Coexistence of Wireless Networks in Unlicensed Frequency Bands

Stefan Mangold, Kiran Challapali
Philips Research, 345 Scarborough Rd.
Briarcliff Manor NY 10510, USA
stefan.mangold@philips.com, kiran.challapali@philips.com

Abstract—*Radio spectrum is typically divided into radio frequency bands. Licenses for the usage of these frequency bands are provided to operators. Operators are often provided with the exclusive right to use the assigned radio resources. As a result, frequency bands may be used inefficiently. The alternative way of radio regulation is to coordinate the usage of the radio spectrum with unlicensed frequency bands. With unlicensed frequency bands, radio systems coordinate the usage of radio resources autonomously while operating. With this approach, resource sharing between radio systems is difficult to achieve. We refer to this sharing problem as coexistence problem, which is discussed with focus on the 5 GHz U-NII frequency band. A framework for defining coordination rules for the radio resource management, referred to as spectrum etiquette, is discussed. We define spectrum etiquette rules for radio systems with different channel bandwidths. The rules are based on a set of actions like channel selection and listen-before-talk. By evaluating the rules with help of simulation, we provide an initial spectrum etiquette proposal.*

Keywords—*Spectrum Etiquette, Radio Regulation, Unlicensed Frequency Bands*

1 INTRODUCTION

The usage of the radio spectrum and the regulation of radio emissions are coordinated by national regulatory bodies. As part of radio regulation, the radio spectrum is divided into frequency bands, and licenses for the usage of frequency bands are provided to operators, typically for a long time such as one or two decades. With licensed frequency bands, operators have often the exclusive right to use the radio resources of the assigned bands for providing radio services. Depending on the type of radio service and on the efficiency of the radio systems, frequency bands may be used inefficiently. This is not in the interest of the regulatory bodies, because they attempt to achieve high efficiency in the usage of radio resources. The alternative way of regulation is to coordinate the usage of radio spectrum with unlicensed frequency bands. Within unlicensed frequency bands, radio systems coordinate the usage of radio resources autonomously while operating. With this approach, the problem that arises is how to achieve efficient resource sharing between the radio systems that are competing for radio resources.

A radio system represents a group of communicating devices, for example a group of communicating wireless stations in a wireless LAN.

Future radio communication systems will have to support high data rates under *Quality-of-Service (QoS)* requirements such as reliability, and delay constraints. Unlicensed frequency bands are candidates for a large set of radio services because of their public availability. Such radio services may require QoS. However, unlicensed frequency bands may be efficiently used only when the usage of the radio resources is clearly coordinated, for example by means of a spectrum etiquette. A spectrum etiquette is a set of rules for radio resource management to be followed by all radio systems that operate in an unlicensed band. It may help to establish a fair access to the available radio resources, in addition to a more efficient usage of the radio spectrum. A framework to define such a spectrum etiquette is discussed in the following.

This paper is outlined as follows. The approach to coordinate the usage of the spectrum by unlicensed bands is discussed in Section 2, with focus on the 5 GHz band. Section 3 summarizes the objectives and constraints of spectrum etiquettes. Section 4 and Section 5 provide an initial model for the development of spectrum etiquettes and highlight some mechanisms that can be used for spectrum etiquette rules. Simulation results are discussed to highlight the value of some of the proposed rules. The paper ends with a conclusion in Section 6, followed by a list of abbreviations and references for further reading.

2 UNLICENSED FREQUENCY BANDS

The usage of the radio spectrum and the regulation of radio emissions are usually coordinated by national regulatory bodies. For this coordination, the radio spectrum (3 kHz ... 300 GHz) is divided into numerous frequency bands, and individual licenses for the usage of these frequency bands are given to operators. This is referred to as licensing and described in Section 2.1. A brief introduction to unlicensed bands is provided in Section 2.2, and Section 2.3 outlines the structure of the unlicensed bands in the 5 GHz band.

