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Spectrum sharing with value-orientation for cognitive radio[†]

Stefan Mangold¹*, Lars Berlemann² and Saishankar Nandagopalan³

¹Swisscom Innovations, Berne, Switzerland ²Chair of Communication Networks, RWTH Aachen University, Aachen, Germany ³Qualcomm, San Diego, CA, USA

SUMMARY

Radio spectrum is not efficiently utilised because of the complicated and time-consuming radio regulation processes. In this article, technologies to help overcoming this barrier, namely, cognitive radios, are discussed. Cognitive radios (i.e. agile radios) operate in the radio spectrum that was originally licensed to other (incumbent, primary) radio services. A cognitive radio seeks unused radio resources and communicates using these opportunities, without interfering with the operation of licensed radios. We discuss two main problems: protection of incumbents and coexistence of cognitive radios. Spectrum sharing among different radio systems can be understood as a scenario forming a society of independent decision-makers. Therefore, basic concepts to classify social action that are taken from social science are applied to define system strategy rules. The rules represent algorithms for decision-making entities (referred to as actors) that reside in the radio systems. For a simple scenario of spectrum sharing, we investigate the need for regulation as opposed to voluntary rules. Copyright © 2006 AEIT.

1. INTRODUCTION

Today, access to radio spectrum is frustratingly difficult. The access is restricted by an old radio regulatory regime that emerged over the last 100 years. Large parts of our radio spectrum are allocated to licensed radio services. Open access to most of the radio spectrum is only allowed with very low transmission powers, in a so-called underlay approach, as for example used by ultra wideband (UWB). The overlay approach, that is the free access to open spectrum, is generally not permitted.

Only some small fractions of the radio spectrum, the unlicensed bands, are openly available, under some limitations. This restricting bottleneck slows down the development of new radio services that can substantially improve our health, safety, work environment and quality of leisure time. With the existing radio regulatory regime, whenever radio services for new wireless applications evolve, the status of spectrum allocation and licensing has to be changed; new radio spectrum has to be made available. However, changing the status of licensed radio spectrum can be perilous and painfully slow. It takes a concerted effort among government regulatory agencies, technology developers and service providers to achieve efficient and timely deployment. This is one of the reasons why, paradoxically, 90%–95% of the licensed radio spectrum is not in use at any location at any given time [1–4]. The existing radio regulatory regime is simply too complex to handle the increasingly dynamic nature of emerging wireless applications. As a result, we waste precious spectrum.

On the contrary, the commercial success of wireless applications in the unlicensed bands, and the many radio

^{*} Correspondence to: Stefan Mangold, Swisscom Innovations, Berne, Switzerland. E-mail: stefan.mangold@swisscom.com [†]An early version of this article was presented in Reference [1].

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systems utilising this fraction of the radio spectrum, indicate that it may be helpful to change our so much established and manifested radio regulatory regime, towards a more flexible, open spectrum access. We may just want to let radio systems coordinate their usage of radio spectrum themselves, without involving regulation. Self-organising radio systems would then autonomously regulate in a technology-based approach: the machines would make the decisions, not humans. It can only be imagined how our economies would gain from such a flexible, technology-based approach. If successful, this approach would support new emerging wireless applications, at the same time allowing existing incumbent radio services to continue operating without significant quality-of-service (QoS) degradation. Such an open approach would potentially increase the usage of our radio spectrum significantly.

1.1. Problem statement

Two main challenges exist with the proposed technologybased approach for regulation:

- Protection of the incumbents: The first challenge for cognitive radio is to protect the operation of incumbent, licensed radio services. The additional opportunistic usage of radio spectrum should not harm the operation of already established radio services.
- 2. Coexistence: The other challenge for cognitive radio is to overcome the problem of coexistence and potential free riders in an openly accessible spectrum. Apparently, when radio systems share spectrum, it is difficult to guarantee that spectrum usage is not monopolised by some radio systems, while at the same time other radio systems would not be able to operate.

How should radio systems be designed to efficiently use and share radio spectrum, and at the same time not cause significant interference on incumbent radio systems? Our answer to this question is 'cognitive radio' [5,6–14].

1.2. Approach: dynamic spectrum assignment with cognitive radio

Cognitive radios are radio systems that autonomously coordinate the usage of spectrum. They utilise radio spectrum when it is not used by incumbent (primary) radio systems. Such unused radio spectrum is called 'spectrum opportunity', also referred to as 'white space' [15]. Spectrum opportunities must be used in an intelligent way, and often, the term 'smart radio' is used in this context [15]. We use 'cognitive radio' as

as 'spectrum agile radio.' True cognition requires semantic concepts that could for example be implemented with ontology, in order to represent knowledge and describe algorithms. It is our intention to analyse radios with true cognition. We extend the traditional way the cognitive radios are

synonym for what in our previous work is referred to

we extend the traditional way the cognitive radios are defined by introducing social awareness. Radio devices that are aware of their society, that is the existence and demands of other radio devices, can benefit by supporting not only their own interests, but also the interests of the other radio devices. Sociological concepts for self-organising radio systems and technology-based regulation are discussed in this article. In particular, we model groups of cognitive radio devices as what in social science is referred to as contemporary society.

