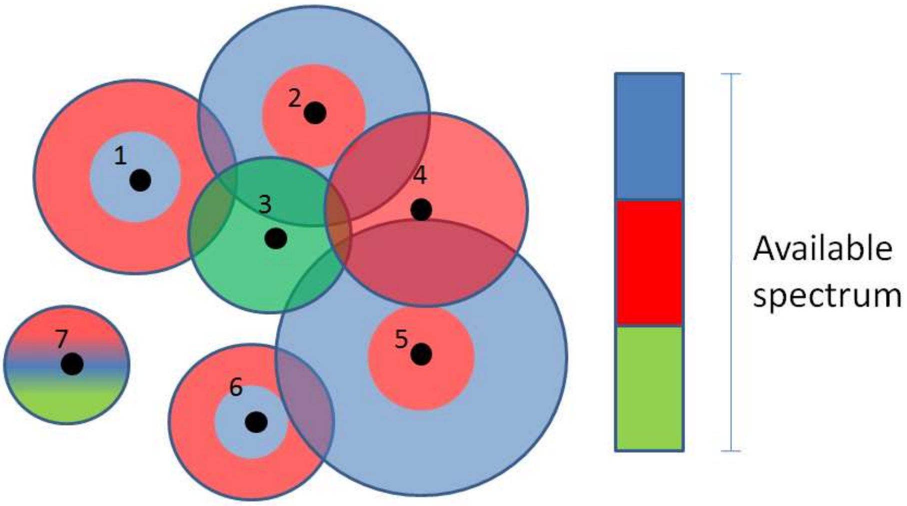


Figura III.7: Frequency channels are divide into low-power and high power users. Compared to Figure III.6, more frequencies are available for each cell.

to use directional antennas and reduce interference. It consists in dividing each site angularly into sectors (most commonly three) and using directional antennas in each sector. Using sectorization, the shapes of exclusion zones are effectively modified and the frequency reuse can be reduced (more dense reuse of frequencies). One drawback is the increased number of handovers, because each sector is in fact a different cell under the control of a different base station.

When antenna arrays are employed it is possible to use beamforming techniques to drastically modify the spatial signature of signal and interference. Fixed beam systems select amongs several fixed antenna patterns when transmitting or receiving. The final effect is similar to sectorization with potentially much narrower beams. Adaptative array systems dinamically form the antenna pattern for a transmission.

Sectorization requires network planning. This can be quite costly in local area deployment. Uncoordinated deployment and, therefore, omni-directional antennas are preferred. However, beamforming solutions can potentially be used even on local area networks. This kind of solution is not on the scope of this text.

III.5.2 The role of Duplexing

Commonly, the communication between two nodes has to be held in both directions. This is called a duplex communication. This means that both nodes will make transmissions. Since every transmission leads to an exclusion zone during the transmission time, it is important to analyze how duplexing affects the spatial distribution of interference.

In principle, any strategy used for multiple access could be used also for duplexing. Time Division Duplexing stands for the case where the duplexing is accomplished in time domain. For instance, during part of a frame period a downlink transmission is peformed and during another part of the frame an uplink transmission is done.

In Frequency Division Duplexing (FDD) different frequency bands are used for uplink and downlink transmissions. Given enough guard band, UL and DL transmissions are orthogonal. Traditionally, cellular networks use FDD as duplexing technique. Historically this comes from two reasons:

- Uplink and downlink interference can be considered separately, because of the inherent orthogonality. This also makes network planning easier.
- First and second generation of cellular networks are mainly oriented to circuit-switched voice, which needs symmetric data rates and, therefore, equal uplink and downlink bandwidths.

The implementation of a transceiver system with capability for simultaneous RF duplexing is quite complex. The received signals are of much smaller magnitude than the ones being transmitted, due to path loss. For instance, the transmitted signal can be at 30 dBm, while the received signal can be in the order of -100 dBm. Namely, 13 orders of magnitude. Complex RF circuitry is needed to keep the separation of the signals. For that reason, in Global System for Mobile Communications (GSM) systems, for example, only the base stations have to work fully on FDD manner transmitting and receiving at the same time. Practical Mobile Station (MS)s are either transmitting, receiving or switching between Tx and Rx modes. Therefore, MS are actually operating on combined FDD/TDD. Still the system is said to be a FDD system.

Recently, a lot of attention has been drawn to the use of pure TDD, specially when concerning local area deployment. The main driver for this is the packet oriented nature of the upcoming networks. Here are some of the TDD advantages over FDD:

1. **Asymmetric load flexibility**: Packet switched networks usually have assymetric load. In terms of access networks, the Downlink (DL) Packet Switched traffic is expected to be in most cases higher than the Uplink (UL) traffic. However the degree of assymetry is expected to vary over time due to unpredictable traffic variations. While FDD could be in principle made to work with assymetric bands, it is unlikely a solution where the bands can vary dynamically. TDD is suited to the implementation dynamic change of uplink/downlink capacity rate.

2. **Unpaired spectrum**: FDD needs to have paired spectrum. If a 100 MHz band is assigned for a FDD service, the allocation has to split into 2 bands, of e.g. 40 MHz, and leave spacing between them (e.g. 20 MHz). A TDD system can in principle exploit the whole 100 MHz bandwidth, in a single direction, which implies that TDD is more suitable to achieve high peak data rates.

3. **Symmetry of channel**: Several RRM algorithms are usually based on Channel State Information (CSI). In FDD, the DL information has to be feedback to the Access Station (AS), which

is an additional overhead. In TDD, if the frame is sufficiently short the channel can be considered symmetric and the CSI obtained with UL information can be used to take decisions applied to DL.

4. **Complexity of RF implementation**: TDD reduces the complexity of transceiver implementation. For the local area deployment the complexity of Home Access Stations can also be an issue and should be minimized to keep costs low enough.

Despite of all these advantages, the are also drawbacks:

1. Synchronization requirements are tighter
2. In order to obtain the CSI, there is need for calibration to compensate the different transceiver responses in each side.
3. Cross-interference between uplink and downlink if the systems are not fully synchronized (including same UL/DL switching point). This is the main drawback of TDD and it extremely relevant, *specially on a shared spectrum environment*, and the main objective of this section is to cover it.

Let us consider the home scenario in Figure III.8. In this example, each HAS wants to serve the UE in its own room, which would be a typical scenario for random deployment in home locations. Each of the HASs works indepedently, being a network, and we want to determine which part of spectrum can be used by each of the networks.

Figure III.8 shows one example of the paths to be considered in downlink intereference in a FDD system. Since DL and UL signals are orthogonal in frequency, interference can be considered separately for uplink and downlink. The exact situation here depends on transmission powers, but let us start analyzing the situation where everyone is transmitting at full power.

The UEs at rooms 2 and 3 are in good channel conditions. Interferers are far away compared to the intended transmitter and there is a wall separation to add on that. Contrarily the UEs on room 1 and 4 have their respective serving HASs far away and interferers quite close. The wall penetration loss aleviate the problem, but in this particular scenario if eveyone uses same transmission power and uses the same band, it is likely that UE_1 and UE_4 will be receiving in low or even negative SINR conditions.

Let us take the perspective of the network formed by HAS_1 and UE_1. The only chance to operate on good SINR conditions is to choose different transmission channels than HAS_2 and HAS_3, but HAS_4 is far away and could in principle reuse the same frequencies as HAS_1. So, HAS_1 knows who are the strong interferers(HAS_2 and HAS_3) and who it can co-exist with(HAS_4) . This knowledge can be formed because the number of interferers is limited and interference is correlated over time. Uplink problem can be solved the same way, indepedently of downlink problem.

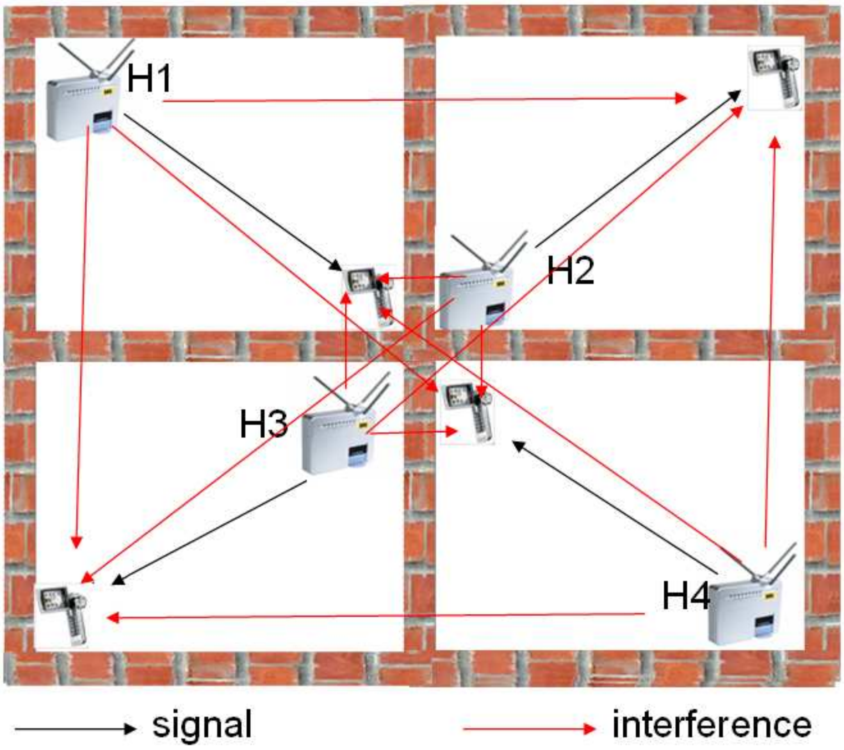


Figura III.8: Channel realizations to be considered in FDD downlink in one home deployment scenario.

Consider now TDD case where HASs are not fully synchronized. The DL and UL are no longer orthogonal. Interference can take any of the four forms:

- Uplink interference on a downlink signal
- Uplink interference on an uplink signal
- Downlink interference on a downlink signal
- Downlink interference on an uplink signal

Figure III.9 illustrates all the paths to be considered in the problem.

The Spectrum Sharing problem of Figure III.9 is much more complex than the one in Figure III.8. It is not only about the number of paths to be considered in the problem. The real trouble comes from the time-varying nature of interference in an unsynchronized TDD scenario. This can become clearer from a simpler example.

Figure III.10 shows the position of 4 nodes. The communication pairs are 1,2 and a,b. In the case of FDD, uplink and downlink are always orthogonal as shown in Figure III.11. In the case of unsynchronized TDD , however, the transmissions are not orthogonal and there are times within the frame where a receiver of the opposite system lies within the exclusion zone. This is shown in Figure III.12.

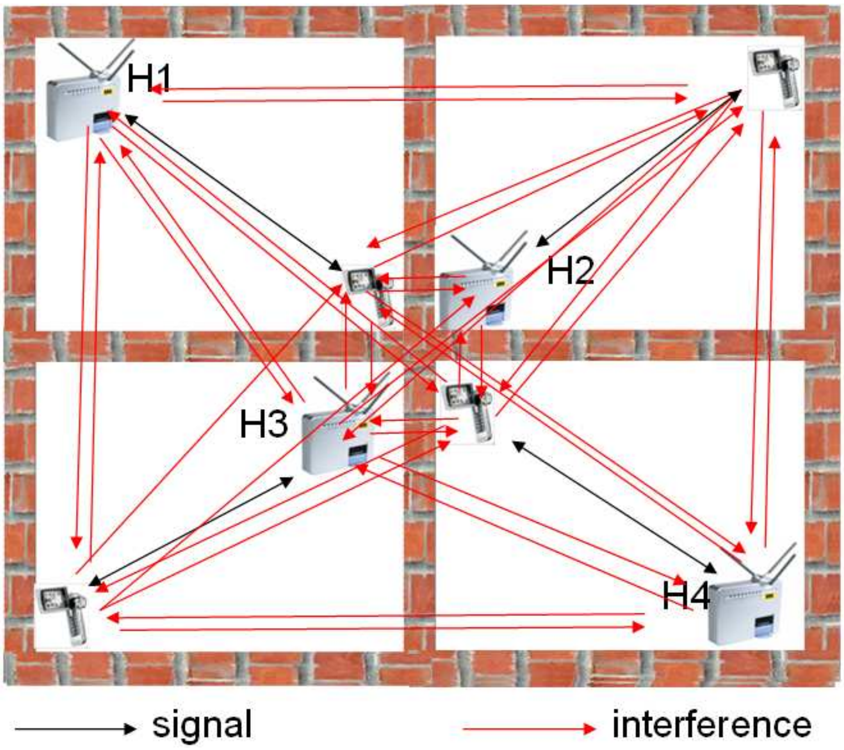


Figura III.9: Channel realizations to be considered in unsynchronized TDD in the same home deployment scenario as Figure III.8.

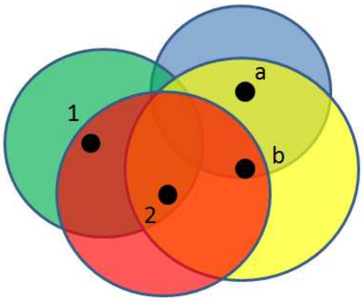


Figura III.10: Exclusion zones of 2 duplex systems

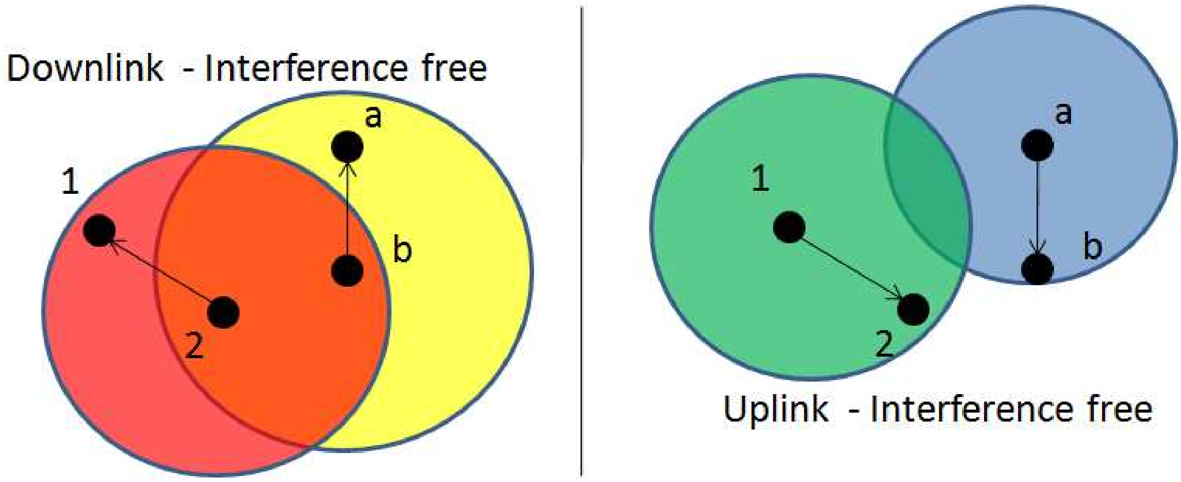


Figura III.11: Exclusion zones in the case of FDD

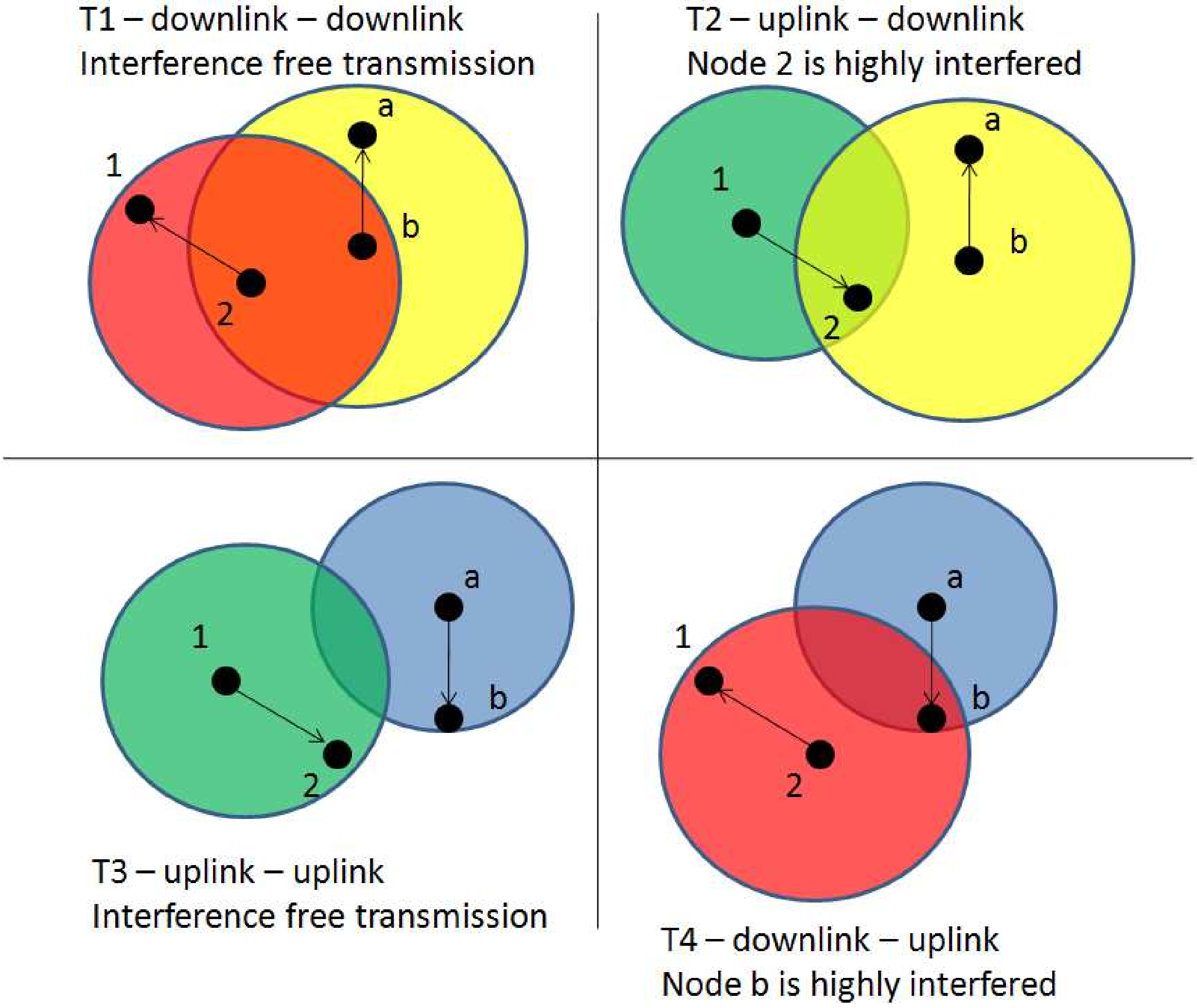


Figura III.12: Exclusion zones in the case of unsynchronized TDD. Depending on the time instant the transmission is interference free and in other times it is strong.

