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Medium Usage Model for the Design of Dynamic Spectrum Management in ISM bands

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Abstract— This paper presents a new approach for dynamic spectrum management for heterogeneous wireless devices. Local congestion degrades the reliability of wireless applications in the License Exempt bands. This leads to the research questions: (1) how to realize equal spectrum sharing between dissimilar systems, and (2) how to improve the collective spectrum efficiency. A solution is in dynamic distribution of the available spectrum between contesting devices. Politeness mechanisms embedded in the individual devices are considered as building blocks for the creation of a distributed dynamic spectrum management system. Medium Usage defines the medium occupied by each transmitter and receiver. A regulatory view is chosen, favoring technology neutrality and including receiver parameters.

Keywords—adaptivity; heterogeneous; License Exempt; Medium Usage; sharing; spectrum management

I. INTRODUCTION

A. The success of License Exempt spectrum

Traditional frequency management divides the available frequency spectrum in small parts and assigns those to one or two homogeneous user groups [1,2]. Prior to this, compatibility studies are performed, the results of which are reflected in spectrum regulation and equipment standardization. This process is bureaucratic and time-consuming. Reallocating spectrum proves to be even more difficult [3].

Contrasting with this command and control type of spectrum management, License Exempt (LE) spectrum [4] provides open access to medium, with only a few generic rules to adhere to. Most technical parameters are left free: choice of modulation, bandwidth, coding, etc.

LE spectrum sees an explosive growth of wireless applications, particularly in the Industrial, Scientific and Medical (ISM) bands [5]. Two main success factors explain the popularity of LE spectrum: (1) the absence of frequency assignment and licensing procedures, assuring a short time-to-market for new or modified products, and (2) the few and generic spectrum rules that leave a large degree of freedom of choice in Radio Frequency (RF) and protocol parameters for the design of a product. The success is perpetuated and amplified by the large number of affordable RF chips now available due to economy of scale.

As a result, LE spectrum has become a breeding ground for innovative wireless products [6]. All kinds of modulation systems and bandwidths are used to transport data for a wide variety of applications, see Fig. 1 for an example. The popularity of the 13 MHz, 433 MHz and 2.4 GHz ISM bands are a showcase of this phenomenon.

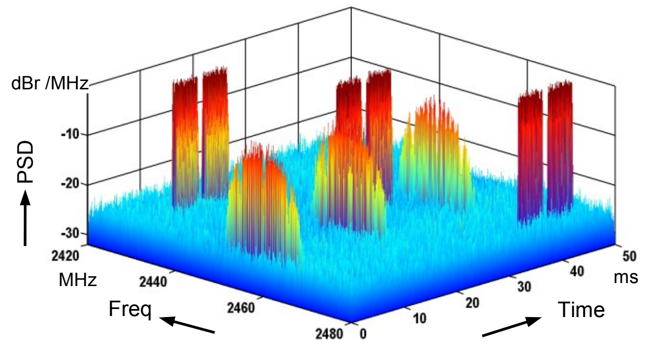

Figure 1. Frequency-time measurement at 2.4 GHz showing a 20 MHz wide DSSS signal (Wi-Fi beacon) and a 40 channel, 1 MHz wide FHSS signal (model plane control). Sampled measurement using 8-bit samples at 100 MS/s.

B. The downside of success

The success of LE spectrum also creates its major challenges. Successful radio applications stay and expand, while newcomers keep arriving. Locally, interference and congestion aggravate, degrading the reliability of the wireless applications. Dissimilarity of modulation systems and protocols results in unequal sharing in congested spectrum [7].

This leads to the following research questions: (1) how to realize equal spectrum sharing between dissimilar systems, and (2) how to improve the collective spectrum efficiency. For the purpose of this research, *spectrum efficiency* is defined as the number of transported raw bits per second, divided by the amount of medium used. The latter will be defined in section 5. *Collective spectrum efficiency* is defined as the total number of transported raw bits per second of all devices in a defined area and frequency band, divided by the total amount of medium used by those devices. The research questions have to be solved without detrimental effect on the two success factors mentioned. Open access to the LE spectrum must be retained, as well as the freedom of choice of most RF design parameters. A solution is in the creation of a distributed dynamic spectrum management system using the adaptivity embedded in the individual devices.