A contemporary society is a group of socially acting individuals (here called 'actors') where each individual acts according to classified motivations. An action is, for example the selection of some medium access control (MAC) and radio transmission parameters such as transmission powers and the frequency of operation. We express actor's interests through their application requirements (e.g. the throughput or share given in Mb/s that an application would require), as typically applied in game theory. However, we represent not only the economic selfinterests of actors, but also the actor's value-orientations. Value-orientation is a concept in contemporary societies with social awareness, as will be explained in more detail later in this article. Sociological models known from Reference [16] are applied to build a framework for a society of machines. These models allow designing new types of radio systems that are not only self-aware, but also socially aware. This is a unique approach for autonomous spectrum sharing in support of our goal to achieve technology-based radio regulation. We argue in this article that by introducing value-orientation, cognitive radios can be designed so that they are capable of coordinating theirspectrum usage. Whereas until today, cognitive/cognitive radio systems are thought of as pure technocratic decision-makers, value-oriented cognitive radios will support the introduction of true cognition, for the purpose of higher efficiency in spectrum usage.

1.3. Outline

This article is outlined as follows. In the next section we summarise related work. In Section 3, white space identification, spectrum opportunity management and existing protocols are discussed. This is followed by a brief intro-

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duction into the concept of social action in Section 4. We introduce an approximation in discrete-time domain and z-domain for a spectrum sharing scenario of different radio systems in Section 5, where it is assumed that radio resources are shared with contention-based channel access. Actor's system strategies are described in the following Section 6, and evaluated in Section 7. The article ends with a conclusion in Section 8.

2. RELATED WORK

Our work is inspired by the Defense Advanced Research Projects Agency (DARPA) Next Generation Communication (XG) project. The XG project objectives are described in References [17, 18]. The Federal Communications Commission (FCC) issued several documents where similar concepts are discussed [15, 19]. A new standard IEEE 802.22 is being defined at the time this article was written, for what is referred to as regional area networks. Such networks operate in the VHF/UHF bands, and include mechanisms to protect incumbent radio systems (terrestrial TV broadcast) from harmful interference [20], by means of incumbent identification. It is also noted that Reference [21] provides a lively discussion on open spectrum access, where concepts similar to cognitive radio are discussed.

Additional approaches to autonomous spectrum sharing besides the concept of social action as introduced in Section 4 are for instance the idea of spectrum load smoothing (SLS) and the application of solution concepts from game theory (GT) as introduced in the following. Both approaches realise a cognitive medium access in enabling a distributed coordination aiming at QoS support in a shared radio spectrum.

2.1. Spectrum load smoothing (SLS) [22, 23]

The application of waterfilling in time domain enables a decentralised and coordinated, opportunistic usage of the spectrum. This is referred to as SLS. With SLS, competing radio systems aim simultaneously at an equal utilisation of the spectrum. In observing the past usage of the radio resource, the radio systems interact and redistribute their allocations of the spectrum under consideration of their individual QoS requirements. Due to the principle of SLS these allocations are redistributed to less utilised or unallocated spectrum. QoS requirements of the coexisting networks are considered. Further, SLS allows an optimised usage of the available spectrum: An operation in radio

spectrum, which was originally licensed for other communication systems, is facilitated, as the SLS implicitly achieves usage of unused spectrum and its release in case it is needed again.

2.2. Application of game theory [24, 25]

The competition between independent radio systems for allocating a common shared radio channel can be modelled as a stage-based game model: players, representing radio systems, interact repeatedly in radio resource sharing games, without direct coordination or information exchange. Solution concepts derived from game theory allow the analysis of such models under the microeconomic aspects of welfare. Decisions that the players repeatedly have to make are about when and how often to attempt a medium access. In multi-stage games, players apply strategies in order to maximise their observed utility as summarising value for successful supported QoS. Strategies determine whether competing radio networks cooperate or ignore the presence of other radio networks. The requirements of the players determine which strategies guarantee QoS.

These approaches lead to system strategy rules such as discussed in Section 6.

3. WHITE SPACE IDENTIFICATION, OPPORTU-NITY MANAGEMENT AND PROTOCOLS

The two challenges cognitive radio faces are: (1) protection of the incumbents and (2) coexistence, which are discussed in the following.

To protect incumbents, spectrum opportunities have to be identified, and their usage has to be managed. A spectrum opportunity is an idle radio resource (also referred to as 'white space') defined by frequency, time and location, which is either not used by licensed radio devices, or used with predictable usage patterns, such that idle intervals during which spectrum may be re-used by cognitive radios. The predictability and the dynamic nature of spectrum usage contributes to the challenge of identifying spectrum opportunities accurately: the less frequent and more predictable the spectrum usage by primary radio devices occurs, the higher the success of identification, and efficiency of opportunistic usage by cognitive radio [5]. Spectrum opportunity identification can be further improved by taking characteristic patterns of spectrum usage by incumbent radio systems into account.