The example illustrated in figures III.11 and III.12, shows that in an infra-structured network having DL/UL orthogonality is very beneficial, almost mandatory to keep predictability of interference. Using the GT nomenclature of section II.5.2, it is hard for players to update their beliefs about other players, if the players who they are dealing with change all the time.

TDD transmission can be made to comply UL/DL orthogonality accross HASs in time domain. In order to achieve that goal we need to fulfill these 3 conditions at the same time:

- Same frame size, which can be assumed in Intra-system SpS and also Wide-area cellular systems.
- Wide area synchronization, which can be quite complex. Over the Air (OTA) synchronization is an important research area if SpS is to be employed in TDD systems.
- Same UL/DL switching point. This implies some mechanism of communication between the HASs and a protocol to agree on what will be this switching point. This also implies that a HAS will not have full flexibility to adapt the switching point to its own traffic requirement in any Transmission Time Interval (TTI).

Earlier in this section we stated the TDD advantages over FDD. Now we state the TDD use-case paradox:

1. TDD is a preferred duplexing technique because of the easier time flexibility for asymmetric load
2. Full TDD flexibility lead to wide variations in interference in time and space
3. To solve the problem one needs to synchronize all the HASs and use the same UL/DL switching point
4. But by using the same UL/DL switching point you no longer can adapt exactly to the traffic share you have, which was originally mentioned as the main reason to employ TDD.

However, it is not in the scope of this work to investigate solutions for this TDD use-case paradox. We assume that we have the case where all the HASs can synchronize and use the same UL/DL switching point. Game Theory can potentially be applied to solve the problem on how to define the UL/DL switching point.

III.6 INTERFERENCE COORDINATION IN EXISTING SYSTEMS

In order to understand the novelty aspects of spectrum sharing it is important to understand the drawbacks of existing solutions for sharing the spectrum within a network. In GSM there exists several solutions to reduce interference. Most of them work on randomizing the interference. A counter example is a proprietary solution is Dynamic Frequency and Channel Allocation (DFCA), which makes intelligent management of the radio resources accross several sites. However, the deployment of this solution requires tight synchronization of all sites.

In WLAN, CSMA/CA is used to provide dynamic access to the channel. When the channel is already occupied, a transmitter has to wait for its turn. Furthermore, if a collision occurs both transmitter will start backoff timers in order to solve the conflict. These operations lead to increased latency. Since in CSMA/CA the sensing is transmitter based, there are situations where two transmitters sense each other and avoid simultaneous transmissions even if the receivers are outside of the respective exclusion zones. This situation reduces the spectral efficiency in dense deployments and affects the scalability of the network.

In LTE, a signaling mechanism is standardized to provide Inter-cell Interference Coordination. It requires a special interface between base stations named X2. The deployment of X2 interface is unlikely to be feasible in uncoordinated local area deployment.

We can summarize by stating that existing interference coordination solutions have at least one of the following drawbacks

- Expensive deployment due to Global Positioning System (GPS) synchronization requirements
- Excessive latency
- Fail in terms of scalability
- Requires lots of signaling

The solution proposed in this work is aimed in addressing all these issues but the synhcronization requirements, which is left for future work.

III.7 SPECTRUM SHARING AND RRM

Cellular systems employ several strategies to make the best usage of spectrum resources within a network. These functions are collectively named Radio Resource Management (RRM).

In this work, we are solving the problem of sharing spectrum resource amongst networks. However, RRM and SpS are both trying to optimize the spectrum resource. Therefore, interaction between SpS and RRM is unavoidable. We believe that the best approach to introduce intra-system spectrum sharing while minimizing the changes to current RRM functions is to let SpS work on a much coarser time and frequence granularity than common RRM functions. This coarser granularity should be applied at least in time domain in order to avoid interaction between the adaptation loops. However, in terms of reduced complexity it is also benefitial to apply a coarser granularity on frequency domain. Figure III.13 shows this concept. We define a Shared Physical Resource Block (SPRB) as the minimal sharing unity in frequency domain.

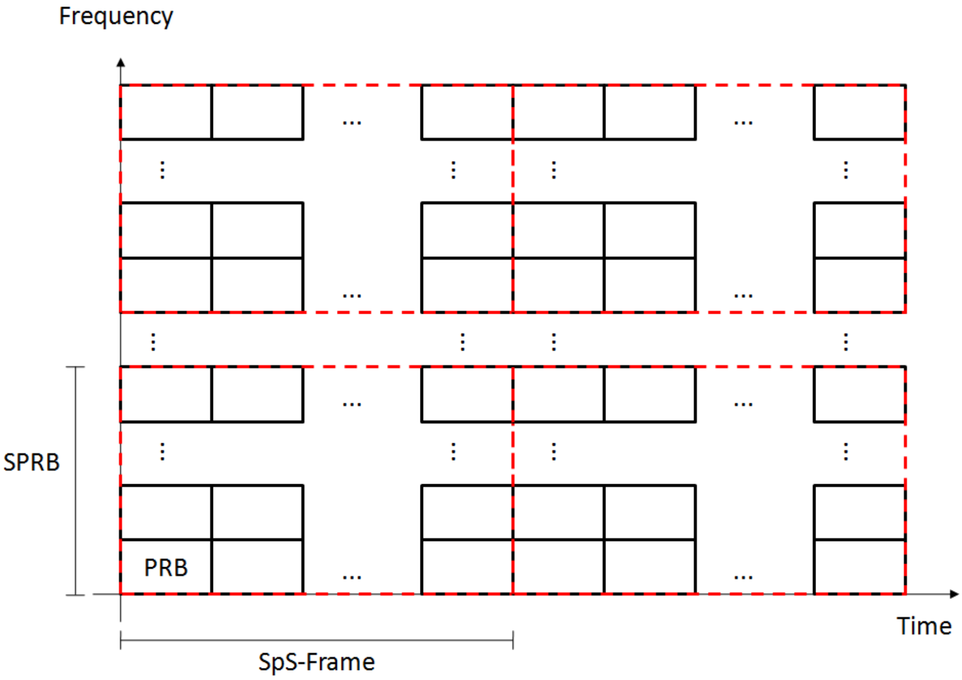


Figura III.13: Spectrum Sharing granularity is coarser than common RRM functions

We believe that the following policy should be used to design RRM functions in systems with shared spectrum

Policy 1 *RRM decisions that do not affect other networks or affect them positively can be taken any time. RRM decisions that potentially affect negatively other networks must be made according to a set of rules considered in spectrum sharing design.*

Policy 1 permeates the design of the proposed spectrum sharing protocol in chapter sec:GameBasedDistributedS

The interaction between Spectrum Sharing and Power control is that SpS set the maximum power per PRB that power control can select. Power control reduce power from this maximum any time since this complies to the policy 1.

III.8 CONCLUSION

In chapter III, the spectrum sharing problem was analyzed. Spectrum sharing was identified to be a generalized interference problem, where interference coordination is needed across different networks. The mobile radio channel was modeled, and on top of that the basic capacity equations in an interference scenario were presented.

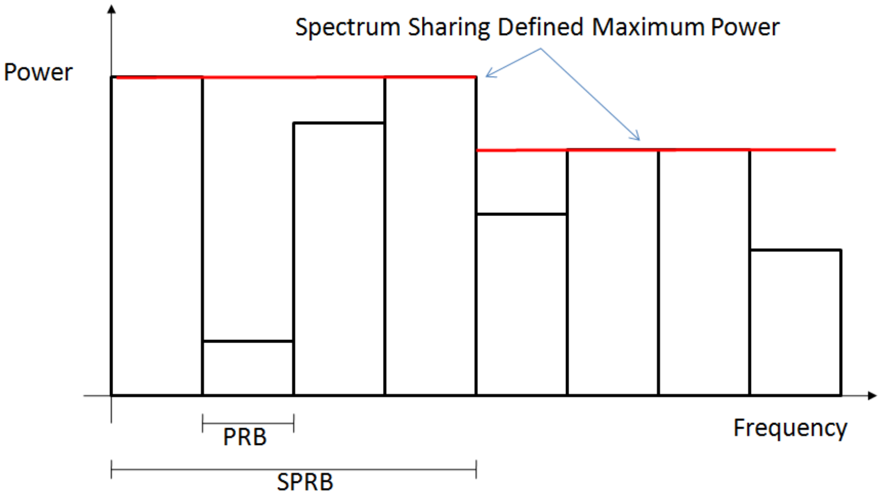


Figura III.14: Spectrum Sharing sets the maximum power per PRB. Power control selects the power per PRB (or user) indepedently.

The spatial distribution of interference was analyzed, and important considerations about duplexing were made. A policy was defined in order to minimize the interactions between intra and inter-network interference coordination. Some of the previous art in intra-network interference coordination was presented.

IV. GAME-BASED DISTRIBUTED SPECTRUM ALLOCATION

IV.1 INTRODUCTION

This chapter builds upon the knowledge and concepts summarized in the chapters II and III to make a practical proposal of spectrum sharing protocol based on game theory. The proposed framework is named GDSA and is modeled after a Bayesian game. Three design parameters are identified, and they are developed in order to cope with the limited information availability as well as efficiency and convergence.

IV.2 INTRA SYSTEM SPECTRUM SHARING GAME

We consider here intra-system spectrum sharing, in LTE-A local area deployment, as exemplified in Figure IV.1. The locations of the HAS an UEs are chosen by the users and their needs, meaning that there is no network planning. Each HAS serves a number of UEs and together they form a network. There is no communication interface between HASs, i.e., X2 is not implemented even between HASs of the same operator.

We assume that the spectrum pool is divided into blocks of subcarriers named SPRBs. The SPRBs are the smallest working unit for spectrum sharing, and they consist of an integer number of Physical Resource Block (PRB)s, as shown in Figure III.13.

Since there is no direct communication the full structure of the game cannot be known by the players. Also, bargaining (cooperative) solutions cannot be considered. Therefore, we model spectrum sharing as a non-cooperative bayesian game with the following elements:

1. The players are the Home Access Stations
2. The information sets are the moments of time where a particular HAS is allowed to change its SPRB allocation.
3. The available strategies are all possible power allocation into SPRBs.
4. The utility tries to maximize aggregate HAS capacity and minimize UE power comsumption
5. The Nature,i.e. processes that are not under players control, determines the position of HASs and UEs and their traffic requirements

Figura IV.1: Example of random deployment. The position of the HASs is chosen by the users and, therefore, manual network planning and optimization is not feasible.

6. The type, i.e. private information, of each HAS is
    - Traffic load
    - Measurements made at UEs and HAS

From a local point of view, the relevant players are all those which have overlapping exclusion zones. If we refer to Figure III.6 we can actually conclude that in a shared spectrum environment each player is affected by a different set of players. All a player can do to understand the presence of other players is to observe the interference received at the HAS and the UEs through sensing.

Considering this proposed game model, there are three things we can use as design parameters for a practical protocol:

- The game structure (information sets and their precedence). This corresponds to the allowed protocol states
- The utility function
- Strategies

In the next three sections we discuss the choice on these design parameters.

IV.3 THE GAME STRUCTURE

Since we do not have direct communication to allow for a NBS as in [5], we have to consider non-cooperative solutions, i.e., Nash Equilibrium.

[8] shows that in a static game of two-player interference channel, the Nash Equilibrium is very innefficient, specially on the case where the traffic queue of the other player is unknown. As we mentioned before, the traffic load in our model is part of the type of each player and therefore it is not known by other players.

It is known that in repeated games, NE can be more efficient than in the corresponding base game. Therefore, let us start assuming that we will formulate a base game structure which will be continuously.

The goals of this repeated game is to achieve:

- Highest peak data rates
- High spectral efficiency at any load
- Track load variations
- Long term fairness

Let us assume for the time being, that this repated game is capable of achieving these goals and let us focus on one aspect that in our view is understimated in the literature. Consider then the following situation: We have a number of HASs which efficiently share *the whole* spectrum pool in a fair manner. What happens if a new HAS comes into scene? A new player can change drastically the interference situation, leading to a lot of spectrum reconfiguration. At the same time the existing ones may be already making full utilization of the spectrum. Therefore, there is a possibility there is no spectrum hole at all where the new player can start. Furthermore, if the new player has to wait to slowly start fighting for resources this would incur in excessive setup time, i.e., control plane latency. Therefore, this situation needs special treatment.

We propose to use a protocol that has two main states. The repeated game happens every SpS-Frame. The new entrant game can start at any time instant and is treated as an interruption to the main protocol. The trigger for the new entrant part is a sudden and large traffic increase in a HAS. The clearest case is the initial setup of a HAS that is currently not using any spectrum, but the new entrant state can also be used, e.g., if some user start a very demanding application in a HAS already serving other services.

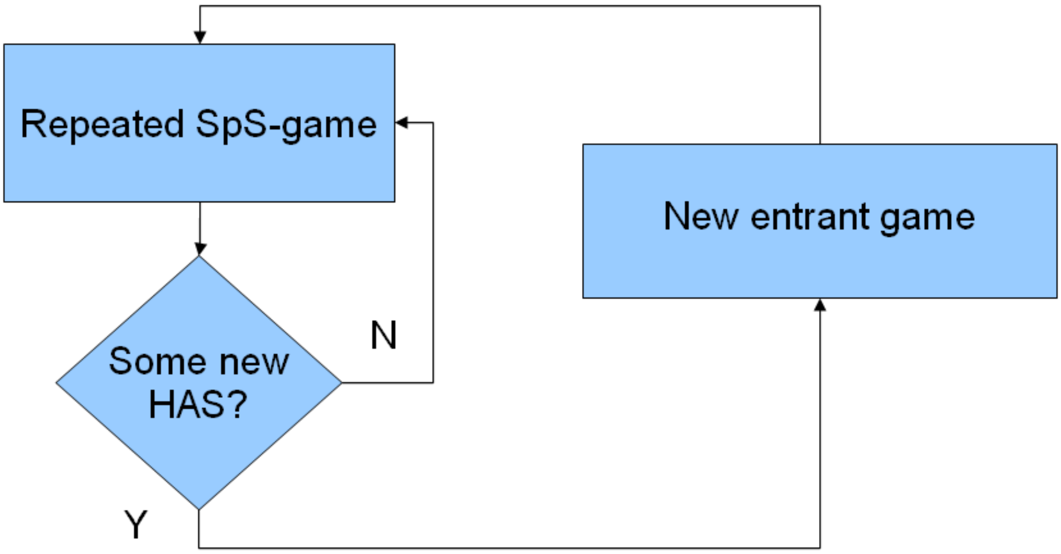


Figura IV.2: Game-Theoretic Spectrum Sharing protocol. It has two main states: repeated game and new entrant

Next, we design the proposed protocol states in Figure IV.2. The structure that will be used is the same, as defined in section IV.3.1, but the strategies considered in each part are slightly different as developed in section IV.5.1.

IV.3.1 New Entrant Game Structure

We assume that when a new HAS comes into scene it has been already proactively analyzing the RF scene through sensing. Sensing here is assumed to be based solely on the information of

HAS itself, as there is no ongoing transmission involving the UEs. As the systems are synchronized, a HAS can differ downlink from uplink interference analyzing the interfernce in the different parts of frame. This uplink measurements are fine, but the downlink information does not reflect directly the actual interference values that UEs will experiment once the transmissions start.

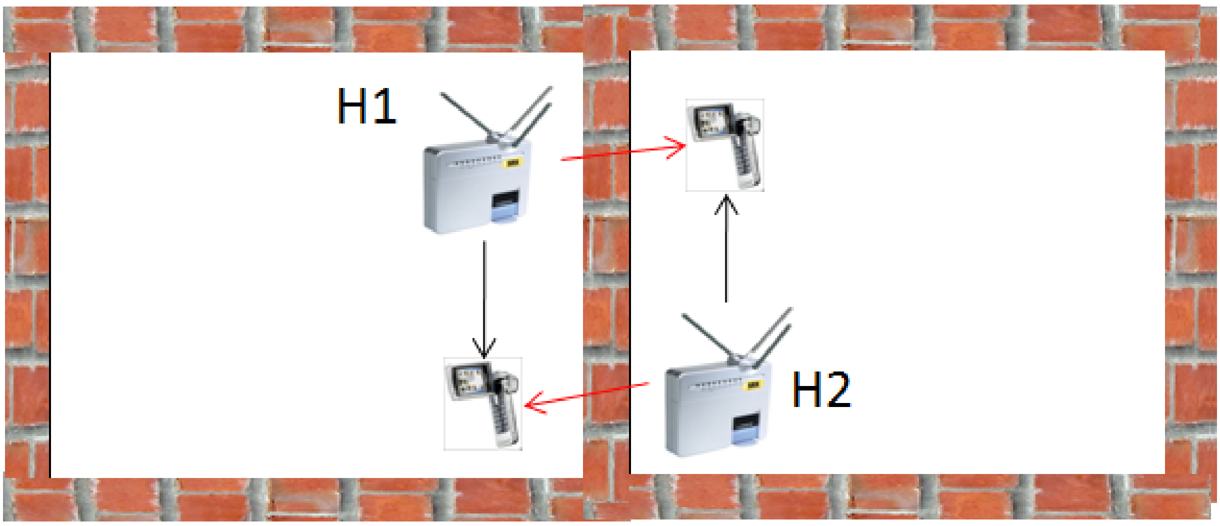


Figura IV.3: Local area example where interference can be close to signal level

Let us consider the case of two HASs illustrated in Figure IV.3. Before starting any transmission, the RF scene the new entrant can perceive is a function of three things:

- The power allocation made by the existing HAS
- The path loss of the path between the new entrant HAS and existing HAS
- The path loss of the path from the existing UEs to the new entrant HAS

So we can state that as for the very first spectrum allocation, the new entrant can indirectly condition its decisions on these three elements. That corresponds to the first decision to be made in the new entrant game.

There are two important paths that can not be considered in this initial allocation. Namely, the path loss from the new entrant HAS to the UE(s) it is going to serve and the path loss from the existing HAS to the UE(s) served by the new entrant. The effect of these paths will only be perceived when the transmissions effectively starts. Therefore, we propose that after decision is taken based on the available information, the transmissions are started right away. This is in a sense a dual concept of CSMA/CA. In CSMA/CA, when we detect potential interferers we avoid transmission. Here, we start transmissions that we know will cause interference and try to cope with their effects later.