Where most research concerning adaptivity and e.g. DSA optimizes the utility for one or two homogeneous group of users, this paper focuses at improved collective utility of the spectrum shared by dissimilar networks. It presents new fundamental ideas for dynamic spectrum management in LE spectrum, that can also be used for improved sharing between secondary users in the TV White Spaces or other shared spectrum.

The paper is structured as follows. First, in section 2, the concept of distributed dynamic spectrum management is introduced. In section 3, to ensure technology neutrality, interference is defined at the physical layer. Section 4 argues for management of local rather than global interference. Section 5 defines "Medium Usage" as a measure of occupied spectrum, and section 6 describes the properties of the wanted dynamic spectrum management system. The paper is concluded with the key issues of this research.

II. Distributed Spectrum Management

A. Embedded radio procedures

Current wireless consumer products are designed to be self-contained and user-friendly "black boxes". The user ignores the complex wireless communication procedures involved. Procedures once executed by an experienced radio operator are now automated and embedded in the device itself. Examples of these procedures: selecting a frequency from a national frequency table, listening for a clear channel, establishing and maintaining the link, adapting modulation type and data rate to the propagation, optimizing antenna directionality to mitigate interference, and invoking retransmission if needed.

Generally, these embedded procedures are implemented to optimize the quality of one´s own radio link. In heterogeneous groups this leads to unequal competition and individual solutions that are detrimental to the collective spectrum efficiency. Due to the diversity of radio interfaces, interference in heterogeneous groups of wireless devices is far from symmetrical. One system may cause heavy interference to another, while little interference is perceived from the other in return. This gives an advantage to a device with a modulation system that causes more interference than the average device and is robust against interference from others. Such a system will achieve error free communication, while disrupting other radio links. The other devices will back off, and exclusive spectrum is retained as a reward.

B. Wanted social behavior

The absence of any form of collective organization and social rules amplifies this problem. Completing the embedded radio procedures with social rules will produce a more equal sharing of the spectrum, as well as incentives to improve the collective spectrum efficiency. Some examples of such social radio behavior:

- Select empty spectrum for a transmission. This requires spectrum sensing;
- Request /announce whether the spectrum is occupied. A modulation system that can be detected by all networks and a common protocol are needed for this;
- Wait for the termination of other transmissions before starting one's own. This also requires sensing. To avoid excessive delays, a maximum burst length has to be convened;
- Use the minimum amount of power necessary. This requires feedback from the receiver;
- Use the same directivity on transmit as on receive. This is needed to make detection and avoidance possible when using e.g. adaptive antenna systems;
- Allow sufficiently long transmission pauses to allow others to access the medium. The length of these pauses have to be convened for all devices;
- Share the pie, don't eat it all. A measure of spectrum use (section V) and sharing rules are needed.

C. Distributed dynamic spectrum management

Social behavior for radio devices implies sensing the presence of others, and knowing the common social rules to negotiate an optimal distribution of the available spectrum. Mechanisms that sense the presence of other radio devices and adapt their transmissions accordingly have already been implemented in several radio standards. These mechanisms are referred to as "interference mitigation techniques", "polite protocols" or "spectrum access mechanisms". Between homogeneous systems, such mechanisms can be effective for interference reduction.

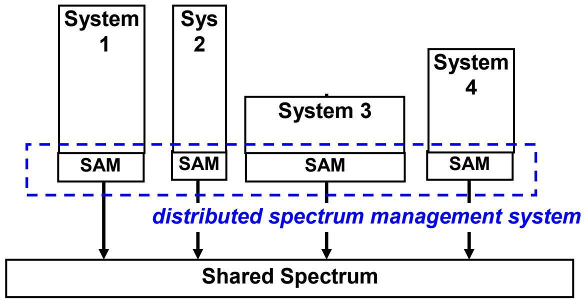

Figure 2. Distributed dynamic spectrum management system, built from identical spectrum access mechanisms (SAM) embedded in otherwise dissimilar radio devices.

