Channel-Change Games in Spectrum-Agile Wireless Networks

by
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Abstract

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Growing numbers of wireless networks such as IEEE 802.11 and Bluetooth are using unlicensed wireless spectrum. Unlicensed spectrum is a shared resource and simultaneous usage by multiple networks can result in interference problems. As the numbers of wireless devices continue to increase, the problem of interference from coexisting networks is expected to become much worse.

This thesis introduces modeling of dynamic channel change as a game to address interference from coexisting wireless networks. The emergence of more intelligent, spectrum-agile network components that can dynamically change their transmission characteristics makes dynamic channel change feasible. In contrast, existing work in this area addresses the issue of how to share the current channel more effectively.

In this thesis, game-theoretic decision-making based on the self-interest of rational decision makers is applied to a variety of channel-change scenarios. The decision-making consists of selecting the channel-change probability to minimize the transmission delay. Five different scenarios are studied. The results provide a theoretical basis for implementing the decision-making algorithm of a smart access point.

Channel-change decisions are studied by first using the simpler approach of single-stage decisions that only consider the present situation. Next, the more realistic but complex approach of multi-stage decisions, that consider expected future actions also, is studied. The “cost” of strictly competitive game-theoretic decisions is determined by comparing them to centralized, socially optimal decisions that maximize the benefit of all coexisting networks. The results indicate that this cost can be considerable. The cost can be lowered by using trust-based schemes such as “coexistence etiquettes”. However, in untrusted environments, game-theoretic decisions provide the best outcome. The thesis provides guidance on when to use which approach.

The main contribution of this thesis is the introduction of game-theoretic models and their analysis for dynamic channel change decisions in coexisting spectrum-agile wireless networks. The models and analysis have led to an understanding of the policies adopted by self-interest-based decision makers and the resulting system performance. The thesis

also provides guidance on when and how to use game-theoretic decisions for channel change.

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I had the privilege of interacting with several members of the Wireless Communications and Networking Department at Philips Research, Briarcliff Manor, New York during this thesis. The many discussions with Stefan Mangold over the period of a year were very helpful in defining my thesis area. My thesis topic has been strongly influenced by his doctoral thesis. Several early discussions with Kiran Chalapalli helped me in identifying and exploring potential thesis areas at the forefront of wireless networking. I had occasional discussions with some of the other members of the department as well. Thanks to Stefan, Kiran and the others for their generosity with their time, and to department head, Narciso Tan, for allowing me to do this.

I owe a big thank you to my husband, Jim, for his love, support, encouragement, optimism and good humor throughout this thesis. Thanks, Jim, for the many discussions and for carefully reading through and commenting on the first draft. My daughter, Sonia, and other members of the family were always cheer-leaders too. Finally, I would like to thank my parents for their enthusiastic endorsement of my “doctoral dream” and all my earlier educational endeavors, even though the path I chose by studying engineering was very unconventional for an Indian woman at that time.

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Chapter 1: Introduction

1.1 Background

Growing numbers of wireless networks are starting to occupy unlicensed wireless communication bands such as the 2.4 GHz Industrial, Scientific and Medical (ISM) bands at which the 802.11b (Wi-Fi) and Bluetooth networks operate. So far, wireless transmission, such as in radio and TV broadcasting, has required government licenses to ensure exclusive access to a frequency band. Licenses prevent interference from multiple users but lead to low spectrum utilization. As the wireless communication needs of consumers and businesses are increasing, unlicensed usage is being permitted in certain frequency bands. Unlicensed spectrum is a shared resource, not dedicated to any individual network or organization. Multiple networks may find themselves using the same communication band at the same time, resulting in interference problems. Some evidence of these problems is already available [52].

The problem of interference from coexisting wireless networks is expected to get much worse in the future. With the widespread usage of mobile devices such as laptops, PDA's and cell-phones, the need for devices to communicate wirelessly among one another is increasing rapidly. This trend will continue as we move towards pervasive computing environments, with devices embedded even in our clothing and surroundings. Large numbers of future devices are expected to communicate in the unlicensed part of the

spectrum, leading to greater interference problems, and a need for improved spectrum sharing among wireless networks.

One way of addressing large scale spectrum sharing is through the use of smart networks that can dynamically switch communication channels based on interference and load conditions on the current channel. Such networks are called *spectrum-agile*. Spectrum-agile networks require intelligent access points or dynamically reconfigurable ad hoc networks that can change their transmission characteristics in software. Devices with dynamic capabilities based on software radio [49] and cognitive radio [50] technologies are under development, and some early versions are becoming available. Hence, from a technology standpoint, wireless network access points capable of making intelligent, dynamic decisions are likely to become common-place in the coming years.