The spectrum allocation initially made by the existing HAS was not conditioned on the interference generated by the new entrant. So, we propose that in a second stage the existing HASs update their spectrum allocation based on the fact that a new entrant was detected.

The initial allocation made by the new entrant was not conditioned on the paths involving the UEs served by the new entrant. Also the new decisions made by the existing HASs affect the RF scene perceived by the new entrant. Thus, a final stage is needed to make the decision of the new entrant indirectly conditioned on all relevant factors: all path losses and power allocations.

In summary, we propose the following protocol (game structure) of three stages for the new entrant game:

1. **Bargaining stage:** the new entrant is the only one to move, deciding the initial spectrum configuration and starting transmissions on it right away.
2. **Response stage:** after sensing the effect of the new entrant, the existing HASs change their spectrum allocation to answer the new entrant threat.
3. **Adjustment stage:** conditioned on the answer provided by the existing HASs, the new entrant makes final adjustments on the spectrum allocation.

After adjustement phase, the operation is resumed to the repeated game.

Figure IV.4 illustrates how this protocol is expected to work in a simple case with two HASs. Initially the whole spectrum is use by the existing HAS, labeled HAS_1. The new entrant HAS, namely HAS_2, analyzes the RF scene and can determine that the whole spectrum is in use. In this example, the new entrant decides that SPRB 4 is too interfered and, for that reason, it is not worth. It decides that it will start transmission on SPRBs 1, 2 and 3.

After HAS_2 has determined this initial spectrum allocation it simply starts transmitting. However, there may be several connections ongoing in HAS_1 and they might not be able to recover from prolonged interference, even with advanced strategies such as H-ARQ. We propose that in this initial phase a transmission pattern that is sparse in frequency in time is used. One such example is to transmit only in a SPRB at once and perform block subcarrier hopping from time to time, to randomize interference on frequency domain. This is illustrated in the time part labeled as "After bargaining" in Figure IV.4. The pattern should be standardized and facilitate the sensing by the existing HASs, as well as being clearly distinguishible from fading.

When the existing HAS senses the new entrant it starts providing the answer. In this situation it decides to give up SPRB 3 which became too much interfered and increase the power allocation in SPRB 1, 2 and 4.

In this example, the HAS_2 senses that SPRB 3 became a spectrum hole and starts using it full time. When the second HAS_2 transmission on SPRB 2 is started the quality is perceived to be severely degraded. This is interpreted as a power increase by the existing HASs. Considering the knowledge of the new entrant before bargaining and after answering we can state the following: The *a priori* belief of HAS_2 about SPRB 2 was that it could potentially be used at the same time by both HASs. The *a posteriori* belief about SPRB 2 is that this SPRB is very valuable to HAS_1 and not very valuable to HAS_2 . Therefore, HAS_2 gives up this SPRB.

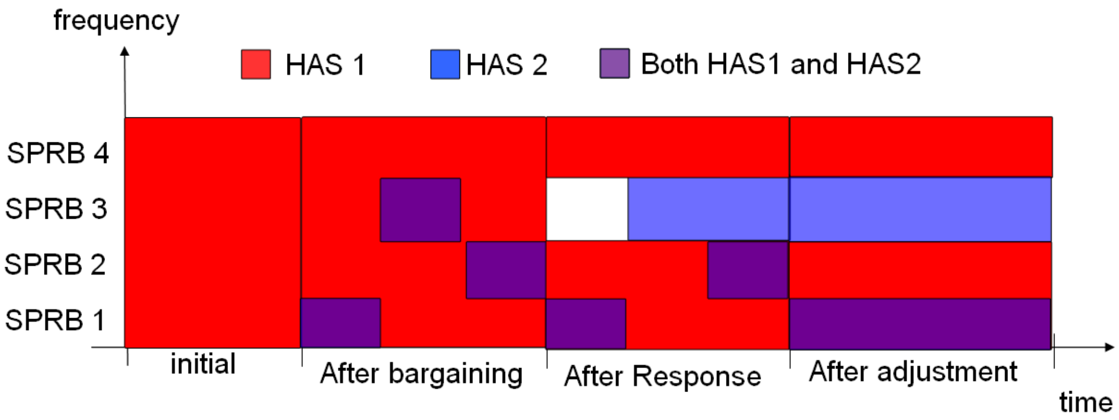


Figura IV.4: New entrant game

Whereas the *a priori* belief about SPRB 1 was exactly the same, the *a posteriori* verification was the opposite: it is still good (due to a different power allocation or indepedent fading with respect to SPRB 2) and it is fine to keep the transmission on it. This example should make it clear why this dynamic structure was chosen for this bayesian game with indirectly observed outputs, and how condititioning plays an important role in this kind of game.

After the adjustment is finished we complete the new entrant phase, and we have the proper initial allocation of HAS_2. In this example we end with 3 allocated SPRBs to HAS_1 and 2 to HAS_2. Note that the share of resources is not fair, as usually defined in telecommunication, but it is fair in another sense. The RRM of the new entrant is doing initial allocations. Also the upper layers are trying to define the initial parameters. For instance, Transmission Control Protocol (TCP) connections will be on slow start phase[24]. The RRM and upper layers of the existings HASs on the other hand, have to cope with suddenly reduced capacity. This cause severe degradation to existing connections, and potentially some of them will even have to be dropped because of the new entrant. As an example, with consecutive packet losses (caused by congestion or errors), TCP Reno moves to congestion avoidance state, which leads to reduced througput for a long time [24]. Therefore, the existing HAS should be favored over the new ones in this initial step.

In short, by using the appropriate strategies, this protocol is expected to be able to determine which portions of spectrum can be shared and which portions cannot be shared by using only sensing and power allocation as implicit communication (Physical RF communication).

IV.3.2 Repeated Game Structure

Following the same reasoning of conditioning decisions on all relevant paths we propose that the base game for the repeated game shall follow exactly the same structure of the new entrant game. The outcome of a single execution of the new entrant game is unlikely to be the most fair or the most efficient, but when the game is repeated over and over, some strategies can lead to increased efficiency and fairness.

However, there are some other effects that must be considered in the long run of a practical intra-system spectrum sharing protocol:

- Definition of DL/UL switching point (section III.5.2)
- Other aspects that affect spatial distribution of interference, such as the number of spatial streams (section III.5)
- Power control dynamics (section III.3)

Finding joint solutions for these aspects is not on the scope of this work, since here we are mainly dealing with frequency domain spectrum sharing. However, we propose a framework that delineates how these aspects can be included in the future providing a boundary to our problem. Figure IV.5 shows the framework: DL/UL switching point is rarely modified, while the adaptation is continously done in frequency, power and space domains.

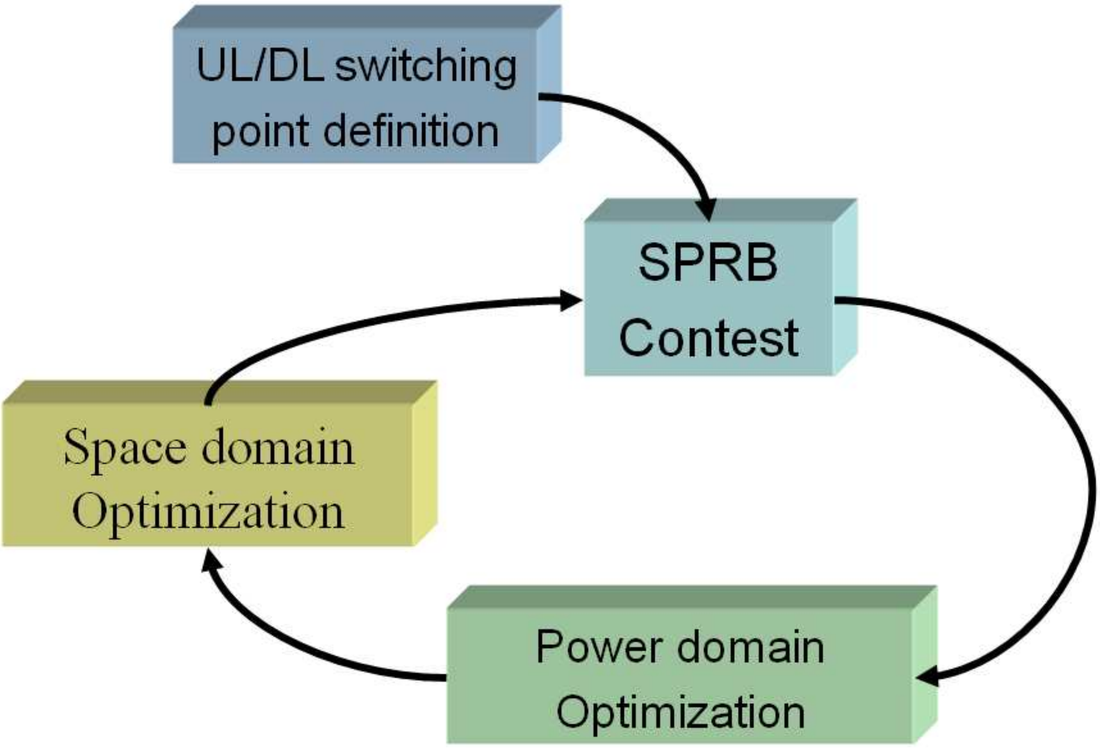


Figura IV.5: Repeated SpS game structure. The loop lasts one SpS-frame.

This would correspond to a superframe structure as shown in Figure IV.6

IV.3.2.1 Adjusting the uplink/downlink switching point

The definition of UL/DL switching point plays a major role in how interference is distributed in time and space, as described in (section III.5.2. Remember, also, that our working assumption

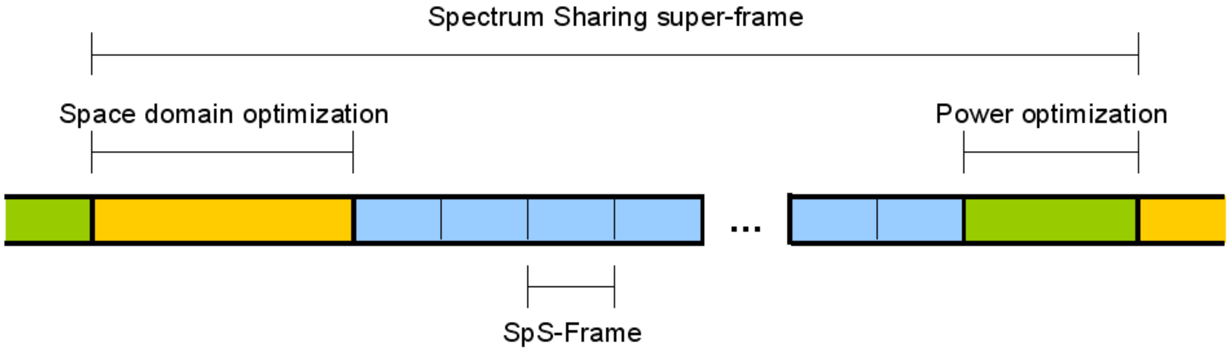


Figura IV.6: SpS Superframe structure

is that all HASs synchronize their UL/DL switching point even before any spectrum sharing algorithm can be used. Therefore, a change in the UL/DL switching point must be synchronously made over a large area. Furthermore, changing the UL/DL is a complex operation within a HAS as it has to be signaled to all UEs. For all those reasons the defined UL/DL switching point shall remain the same for a long time.

In the light of policy 1, defined in section III.7, HASs are allowed to transmit less than full time in each direction. For instance, if the UL/DL switching point is 60% of time in downlink and 40% in uplink, it is allowed to transmit anything less than 60% of time in downlink and anything less than 40% of time in uplink. But it cannot go over these limits nor change the alignment of the frame.

Since we must have a single UL/DL switching point, and every HAS has it own UL/DL traffic share, we propose that a voting system should be used. Though the specification of the voting protocol is out of the scope of this text, we mention that Game Theory can be used to analyze and design voting systems [9]

IV.3.2.2 Spatial adjustments

Policy 1 is specially important to consider when it comes to spatial adjustments. Spatial processing is very tricky to consider from interference management point of view because it effectively changes the number of signal and interference channels.

If the changes are allowed at any time instant they can interact in a negative way with the SpS mechanisms we are defining on frequency domain. Therefore we propose that any MIMO link adaptation procedure that increase the number of interference links should be performed at this special part of SpS-Frame taking care of that. If the adaptation keeps or reduces the number or links it is fine to be performed at any time.

IV.3.2.3 SPRB Contest

This is the focus of our work and corresponds to spectrum sharing in frequency domain. Continous adaptation of spectrum allocation is needed. Since traffic is bursty in Packet Switched (PS) networks, therefore the traffic demand can increase or decrease during time. Also, given the dynamics of the mobile radio channel new spectrum holes or strong interferers may appear.

This part of the protocol correspond to several repetitions of a base game of exactly the same form of new entrant game. However, while the new entrant game can in principle allocate all SPRBs at once, we only allow for allocation of a small number of SPRBs at each step here.

Policy 2 *In every run of the repeated game, the amount of SPRBs that can be allocated at once is limited. The only exception is when there is a new entrant HAS. The exact amount of SPRBs at each repeated game step shall be specified in standard or downloadable from a policy server.*

Policy 2 role is two-fold:

- Provide hysterisis in terms of resource allocation, because there is a high probability that a node that stops transmission will start transmitting again soon. For example, web browsing service involves bulky transfers followed by large human reading times. The main Quality of End user experience (QoE) Figure for web browsing is click to content delay. Even if the new entrant protocol is designed to be run fast, one should avoid running it every time the user clicks in a new content. Therefore, other HASs should not be so eager on occupying a new spectrum hole.
- Reduce the amount of interactions between SpS and RRM , as discussed in section III.7.

IV.3.2.4 Power adjustment

Once the interference scenario is consolidated in time, frequency and space, it is a good time to further optimize power dimension.

Because of the dynamics involved, the current power allocation depends on the past history. This means that it is unlikely to be optimal. Furthermore, unsynchronized efforts to reduce power may not be enough if each players employ completely different power allocation policies and power control algorithms.

This step should be seen as an attempt to reduce transmission powers in order to provide benefits for everyone. It should be done at the same time over a large area, because each HAS is affected by a different set of neighbours, as shown for example in Figure III.6.

We do not specify the algorithm here, but we believe that an approach aiming at a NBS can increase the overall efficiency of the repeated game loop. However this requires signaling between HASs. Considering our work assumption, that direct signaling is unavailable, an heuristic approach based on Genetic Algorithm can be an alternative solution, as described in section II.7.1.

IV.4 UTILITY FUNCTION

In order to analyze the effect of different utility definitions we study the following simplified static spectrum sharing game:

- Two players 1,2.
- Each player can select to use 1, 2 , 3 or 4 SPRBs. The SPRBs are selected in a way that maximizes the number of orthogonal allocations. For instance, if one player select 2 SPRBs and the other one selects 3 SPRBs, than only one block is shared.
- Interference is strong and symmetric if the same subchannel is used by both players. When orthogonal channels are used, interference is negligible (the receiver does not saturate and orthogonality can be kept).
- There are only 2 modulation schemes available: QPSK, providing 2 bps/Hz and 64-QAM, providing 6 bps/Hz. Considering the previous assumption, if a SPRB is shared QPSK will be necessarily used. If it is not shared, 64-QAM is used. The coding scheme is the same and it is enough to make residual Bit Error Rate (BER) negligible as long as the proper modulation is selected.
- The utility function is to be designed to have the most efficient and fair output of this game.

Considering all these characteristics the aggregate capacity of player i is given as:

$$C^{(i)} = 2BW_{SPRB}R(N_{QPSK}^{(i)} + 3N_{64-QAM}^{(i)}) \tag{IV.1}$$

Where, BW_{SPRB} is the band of an SPRB, R is the coding rate, $(N_{QPSK}^{(i)}$ is the number of selected SPRBs using QPSK and $N_{64-QAM}^{(i)})$ is the number of selected SPRBs using 64-QAM.

The situation described here, can arise for instance in the scenario exemplified in Figure IV.3

As $2BW_{SPRB}R$ is a multiplying factor we consider a normalized capacity based utility defined as:

$$U_C^{(i)} = \frac{C^{(i)}}{2BW_{SPRB}R} = (N_{QPSK}^{(i)} + 3N_{64-QAM}^{(i)}) \tag{IV.2}$$

Table IV.1 shows the strategic form of the case study static game when using utility function as defined in equation (IV.2). The strategies in the rows are the number of selected SPRBs by player 1, while the strategies on the columns corresponds to the number of selected SPRBs by player 2.

The only Nash Equilibrium is the point where both players select all 4 blocks. In order to see this, observe that selecting all blocks will maximize the outcome no matter what the other player does. In other words, selecting all blocks is always the best response to any enemy strategy. Recapitulating, a Nash Equilibrium is a strategy profile where all strategies are best responses to the other ones.

	1	2	3	4
1	3,3	3,6	3,9	1,10
2	6,3	6,6 NBS	4,7	2,8
3	9,3	7,4	5,5	3,6
4	10,1	8,2	6,3	4,4 NE

Tabela IV.1: Example of symmetric spectrum sharing game with utility based on aggregate capacity. Strategies are the number of selected SPRBs.

In this game, there are several Pareto Optimals, i.e., non-dominated strategy profiles. In fact, any strategy profile satisfying one of this two equations is a PO:

$$N^{(1)} + N^{(2)} = 4 \tag{IV.3}$$

$$N^{(1)} + N^{(2)} = 5 \tag{IV.4}$$

This can be seen by extensive comparison of the values in Table IV.1.