Between dissimilar systems, the success is not so certain. Detection is difficult [8] and the different spectrum access systems interact, resulting in a new collective dynamic system. This may result in radio silence while all these polite devices "hold the door open" for each other. Or total chaos due to oscillating interaction. Aiming to optimize the interaction of such a heterogeneous group, we will treat the pool of spectrum access mechanisms as one distributed dynamic spectrum management mechanism, see Fig. 2. Ideally, this distributed dynamic spectrum management system should be designed to follow the social rules we define. They could be sketched as: (1) no limitations on spectrum use when there is enough for all; (2) if others are within range, avoid interference by avoiding spectral, temporal and spatial overlap; (3) in case of congestion, share the medium equally between all devices. This aligns with the latest requirement for 2.4 GHz wideband data systems of the European Commission [9].

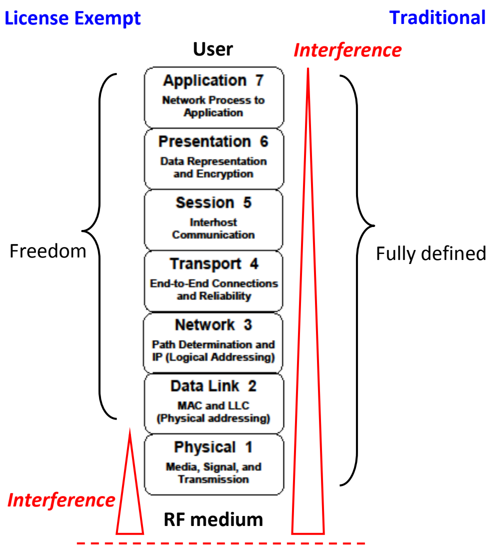

Figure. 3. In LE spectrum interference is defined at the Physical Layer of the OSI model.

III. Technology Neutrality

To retain total freedom of implementation – one of the success factors of LE spectrum – the definition of interference is critical. In traditional frequency management, interference is measured in terms of performance of the application, i.e. at the Application Layer of the OSI model. See Fig. 3.

This approach cannot be maintained in LE spectrum, as unrestrained implementation decisions made by the system designer have a direct impact on the perceived Quality of Service (QoS). RF modulation, coding, error correction, receiver filtering, sensitivity and blocking levels; they all may be chosen to suit the system design, without restrictions by the regulator. Therefore, spectrum sharing in LE spectrum can only be regulated in terms of access to a portion of the medium, not on a higher level.

IV. "Global" vs. "Local" Interference

Traditional frequency management aims at reducing the probability of "Global Interference" to an acceptable level. In other words: the average interference over the assigned spectrum, the assigned geographical area and the total population of devices, must be acceptable. The European Communications Office uses the SeamCat [10] Monte-Carlo simulation tool for this purpose. But Global Interference does not say anything about actual interference occurring on a local scale, or "Local Interference". Two examples:

(a) The use of directional antennas lowers the Global Interference probability, as the chance of being covered by the main beam of the antenna is lower than if an omni-directional antenna were used. However, within that beam interference still occurs, so Local Interference may still be high.

(b) A device using the whole available spectrum with 100% duty cycle would be unacceptable when considering Global Interference. But if used in locations where no other devices are within range, it would cause no Local Interference.

We want to restrict spectrum use as little as possible and deal with the practical situations where spectrum sharing must be organized. As a consequence, our research will focus on Local Interference [11].

V. Dimensions of Medium Usage

Before we decide on *how* to share the medium, we first have to define *what* is to be shared. For this purpose we define "Medium Usage" as the medium occupied by the device or network that cannot be used simultaneously by other devices or networks. This concept is congruent with the concept of "denied spectrum" in ITU-R SM.1046 [12], and has likeness with concepts used in [13].