In this thesis, we address the area of decision-making regarding dynamic channel switching in spectrum-agile wireless networks using the tools of Game Theory [16][60]. Game Theory has been used extensively to model strategic and social interactions to understand how people compete and cooperate. It was developed in the context of economics [74] and has been applied to a variety of behavioral sciences such as anthropology [18], political science [51], sociology [19] and psychology [8]. More recently, it is being applied to the complex environment of the Internet as well, to model decision-making by a number of software agents with diverse interests [1][15]. In our opinion, at a very high level, communication channel sharing resembles resource allocation on the Internet because it involves a large number of networks and many decision makers with diverse interests. Hence game theory should be a useful tool in this domain as well.

1.2 Problem Statement

The problem addressed in this thesis concerns the sharing of the communication bandwidth resource by a number of spectrum-agile wireless networks. Each network decides autonomously whether to stay on a particular communication channel or to dynamically change to some other channel in order to achieve the lowest transmission delay possible for itself. The focus is on dynamic, non-cooperative decision-making by the individual networks modeled as games, assuming rational behavior.

Specific research questions addressed in the thesis are:

- What are the characteristics of channel-change decisions when bandwidth is shared by wireless networks that make local, non-cooperative decisions to optimize their own benefit? Under what conditions does a network choose to stay on the same channel as another network, and when does it change to another channel?
- What transmission delay characteristics result from such non-cooperative channel-change decisions?
- How do these transmission delay characteristics compare with those achieved through “socially optimal” decisions made by a centralized decision maker that optimizes the transmission delay for all networks?
- What insights do these studies provide regarding the design of communication protocols for smart access points of spectrum-agile networks?

1.3 Significance

The IEEE 802.11 network does allow a certain level of coexistence. However, problems related to multiple access points on the same communication channel are being felt in some apartment buildings and other locations in which independently operated networks are in close geographical proximity. Usually the interference is experienced as degraded performance and dropped connections [52]. This problem is likely to escalate in the future, creating an urgent need for dynamic channel sharing solutions.

The acceptance of Wi-Fi (802.11) in the business world has been slower than expected on account of several problems. Part of the reason for this is security issues that are just recently being addressed adequately. The other part is that 802.11 networks do not easily scale up to large installations because of channel sharing and interference issues. Dynamic channel-change decisions and spectrum-agile networks could help alleviate some of these problems.

Efforts are under way by the FCC to open up the radio frequency spectrum [14], which has historically been very strongly regulated. The FCC plans to allow secondary users in licensed spectrum bands. In scenarios with secondary users, dynamic channel-change decision-making could be used in licensed bands as well to promote channel sharing.

DARPA started the XG initiative for Next Generation Communications [45][77] in late 2002 to address how spectrum can be shared among a variety of networks. It has become clear that current spectrum licensing practices have created an artificial scarcity. Smart devices and networks are needed to allow dynamic spectrum sharing. Channel-change decision-making fits under the areas of interest covered in this initiative as well.

1.4 Scope of Study

The scope of the study is the game-theoretic analytical modeling of dynamic, non-cooperative decision-making by coexisting spectrum-agile wireless networks. A number of different models have been developed to capture a variety of decision-making situations resulting from network coexistence. The game-theoretic analyses of these models show the decisions made by rational decision makers maximizing their own benefit in each of these situations. The analyses also show the resulting performance in terms of transmission delay for each of the networks.

In addition, each of the models has also been analyzed from the point of view of a centralized decision maker interested in "socially optimal" decisions that promote the best interest of all networks, rather than the self-interest of any individual network. Note that "centralized" decisions need not necessarily be "socially optimal" or implemented by any single entity such as a base station. For example, in Ethernet [73], the back-off algorithm used to resolve collisions is a simple scheme that promotes fairness for all users without attempting socially optimality. Further, it is implemented in each network device as part of the Medium Access Control (MAC) protocol. In this thesis, we compare the results obtained from centralized, socially optimal decisions with the self-interest-based non-cooperative decisions of game theory.

The decision-making situations modeled in the thesis fit into two broad categories: single-stage and multi-stage decisions. In single-stage decisions, two parameters are considered. The first parameter is the level of interference resulting from coexistence, which can also be seen as the channel-sharing overhead. The second is the overhead in

changing to another channel. The models analyzed for single-stage decisions are as follows:

- **Two-network many-channel model:** When two networks find themselves on the same channel resulting in slower transmission of their respective messages, and there are many alternate channels available.
- **Two-network two-channel model:** When two networks are on the same channel as above, but there is only one other alternate channel available, so that if both networks change the channel, they will interfere again.