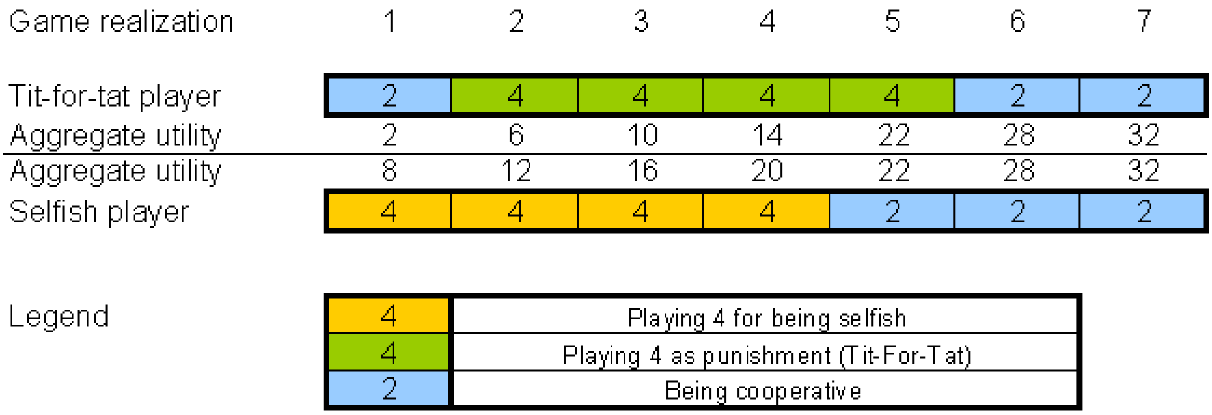
However, the only fair PO is the point where both players select 2 SPRBs, and therefore, that is the only candidate to be a NBS. Using the definition from section II.6, we define the price of the anarchy for this game as the rate between the NBS(6,6) and the NE(4,4). Therefore the price of anarchy is $3/2$ for each player.

This simple example shows that when interference is considerable, increasing spectrum allocation may not be interesting. If one increases the spectrum allocation, one can expect its opponents to increase the spectrum allocation also in order to compensate the losses. NE predicts exactly the extreme case: In a single execution of a game in table IV.1 the only rational playing is selecting all blocks, since one can assume that the opponent will do exactly the same.

In a repeated game, however, it is possible to have different types of interaction. For example, in a repeated game with observable outputs after every stage, it is possible to copy the behavior of the opponent to punish him. Let us, then assume that the game table IV.1 is repeated between the same players with infinite horizon (no player is expected to stop playing any soon). Consider the following trigger strategy based on Tit-for-Tat(section II.4): In the first round select 2 blocks. On the following rounds repeat the strategy adopted by the opponent in the last round.

First, we exemplify the Tit-for-Tat by showing that in a finite game a selfish player does not gain by trying a selfish strategy against Tit-For-Tat. Also the selfish palyer does not get better utility than the Tit-for-Tat one. Figure IV.7 shows such a situation. In the game execution 5, the selfish player finally gives up the selfish strategy and after that both have the same utility. the Tit-For-Tat forgives the selfish player and comes back to cooperation as soon as his opponent did.

If we make a similar analysis with 2 Tit-for-Tat we can deduce that they always cooperate, achieving highest utility in this game. Therfore, Tit-for-Tat is good both against selfish and cooperative players.



Game realization	1	2	3	4	5	6	7
Tit-for-tat player	2	4	4	4	4	2	2
Aggregate utility	2	6	10	14	22	28	32
Aggregate utility	8	12	16	20	22	28	32
Selfish player	4	4	4	4	2	2	2

Legend	
4	Playing 4 for being selfish
4	Playing 4 as punishment (Tit-For-Tat)
2	Being cooperative

Figura IV.7: Evolution of aggregate utility when a player uses Tit for Tat

In order to make a more general analysis, we consider a game with infinite horizon. A discounted utility is used as defined in equation II.1 and repeated here for convenience:

$$\pi_i = \sum_{k=0}^{\infty} \delta^k U_{ki} \tag{IV.5}$$

where the series is infinite, because of the infinite horizon assumption.

Player 2 plays the Tit-for-Tat strategy and player 1 wants to find the best response for it. First let us try the strategy that was the best response in the single execution game: always selecting 4 blocks. In the first round this will give 8 to the player 1 and an utility of 2 to player 2. In all the consecutive rounds, both players will have utility of 4 for both players. Therefore we can write the discount utility as seen at initial round as:

$$\pi_1 = 8 + \sum_{k=1}^{\infty} 4\delta^k \tag{IV.6}$$

$$\pi_2 = 2 + \sum_{k=1}^{\infty} 4\delta^k \tag{IV.7}$$

We can rewrite the sum in terms of a geometric series as follows:

$$\sum_{k=1}^{\infty} 4\delta^k = -4 + 4 + \sum_{k=1}^{\infty} 4\delta^k = -4 + \sum_{k=0}^{\infty} 4\delta^k \tag{IV.8}$$

By substituting this sum in the previous equations and taking the constant value 4 out of the sum, we have:

$$\pi_1 = 4 + 4\sum_{k=0}^{\infty} \delta^k \tag{IV.9}$$

$$\pi_2 = -2 + 4\sum_{k=0}^{\infty} \delta^k \tag{IV.10}$$

Since the discount factor δ is confined to the interval $\delta \in (0, 1)$, the geometric series converges to:

$$\sum_{k=0}^{\infty} \delta^k = \frac{1}{1-\delta} \tag{IV.11}$$

$$\pi_1 = 4 + \frac{4}{1-\delta} \tag{IV.12}$$

$$\pi_2 = -2 + \frac{4}{1-\delta} \tag{IV.13}$$

Now let us consider the case where player 1 also plays the Tit-for-Tat strategy. Both players become cooperative and will always play the NBS. Then we have:

$$\pi_1 = \pi_2 = \sum_{k=0}^{\infty} 6\delta^k = \frac{6}{1-\delta} \tag{IV.14}$$

We can check that if δ is appropriately chosen, the utility of player 1 is higher when choosing also the Tit-for-Tat than if it chooses 4 blocks:

$$\begin{aligned} \frac{6}{1-\delta} &> 4 + \frac{4}{1-\delta} \\ \frac{2}{1-\delta} &> 4 \\ 2 &> 4 - 4\delta \\ \delta &> \frac{1}{2} \end{aligned} \tag{IV.15}$$

Therefore, with $\delta > 1/2$ choosing 4 blocks is not a best response to the trigger strategy. Similar calculations can be made to compare the Tit-for-Tat strategy with all other strategies and show that this trigger strategy is the best response against itself and, therefore, it is a Nash Equilibrium of the repeated game.

The underlying assumption of this working example is that whenever there is interference it will be symmetric and bad enough so that it will cause a large variation in the Modulation and Coding Scheme (MCS) choice. In practice the interference will be most of the time asymmetric, due to the positions, and there will be more choices for MCS available. Also, in a practical situation the number of players and their channel conditions will vary over time because of the mobility of the UEs and scatterers.

Motivated by the efficiency of the Tit-for-Tat strategy we develop another approach, that is more practical given the incomplete information nature of the problem. A basic feature of the Tit-for-Tat example is that the opponent is able to copy the last iteration behavior and use that against the other player. This will be our working assumption: every time a HAS decides to transmit in a band that is already occupied, it will cause an unknown opponent to take the same action, which will ultimately reflect on the first one.

More specifically, let us assume that there is single spectrum pool of bandwidth B. We are devising strategy for player 1 and want to decide what share of B player 1 should use to maximize its outcome. In a noise limited scenario we know from Shannon capacity that we should use as much bandwidth as possible:

$$C_i = B\ log_2(1 + \frac{S}{N}) \tag{III.3}$$

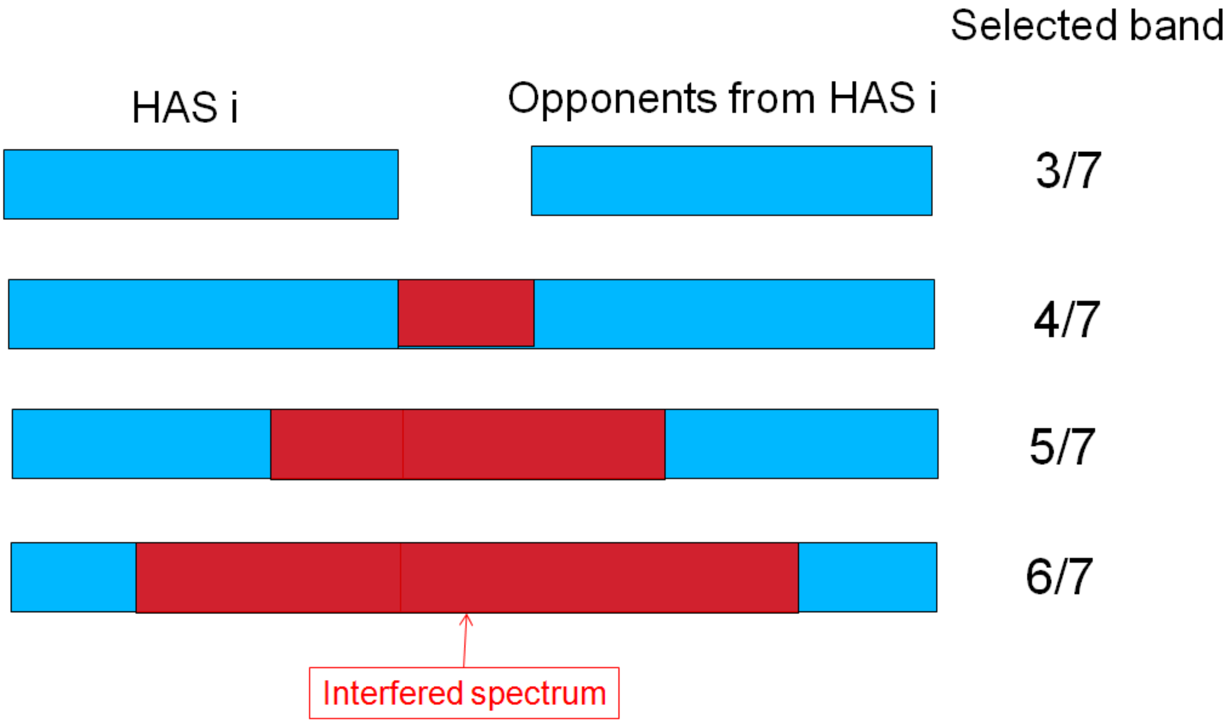


Figura IV.8: A simple model, based on Tit-for-Tat, where the opponents of player i are supposed to select exactly the same amount of band selected by player i.

However, let us assume that as much band player 1 to use, the exact same decision will be taken by the opponents. Figure IV.8 shows the concept. Naming as B_i the fraction of band we decide to use, we can write the amount of shared bandwidth B_{sh} as:

$$B_{sh} = \begin{cases} 0, & \text{if } B_i \leq B/2 \\ 2B_i - B, & \text{otherwise}. \end{cases} \tag{IV.16}$$

And we can write the amount of interference free band as:

$$B_f = \begin{cases} B_i, & \text{if } B_i \leq B/2 \\ B - B_i, & \text{otherwise}. \end{cases} \tag{IV.17}$$

Depending on receiver characteristics, it is not possible to assume that the interference will only affect the rate in the shared band. For instance, if the Low Noise Amplifier (LNA) saturates, then it is possible that orthogonality is lost. For the sake of simplicity, let us assume the contrary: the orthogonality of bands can be kept by the receiver. In this case, we can write the total capacity as the sum of capacity in the interference free band B_f and the shared band B_{sh}:

$$C_i = B_f\, log_2\left(1 + \frac{S_f}{N_f}\right) + B_{sh}\, log_2\left(1 + \frac{S_{sh}}{I_{sh} + N_{sh}}\right) \tag{IV.18}$$

Where S_f stands for the signal over the interference-free band, N_f is the noise power over the same band and S_{sh},I_{sh} and N_{sh} represent respctively signal, interference and noise power over the shared bandwidth. Using gaussian noise model[25], the total noise over each of the bandwidths are given by:

$$N_{sh} = N_0\, B_{sh} \tag{IV.19}$$

$$N_f = N_0\, B_f \tag{IV.20}$$

In the general case, S and I vary along the band because of power allocations and frequency selectivity (section III.2.4). Let us make the following simplifying assumptions, that make S and I also linearly dependent on the relevant bands:

- Flat fading over the whole band B
- Fixed transmission power spectral density

Then, we define:

$$S_{sh} = S_0\, B_{sh} \tag{IV.21}$$

$$S_f = S_0\, B_f \tag{IV.22}$$

$$I_{sh} = I_0\, B_{sh} \tag{IV.23}$$

Now we can see that these simplifying assumptions turn the logarithmic terms in equation (IV.18) indepedent of B_i:

$$\frac{S_f}{N_f} = \frac{S_0\, B_f}{N_0\, B_f} = \frac{S_0}{N_0} \tag{IV.24}$$

$$\frac{S_{sh}}{I_{sh} + N_{sh}} = \frac{S_0\, B_{sh}}{I_0\, B_{sh} + N_0\, B_{sh}} = \frac{S_0}{I_0 + N_0} \tag{IV.25}$$

Substituting these equations, (IV.16) and (IV.17) in equation (IV.18) we have:

$$C_i = \begin{cases} B_i\, log_2(1 + \frac{S_0}{N_0}), & \text{if } B_i \leq B/2 \\ (B - B_i)\, log_2\left(1 + \frac{S_0}{N_0}\right) + (2B_i - B)\, log_2\left(1 + \frac{S_0}{I_0 + N_0}\right), & \text{otherwise}. \end{cases} \tag{IV.26}$$

With our assumptions of flat fading, and fixed power spectral density, the logarithmic terms are constants in terms of B_i, the variable which value is being chosen. This assumption makes easier to find maximum and minimum. This is a continous function of B_i in the closed interval $B_i \in [0, 1]$. Therefore it has a global maximum and minimum [26]. Since the derivative is discontinuous the maximum is not guaranteed to be found by derivation over the whole interval. However, the maximum can be found by first finding the maximum piecewisely, within each continuous part. In the interval $B_i \in [0, B/2]$, the maximum is $B_i = B/2$, since in this interval C_i is an increasing function of B_i.

For the other interval we derive the function in order to check if there is any critical point. Therefore we can we write the derivative in the interval $B_i \in [B/2, 1]$ as:

$$C_i^{'}(B_i) = -log_2\left(1 + \frac{S_0}{N_0}\right) + 2\, log_2\left(1 + \frac{S_0}{I_0 + N_0}\right)\ ,\ B_i \in [B/2, 1] \qquad \text{(IV.27)}$$

This equation represents the slope of capacity as a function of B_i for the interval $B_i \in [B/2, 1]$. Considering, N_0 as a fixed value, if interference is low compared to the received signal level the slope is positive and the capacity increases. However, if interference level is close or higher than the received signal level, the slope is negative and the best approach is to use a bandwidth equal to $B/2$. This is illustrated by Figure IV.9

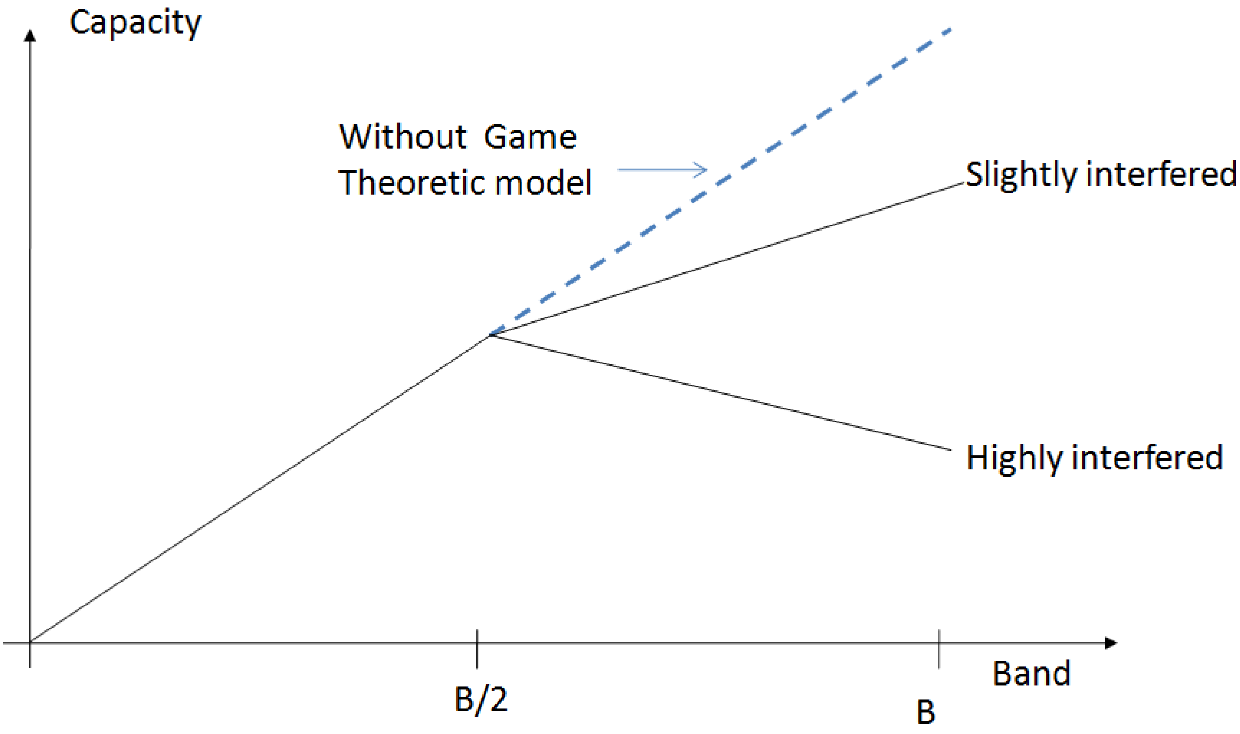


Figura IV.9: Considering game-theoretic predictions we can prove that more bandwidth can lead to less capacity in an interference scenario.

This example with simplified assumptions illustrates the concept that adding more bandwidth is actually expected to reduce the capacity if the interference is considerable. However it does not take into account frequency selectivity, different power allocations and the fact that we have a discrete number of blocks. As a more practical application of the concept shown by the example, we define the following algorithm to calculate the utility of a SPRB allocation.

1. Count the total number of SPRBs in the allocation, N_a, and the total number of blocks in the spectrum pool, N_t
2. For every SPRB of the allocation, calculate the estimated capacity. Assign the sum of all estimated capacities to the utility U.
3. Count N_i, the number of interfered blocks, i.e., SPRBs in which $I > I_{thr}$
4. If $N_i + N_a > N_t$, and $N_a > N_f$ then apply a penalty by assigning $U \leftarrow U/(1 + N_i)$

There are 2 parameters in this algorithm. N_f is the number of blocks which is believed to be a fair share for each player. In highly interfered situation, the algorithm will allocate a number of SPRBs close to N_f. Therefore this parameter should be chosen to approximate the intended average reuse. I_{thr} is a interference threshold used to determine whether a block is highly interfered. The exact sense of this is that if the block is interfered above this threshold, it is believed that a transmission on this block will cause a reaction from the players already transmitting in that block.

We revisit the static game example in the beginning of this section, considering the proposed utility with $N_f = 2$ and I_{thr} such that all shared blocks are highly interfered. This is presented in table IV.2. After this modification the Nash Equilibrium of the game is now the efficient and fair point that was also achieved by the repeated game, that is, both players using two SPRBs.