A. Frequency, Time and Area

When the occupied bandwidth of one network is limited, a second network can find a place in the remaining spectrum. So frequency is regarded as one dimension of the Medium Usage (MU). Similarly, if a radio link is active only 1 ms of every second, the remaining time can be used by others. So time can be regarded as a second dimension of MU. Sharing of the time-frequency space is illustrated in Fig. 4. Yet Fig. 4 only shows the signals perceived by a receiver in one particular geographical position. If we move that position e.g. 40 meters, some of the signals in the graph diminish substantially, while other signals become visible. These new signals now take up frequency-time space that was free in the previous location. We can draw an area around each node in the network to define the area in which it denies frequency-time space to others. In Fig. 5 this area is indicated as "interference footprint".

So geographical area or space is the third "dimension" of MU., which can now be defined as:

$$MU = B \,.\, (t/T) \,.\, A \qquad [\text{Hz.m}^2]$$

Where B is occupied bandwidth, (t/T) the proportion of occupied time, and A the interference footprint area.

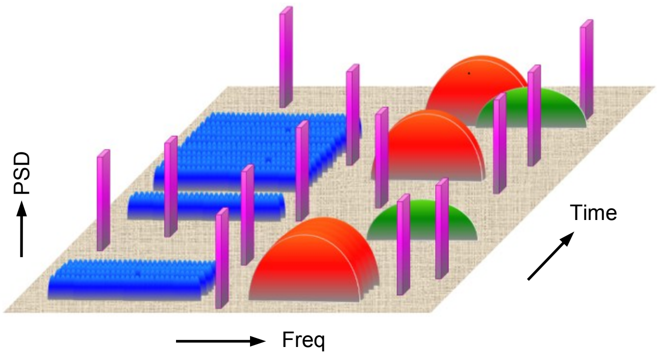

Figure 4. Illustration showing time and frequency sharing. An OFDM signal, two DSSS signals and an (adaptive) FHSS signal are shown. Vertical axis shows Power Spectral Density (PSD).

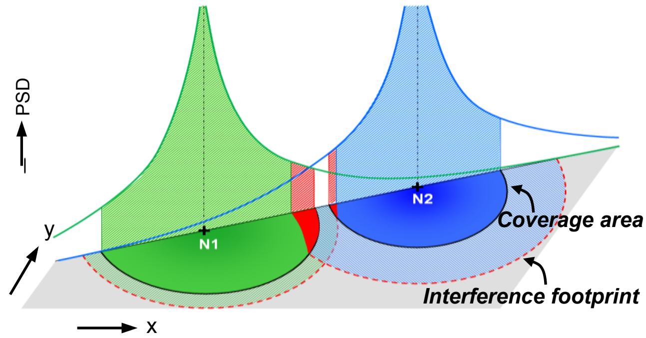

Figure 5. Two wireless devices (N1, N2) with overlapping interference footprint. In the solid red area interference occurs, provided time and frequency overlap as well. Vertical axis shows Power Spectral Density (PSD).

B. Power Spectral Density and Modulation

The size of the interference footprint depends on the Power Spectral Density (PSD) of the interfering transmitter at the victim receiver, assuming the wanted signal arrives with the minimum PSD-level needed for reception. Each combination of two modulation systems requires a minimum power ratio at the detector for discrimination. That ratio is not the same both ways, interference caused by one to the other and vice versa may be very asymmetrical. So the size of the interference footprint also depends on the modulation systems of both the victim and the interferer.

C. Receivers also occupy spectrum

The reception of a wanted signal puts restrictions on signals from nodes of other networks [14]. We can draw an area around the receiver where transmissions would inhibit reception, if in the same frequency and time. This is the area that the receiver occupies. As most wireless devices will employ transceivers for half-duplex communication on a single frequency, this concept does not change much on the "frequency" and "area" axes. However, both the transmitting and the receiving timeslots have to be considered for the nodes at both ends of a link. For unidirectional links the spectrum occupied by the receivers should be taken into consideration. The influence of receiver parameters on spectrum efficiency will be addressed in more detail in section VII.