Figure 1. OFDM-based cognitive radio: —overlay approach of re-using licensed spectrum and sharing it with incumbent services. Harmful interference is avoided by identification of spectrum opportunities, and negotiation of spectrum usage among the cognitive individuals.

For the second challenge, coexistence, algorithms are needed that would enable WLANs/WPANs to utilise the licensed radio spectrum, including lower frequencies such as the TV bands, in an overlay sharing approach. A conventional UWB system shares the spectrum in an underlay approach. Spectrum is used with low transmission power, to ensure not to cause interference on the incumbent radio systems. Figure 1 illustrates how a multi-carrier system such as proposed for UWB could morph into cognitive radio, by dynamically making use of the spectrum opportunities upon identification.

4. CONTEMPORARY SOCIETY

The terminology and modelling approach of [16] are discussed in this section. We describe the concepts of social action, economic action, contemporary society and valueorientation.

As stated before, a contemporary society is a group of socially acting individuals (here called 'actors'). We express actor's interests through their application requirements. However, we represent not only the economic selfinterests of actors, but also the actor's value-orientations.

4.1. Social action

A cognitive radio makes decisions about what action to take; hence, a cognitive radio is referred to as actor. There is a predefined set of valid actions that an actor can take; this set spans the so-called action space. According to [16], an action is usually associated with a subjective meaning. Two classes of action exist: social action and economic action. An action is social, if *'its subjective meaning takes* account of the behaviour of others and is thereby oriented in its course' [16]. An action that intends to improve the actor's outcome is an economic action. However, the subjective orientation of an actor is what we are particularly interested in when discussing the concept of social action.

A classification in Reference [16] distinguishes between four types of motivation for social action:

- Technocratic social action ('zweckrational' [16])
- Value-oriented social action ('wertrational' [16])
- Affective social action (based on emotional state)
- Traditional social action (guided by custom)

This typology is summarised in Reference [26]. In the following, we focus on the types (1) and (2) of social action. It is highlighting to interpret the existing way of radio regulation and spectrum sharing as technocratic social action: whatever other individuals may observe, each individual attempts to optimise it's own spectrum usage only. This would lead into chaotic and unpredictable scenarios of spectrum usage if there had been no regulation: the purely technocratic social actions of today's radio systems leverage the existence of radio regulation. However, we are interested in opening the spectrum for free usage, with a minimum amount of radio regulatory constraints. In the rest of this article, motivated by the findings of [16], we therefore attempt to apply social concepts that allowed human beings to live without complete regulation of their daily interactions. For the spectrum-sharing problem, the decision-making processes will be modified for supporting the social concepts of value-orientation and voluntary rules. The scenario used for this attempt is described in the following Section 5.

5. SECTRUM SHARING WITH CONTENTION-BASED MEDIUM ACCESS

In this section, the spectrum-sharing scenario and its model are discussed. We assume a simple scenario of different radio systems that share spectrum with contentionbased medium access. This is a case study, which serves as an initial example for spectrum sharing among different radio systems. Note that the radio systems do not communicate with each other, but operate using the same radio resources.

Consider M radio systems that share the spectrum using carrier sense multiple access with collision avoidance (CSMA/CA). If not stated otherwise, all radio systems operate in saturated condition, that is all stations have always packets to send, their queues are never empty.

We will now provide a simple analytical model to understand the dynamics of spectrum sharing by these different radio systems (also referred to as $actors)^{\ddagger}$. For the sake of simplicity we assume that the slots are synchronised between different systems and they use a simple random backoff for contention process using a contention window (CW) and not the exponential backoff as in case of IEEE 802.11. Also we assume that the slot sizes of different radio systems are the same in order to avoid complicating the analysis.

5.1. Interaction and the observed throughput (the observed share) at stage n

Let there be *M* independent radio systems sharing the radio spectrum, each operating with different $CW^1(n)$, $CW^2(n), \ldots, CW^M(n)$ as the contention window sizes at discrete time stage *n*. The parameter *n* denotes a non-negative integer number indicating the discrete-time progress of the interaction. The observable spectrum share ϑ_{obs} of an individual radio system can be calculated as follows. To get the expression, we need to determine the probability of one radio system winning the contention. For radio system 1, the respective contention window at stage *n* is indicated as $CW^1(n)$. The probability of channel access at a slot by the radio system 1 is $1/CW^1(n)$. With this probability, the observed spectrum share $\vartheta_{obs}^1(n)$ by radio system 1 at stage *n* is approximated by

$$\vartheta_{\text{obs}}^{i}(n) \approx \frac{1}{\text{CW}^{i}(n)} \cdot \prod_{\substack{m=1\\m\neq i}}^{M} \left(1 - \frac{1}{\text{CW}^{m}(n)}\right)$$
$$\sum_{k=1}^{\text{CW}^{i}(n)} \left[1 - \frac{1}{\text{CW}^{i}(n)} \cdot \prod_{\substack{m=1\\m\neq i}}^{M} \left(1 - \frac{1}{\text{CW}^{m}(n)}\right)\right]^{k-1}, \ i \in [1, M]$$
(1)