	1	2	3	4
1	3 , 3	3 , 6	3 , 9	1 , 5
2	6 , 3	6 , 6 NE	4 , 3.5	2 , 8/3
3	9 , 3	3.5 , 4	5/3,5/3	1 , 2
4	5 , 1	8/3 , 2	2 , 1	4/5,4/5

Tabela IV.2: Symmetric spectrum sharing game using the proposed utility

IV.5 STRATEGIES

IV.5.1 Strategies for New entrant game

The assumed behavior of each HAS is that it is willing to maximize its own utility, which is the basic assumption of game theory about rational decision makers. We propose here some strategies that try to optimize the utility designed in Section IV.4 and at the same time make considerations about traffic. The strategies are defined in terms of behavior strategies [9], which means that the strategy is specified for each information set. Next, we present the proposed behavior strategies for each of the stages of the base game.

IV.5.1.1 Strategy in stage 0 - Bargaining phase

Stage 0 can be viewed as phase where the new entrant will be bargaining spectrum from the existing ones. Identifying every other HAS present in the environment would be a demanding task for the new entrant. Therefore, we assume that the new entrant does not know who owns each spectrum, nor if current division is fair. In the light of this assumption we propose the following algorithm to determine the initial parameters:

1. Determine two levels of needed capacity to start operation: a minimum capacity (used in a later step) and a target capacity. The needed capacity is to be determined both in uplink and downlink.
2. Multiply the target capacity by a safety margin to obtain the initial virtual capacity
3. Until we have selected enough SPRBs to load the initial virtual capacity (both uplink and downlink) or all SPRBs are selected
4. Randomly select a SPRB that was not previously selected. Probability of selection of a SPRB is proportional to the sensed interference level on it.
5. Evaluate the utility of such allocation. If the utility is higher than at previous step we continue. If it is smaller than previous step, we do not allocate the SPRB under current evaluation and the final allocation is the previous one.

The calculated initial capacity was called virtual, because it will not be the effective initial capacity. The new entrant has to start operation at smaller capacity than desired. Also it has to use a transmission pattern that allows the RRM of the other HASs to recover from the sudden interference increase. In other words the new entrant cannot transmit in all selected SPRBs all time, because there are ongoing transmissions that should be affected as least as possible. However, this transmission pattern has to be such that all affected HASs can detect the presence of the new entrant in the affected SPRBs. Therefore, the transmission pattern should include all selected SPRBs. One example of simple pattern is to frequency hop the selected SPRBs, staying in each SPRB long enough to be detected.

Another point to stress is that instead of simply ranking the SPRBs according to interference level and withdrawing SPRBs from the ordered list, we randomly select SPRBs one by one with a probability proportional to the interference level. This can lead to the selection of some bad SPRBs, but we will never know it beforehand, because the opponent may give it up later and then it becomes a good one. Adding randomness at selected points is common in heuristic approaches. In [11], a similar mechanism than described here is used to select which will be the parents of a new breeding in a genetic algorithm.

IV.5.1.2 Strategy in stage 1 - Response phase

A new entrant represents a strong disturbance in the existing scenario, and in this phase the existing HASs have to give an answer to this disturbance. The first question that arises is: why should the existing HASs give up spectrum? The new HAS will occupy spectrum anyway. As shown in section IV.4, overlapping should be allowed only when the channel is favorable for it. Consider that, here is the proposed algorithm(behavior strategy) to respond a new entrant:

1. Determine the threat level, i.e., the amount of SPRBs that it is believed the new entrant will not give up anyway in the stage 2.
2. Start a backoff timer proportional to current utility.
3. When the backoff timer expires, give up the most affected, worst quality SPRB if it fulfills the following three conditions.
    - Quality of this SPRB is below an acceptable level
    - We can not give up more SPRBs than the threat level
    - We do not give up so many SPRBs that capacity falls below a minimum operation level

   If we can not give up more SPRBs we stop the algorithm.
4. Reselect robustness and power level that will maximize the proposed utility. Go back to step 2.

Maximum power increase at this step is to be part of policy. The power increase is meant to warn the new entrant that this is a SPRB it should give up in stage 2, but it will affect others as well. The backoff timer is intended to cope with the situation where there are already more than one HAS sharing a SPRB. Maybe if someone else give up the resource first, we do not have to give it up on our own. Again, this is a dual concept from contention in CSMA/CA. In CSMA/CA we use a backoff timer to decide when we try to access a resource again. Here we use the backoff timer to decide when we should give up a resource. This is quite similar to the situation of a dynamic timing gaming, such as the dynamic version of chicken game [9].

IV.5.1.3 Strategy in stage 2 - Adjustment phase

Now it is time for the new entrant to adjust its parameters to the response given by the other players. This is the same as stage 1 strategy, except for the fact that we do not allow for any power increase and there is no backoff timer, as the new entrant is the only one to move. Here is the algorithm:

1. For step k=0 ,

2. Give up the worst quality SPRB.
3. Reselect robustness in all other SPRBs that will maximize the proposed utility.
4. Calculate the utility at step k , U(k), considering only the current SPRB selection
5. If U(k) < U(k-1) or capacity falls below minimum (determined in stage 0), then stop and use SPRB selection from step k-1 as the final.
6. else increment k

After stage 2, the new entrant starts using all remaining SPRBs , potentially full time in the way its RRM function decides to use them and distribute amongst the users.

IV.5.2 Strategies for the Repeated Game

As the base game has the same structure in either protocol state defined in Figure IV.2, the strategies are defined to be quite similar with some minor but important modifications.

First, in the new entrant game only one HAS initiates the proccess and it can in principle allocate the full spectrum at once. For the sake of convergence and interactions with RRM, Policy 2 has to be followed in the repeated game state. On the other hand, in the repeated version, everyone is allowed to try to allocate new resources. It can be thought of several smaller versions of new entrant game running in parallel.

A second aspect is that if there is a new spectrum hole, several HASs can attempt to occupy it at the same time. The backoff mechanism of response phase should take care of conflict resolution.

At last, but not least, if someone gives up a resource on adjustement phase the HASs that increased power in that SPRB during response phase should come back to the original transmission power level used before the iteration. Otherwise, at every loop we risk having power increased even if there was no change in the spectrum allocations.

IV.6 CONCLUSION

In this chapter a frequency domain intra-system spectrum sharing solution was proposed. The algorithm, named GDSA is composed mainly of game theoretical elements and a few heuristic ones. The protocol structure and states were designed to alleviate the lack of information inherently present because there is no direct communication accross networks. The utility function was used as a design parameter as well, and it was developed based on trigger strategies for repeated games. The available strategies at each information set were defined in order to perform a distributed optimization of resources.

V. RESULTS AND DISCUSSION

V.1 INTRODUCTION

This chapter present results intended to showcase the usage of spectrum sharing and the flexibility proposed GT-based algorithm. The results also provide further insight into the features of the protocol presented in chapter IV.

In section V.2 we describe briefly the used simulation scenario and some assumptions made at the simulator. Section V.3 describes the three reference cases used and why we need more than one reference case. All of them are fixed spectrum allocation approaches.

The new entrant game is throughly exemplified by the results shown in section V.5. Finally, section V.6 confirms the paramount importance of policy 2,defined in section IV.3.2.3, and also show that in long term average sense, the repeated game is capable to approximate the capacity of a planned network while actually tracking the load during time.

V.2 SIMULATION SCENARIO

The simulation scenario is shown in Figure V.1 and is composed of four Home Access Stations (HAS). In the simulation case, each HAS serves four UEs. The UEs have ideal sensing capabilities, being able to determine the level of signal, noise and interference without any mistakes. They also report these values back to the serving HAS.

Capacity is calculated by Shannon formulation, i.e., equation (III.4). Since the number of UEs is very limited, it is not possible to provide statistics in terms of median and tail capacity distribution. Instead, we consider the average shannon capacity of the UEs. This roughly corresponds to the case where the users are scheduled through round-robin. In order to evaluate outage capacity, the figure for the worst condition mobile is provided. This corresponds to the case where this mobile receives 100% of allocation slots.

We assume that the HAS are from different operators and there is no direct signaling between them. The total bandwidth available for the operators altogether is a contiguous band of 100 MHz.

The results presented here correspond to the trace of one snapshot of the simulator. The traffic is full buffer, but it is elastic, meaning that as many SPRBs are chosen by the SpS algorithm they will all be used. All the HASs are synchronized and have the same UL/DL switching point. Only downlink is considered in the simulations. There is no power control.

As previously mentioned, one of the main features of the proposed algorithm that is not being throughly considered in the literature is to provide an approach for initial spectrum selection under any condition. In order to test this feature,the HASs in the simulation scenario are activated one by one. The chosen order was to activate HAS 1 first, HAS 4 as second and then HAS 2 and finally HAS 3. This order was chosen because the strong interferers to HAS 2 in this scenario are HAS 1 and 4. If they are both active and sharing the spectrum in a efficient manner, then it is very challenging for the algorithm to find the initial allocation for HAS 2.

Every time a HAS is activated it starts the new entrant protocol. It will make the initial spectrum selection, the other active HASs will provide an answer and the new HAS being activated will adjust to that, as described in section IV.3.1

In order to verify the behavior of the repeated version of the game, a very simple model for perturbing the traffic is employed in V.6. The basic assumption is to keep all HASs active for a long time with high but varying traffic requirement. The applied traffic pattern is presented in more detail in section V.6.

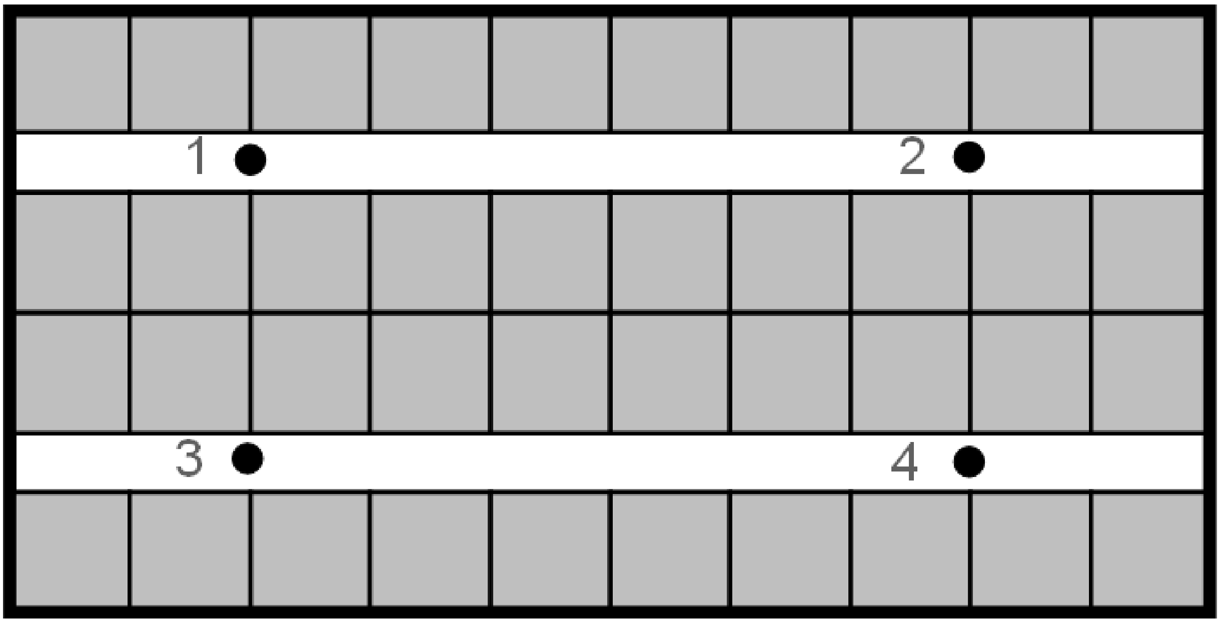


Figura V.1: Office scenario used for the simulations.

V.3 REFERENCE CASES

When comparing fixed spectrum allocations with dynamic spectrum access, we have to compare them in the situation for which the fixed allocation was designed in order to be fair. However the true potential of spectrum sharing comes from the adaptation to any situation. Therefore, we compare our spectrum sharing approach with three fixed spectrum strategies which represent some extreme cases.

V.3.1 Separate Spectrum Pools

As described in chapter I the traditional way of deploying several networks in the same geographical area is that each of them has its own separate spectrum pool. There are also political and economical motivations to keep things this way, and therefore a strong technical argument is needed. A separate spectrum is the safest way to go in a competitive environment, as each operator can optimize its own spectrum independently. Every operator knows the other ones are enforced by law not affecting their own operation.

In the study office scenario, having separate spectrum pools corresponds to a reuse 4 configuration. When all HASs are in full load, this is quite efficient as it provides interference-free transmission in this scenario. Since this configuration leads to noise-limited transmission, outage capacities are quite close to average capacities as shown in Figure V.2.

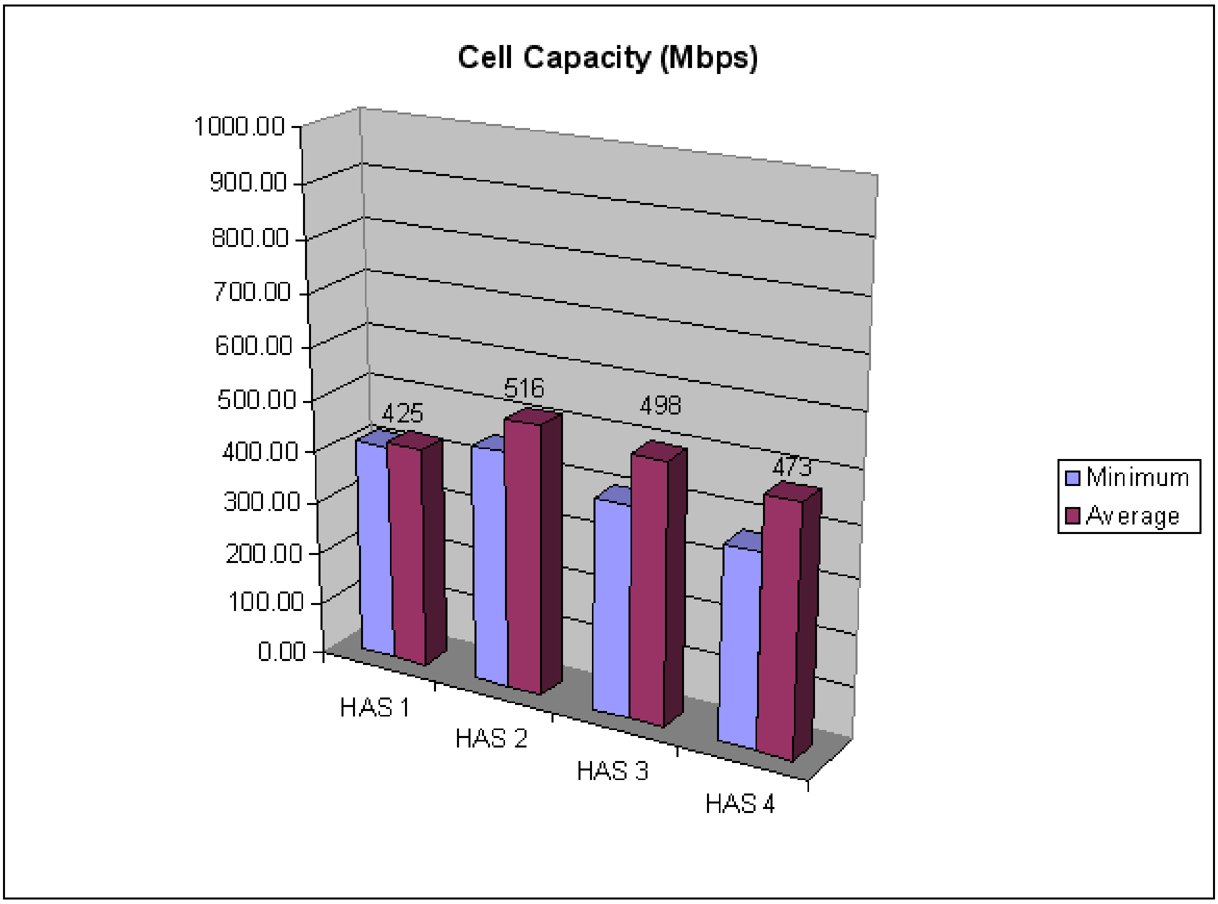


Figura V.2: Capacities with a reuse 4 configuration in office scenario when all HASs are active and at full load.