2.1 Spectrum Regulation based on Licensing

Different frequency bands are assigned to different types of radio services. Typical radio services are for example radio-navigation and radio-location, mobile communication, or TV-broadcasting. An operator that has been given a license has typically the exclusive right to use the respective radio resources for providing radio services. Therefore, the operator does not have to share radio resources with other operators. Because of the exclusive right to use radio resources, such radio services are referred to as primary radio services. Radio systems providing primary radio services are referred to as primary radio systems.

2.2 Spectrum Regulation based on Unlicensed Frequency Bands

Unlicensed bands are often assigned in parts of the radio spectrum which are already assigned to a primary (licensed) radio service. Unlicensed radio services are therefore referred to as secondary radio services; consequently, radio systems

Submission to the WWRF#9 meeting, Zurich, Switzerland, July 1-2, 2003. This is an corrected version: the numbering of figures is fixed.

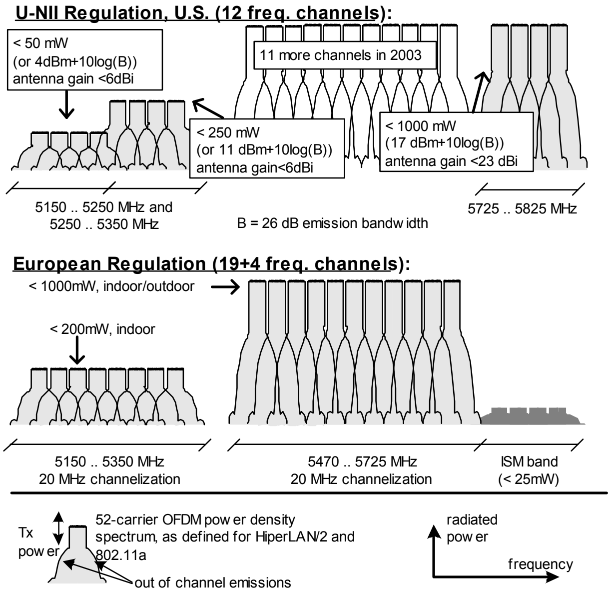

Figure 1: (Mangold, 2003) The 5 GHz band for wireless LANs in the U.S. and Europe.

providing secondary radio services are referred to as secondary radio systems.

Regulatory bodies attempt to coordinate the usage of radio resources so that the most efficient usage is achieved. For this reason, unlicensed frequency bands have been introduced. Unlicensed frequency bands are parts of the radio spectrum in which any type of radio service is permitted, where any type of radio system that meets a predefined set of regulatory requirements can be used. Those requirements regulate, among other parameters, radio parameters such as limits of the radiated power, out of band emissions, and antenna characteristics. In contrast to the licensed approach, a diverse set of different radio systems may operate using the same radio resources in an unlicensed frequency band.

The advantage of unlicensed frequency bands is that, provided that sharing of radio resources is feasible, available radio resources are used more frequently and at more locations, which may lead to better efficiency.

Unlicensed frequency bands cover *Industrial, Scientific and Medical (ISM)* bands such as the 2.4 GHz band, and *Unlicensed National Information Infrastructure (U-NII)* bands (in the United States), such as the 5 GHz band. The difference between ISM and U-NII bands is that radio systems operating in U-NII bands mainly provide communication services, whereas in ISM bands any type of radio system may operate. Radio systems that operate in ISM bands must not necessarily provide communication services. For example, microwave ovens may radiate energy in ISM bands.

The primary radio services in the 5 GHz band are radio-navigation and radio-location. The regulatory requirements for secondary radio systems are defined such that the primary radio systems can still operate in the presence of interference from secondary radio systems.

2.3 The 5 GHz Unlicensed Frequency Band

The 5 GHz unlicensed frequency band covers the radio spectrum between 5.15 GHz and 5.825 GHz. Figure 1 illustrates this frequency band as it is defined for the United States and for Europe. The band is practically harmonized across the two regions. The channelization indicated in Figure 1 refers to the *Orthogonal Frequency Division Multiplexing (OFDM)* transmission scheme as applied by wireless *Local Area Networks (LANs)*.