This equation approximates the probability that radio system (actor) i wins the contention against all other radio systems at stage n. See Reference [27] for a detailed discussion on how to derive this equation for the 802.11 contention-based medium access. To simplify the notation in the rest of this section, we substitute

$$b^{i}(n) := \frac{1}{\operatorname{CW}^{i}(n)} \cdot \prod_{m=1 \atop m \neq i}^{M} \left(1 - \frac{1}{\operatorname{CW}^{m}(n)}\right), \quad i \in [1, M]$$

With this substitution, Equation (1) is written for any actor $i \in [1, M]$ as

$$\vartheta^{i}_{\text{obs}}(n) \approx b^{i}(n) \cdot \sum_{k=1}^{CW^{i}(n)} (1 - b^{i}(n))^{k-1} \quad \forall i \in [1, M]$$

which can be expressed as

$$\vartheta_{\text{obs}}^{i}(n) \approx b^{i}(n) \cdot \left[1 + \left(1 - b^{i}(n)\right)^{1} + \cdots + \left(1 - b^{i}(n)\right)^{\text{CW}^{i}(n) - 1}\right]$$
(2)

It is clear that $(1 - b^i(n))^{CW(n)} \ll 1$ for a smaller number of actors, and in case of small contention window sizes. We therefore further simplify Equation (2) to

$$\vartheta_{\rm obs}^i(n) \approx b^i(n) \tag{3}$$

Care must be taken not to oversimplify the approximation. The benefit of Equation (3) is however its simplicity, allowing for further analysis with the help of system theory.

With the substitution $c^i(n) := 1/CW^i(n)$, we finally find the observed shares at stage *n* for all actors, expressed as vector $\vartheta_{obs}(n)$.

$$\vartheta_{\text{obs}}(n) = \begin{pmatrix} b^{1}(n) \\ \vdots \\ b^{M}(n) \end{pmatrix} \approx \begin{pmatrix} c^{1}(n) \cdot \prod_{m=1}^{M} (1 - c^{m}(n)) \\ \vdots \\ c^{M}(n) \cdot \prod_{m=1 \atop m \neq M}^{M} (1 - c^{m}(n)) \end{pmatrix}$$
(4)

Note that

$$0 < \frac{1}{\operatorname{CW}^{i}(n)} < 1 \Rightarrow 0 < c^{i}(n) < 1, \text{ with } \operatorname{CW}^{i}(n) > 1.$$

The result of the spectrum sharing is emphasized in Figure 2 for a scenario of three different radio systems (three actors). Note that in the rest of this article we only consider three actors. Consider the example scenario wherein the actor 3's CW is set constant at 5. Now consider the varying range of CW for actors 1 and 2. It is assumed that all radio systems always attempt to access the medium (queues are always full, system is in saturation). It is found that the spectrum share of actor 1 is very small if its CW is large (20 in Figure 2(a)). This is indicated in region 1 in Figure 2(a). The spectrum share increases when its CW starts to decrease, as can be seen in regions 2 and 3 in Figure 2(a). Region 4 represents the low utilisation of the spectrum. In this region the contention window sizes

[‡]The phrases 'actor' and 'radio system' are synonyms and used interchangeably in this article.



Figure 2. Observed shares of capacity ϑ_i and $\Sigma \vartheta_i$ for the three actors, with varying contention window sizes for actor 1 and actor 2. (a) observed share of actor 1; (b) observed share of actor 1; (c) observed share of actor 3 with CW₃ = const = 5; (d) sum of all actor's shares.

of actor 1 and 2 are very large resulting in very low frequency of access. Figure 2(b) gives the similar spectrum share for actor 2. Observe the Figure 2(c). In this figure we see that when the contention window sizes of actors 1 and 2 are 1, the spectrum share drops down to zero (see for example region 3 Figure 2(d)). This is a special case and represents protocol modelled by time division multiple access (TDMA) or by hybrid coordination functioncontrolled channel access (HCCA) of IEEE 802.11e with a fixed contention window size of CW = 1. With this value, both the actors try to access the medium at the same slot, resulting in collision. Hence, spectrum usage becomes deterministic (referred to as 'controlled' in IEEE 802.11e). The figure indicates that these protocols require additional coordination mechanisms for spectrum sharing such as intelligent scheduling, if feasible. Figure 2(d) gives the total spectrum or the total spectrum utilisation. It is interesting that in case of one radio system monopolising the spectrum usage (see regions 1, 2 in Figure 2(d)), the overall spectrum utilisation is maximised. This indicates that overall spectrum usage efficiency cannot be the only metric when evaluating sharing approaches: based on spectrum usage efficiency only, monopolising would be desirable.