V.3.2 Full reuse

The simplest way to implement a common pool of resources is allowing every one to access the full spectrum all the time. This is specially interesting in isolated cells, as the peak data rate

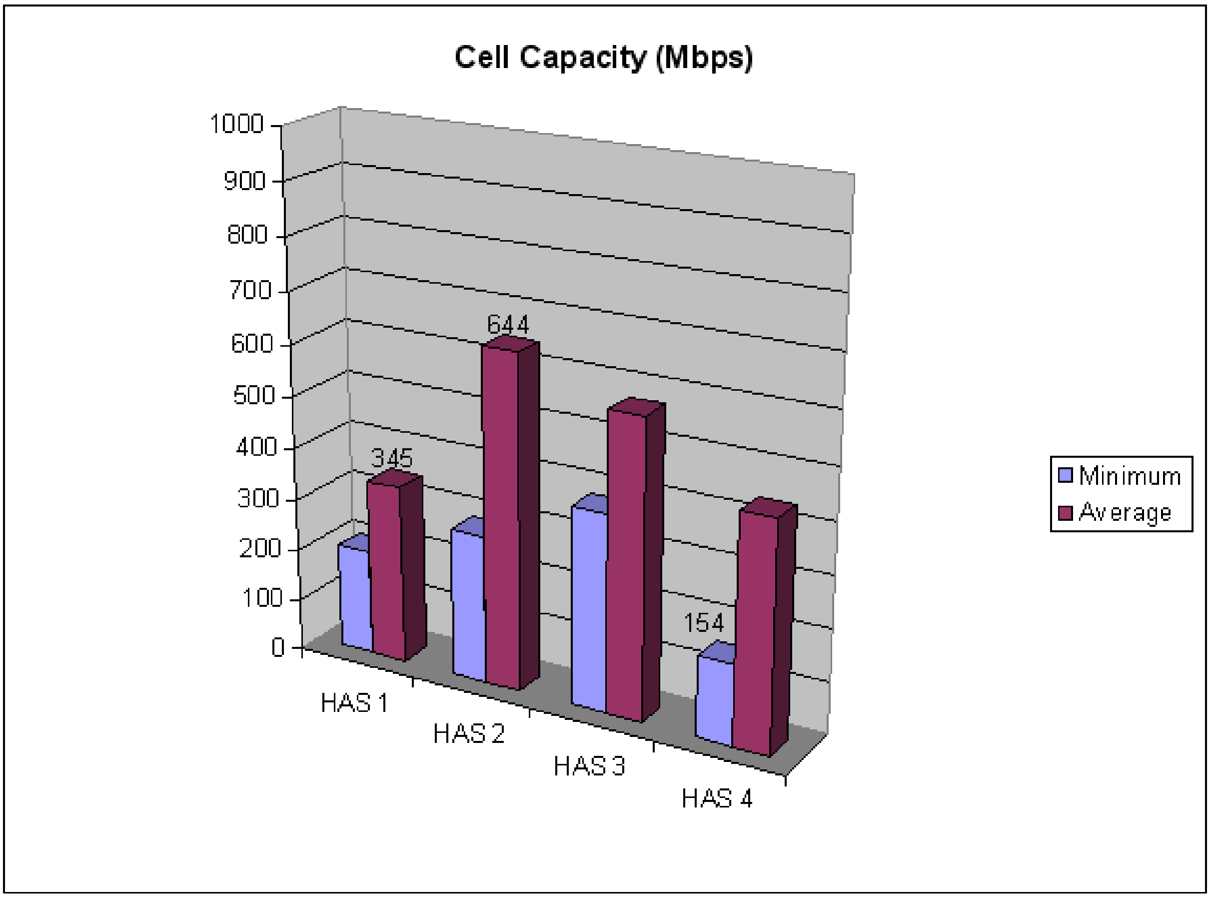


Figura V.3: Capacities with a full reuse(reuse 1) configuration in office scenario when all HASs are active and at full load.

can be totally used even for single user. However, the situation can become pretty bad in high load conditions or dense deployment. Figure V.3 shows the capacities at full load for reuse 1. Comparing to Figure V.2, the average is actually higher than reuse 4, but the outage capacity is much poorer. In addition to that, the share of resources amongst the networks is very unequal. These problems justify the fact that operators are very resistant to this approach.

V.4 NETWORK PLANNING AND OPTIMIZATION

Network planning and optimizaiton leads to the best performance in outdoor scenarios. However, applying this is very costly to be considered, for instance, in residential scenarios and probably best avoided also in enterprise scenarios. Also, if several operators are to work in the same area, this approach means they would have to give up sensitive information about their subscribers locations and traffic. This is even more likely to find resistance by operators than suboptimal operation.

Nevertheless, verifying the optimal solution for the study scenario allow us to upper bound the capacity and this makes an important comparison case. In the simulation, the optimal was found through extensive search of all possible allocations and it corresponds to the situation where reuse 2 is applied and the spectrum is reused by the off-diagonal HASs. That is, HAS 1 and 4 uses the same 50% of the spectrum and HAS 2 and 3 reuse the other half.

We highlight that network planning targets a particular load situation. In general, it is optimized for full load in all cells at the same time. While, this approach does consider the worst case interference, it does not consider traffic fluctuations encountered in reality. In practical networks, RRM approaches can be used to convey with these traffic load variations. In a scenario with multiple operators, where there is no signaling amongst the different networks this kind of RRM strategy may not be feasible.

V.5 NEW ENTRANT GAME

In the simulations of this section, the 100 MHz is divided into 6 SPRBs. We show how the utilization of these 6 SPRBs evolve through time and how this affects the capacities at each cell. It is important to keep the geometry of the scenario (Figure V.1) in mind when analyzing the results. HAS 1 and 4 do not provide strong interference to each other. The same stands for the interaction between HAS 2 and 3. However, usage of the same SPRBs by two HASs that are not off-diagonal generates considerable interference for both. As an example, the strong interferers for HAS 2 are HAS 1 and 4.

The two parameters for utility calculations described in section IV.4 were set as follows.

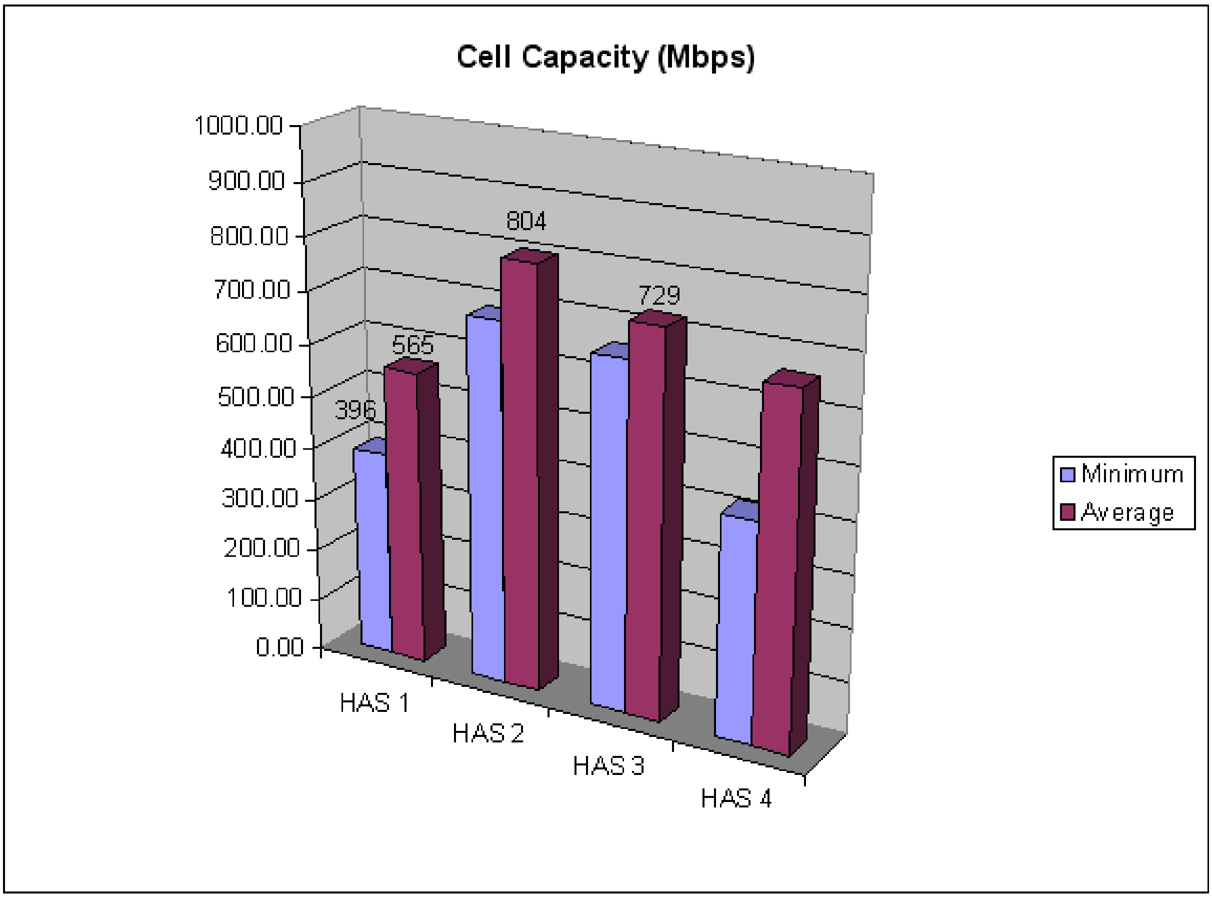
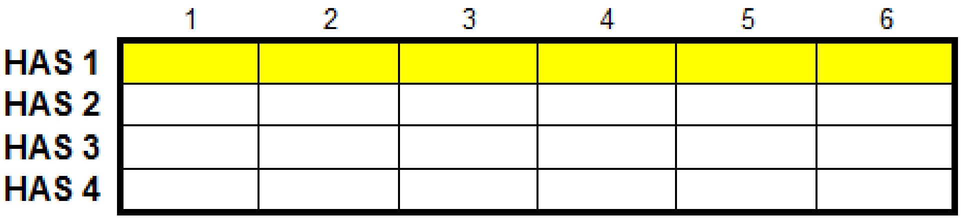


Figura V.4: Optimal capacities in office scenario when all HASs are active and at full load.

- The number of blocks which is believed to be a fair share for each player, was defined as half the band. Since we have 6 SPRBs we set $N_f = 3$.
- The interference threshold I_{thr} used to determine whether a block is highly interfered, was set 25 dB above noise floor.

The first HAS to be activated is HAS 1, and it has access to the full spectrum as shown in Figure V.5. The capacity achieved is shown in Figure V.6. It is worth to remember that from the fixed approaches, only reuse 1 is able to also access the full spectrum at this point.



	1	2	3	4	5	6
HAS 1	🟨	🟨	🟨	🟨	🟨	🟨
HAS 2						
HAS 3						
HAS 4						

Figura V.5: Spectrum allocation just after the first HAS finalized the new entrant protocol

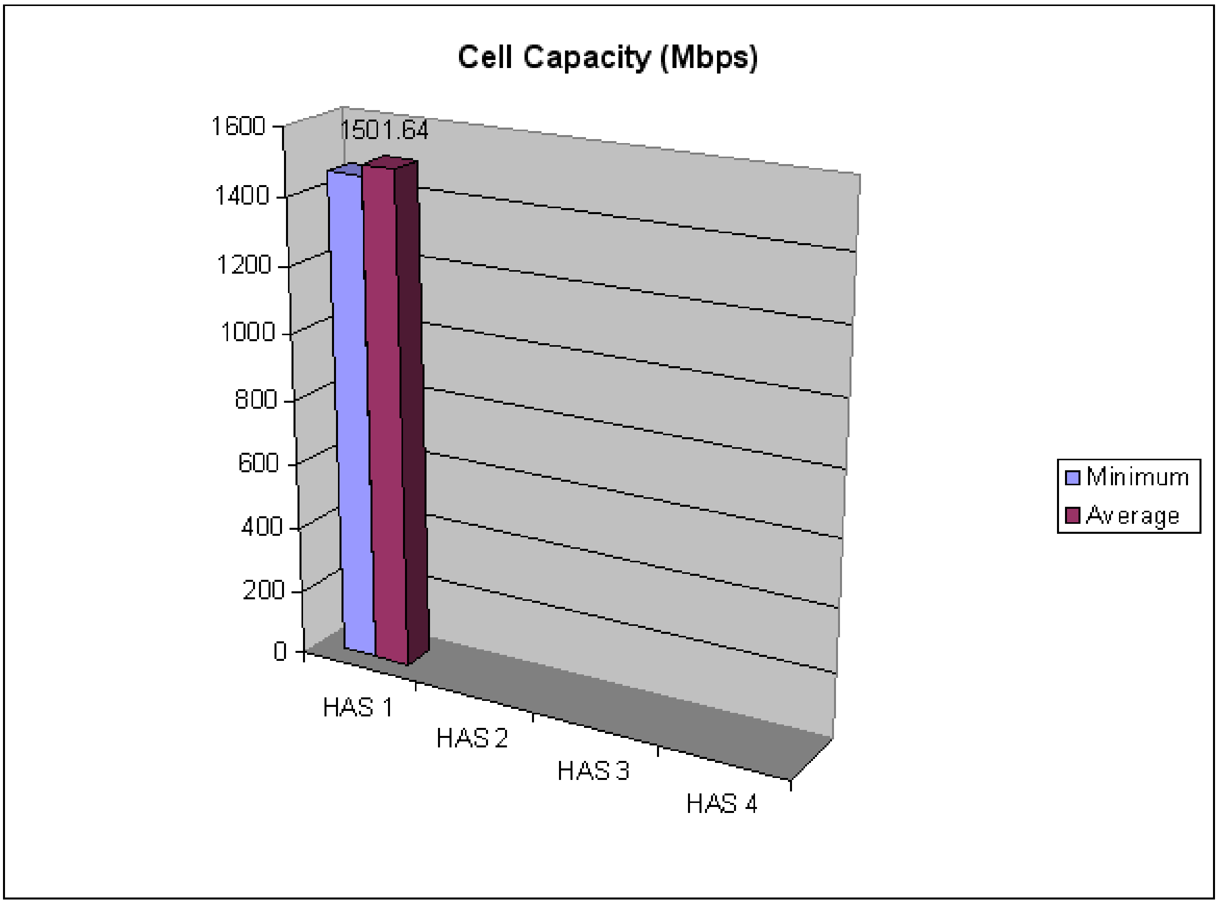


Figura V.6: Cell capacity just after the first HAS finalized the new entrant protocol

The second HAS to be activated is HAS 4. Since it is off-diagonal to the other active HAS, the interference threshold is not reached for any block and the proposed algorithm again selects all blocks. The allocation after this new addition is shown in Figure V.7 while the achieved capacity is presented in Figure V.8. While there is a substantial decrease of the capacity of HAS 1 after the addition, the total capacity is substantially increased due to frequency reuse.

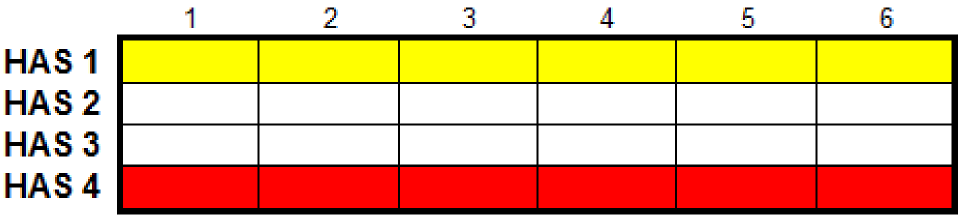


Figura V.7: Spectrum allocation just after the second HAS (HAS 4) entered the scene and finalized the new entrant protocol

Next step is to add HAS 2 to the scene. Now the scenario becomes really challenging. The RF scene sensed by HAS 2 is the following: There are two strong interferers around and both of them are using the full spectrum pool. In other words, there is no spectrum hole at all! Still, it must have spectrum access.

Here we need to go more into the details of the algorithm decisions. Figure V.9 shows how the allocation evolves. The new entrant, HAS 2 decides to bargain for SPRBs 1, 2 and 3. The two existing HASs provide answers, at different points of time. HAS 4 moves first giving up blocks 1 and 3. HAS 1 decides to give up blocks 1 and 2. Notice that the first one to move can actually have influence in the decision of the other. For that reason it is important to apply the backoff timer. Since the bargaining worked, the new entrant keep the 3 blocks allocation.

The results after these adaptations are shown in Figure V.10

The last HAS to be activated, HAS 3 simply decide to have the same allocation as HAS 2, as shown in Figure V.11. After all, the strong interferers already gave up those resources on the past.

The results after all HASs are activated are shown in Figure V.12. We can see that the average throughput is not distributed in a even way. However, in terms of of outage capacity the output is pretty fair. Furthermore, all values are strictly greater than the case where each operator has its own spectrum.

The results shown so far exemplify the behavior of the algorithm throughout its operation. Now, we directly compare the proposed game-theoretical spectrum sharing approach with the three reference cases for all number of active HASs .

First we take a look on the average cell capacities, depicted in Figure V.13. In the noise-limited or low interference scenarios, only reuse 1 and SpS can make full utilization of the channel. Therefore, these approaches allow for much higher peak data rates when in very good conditions. Comparing this capacity with the separate spectrum approach in the case of only one active base station, a capacity 3.75 times higher is achieved. Though the reuse 2 was found to be the optimal approach for all base stations being active, it is not optimal when there are only a few HASs

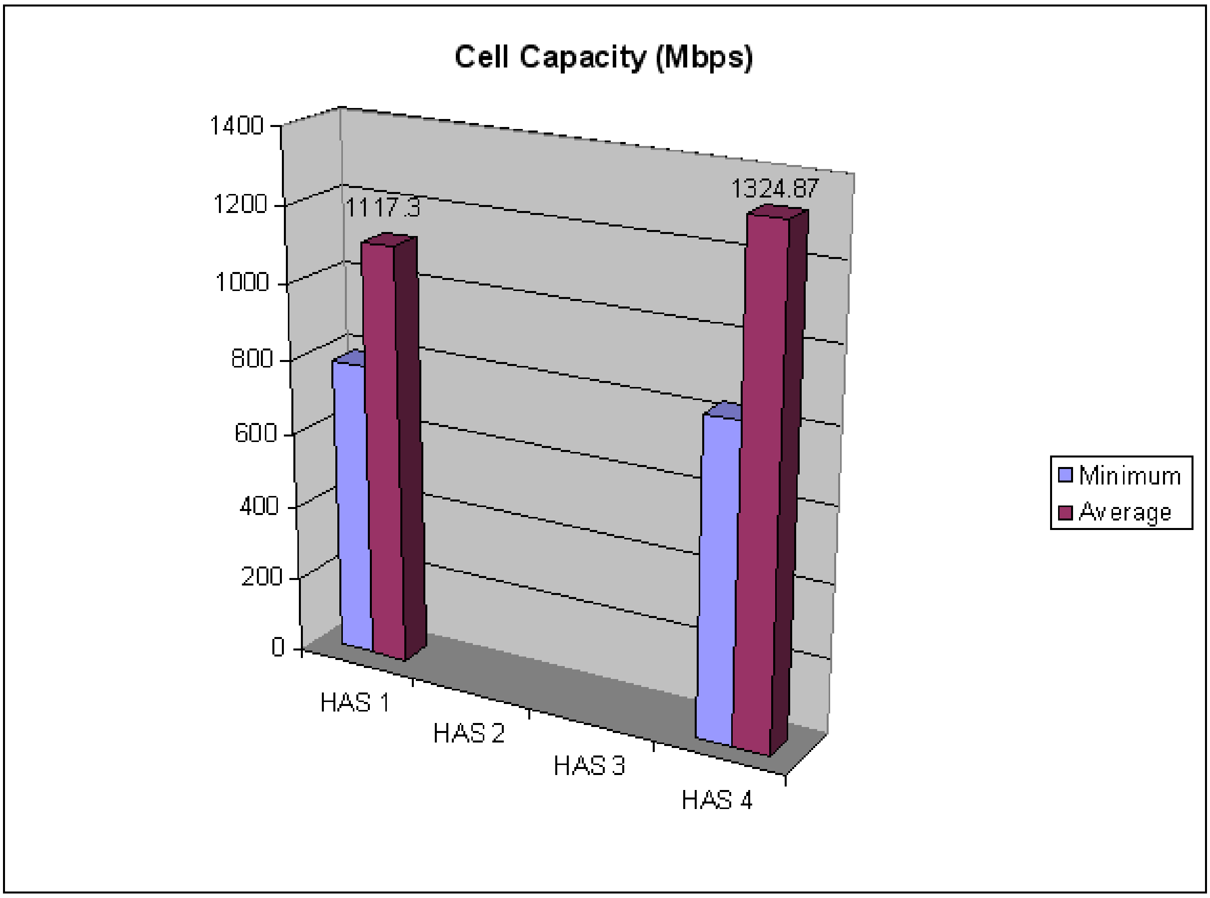
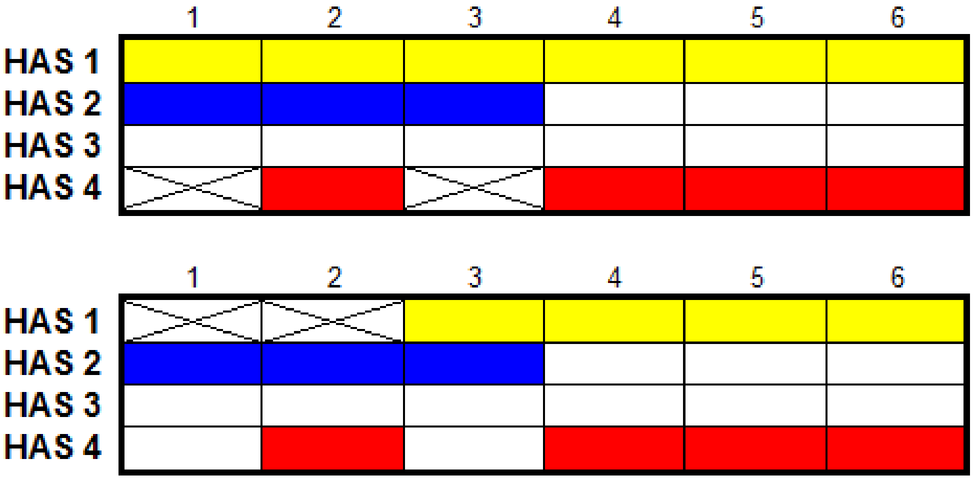