VI. DYNAMIC MU ALLOCATION

A. Medium Usage visualized

Fig. 6 depicts the Medium Usage (MU) for three networks in the 2.4 GHz band. As only one instant of time is shown, it should be regarded as a still picture from a movie. The MU of the transmitter is shown in red/yellow, that of its companion receiver in blue/green. As no reference victim was defined, Power Spectral Density contours were used for this visualization. The networks in Fig.6 have overlapping MU-shapes and interference occurs. This is unnecessary, as there is enough medium is available for all three networks. The overlap could be resolved by a frequency adaptation, see figure 7.

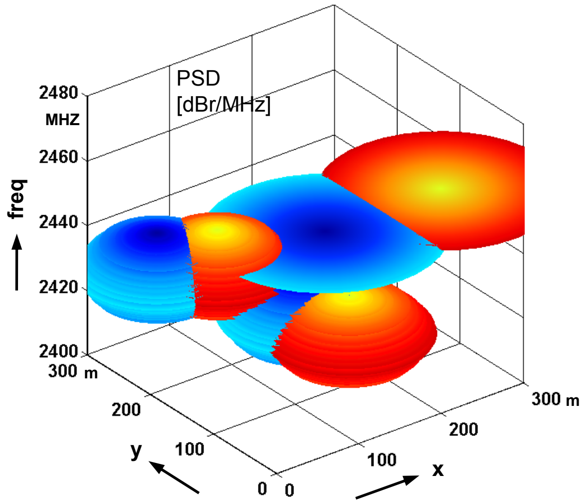

Figure 6. Overlapping Medium Usage (MU) of two DSSS networks and one FHSS network, in one instant of time. Interference occurs.

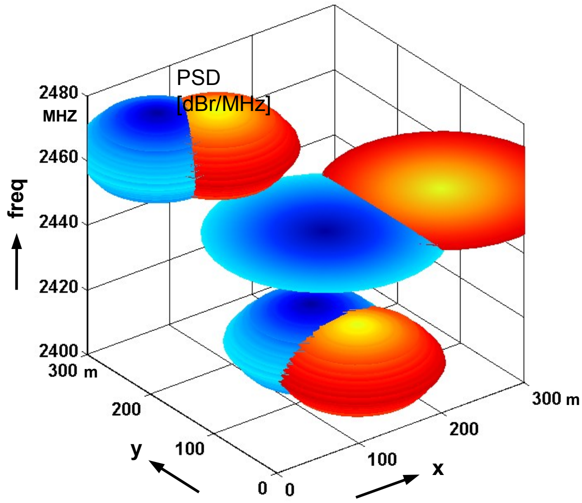

Figure 7. Same networks without overlapping MU. Interference is avoided.

B. Adaptive behavior

Using the MU concept, we can now define the task given to the distributed spectrum management system. It must be designed to solve a dynamic block puzzle, fitting all these MU-shapes into the available spectrum, repeating the exercise when new networks show up. When the networks are sufficiently far apart, all medium may be used as desired and MU is not limited. When several users are located within each other´s range, MU-shapes could overlap, and frequency use becomes interdependent.

All three dimensions of the MU offer possibilities to position the MU-shapes in the medium and to avoid interference, by:

- Reducing spectral overlap. This can be achieved by changing frequency, reducing bandwidth, using non-contiguous bandwidth modulation [15,16,17], decreasing PSD (increasing bandwidth), or by omitting channels in the hopping sequence [18].
- Reducing overlap in time. This can be achieved by synchronization, and by adapting frequency and duration of transmissions.
- Reducing spatial overlap. This can be achieved by power reduction using adaptive power control [19], by changing the directional characteristics of the antenna using adaptive beam forming, or by polarization change.
- Changing modulation. If we know the modulation system of the victim, changing our own modulation system could lower the interference perceived at the same PSD level and so create more isolation [20].