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The figures also show that dynamically adapting to optimised parameters is important for of the three actors to achieve fair and efficient utilisation of spectrum.

5.2. Transformation to z-domain

Throughput is observed in consecutive stages n. We assume the three spectrum sharing radio systems build a time invariant system. We further assume that the system builds a discrete-time stationary process. Our problem can then be transformed into the *z*-domain:

$$\Theta(z) := \sum_{n=1}^{\infty} \vartheta(n) \cdot z^{-n}$$

The transformation will help us to know about the stability of the discrete-time, time-invariant system shown in Figure 3. For the observed share, we transform

$$\vartheta_{\rm obs}(n) := \begin{pmatrix} \vartheta_{\rm obs}^1(n) \\ \vartheta_{\rm obs}^2(n) \\ \vartheta_{\rm obs}^3(n) \end{pmatrix} \circ - \bullet \Theta_{\rm obs}(z)$$

Euro. Trans. Telecomms. 2006; 17:383-394



Figure 3. The spectrum-sharing scenario as discrete-time, time-invariant system.

Equivalently, we transform the requirement

$$\vartheta_{\mathrm{req}}(n) := \begin{pmatrix} \vartheta_{\mathrm{req}}^{1}(n) \\ \vartheta_{\mathrm{req}}^{2}(n) \\ \vartheta_{\mathrm{req}}^{3}(n) \end{pmatrix} \circ - \bullet \Theta_{\mathrm{req}}(z)$$

With $\vartheta_{req}(n) = const$ during the sharing scenario, we observe that $\vartheta_{req}(n) := \vartheta_{req} \Rightarrow \vartheta_{req} = \Theta_{req}$. The actor's outputs are transformed as

$$\gamma(n) := \begin{pmatrix} 1/\mathrm{CW}^1(n) \\ 1/\mathrm{CW}^2(n) \\ 1/\mathrm{CW}^3(n) \end{pmatrix} \circ - \bullet \Gamma(z)$$

With $\chi^i(n) := \vartheta^i_{req} - \vartheta^i_{obs}(n)$ referring to the actor's inputs we further transform

$$\chi(n) \circ - \bullet \mathbf{X}(z)$$

5.3. Throughput observation in spectrum sharing

In the following, the process G(z) models the contentionbased spectrum sharing. The inputs of G(z) are the actor's decisions (the selection of the sizes of their contention windows), and the outputs of G(z) are the observed shares (observed throughputs) per radio system:

$$\Theta_{\rm obs}^i(z) = z^{-1} \cdot G(z) \cdot \Gamma(z)$$

where

$$\begin{pmatrix} 1/CW^{1}(n) \cdot (1-1/CW^{2}(n)) \cdot (1-1/CW^{3}(n)) \\ 1/CW^{2}(n) \cdot (1-1/CW^{1}(n)) \cdot (1-1/CW^{3}(n)) \\ 1/CW^{3}(n) \cdot (1-1/CW^{1}(n)) \cdot (1-1/CW^{2}(n)) \end{pmatrix}$$

 $\circ - \bullet G(z)$

which results in

$$G(z) = \begin{pmatrix} \Gamma(z) * (1 - \Gamma^{2}(z)) * (1 - \Gamma^{3}(z)) \\ \Gamma(z) * (1 - \Gamma^{1}(z)) * (1 - \Gamma^{3}(z)) \\ \Gamma(z) * (1 - \Gamma^{1}(z)) * (1 - \Gamma^{2}(z)) \end{pmatrix}$$

with '*' referring to discrete convolution. Note that G(z) describes a non-linear system.

5.4. Controller

The controllers in our system are built by actor's strategies. The actor's inputs are found as

$$\mathbf{X}(z) = \Theta_{\text{req}} - F(z) \cdot \Theta_{\text{obs}}(z)$$

However, as indicated in Figure 3, the feedback channels are error-free, hence we find

$$F(z) = \begin{pmatrix} 1\\1\\1 \end{pmatrix} \Rightarrow X(z) = \Theta_{\text{req}} - \Theta_{\text{obs}}(z)$$

In case the spectrum is shared by similar systems, each radio system can identify what radio system transmitted a packet, as there are source and destination addresses transmitted along with the payload. This allows radio systems to identify the observed share for other radio systems. However, actors cannot observe other actor's requirements.