Figura V.8: Cell capacities just after the second HAS (HAS 4) entered the scene and finalized the new entrant protocol



	1	2	3	4	5	6
HAS 1	🟨	🟨	🟨	🟨	🟨	🟨
HAS 2	🟦	🟦	🟦			
HAS 3						
HAS 4	☒	🟥	☒	🟥	🟥	🟥

	1	2	3	4	5	6
HAS 1	☒	☒	🟨	🟨	🟨	🟨
HAS 2	🟦	🟦	🟦			
HAS 3						
HAS 4		🟥		🟥	🟥	🟥

Figura V.9: Sequence of spectrum allocations after the third HAS come into scene, causing major reconfigurations. First, the new entrant HAS 2 bargain for half of spectrum (top picture). In answering, HAS 4 gives up 2 SPRBs as shown on top. Then HAS 1 gives up also 2 SPRBs as shown on bottom.

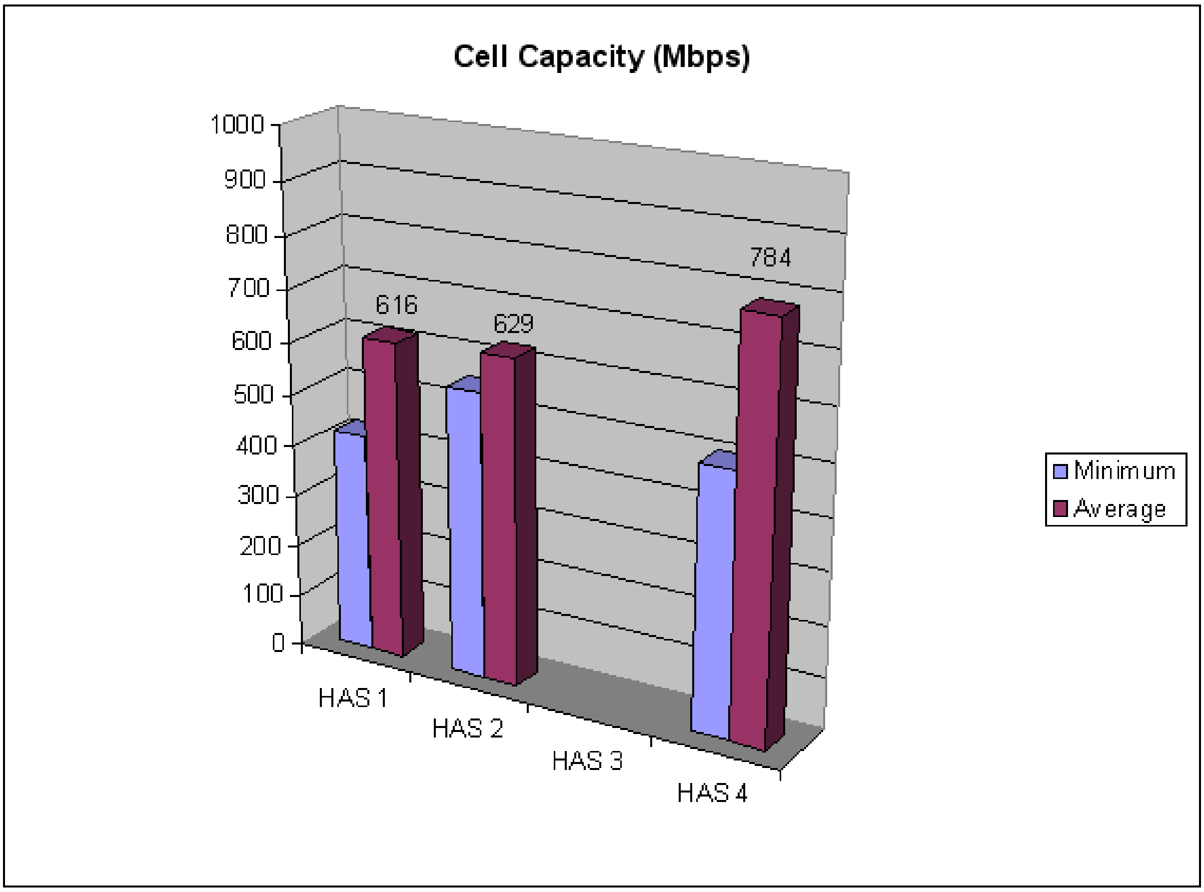
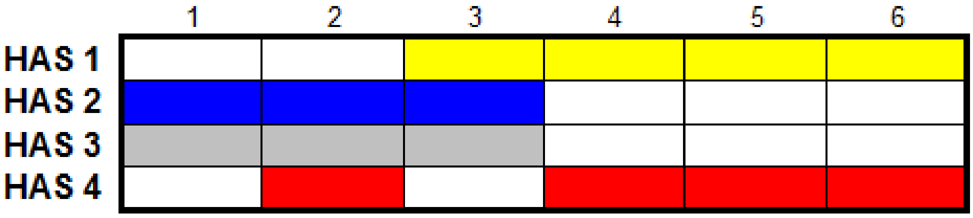


Figura V.10: Cell capacities just after the third HAS (HAS 2) entered the scene and finalized the new entrant protocol



	1	2	3	4	5	6
HAS 1			🟨	🟨	🟨	🟨
HAS 2	🟦	🟦	🟦			
HAS 3	▨	▨	▨			
HAS 4		🟥		🟥	🟥	🟥

Figura V.11: Allocation after all HASs are activated and used the proposed protocol

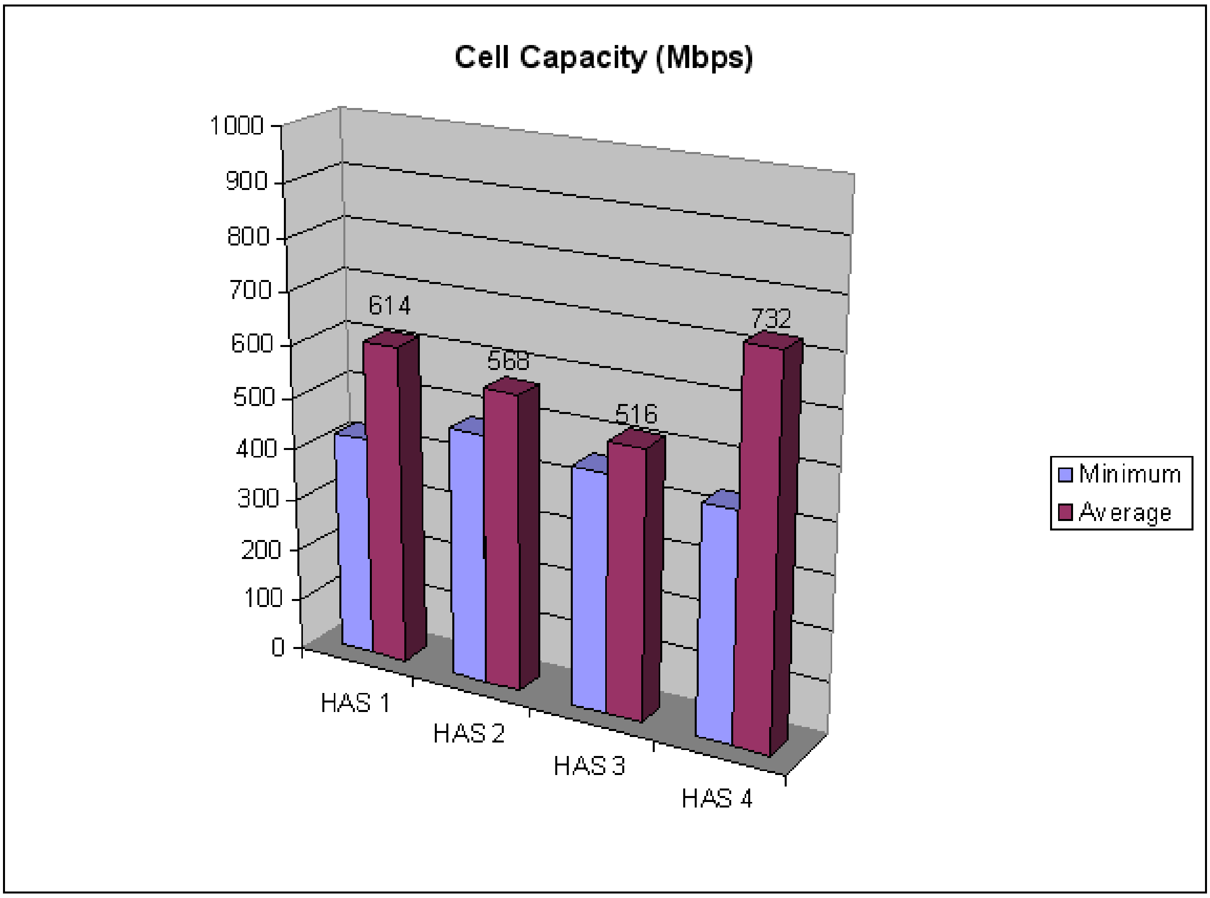


Figura V.12: Cell capacities after all HASs are activated and used the proposed protocol active.

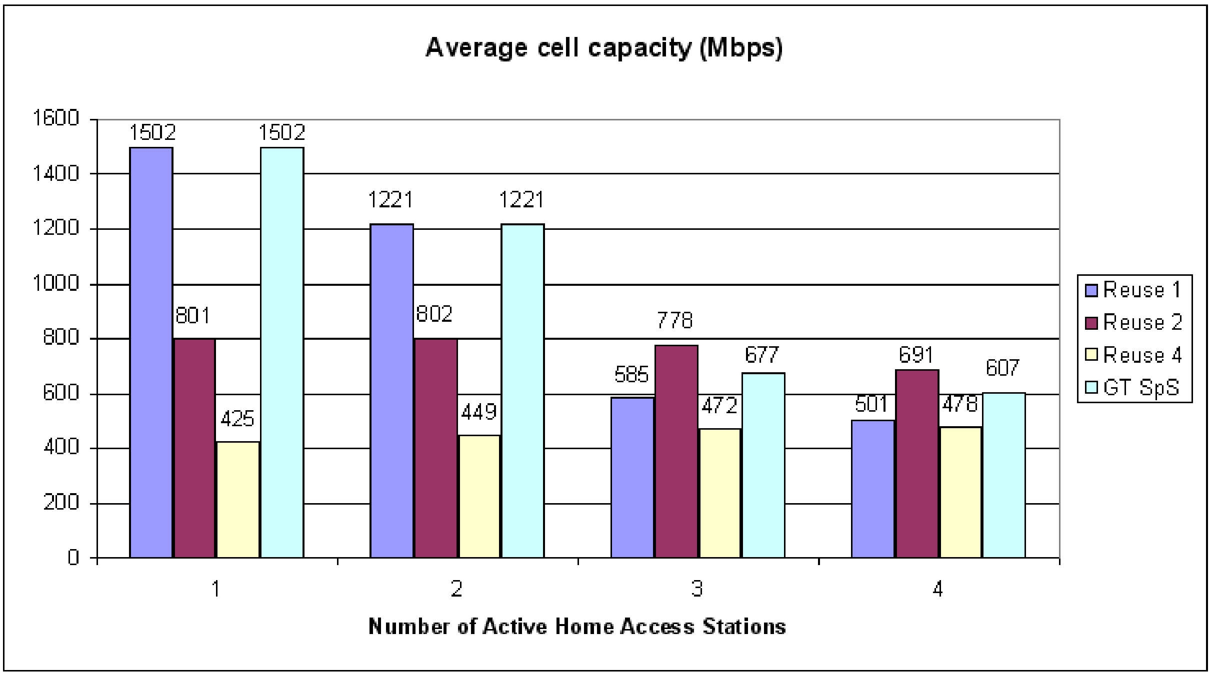


Figura V.13: Average cell capacities for SpS and the reference cases when the number of active HASs is varied

Then we analyze the average cell outage capacity. This is calculated by selecting the worst condition UE in each cell and averaging the throughput over the cells. Figure V.14 shows the average cell outage capacity of the new entrant algorithm and the three references.

When it comes to outage capacity, we can understand the role of full reuse and separate spectrum approaches. The first one excels where the latter seems less attractive: when there is very little interference. Contrarily, at higher levels of interference, having separate spectrum provide reasonably good outage capacity, while full reuse becomes really poor. Still, SpS is capable of beating or at least pairing them in all scenarios. If we consider the fact that network planning is not feasible to be done in most local area deployments, than SpS is the best in all cases.

V.6 REPEATED GAME

One of the main motivations of repeating the game is to try to enhance even more the efficiency and fairness. Another key motivation is, perhaps, more important: The SpS game shall be repeated to track the changes in load conditions, channel, RRM decisions and so on. A through evaluation of this second aspect is more appropriately performed in a simulator where all dynamics such as mobility, traffic, etc are considered.

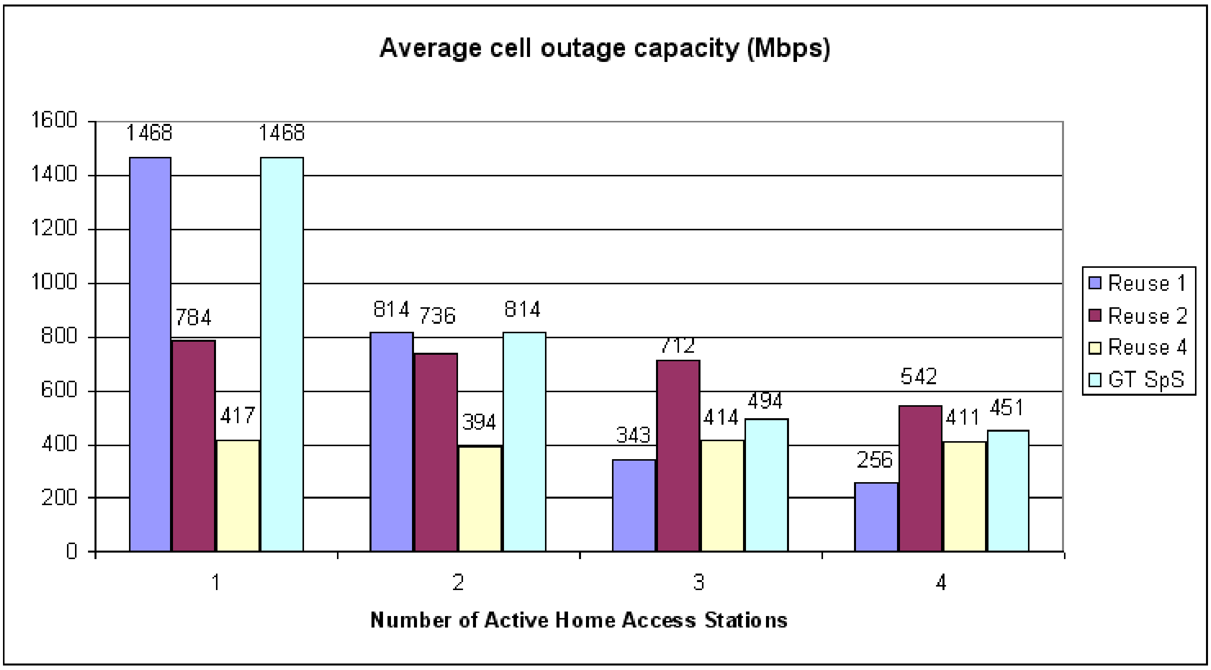


Figura V.14: Average outage capacities for SpS and the reference cases when the number of active HASs is varied

Since we used a static simulator, we decided for a very simple model to disturb the existing fractional load in the network and test the capacity of the repeated game for tracking it. For a single snapshot we simulate a number of steps where we vary the demand. Every 8 steps there is a chance that some HAS will stop using one SPRB. Similarly, every 5 steps a HAS is choose randomly to try bargaining one more SPRB and, therefore, initiating one iteration of the repeated game. This does not mean that it will necessarily have it allocated. It will depend on the answer of the other HASs. The exact pattern that was applied is shown in Figure V.15.

First we consider a case where the *policy 2*, defined in section IV.3.2.3, is not applied and then when bargaining attempt happens, it can be any number of SPRBs. This is shown in Figure V.16. Comparing to the V.15 we can see that until someone spontaneously give up one SPRB, nothing happens. From V.16 we see also that there is a lot of variation from steps 100 to 150, until some new stable configuration is achieved.

However, if we apply *policy 2* and only allow one block bargaining at a time we have much less dynamics as shown in Figure V.17. In this case it is clear, that some specific order of spectrum hole followed by an attempt to fill it lead to a new stable configuration. Therefore, it is important to limit the number of SPRBs in order to have better convergence.