C. Graceful degradation

When the number of devices in an area becomes so great that the demand exceeds the available medium, an MU block fitting solution without overlap can no longer be found and congestion occurs. Without any regulation imposed, systems which are more robust to induced interference will now have an advantage. On the other hand, also systems that cause most interference to others will win most spectrum. Rewarding such systems decreases the collective spectrum efficiency.

A solution can be found in limiting the maximum MU. The maximum available MU per device become less, but whether that results in more delay, less throughput or less reliability remains up to the choice of the designer, not of the regulator. This solution stimulates spectrum efficient solutions and can be defended as a fair way of sharing the spectrum [10].

The dynamic properties of the distributed spectrum management system must be such that both deadlock and starvation are avoided. The settling time may be longer than the transmission intervals of the individual systems, as long as the solutions found converge to equal sharing and improved collective spectrum efficiency.

VII. KEY ISSUES

A. Interference Matrix

In section V pointed out that the interference distance and hence the boundaries of the interference footprint strongly depend on parameters of the victim system. It would therefore be desirable to gather more information on the sensitivity for interference from one modulation system to the other, similar to [20,21], preferably before error correction and without adaptivity. As interference is not symmetrical, this would result in an interference matrix.

If it would be possible to distill different classes of interferers and victims from this matrix, it would become possible to make an educated guess of the amount of interference caused on an average victim by a specific modulation system. Or even better: if the modulation system of the victim can be detected, the interference distance can then be calculated, and more precise actions can be taken to avoid interference.

B. Receiver parameters and spectrum efficiency

Receivers have a serious impact on spectrum efficiency and sharing possibilities, especially for wireless device operating in close proximity to each other [22,23]. In many cases, the dynamic range of the receiver front-end is insufficient to decode weak signals from companion devices in the presence of strong signals from other networks at distances less than 10 meters. This could be caused by front-end overloading, by desensitization due to unwanted action of the Automatic Gain Control (AGC) on strong off-channel signals, or by insufficient ADC dynamic range. With such deficiencies, sharing on the frequency axis is impossible, and the MU of the receiver has become very large. Which in turn drastically lowers the collective spectrum efficiency. Gathering more empirical data on these reported problems will help to assess the size of this problem and make suggestions for improvement.

The same holds true for transmitter impurity, e.g. unwanted sidebands caused by the modulation process, intermodulation in the final amplifier or oscillator or wideband noise.

C. Common Signaling Language

When the interfering node cannot hear the conversation partner of the nearby node, he risks transmitting over the reception timeslot of the nearby node, causing interference [24]. This so-called “Hidden Node problem” cannot be solved easily, although the request/announce process mentioned in Section 2 could prove very valuable. Especially in LE spectrum, where even nearby networks could easily be overlooked due to great differences in bandwidth and modulation system. For example, the Hidden Node could send a code signaling “you cause interference”, which could be relayed by its companion. This concept has similarities with the ITU-R maritime and aviation Q-codes, that were meant to give short coded coordination message that would be understood in any language [25,26], and with the “Busy Burst” signal in [27].

D. Demonstrator

Further practical and theoretical work must be done to extend work of others [28,29,30] to define the detection and reaction rules for a distributed dynamic spectrum management system that works for a population of dissimilar radio systems.

Preferably, such a system has to be demonstrated in practice, using 3 or 4 networks using e.g. DSSS, OFDM and FHSS modulation. Switching on one of the devices, or changing the modulation parameters in one network, should result in adapted spectrum use and timing, avoiding MU-overlap or reducing Medium Usage.

VIII. Conclusion

Fundamental concepts are discussed for dynamic spectrum management mechanisms based on Medium Usage. This approach promises improved spectrum efficiency and a more equal sharing of the spectral-temporal-spatial medium for heterogeneous wireless devices. It is therefore especially suited for LE spectrum. At the same time implementation freedom is retained, and optimization of the individual system now leads to maximum collective spectrum efficiency and to a more equal spectrum sharing. Further research includes measurements on existing devices, simulations showing dynamic behavior and a demonstrator, and will be subject to further publications.

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