The scope of this thesis is limited to the interference resulting from channel sharing with other networks. There can be other forms of network interference as well, such as RF interference from cordless telephones, garage door openers and microwave ovens. Channel-change decisions resulting from such interference have not been addressed.

In multi-stage decision-making situations, only scenarios of high coexistence interference are considered. These models are called *channel blocking models*. The high interference results in coexisting networks blocking each other, preventing any network from making progress. In order to make progress, a network is required to find a channel with no other network on it. The main parameter of interest is the channel-change time. Decision-making is *multi-stage*, where after a decision is made and acted on, the resulting situation is analyzed, another decision is made and so on, until a channel is acquired exclusively. The models analyzed in this category are as follows:

- **Two-network many-channel model:** When two networks find themselves on the same channel resulting in delay in acquiring a channel exclusively, and there are many alternate channels available.

- **Two-network two-channel model:** When two networks are on the same channel as above, but there is only one alternate channel available.
- **N-network many-channel model:** When many networks are on the same channel and as many alternate channels are available as needed. The "two-network many-channel model" is a special case of this scenario.

Many other situations can also be considered in future work as discussed in Chapter 6, but these analyses are sufficient to provide some initial insight into channel-change decision-making.

1.5 Thesis Outline

In Chapter 2, the context of wireless network coexistence is described, along with related work in this area. Work done by other researchers in applying Game Theory to network coexistence and related problems is also discussed.

In Chapter 3, the solution approach of Game Theory is explored in detail. An overview of game-theoretic concepts used in this research is provided, along with a high level introduction to the various models.

Chapters 4 and 5 contain the detailed analyses of the various models and the results. In Chapter 4, the single-stage models are described, while in Chapter 5, the multi-stage blocking models are described.

Finally, in Chapter 6, the conclusions, contributions and opportunities for future work are discussed.

1.6 Definition of Terms

In this section, acronyms and concepts frequently used in this thesis are defined briefly as a reference. More detailed explanations are provided in the relevant chapters.

802.11: An IEEE standard for wireless networks. There are many members in this family such as the original 802.11, 802.11a, 802.11b, 802.11g, and so on.

802.11b: IEEE wireless network standard that operates in the 2.4 GHz band at 11 Mbps. The most popular of the 802.11 standards today.

802.11h: IEEE wireless network standard for Europe operating in the 5 GHz band that allows dynamic frequency selection and power control.

Channel: A transmission resource capable of transmitting a single wireless signal.

Channel-change games: Game-theoretic models developed to analyze channel-change decisions.

Coexistence: When two or more networks occupy the same communication channel.

DARPA: Defense Advanced Research Projects Agency

FCC: Federal Communication Commission

Game Theory: A branch of study that models strategies of competition and cooperation by representing decision-making situations as games.

MAC: Medium Access Control. A protocol layer for sharing access to the transmission medium.

NE: Nash Equilibrium. An equilibrium concept in game theory.

Network: Refers to a wireless local area network such as 802.11 in this thesis.

RF: Radio Frequency

Spectrum: The range of frequencies that can be used for various types of electromagnetic transmission.

Spectrum-agile network: A wireless network that can dynamically modify its transmission characteristics and hence change its channel based on channel conditions.

Wi-Fi: Wireless Fidelity. The term is popularly used to refer to the 802.11 family of wireless networks.

XG: Ne**X**t **G**eneration Communications. A DARPA project initiated in late 2002 [45][77][78] to address efficient sharing of communication spectrum.

Chapter 2: Context and Related Work

2.1 Chapter Overview

The broad context of the research area is provided in Section 2.2. A detailed literature review of related work pertaining to game-theoretic decision-making in relevant computer networking domains is provided in Section 2.3. Finally, in Section 2.5, the contribution made by this thesis to the state-of-the-art is discussed.

2.2 Context

In this thesis, the terms *wireless network* or *network* have been used to refer to wireless local area or personal area networks such as IEEE 802.11 or Bluetooth. Wireless networks transmit packets on certain radio frequencies. These frequencies are known as transmission *channels*. There may be a number of channels on which a wireless network could potentially transmit. In this section, background information related to dynamic channel switching in spectrum-agile wireless networks is provided. Game-theoretic decision-making background relevant to this environment is also covered.

2.2.1 Wireless Transmission

In this section, we cover basic concepts in wireless transmission to appreciate the issues involved in wireless networks better. More details can be found in Stallings [72].