6. ACTORS' STRATEGIES

An actor makes decisions according to its system strategy rules and radio regulatory rules for setting the contention parameters. An actor is a MAC entity that resides in a radio system's MAC, for example in the management plane. We will discuss the rules in detail in the following and address the concept of awareness, technocratic decision-making and value orientation. The actor's decision-making processes are described by A(z). The inputs of A(z) are the observations and the requirement (each actor knows only the requirement of its respective radio system). The outputs of the actor's process are the contention window sizes.

$$\Gamma(z) = \mathbf{X}(z) \cdot \mathbf{A}(z)$$

In the remainder of Section 6, we define a generic system strategy, along with radio regulatory rules for different actors (using the policy notation of [28]) and show the resulting decision process in discrete time domain (as function of n) and in z-domain (as function of z). The strategies are evaluated and compared to each other in Section 7.

6.1. Radio regulatory rule

All actors have to comply with radio regulatory rules so that no radio system monopolises the usage of spectrum. Radio regulatory rules are expressed with declarative policy tuples, using the notation of [28]. In our example that was described in the previous Section 5, spectrum sharing is obtained by setting contention window sizes. If the contention window size of one of the radio systems is too small, this radio system would not allow other radio systems to have sufficient access to the spectrum. A conventional solution for this problem would be to regulate the minimum size of the contention window. A regulatory rule is therefore setting a lower limit for the contention window size. To prevent a single radio system from monopolising spectrum usage contention-window sizes must not be smaller than a certain threshold CW_{min} . Such a rule can be expressed with the help of the shorthand notation of the DARPA XG policy language [28]. In our example of three radio systems sharing spectrum with contentionbased medium access, the single shared radio channel corresponds to the spectrum opportunity.

6.2. System strategy rule

The default decision process of an actor does not take into account the observation of other actors, hence the default actor is referred to as 'technocratic'. The system strategy rule is defined in the ontology Rule 1, using the notation of [28]. The contention window is modified if the observation does not meet the requirement, regardless what other radio systems may experience, hence regardless of the other actors' observations.

To compare technocratic decision-making with valueoriented decision-making, the default system strategy of

Rule 1. Default system strategy rule for technocratic decisionmaking, without considering opponent's observations.

<pre>/* actor ''Technocratic'' expressed in</pre>
shorthand notation of the DARPA XG pol-
icy language [16] */
(SelDesc (id SelectorTECHNOCRATIC)
(authDesc US-FCC) (freqDesc U-NII)
(regnDesc US)
(timeDesc Forever)
(devcDesc TechnocraticActor)
(UseDesc (id UseTechnocratic)
(xgx ''(and (<cw (-="" (-<="" (:="CW" cw="" cwmax)="" td=""></cw>
<pre>MyShare_req MyShare_obs))))'')</pre>
(SystemStrategyRule (id StrategyTECHNO-
CRATIC)
(selDesc SelectorTECHNOCRATIC)
(oppDesc AnyOpp)
(deny FALSE) (useDesc UseTechno-
cratic))

social actors is in the following modified according to the social bias of the actor, with respect to the level of value orientation. In the following, the actor's input $\chi^i(n)$ is a vector of two independent values, where each actor's own observation (compared to it's requirements) on the one hand, and their opponent's observations $\vartheta_{obs}^{-i}(n)$ on the other hand constitute the orthogonal values:

$$\boldsymbol{\chi}^{i}(n) = \begin{pmatrix} \boldsymbol{\chi}^{i}(1,n) \\ \boldsymbol{\chi}^{i}(2,n) \end{pmatrix} = \begin{pmatrix} \vartheta^{i}_{\mathrm{req}} - \vartheta^{i}_{\mathrm{obs}}(n) \\ \vartheta^{-i}_{\mathrm{obs}}(n) \end{pmatrix}$$

This transforms to

$$\begin{pmatrix} \vartheta_{\mathrm{req}}^{i} - \vartheta_{\mathrm{obs}}^{i}(n) \\ \vartheta_{\mathrm{obs}}^{-i}(n) \end{pmatrix} \circ - \bullet X^{i}(z) = \begin{pmatrix} \Theta_{\mathrm{req}}^{i} - \Theta_{\mathrm{obs}}^{i}(z) \\ \Theta_{\mathrm{obs}}^{-i}(z) \end{pmatrix}$$

We further introduce the indicator α , with $0 \le \alpha \le 1$ to model the value orientation of a social actor. A technocratic rational actor is characterised by small values of α ,

technocratic decisions : $\alpha^i \rightarrow 0$

A value-oriented (not necessarily altruistic) actor is characterised by larger values of α ,

value-oriented decisions :
$$\alpha^i \rightarrow 1$$

The actor is a function of the indicator, $A^i(z) = f(\alpha)$. The generic ontology rule is defined in Rule 2. To better illustrate this description of the generic decision process, the usage description can be expressed as function in