In the United States, three U-NII frequency bands of contiguous spectrum are assigned between 5.15 GHz and 5.825 GHz, leading to twelve frequency channels of 20 MHz, that are currently used by wireless LANs. In total, a spectrum of 300 MHz has been released for the U-NII frequency band for secondary radio services (FCC, 2003). It is proposed to add eleven more channels (255 MHz between 5.47 GHz and 5.725 GHz) by the end of 2003 (see Boxer and Allen, 2003).

In Europe, radio regulation permits the operation at nineteen 20 MHz frequency channels within two bands of contiguous spectrum. In total, a spectrum of 455 MHz is available for the secondary radio services. Wireless LANs must use the complete band in order to share the spectrum with primary radio systems, with the help of dynamically selecting the frequency channel and the transmission powers. To allow the invention of less complicated radio systems, in the lower part of the spectrum, below 5.35 GHz, secondary radio systems are permitted to operate without implementing dynamic channel selection and power control (REGTP, 2002), similarly to the requirements in the United States. Higher antenna gains are permitted in Europe with the corresponding reduction of transmission power (the *Equivalent Isotropically Radiated Power (EIRP)* remains below a limit).

3 SPECTRUM ETIQUETTE FOR THE 5 GHZ BAND

The 5 GHz unlicensed frequency band is a candidate for a large set of radio services, and is one of the unlicensed frequency bands that may be efficiently used only with an established spectrum etiquette. Such a spectrum etiquette is discussed in the following.

3.1 Motivation and Goals

The usage of radio resources in unlicensed frequency bands has to be carefully regulated to allow as many radio systems as possible in the future to operate in such unlicensed bands. Because the radio spectrum is a finite and limited resource, spectrum efficiency must be achieved, and a fair share of resources among the radio systems must be provided. This is the motivation for a spectrum etiquette.

As explained earlier, a radio system represents a group of communicating devices.

A spectrum etiquette defines the rules for the behavior of radio systems mainly in order to achieve two goals. First, if all radio systems follow the spectrum etiquette, fairness in access to the shared radio resources is maintained, and second, the frequency band is more efficiently used.

There are more goals of an spectrum etiquette. In addition to efficiency and fairness, a spectrum etiquette typically intends to mitigate unwanted mutual effects between radio systems, that occur when radio systems operate without being aware of ongoing operations of other radio systems.

A spectrum etiquette is defined independently of any radio system and aims to cover any possible transmission scheme (for example spread spectrum, *Orthogonal Frequency Division Multiplex, OFDM*, or *Ultra Wideband, UWB*) and any possible multiple access scheme (*Time/Frequency/Code Division Multiple Access, T/F/CDMA*, or *Carrier Sense Multiple Access, CSMA*).

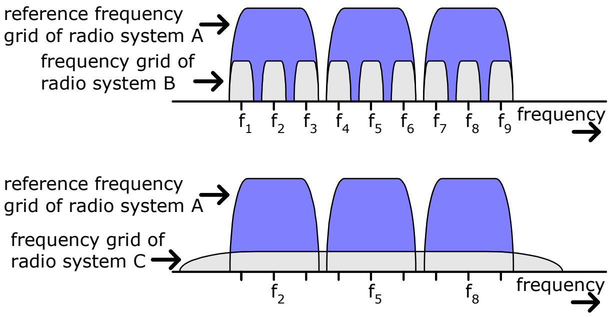

Figure 2: Frequency channels used by three different types of radio systems (A, B, C). Each radio system represents a group of communicating radio devices.

3.2 Constraints

A spectrum etiquette does not define a protocol and is not restricted to one radio standard. Further, a spectrum etiquette is not an algorithm that describes the entire radio resource management of all radio systems. Each radio system can apply its own algorithms within the constraints of the spectrum etiquette. The spectrum etiquette provides a framework for behaviors, which may restrict the degrees of freedom in radio resource management of the individual radio systems. Nevertheless, different algorithms applied by different radio systems will allow differentiation among them, even if the spectrum etiquette is used.

A spectrum etiquette must provide a sufficient degree of freedom for the development of new radio systems.

A spectrum etiquette is not required for licensed frequency bands because these frequency bands are usually controlled by one single entity (a central base station, or one operator), and all radio systems that operate in the licensed frequency band typically comply with the same radio standard.