We can also compare, what is the throughput in the last step with and without the application of *policy 2* . Figure V.18 shows this result. We can see that applying the policy also leads to a better system state.

In Figure V.17 there is no clear tendency if in the long term the repeating process will benefit

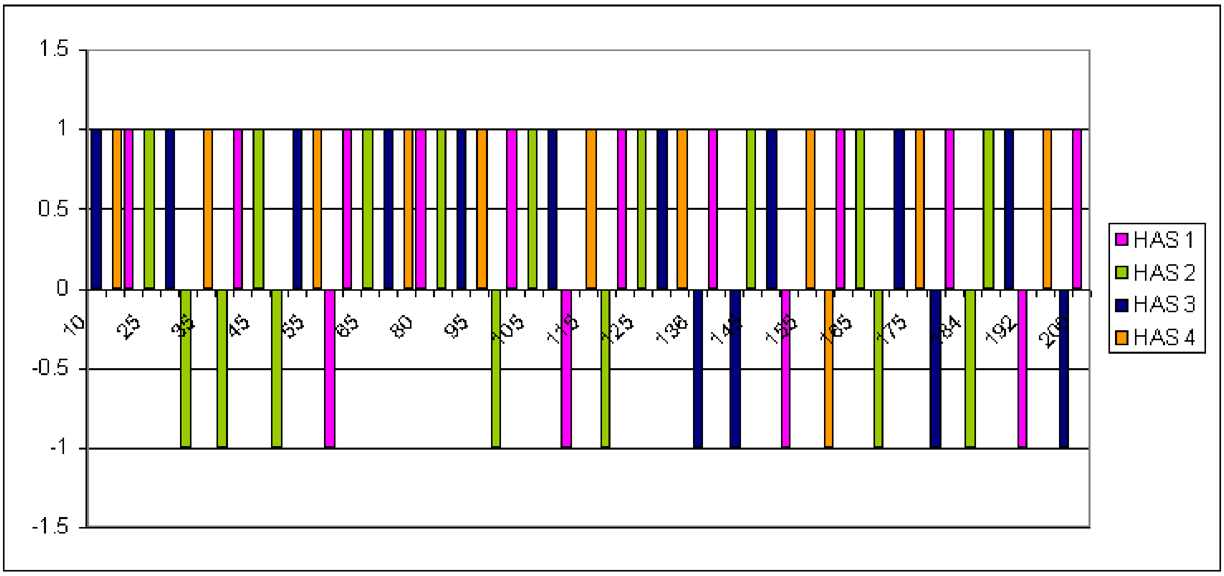


Figura V.15: Simple model for creating some variation in the SPRB demand. HAS are choosen randomly to try to allocate one more SPRB (represented by +1) or giving up spontaneously one SPRB (represented by -1).

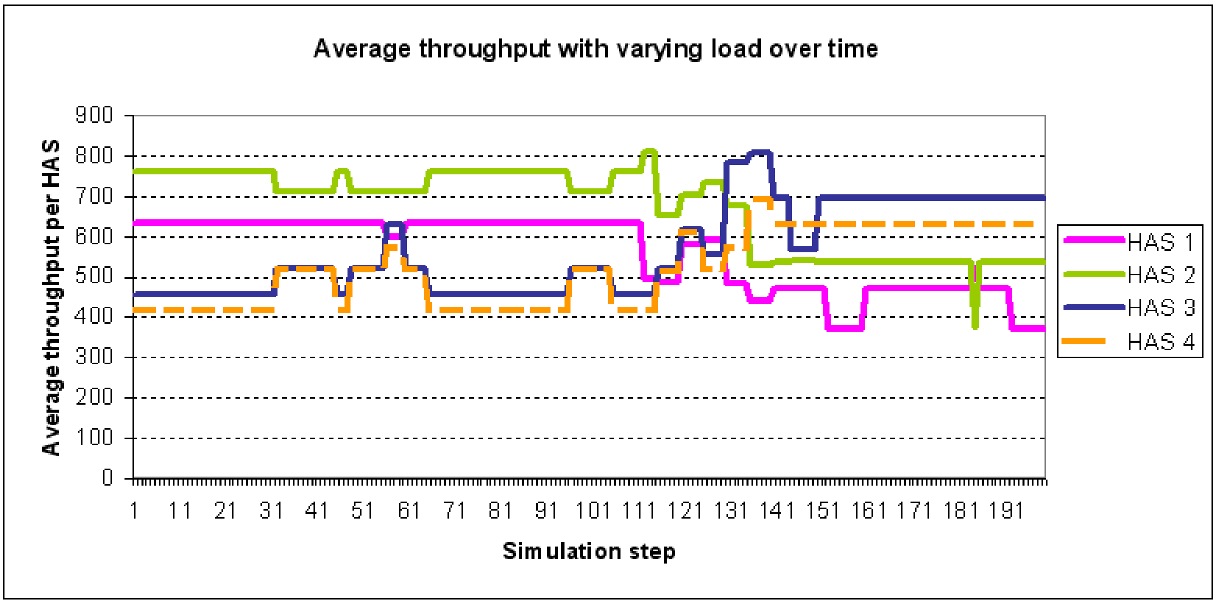


Figura V.16: Evolution of average capacity if no policy is applied limiting the number of SPRBs to be bargained each iteration of the repeated game.

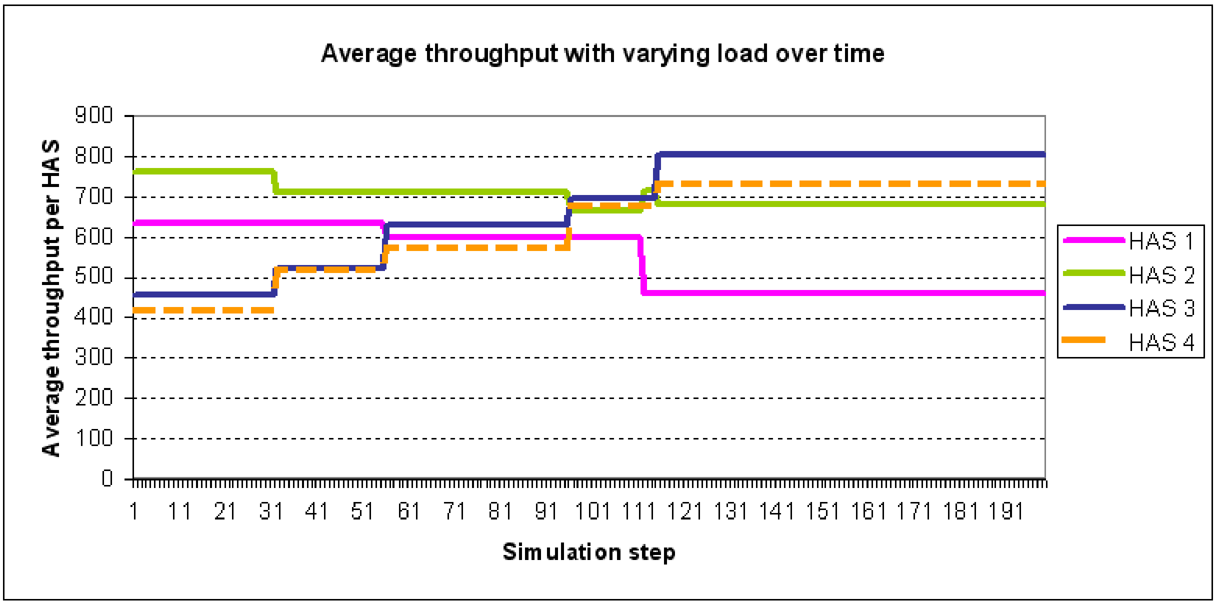


Figura V.17: Evolution of average capacity if a policy is applied limiting to one the number of SPRBs to be bargained each iteration of the repeated game.

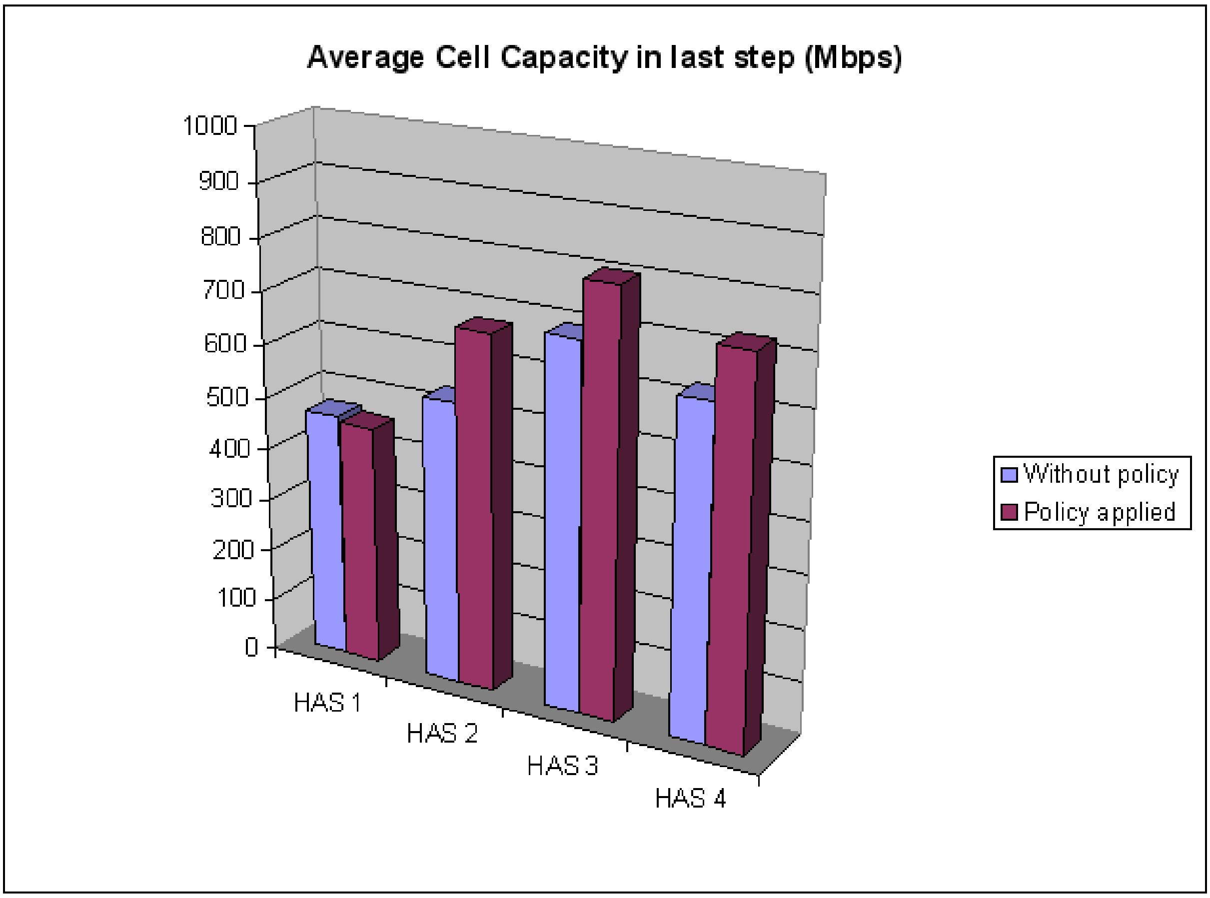


Figura V.18: Comparison of throughput in step 200 if the policy limiting the number of SPRBs reallocated each step is applied or not.

one HAS over another or if the load will be tracked in a fair share. In order to evaluate that we run the same process for 2000 steps, and averaged the cell throughput of each cell over the iterations. The result is compared with the throughputs achieved in fixed reused 2 at full load in Figure V.19. This result illustrates that the process can be quite close to the optimal values in the long run, while Figure V.17 showed that it can track load trends as long as the policy 2 is applied making the load variations slow enough.

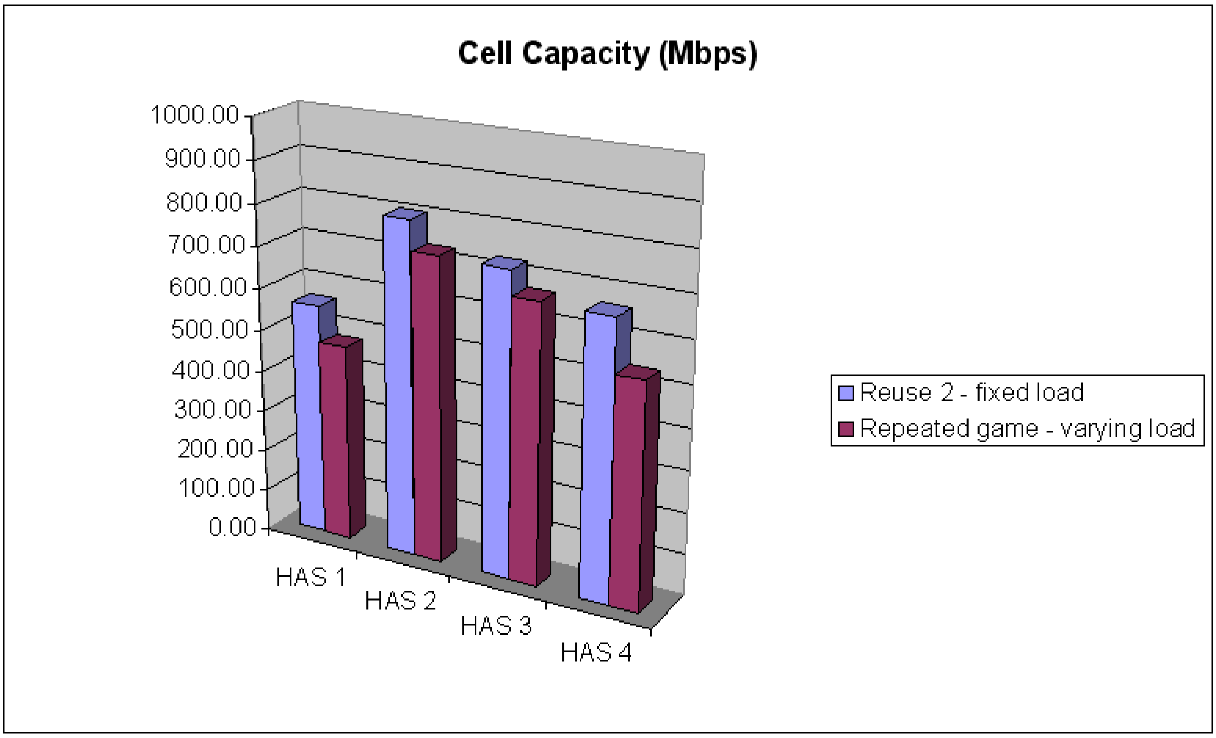


Figura V.19: Comparison of long-term average capacity in repeated game with the optimal fixed approach. It is important to highlight that in the case of reuse 2 the load has to be fixed to achieve these values in long term. In the case of the repeated game the load is kept high but it is time-varying.

V.7 CONCLUSION

In this chapter, the performance of GDSA, the framework proposed in chapter IV was evaluated through system level simulations in an office scenario. In this scenario, GDSA is capable of beating the simple fixed spectrum approaches, while providing self-organization of spectrum allocation and, therefore, being very suitable to uncoordinated deployment.

GDSA was also shown to be able to efficiently track slow traffic variations and accomodate assymetric spatial distributions of tarffic while approximating the efficiency of the full uniform load.

VI. CONCLUSIONS AND FUTURE WORK

When several networks are allowed to access a common spectrum pool each network can achieve higher peak and average data rates. The simplest way to use the common spectrum pool is to have full access any time. This corresponds to frequency reuse factor of 1. However, reuse 1 has a poor performance in terms of outage capacity and fairness.

The solution is to determine the access to the common spectrum pool dinamically instead of statically. In order to make dynamic spectrum access networks to co-exist, there is need for mechanisms to defining which share of spectrum each network will have access. Game theory is an extensive mathmetical field that can provide several different formulations to this problem.

The absence of direct signaling amongst the access stations of the different networks implies that a game-theoretic formulation of the spectrum sharing problem will have to consider incomplete information and the use of non-cooperative solutions. Both these characteristics can lead to inneficient solutions.

In order to cope with this situation, three parts of the game formulation were used as design parameters for a practical protocol: the game structure, the utility function and strategies. The game structure was formulated to alleviate the lack of information. While the utility function was built upon the inherit cooperative behavior of repeated games and the interference characterization.

The results showed that the developed approach is capable of beating simpler approaches in all cases. Furthermore, the results verify that it there is a need to apply a policy in terms of the amount of spectrum that can be reconfigured in an iteration. However, an exception to this rule shall be applied when an access station is making the initial spectrum selection. At least but not least, with the appropriated repetition of the game the spectral efficiency of a planned network can be approximated.

VI.1 FUTURE WORK

Here are described several possibilities to extend the present work:

1. **Backward compatible solution**: While LTE-A characteristics were considered throughout this text, it was considered that the local area solution will potentially be disruptive compared to LTE release 8. However, in practice, backward compatible solutions are always prefered. In this situation, there is much need to carefully consider common and dedicated control channels in LTE release 8 in the final solution.
2. **Voting system for DL/UL switching point definition**: Since it is important to have a

single UL/DL switching point and changing it is a costly operation for each of the involved networks, it is quite important to define a proper distributed protocol to determine this unique point aiming at the same time in optimizing all the networks and maximizing the time the defined switching point can be kept.

3. **Power and space domain optimization of SpS**: As described in section IV.3 there are much more considerations to be done in other domains in order to lead to better performance.

4. **Extension of solution for unsynchronized TDD**: If the tight syncrhonization requirements of SpS are not met, it will be important to extend the solution for the case where the networks are not synchronizing their TDD operation. In this case, as explained in section III.5.2 the time-space domain distribution of interference has to be considered.

5. **New entrant aware H-ARQ**: Even using a sparse time-frequency pattern during the execution of the protocol, a new entrant is expected to potentially cause a lot of harm to existing connections. An "emergency mode" H-ARQ is potentially benefitial to keep seamless communication during spectrum reconfigurations.

6. **SpS aware TCP**: One of the main features of TCP is to deal with congestion, mainly in the core of TCP/IP networks. Spectrum sharing is dealing with a different kind of congestion: spectrum access congestion. Therefore, we believe that a cross-layer design of a new TCP variant , awere of SpS, is a promising research area.

7. **SpS aware Admission Control**: The RRM function that tries to avoid spectrum congestion within a network is admission control. Once the spectrum is congested across different networks , the admission control strategy should take into account the fact the spectrum is shared.