Energy Efficiency in Future Wireless Networks: Cognitive Radio Standardization Requirements

Moshe Masonta, Yoram Haddad, Luca De Nardis, Adrian Kliks, and Oliver Holland

***Abstract*—Energy consumption of mobile and wireless networks and devices is significant, indirectly increasing greenhouse gas emissions and energy costs for operators. Cognitive radio (CR) solutions can save energy for such networks and devices; moreover, the energy consumption of CR technologies themselves have to be considered. This paper discusses ways in which standardization efforts can assist the use of CR to both save energy for mobile/wireless communications, and ensure that the energy consumption in CR networks and devices is minimized. Compelling argument for such solutions are presented.**

***Index Terms*—Cognitive Radio, Energy Consumption, Energy Efficiency, Green Communications**

I. Introduction

Although the concept of cognitive radio (CR) has been around for more than a decade [1], the path to its practical implementation in real environments still seems to be rather confused. Unfortunately, efficient solutions and conclusions on many crucial problems in CR implementation have still not been found, not least to mention the vivid debate on the advantages and drawbacks of spectrum sensing comparing with deployment of geo-location databases [2], or doubts related to the coexistence of different CR devices and networks. Besides the aforementioned problems, energy efficiency will also play significant role in the final success of implementations of CR, as CR functionalities such as spectrum sensing and underlying adaptable radio technologies such as Software Define Radio (SDR) can imply a significant energy consumption compared with conventional devices. Focusing first on the mobile terminal one can observe that the terminals offering "smart phone" functionalities (i.e equipped with 2G/3G-communication chips, GPS and IEEE 802.11 modules, offering far more data transfer (emails, updates, browsing) via modern and faster radio interfaces devoted for data transfer, possessing big bright screens, complex applications that are running on powerful processors, etc.) consume so much energy that typically a daily charging cycle is necessary. Further increases of energy consumption will be probably not acceptable for the end-user. Moreover, people usually express their willingness to be more environmental-friendly and would often help in reduction of greenhouse effect. Since it seems that the CR functionality such as sensing, "thinking" and underlying adaptive radio are related to higher energy usage comparing with current solutions, standardization bodies should be aware of such issues and should push solutions which could be called "green". Of course, service providers and chip set vendors have always tried to minimize energy consumption (since this allows for further OPEX reduction), however, with the advent of heterogeneous and cognitive networks such an activity shall be supported also by the regulators.

The problem of energy wastage is not only limited to the mobile terminals. The same problem, if not more challenging, can be identified from the service provider and operator perspectives. Although the end-user does not see it, the main cost related to the energy consumption is on the network part. The total energy used for running of existing core and radio access network modules has become an extremely significant problem. Moreover, the algorithms that are complex hence require a high amount of energy consumption are intentionally placed on the network side, e.g., the main parts of the radio resource management (RRM) are realized on the network side. Furthermore, high energy consumption is also one of the key factors that decides about the final benefits of further (denser) deployment of new micro- and pico-base stations (BSs). It means that the development of the cellular network architecture has to consider ways of energy saving and probably harvesting, e.g. by effective management of the micro-base-station in the areas where the offered traffic can be offloaded to femtocells or IEEE 802.11 networks. The CR concept shall facilitate energy saving in the wireless and wired networks by application of, e.g., energy-efficient routing protocols.

In summary, the effective use of energy and opportunities for energy saving through CR are key aspects defining the shape of the final implementation of CR concept in future wireless terminals. Although higher energy consumption is the price that has to be paid for the new sophisticated functionalities, it has to be considered in the process of development of new standards. Cognitive radio standards can facilitate or even push implementation of energy efficient solutions that will be applied in the future networks. In this work we try to identify the key aspects of energy efficiency related to CR and show how standardization activities can help in their realization. Thus, CR as a technique could or even should ensure efficient energy utilization, but this requires deliberated actions undertaken for effective management of most energy consuming phases of cognitive cycle. The detailed guidelines, e.g. in standards, should foster energy management in CR terminals and systems.