4 USAGE MODEL AND ETIQUETTE DEFINITION

Figure 2 illustrates the usage of radio resources in a simplified model of an unlicensed frequency band.

4.1 Channelization

Three different types of radio system are assumed to operate in the band, each operating with different frequency channel bandwidths. The radio systems of type A operate on three frequency channels (center frequencies f_2, f_5, f_8), the radio systems of type B operate on nine frequency channels (center frequencies $f_1 \dots f_9$), and the radio system of type C operates on one frequency channel (center frequency f_5). The frequency channels overlap with each other, as indicated in the figure.

The number and bandwidth of the frequency channels in Figure 2 do not represent any existing unlicensed band, this usage model serves as example model only.

Radio system A defines a *reference frequency grid* that is here used as target channelization supported by the spectrum etiquette. Radio system A is therefore referred to as reference system. It can be compared to wireless LANs operating in the 5 GHz band (using OFDM). Radio system B represents narrowband radio systems supporting for example a limited number of voice calls. Radio system C represents radio systems that use broadband transmission schemes such as UWB or spread spectrum. Here, the terms "narrowband" and "broadband" are used in relation to the reference bandwidth.

4.2 Spectrum Etiquette

There are various spectrum etiquette rules that can be defined for the three radio systems. Spectrum etiquette rules require mechanisms, in the following referred to as actions, to be provided by the radio systems. A basic set of actions is defined in the following.

4.2.1 Action Space and Behavior

Among many other feasible actions, the four actions defined in the following are used for building an action space that provides the basic set of action for the spectrum etiquette rules.

ACTION "TPS": Transmission Power Selection
A radio system may operate with different transmission powers, depending on channel conditions and observed interferences. This is here referred to as *Transmission Power Selection (TPS)*. The higher the transmission power, the higher the interference on other radio systems. However, communication will be less erroneous with increased transmission powers.

ACTION "CHS": Channel Selection
A radio system may change the frequency channel it is operating on, based on channel conditions and observed interferences. This is here referred to as *Channel Selection (CHS)*. Based on the decision taking process that determines when to select a new channel and which channel to select, CHS can be advantageous not only for the radio system that selects another channel, but also for all other radio systems.

ACTION "BWS": Bandwidth Selection
In extension to what is indicated in Figure 2, a radio system may select a different channel bandwidth depending on its radio services, and the channel conditions. This is here referred to as *Bandwidth Selection (BWS)*. A radio system that applies BWS may be able to operate with any channelization indicated in the figure. BWS includes operating on multiple narrowband channels in parallel.

ACTION "LBT": Listen Before Talk
Listen Before Talk (LBT) is also known as CSMA, and often discussed in the context of spectrum etiquettes. Radio systems that operate with LBT often achieve a fair sharing of radio resources to some extent. With LBT, the control over the access to radio resources is distributed among the radio systems, and it is therefore difficult for the individual radio systems to determine if they will be able to support their radio services.

Behavior
Taking an action is referred to as *behavior*. The action taking entity is a radio system. A spectrum etiquette rule is the instruction to a radio system to select a particular behavior upon detecting a certain event.

4.2.2 Spectrum Etiquette Rules

Before introducing the spectrum etiquette rules based on the previously defined actions, some underlying assumptions that are independent from the action space are discussed.

The channelization of radio system A determines a reference grid of frequency channels. The bandwidth of radio system A determines what is in the following referred to as the reference bandwidth. Rules that apply for radio systems that operate with a larger bandwidth (in our usage model radio system C, see Figure 2) may be different to rules that apply for radio systems with the reference bandwidth (radio system A) or a smaller bandwidth (here radio system B).

The knowledge about the reference channelization and the reference bandwidth may be obtained from the history of past measurements or by using a predefined reference frequency grid, which has to be a priori known to all radio systems.