Rule 2. System strategy rule for value-orientation, with considering opponent's observations.

```
/* actor ''ValueOriented'' expressed in
   shorthand notation of the DARPA XG pol-
   icy language [16] */
(SelDesc (id SelectorVALUEORIENTED)
   (authDesc US-FCC) (freqDesc U-NII)
   (reqnDesc US)
   (timeDesc Forever)
   (devcDesc ValueOrientedActor)
(UseDesc (id UseValueOriented)
   (xgx ''(and (<CW CWmax)) (: = CW (- CW (+
   (* (- MyShare req MyShare obs) (1-
   alpha)) (* OthersShare alpha)))))'')
(SystemStrategyRule (id StrategyVALUEOR-
IENTED)
  (selDesc SelectorVALUEORIENTED)
 (oppDesc AnyOpp)
         FALSE)
 (deny
                  (useDesc
                             UseValueOr-
 iented))
```

discrete-time domain (as a function of n). It is then expressed for each actor i as

$$\mathbf{CW}^{i}(n) = \mathbf{CW}^{i}(n-1) - \underbrace{\mathbf{\chi}^{i}(1,n) \cdot (1-\alpha)}_{\text{technocratic}} - \underbrace{\mathbf{\chi}^{-i}(2,n) \cdot \alpha}_{\text{value-oriented}}$$

with $CW^i(n) \le CW_{max}$ being the contention window size, and $CW_{max}/2$ as start value for n = 0.

In z-domain, the decision process for actor *i* is expressed as:

$$A_{\text{value_oriented}}^{i}(z) = \frac{1}{z-1} \cdot \begin{pmatrix} 1-\alpha\\ \alpha \end{pmatrix}$$

We evaluate the actor's system strategy rule, the protection of incumbent radio systems with the help of voluntary value-orientation and the need for radio regulatory rules in the following evaluation.

7. EVALUATION

We first investigate the stability of a system that operates with value-orientation, followed by a discussion of some aspects of incumbent protection and value-orientation.

In the following figures, three values are shown versus discrete time *n*. In the top view, the actor's inputs that are expressed as $\chi^i(n) := \vartheta^i_{req} - \vartheta^i_{obs}(n)$ are shown. It is in an actor's interest to minimise this value to zero. If it is larger than zero, the requirements are not met, and if it is smaller than zero, too many radio resources are allocated. In the middle figures, the contention window sizes are shown. Finally, in each bottom figures, throughput (share) requirements and observations are shown. Ideally, observations meet the requirements.

7.1. Stability

For any input, a stable system will converge as the interaction goes to infinity. An unstable system diverges and produces unpredictable observations. It is therefore vital that our system and the actor's strategies should be designed with stability as one of the priorities. The question to ask is whether our system is bounded-input bounded-output stable, that is whether or not a bounded input leads to an unbounded output. A discrete-time time-invariant system is stable if and only if the transfer function has a region of convergence that includes the unit circle. The transfer function of our system (see Figure 3) is found as

$$\Theta_{\text{obs}}^{i}(z) = \Theta_{\text{req}}^{i} \cdot \underbrace{\frac{A(z) \cdot z^{-1} \cdot G(z)}{1 + A(z) \cdot z^{-1} \cdot G(z) \cdot F(z)}}_{\substack{z = S(z) \\ \text{system transfer function}}}$$

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Figure 4. System collapses after 14 stages because of technocratic decision-making (cognitive radios and incumbent radio).

which implies that actor's implementations should meet the criterion

$$A(\sigma + j\omega) = -(\sigma + j\omega)G^{-1}(\sigma + j\omega) \quad \Rightarrow |\sigma + j\omega| \le 1$$

The criterion means that infinity points of S(z) lie inside the unity circle $z = \sigma + j\varpi = e^{j\omega T}$ in z-domain, z being substituted by $\sigma + j\omega$ and ϖT representing frequency. This criterion can be used when designing the actor's decision processes, and finding values for the indicator α .

7.2. The effect of increasing the offered traffic

It can be observed from Figure 4 that purely optimising the contention windows based on own interests leads to a collapse of the system: after a number of stages, all radio systems select CW = 1, which leads to collisions. Contention window sizes are changing slowly with smaller loads (smaller requirements—non-asymptotic condition). However, with higher loads, contention window sizes change more dynamically and the system already collapses after 12 stages as opposed to 20 stages.

7.3. Protection of incumbents by value-orientation

Figure 4 illustrates that the system collapses because of technocratic decision-making, when all three radio systems (two cognitive radio systems and one incumbent radio system) apply technocratic decision-making. Figure 5 however illustrates that cognitive radios do not harmfully interfere the operation of the single incumbent radio system in our example, when they apply value-orientation. The two cognitive radio systems operate with



Figure 5. Two cognitive radio systems operate with value-orientation, whereas the single incumbent system still acts with technocratic decision-making.

value-orientation, whereas the single incumbent system still acts with technocratic decision-making. Figure 6 indicates that if the incumbent radio system also applies value-orientation, monopolising of spectrum usage is still prevented, but the incumbent radio does not meet its requirements.