A. Underlying Assumptions

When scanning a frequency channel for interference, multiple neighboring frequency channels have to be scanned at the same time. By cross-correlating in time the measurement results of the different frequency channels, it can be estimated if other radio systems operate with a larger channel bandwidth than the measuring radio system. If the detected interference on neighboring narrowband frequency channels is correlated, it can be concluded that a radio system operates on all these frequency channels, by using the respective channels as one broadband frequency channel instead of multiple independent narrowband channels.

Radio systems may dynamically modify their behavior to adapt to the environment. As a general assumption, when a radio system changes its behavior, it should behave so that it allows other radio systems that are competing for radio resources to estimate upcoming changes in its radio resource utilization. For example, a radio system may behave that the history of its previously selected actions correlates with its current and future behavior.

It is assumed that radio systems of type A and B are capable of dynamically changing the frequency channel over a bandwidth larger than the reference bandwidth. In addition, a radio system of type C should be able to dynamically select a frequency channel if the bandwidth of the complete unlicensed band is larger than its channel bandwidth.

Using the four actions that are defined in Section 4.2.1 and referred to as TPS, CHS, BWS, and LBT, the following rules may be considered as working assumption for a spectrum etiquette in unlicensed bands. All the following rules may be mandatory for sub-bands of the unlicensed frequency band, or for the complete unlicensed frequency band.

B. RULE#1: "Unspreading BWS"

A radio system supporting a radio service that requires a channel bandwidth not larger than the reference bandwidth should not operate with a channel bandwidth larger than the reference channel bandwidth. It should only allocate[1] the required channel bandwidth, and select the reference bandwidth or even a smaller channel bandwidth for operation, using the action BWS. The RULE#1 refers for example to adaptively changing a hopping sequence in *Frequency Hopping (FH)* spread spectrum radio systems (You et al., 2001). RULE#1 may not apply if transmission powers are below a certain threshold, typically for UWB.

C. RULE#2: "Dimming TPS"

Radio systems that operate with a channel bandwidth larger than the reference bandwidth, e.g., type C radio systems, should limit the transmission power down to a predefined level in order to limit the interference on other radio systems. RULE#2 may be applied by any type C radio systems, including radio systems that apply spread spectrum, or UWB.

RULE#1 and RULE#2 are complementary to each other. A type C radio system that operates with spread spectrum or UWB may not be able to change its channel bandwidth according to RULE#1. In this case, RULE#2 should apply.

D. RULE#3: "Grouping CHS"

When taking a decision about the frequency channel switching, a radio system of type B should prefer a frequency channel that is in the spectrum close to other type B frequency channels, in order to minimize the number of reference channels that are interfered. This is here referred to as *grouping*. This RULE#3 may apply only in the presence of radio systems with a reference channel bandwidth (identified through interferences on neighboring channels that are mutually correlated in time), or may always apply, independently of the presence of other radio systems. Grouping can be achieved by using a predefined list of preferred frequency channels. For example, a radio system of type B may always select f_1 as initial channel of operation, and if this channel is being used already, attempt to operate on f_2. If this frequency channel is also allocated, it may continue to select the next neighboring channel until a free frequency channel is found.

E. RULE#4: "Listen Before Talk LBT"

A radio system of type A or type B should apply LBT when operating.

F. RULE#5: "Channelized LBT"

This is a modification of RULE#4 for the narrowband radio systems. A radio system of type B should apply LBT by scanning the complete reference frequency channel (type A), not only the narrowband frequency channel (type B) it its operating at.

G. RULE#6: "Synchronized LBT"

This is another modification of RULE#4 for the narrowband radio systems. In order to protect other radio systems most efficiently, a radio system of type B that follows RULE#4 should synchronize its LBT process in time across neighboring frequency channels that overlap with the same reference channel. The Table 1 summarizes the spectrum etiquette rules, and the relation to the three different system types.

Table 1: Spectrum etiquette rules and their assignment to the three types of radio systems.

Etiquette Rule	Radio System Type		
	A (reference)	B (narrow)	C (broadband)
RULE#1 (Unspreading BWS)	–	–	✓ *
RULE#2 (Dimming TPS)	–	–	✓ *
RULE#3 (Grouping CHS)	–	✓ *	–
RULE#4 (Listen before Talk LBT)	✓	✓	–**
RULE#5 (Channelized LBT)	–	✓	–**
RULE#6 (Synchronized LBT)	–	✓	–**

*) not evaluated in this paper

**) LBT is used for radio system type C in the simulation.

[1] To "allocate" is used as synonym for "occupy", or "use" in this paper.

5 NUMERICAL RESULTS

In the following, we evaluate RULE#4, RULE#5 and RULE#6, and discuss how the reference radio systems (type A) are protected by these rules. Stochastic simulation of the usage model is used for this discussion.

5.1 Scenario

One type C radio system (one broadband system with center frequency f_5, e.g., UWB), three type A radio systems (three reference systems with center frequencies f_2, f_5, f_8, e.g. 802.11a), and nine type B radio systems (nine narrowband systems with one radio system per center frequency $f_1 ... f_9$), as indicated in Figure 2, are simulated. Instead of modeling the detailed protocols, a simplified LBT is used for all radio systems. When a radio system wants to allocate radio resources, it scans its frequency channel to determine if it is busy or idle. The scanning is performed instantaneously, without delays. However, a type A radio system requires the respective three frequency channels to be idle before allocating radio resources. The type C radio system requires even the whole spectrum to be idle before allocating radio resources, hence, LBT is not proposed for this broadband radio system as a spectrum etiquette rule (see Table 1).

Only if the respective channel(s) are idle, a radio system allocates radio resources, otherwise it continues to scan until the channel(s) become idle. Collisions of allocation attempts occur when more than one radio system detect the channel as idle at the same time. In the simulation scenario, a perfect collision avoidance among resource allocations from different radio systems is assumed: if two or more radio systems attempt to allocate (use, occupy) the same radio resources (for example a type B radio system operating on frequency channel f_1, and a type A radio system operating on and scanning frequency channels $f_1 \dots f_3$), one of the radio systems is randomly selected to allocate the radio resource, the other radio systems defer and continue scanning the channel. This method to model the collision avoidance approximates a backoff window with an infinite number of slots, each slot having an infinitesimally small duration.

5.2 Channel Model

A perfect channel is assumed, a channel is either busy or idle. Radio systems always detect radio resource allocations of other radio systems.

5.3 Traffic Model

All radio systems are always offered the same traffic. The offered traffic is modeled with two random processes per radio system: the inter-arrival times are negative-exponentially distributed, with varying mean time, varied between *0* and *0.7*. The radio resource access durations are uniformly distributed between *0 ms* and *2 ms* (*1 ms = 1 millisecond*). In the idealized simulation scenario, there is no scan time, as the scanning is performed instantaneously.

5.4 Results

Average airtime per radio system type is provided. Airtime refers to the ratio of allocation time per radio system type to simulation time:

$$airtime_{type=A,B,C} = \frac{1}{N_{type}} \sum_{i=1}^{N_{type}} \frac{allocation\ time(i)}{simulation\ time}$$

with $N_A = 3$, $N_B = 9$, and $N_C = 1$. The airtime characterizes the share of resources a radio system can allocate.

The term *allocation time(i)* refers to the cumulative time the radio system *i* allocates radio resources. Note that we are not showing the throughput per radio system. Because the radio systems operate with different channel bandwidths, they will obtain different throughputs. This is not in the focus of discussion here. What is important is the mutual influence of the radio systems on each other, which is indicated in the shown results.

5.4.1 Results for RULE#4

Figure 3 illustrates the resulting airtime per radio system, averaged over the radio systems of the three different types. All radio systems perform LBT. It can be seen in Figure 3 that LBT is a measure that is most beneficial for the narrowband radio systems (type B). With increasing offered traffic, the narrowband radio systems (type B) achieve a larger airtime, and suppress the resource allocations of the other radio systems. Clearly, LBT alone is not a sufficient mechanism to achieve a fair share of radio resources.

To mitigate this unwanted effect, two modifications of the LBT scheme are proposed, according to RULE#5 and RULE#6.