7.4. The disadvantage of radio regulatory rules

Figure 7 shows the results when all three radio systems follow a static regulatory rule with a minimum contention window size (here: 8), which is not optimised for the scenario. The rule helps to prevent monopolising, however, the outcome is not optimal: although incumbents systems could be perfectly protected with static rules like this one, the inefficient spectrum usage suggests that dynamic adaptation of spectrum usage (based for example on voluntary standards, i.e. system strategy rules and value-orientation) may be more desirable.



Figure 6. Value-orientation for all radio systems: monopolising is prevented; the incumbent radio does not meet its requirements.



Figure 7. Fixed minimum CW set by the static radio regulatory rule. The rule helps to prevent monopolising; the outcome is not efficient.

8. CONCLUSION

Wireless communication facilitates wide connectivity. It needs to be freed up from existing bottlenecks and hurdles that are imposed by existing radio regulation. Radio regulation itself is desirable. However, the way we regulate spectrum today leaves room for improvements. Cognitive radio and dynamic spectrum assignment aim for a major improvement. What has to be developed are cognitive radio systems that identify white spaces in the spectrum and adaptively operate over a wide range of frequencies, while avoiding harmful interference with primary devices and complying with FCC radio regulatory rules. Spectrum etiquette may be a future vehicle to enable coexistence of competing cognitive radios.

We have illustrated in this article our initial approaches for cognitive radio. We addressed voluntary standards and social concepts to mitigate the two main problems of open spectrum access: incumbent protection and fair coexistence. The initial results suggest that the cognitive radio technology helps exploiting today's underutilised radio spectrum and provides a higher flexibility than conventional radio regulation with its static license allocations.

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AUTHOR'S BIOGRAPHIES

Stefan Mangold is project leader at Swisscom Innovations Ltd., Bern Switzerland, where he is working on cognitive radio, spectrum management, mesh networks and IEEE 802 standards. Before joining Swisscom in April 2005, Dr. Mangold worked at a research lab in the U.S. (2003–2005), and before that at the Chair of Communication Networks (ComNets) of RWTH Aachen University, Germany (1998–2003). He received his Diploma degree and Dr.-Ing. degree (summa cum laude) in electrical engineering in 1997 and 2003 respectively, both from RWTH Aachen University. Dr. Mangold's current areas of research are operator-assisted cognitive radios for spectrum sharing and spectrum etiquette.

Lars Berlemann received his Doctorate and Diploma in electrical engineering from RWTH Aachen University, Germany, in 2006 and 2002 respectively. He additionally holds a Diploma in business and economics from the same university. Since 2002 he serves as a research assistant at the Chair of Communication Networks of RWTH Aachen University, where he is now working as a senior

research scientist at various national and European Union funded research projects. Dr. Berlemann has published more than 40 reviewed publications including 5 journal articles and was scientific organiser of European Wireless Conference 2005 and PIMRC 2005. His current research interests include the IEEE 802 standard family, coexistence, spectrum sharing, cognitive radio and flexible protocol stacks.

Sai Shankar Nandagopalan received his Ph.D. from the Department of Electrical Communication Engineering from Indian Institute of Science, Bangalore, India in the area of ATM networks. In 1998, he was awarded the German Fellowship, DAAD, in the Department of Mathematics, University of Kaiserslautern, Germany to work on queuing approaches in manufacturing. In 1999, he joined Philips Research, Eindhoven, the Netherlands, where he served as research scientist in the Department of New Media Systems and Applications. He worked on various problems involving hybrid, fibber, co-axial cable (IEEE 802.14) networks and IP protocols and provided efficient algorithms to improve protocol and buffer efficiency. In the year 2001, he joined Philips Research USA, Briarcliff Manor, NY as 'Senior Member Research Staff' and worked actively in the area of WLANs and WPANs. His other interests include MAC protocols for mesh networks, cognitive radio systems and cooperative communications. He was an active contributor of the wireless LAN standard and has submitted more than 15 proposals in shaping QoS (TSPEC, admission control and simple scheduler) related issues in the IEEE 802.11e Working Group that has been incorporated in IEEE 802.11e draft standard. He was also an active participant in the Ultra Wide Band (UWB) MAC working group of Multi-Band OFDM Alliance (MBOA) and is one of the prime contributor and author of the new MBOA MAC. To this end he was nominated as one of the five finalists by Electronic Engineering Times (EETimes) in the Innovator of the Year category in year 2005. Additionally, he holds several fundamental disclosures on 'Agile Radio MAC' that are essential for the forthcoming cognitive radios. Currently he is with Qualcomm as staff engineer and works on issues related to UWB, MIMO, mesh networking, cognitive radio, viral communications and cooperative networking. He also served as adjunct professor in Polytechnic University, Brooklyn teaching graduate course on wireless protocols. Besides these, he is IEEE Standards Association voting member and senior member of IEEE and has served as chair of many prestigious conferences. He has authored more than 45 conference and journal papers, 25 accepted standard contributions and has filed more than 50 patents.