5.4.2 Results for RULE#5

One modification is to require narrowband systems to scan the reference channels instead of their individual channels, i.e., RULE#5. With this modification, for example, a type B radio system operating at frequency channel f_1 would scan the three frequency channels $f_1 \dots f_3$. Only if all the three channels are idle at the same time, the type B radio system may initiate a resource allocation, similar to type A radio systems. The results of this modification are shown in Figure 4. It can be seen that this modification has negative implications on the airtime of the narrowband radio systems (type B), and improves the resulting airtime of the reference systems (type A) slightly, compared to Figure 3. Note that the type B radio systems still achieve a significant advantage compared to the type A radio systems, because they still may transmit at the same time. Type B radio systems do not contend with each other during backoff. Thus, if one type B radio systems allocates resources, type A radio systems have to defer, but type B radio systems may initiate a parallel resource allocation at the same time (starting at virtually the same time).

5.4.3 Results for RULE#6

The second modification of the LBT scheme of the narrowband radio systems is to synchronize the radio resource allocations in time according to RULE#6.

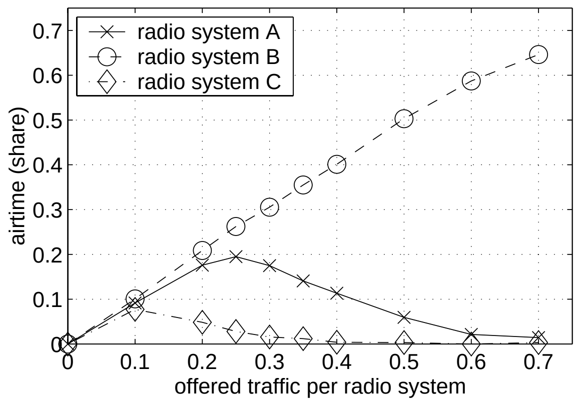

Figure 3: Average resulting channel usage (airtime, share) per radio system. Shown are the average airtimes for the three different radio system types (A, B, C).

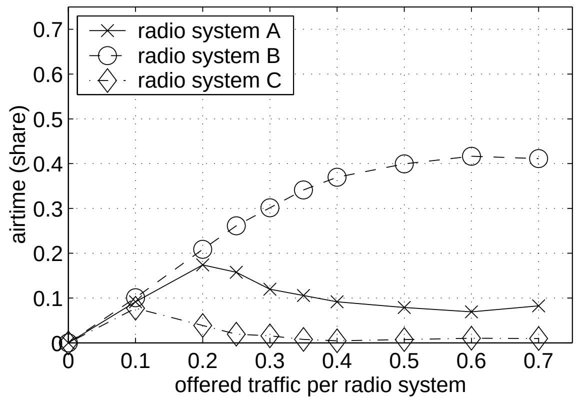

Figure 4: Resulting airtimes with modification of the LBT. The narrowband (type B) radio systems scan the reference channels instead of their own channels (RULE#5).

If the narrowband radio systems allocate resources synchronously, the type A radio systems obtain a higher probability of scanning the three narrowband channels as idle at the same time. Figure 5 shows the results. It can be seen that now the reference radio systems (type A), are better protected than before, and achieve a larger share. Therefore, synchronizing the radio resource allocations of neighboring narrowband radio systems, as discussed in the spectrum etiquette rule "Synchronized LBT", i.e., RULE#6, may help to control the radio resource allocations of coexisting radio systems that operate with different channel bandwidths. It has to be mentioned that the time synchronization of the radio resource allocations of the narrowband systems may be difficult to achieve, and may not be perfect in real life scenarios.

6 CONCLUSION AND OUTLOOK ON FUTURE WORK

Coexistence of different secondary radio systems operating in the same unlicensed frequency band, and therefore competing for radio resources, is one of the challenges in the development of future wireless networks.

The presented usage model allows to investigate and analyze spectrum etiquette rules for unlicensed bands. The etiquette rules presented in this paper form an initial set of rules that may be a starting point when developing a consistent etiquette. Initial results show the complexity of the problem, and the benefit of the listen before talk scheme (RULE#4), together with the proposed modifications. The modifications include that narrowband radio systems have to (RULE#5) scan the reference channels instead of only scanning the frequency channels they are operating at, or have to (RULE#6) synchronize with its neighbor channels.

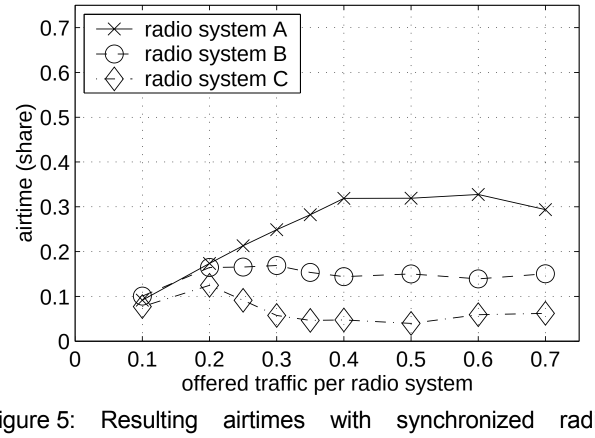

Figure 5: Resulting airtimes with synchronized radio resource allocations for type B radio systems (RULE#6).

Efficiency and fairness are the main goals of a spectrum etiquette, and will be used in our future work to compare different approaches for spectrum etiquette rules with each other. Future work will include investigating the complete set of rules, including transmission power and channel selection. Performance indicators such as payoff (utility) per radio system, and spectrum efficiency, i.e., payoff (utility) in terms of the goals of radio regulation will be used to determine the advantage of individual rules, and how these rules work together.

LIST OF ABBREVIATIONS

BWS	Bandwidth Selection
CDMA	Code Division Multiple Access
CSMA	Carrier Sense Multiple Access
CHS	Channel Selection
CIR	Channel to Interference Ratio
DFS	Dynamic Frequency Selection
EIRP	Equivalent Isotropically Radiated Power
FDMA	Frequency Division Multiple Access
FH	Frequency Hopping
ISM	Industrial, Science, Medical
LAN	Local Area Networks
LBT	Listen Before Talk
OFDM	Orthogonal Frequency Division Multiplexing
QoS	Quality of Service
TDMA	Time Division Multiple Access
TPS	Transmission Power Selection
TV	Television
U-NII	Unlicensed-National Information Infrastructure
UWB	Ultra Wideband

ACKNOWLEDGEMENT

The authors highly appreciate the many valuable comments on the paper from our colleague Javier del Prado Pavon.

REFERENCES

BOXER, B. AND ALLEN, G. (2003) Jumpstart Broadband Act. United States Senate Bill 159 IS. Jan-14 2003.

FCC (2003) Office of Engineering and Technology rule, part 15: Unlicensed RF Devices. *Title 47 of the Code of Federal Regulations*. Federal Communications Commission. Updated Mar-13 2003.

MANGOLD, S. AND CHOI, S. AND MAY, P. AND KLEIN, O. AND HIERTZ, G. AND STIBOR, L. (2002) IEEE 802.11e Wireless LAN for Quality of Service. *In: European Wireless* Florence Italy 26-28 February 2002. 32-39.

MANGOLD, S. (2003) Analysis of IEEE 802.11e and Application of Game Models for Support of Quality-of-Service in Coexisting Wireless Networks. Thesis (PhD), ComNets Aachen University (submitted).

REGTP (2002) Vfg. Nr. 35/2002: Allgemeinzuteilung von Frequenzen in den Bereichen 5150 MHz - 5350 MHz und 5470 MHz - 5725 MHz für die Nutzung durch die Allgemeinheit un lokalen Netzwerken; Wireless Local Area Networks (WLAN-Funkanwendungen). *Amtsblatt der Regulierungsbehörde für Telekommunikation und Post,* 22. Bonn Germany: Regulierungsbehörde für Telekommunikation und Post, 1634-1637.

YOU, Y.-H., PARK, C.-H., JU, M.-C., KWON, K.-W., CHO, J.-W. (2001) Adaptive Frequency Hopping Scheme for Interference-Limited WPAN applications. *IEEE Communications Letters,* 37 (15), 976-977