The rest of the paper is organized as follows. An analysis of selected aspects of the PHY layer from an energy-efficiency

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point of view is provided in Section II. Section III investigates energy saving problems in Dynamic Spectrum Access (DSA) algorithms, while Section IV analyses Transport and Network layers from this perspective. Finally, higher layers of the OSI model are shortly summarized in Section V, preceding the conclusions.

II. PHY Layer Analysis

Typically, standards defining the wireless system concentrate mainly on the lower layers of the OSI model, mainly focusing on the physical (PHY), medium access and network layers, including protocols and network architecture. From the wireless communication point of view, algorithms proposed by the standardization bodies should ensure reliable data transmission with an accepted level of Quality-of-Service (QoS). On the other hand, mobile devices are equipped with batteries and from the point of view of the satisfaction of the end-user the duration between recharges of these batteries should be as long as possible. This creates the trade-off between the reliability and the comfort of usage of mobile devices. In this section we try to identify and briefly characterize various aspects of the PHY layer processing that influences this trade-off.

A. Peak-to-Average Power Ratio

Peak-to-Average Power Ratio (PAPR) is one of these key aspects [3]. The problem of high value of PAPR is one of the most crucial drawbacks of the multicarrier systems - considered frequently as a good candidate for data transmission. In the nutshell, high number of subcarriers carrying independent user-data symbols (e.g. QAM symbols) creates in time domain a multicarrier signal which amplitude varies significantly. Such a great variation of the signal amplitude has a great impact on energy efficiency of the used power amplifier as well as on the presence of the power leakage signal. The input-output characteristic of the nowadays power amplifiers is not linear, thus the typical power amplifier will compress or even cut the transmitted signal if the operating point of this power amplifier will be close to the compression region. Such a phenomenon results in signal degradation and in energy wastage. One of the solutions to this problem is to back-off the operating point of the power amplifier, however such approach reduces in fact the energy efficiency of the power amplifier. Contrarily, wireless terminals should be able to apply simple yet effective algorithms for PAPR reduction. The presence or not of the PAPR reduction procedures can be enhanced by the CR standard, similarly as it has been done for DVB-T2 (digital TV broadcast standard) terminals, where two PAPR reduction methods have been selected.

B. Out-of-band (OOB) Reduction

The presence of out-of-band (OOB) emission somehow reduces the energy efficiency of the transmitter since a part of energy is wasted for unwanted transmission. Moreover, high OOB emission increase the level of interferences observed by the neighbouring (in frequency domain) users [4]. Such a situation results in Signal-to-Interference-plus-Noise-Ratio (SINR) degradation, thus leading to application of more sophisticated detection algorithms, and in turn higher energy consumption. Higher power of interfering signals also reduces the range of the cells, since the maximum transmit power is always upper bounded, and consequently create problems in providing services to the end-users. Clearly, it is not possible to eliminate the OOB leakage of transmitted signal, however the electromagnetic compatibility should be maintained, and the minimization of the OOB emission should be forced by the standards. Interference management and minimization plays a crucial role in the cognitive systems. On the other hand, however, sophisticated algorithms for OOB reduction consumes energy and the best strategy should be identified here.

C. Pilot Signals and Training Sequences

Training sequences and pilot signals (TS/PS), which refers to the specially prepared and intentionally inserted sequences of data, are used for many purposes, e.g. channel estimation and correction, synchronization, etc. However, the CR should support adaptive allocation of the fraction of the total transmit power to the training sequences and pilot signals (TS/PS), i.e. when the channel is of good quality, the cognitive transmitter can reduce the amount of power assigned to the TS/PS and assign it to data symbols. Furthermore depending on the channel status the number of pilot subcarriers in multicarrier transmission can be modified.

D. Cyclic prefix

Cyclic prefix is typically used in multicarrier signals (such as OFDM) for synchronization purposes and in order to mitigate the influence of the multipath propagation effects (inter-symbol interference). The length of the cyclic prefix varies from $\frac{1}{32}$-th to even $\frac{1}{4}$-th of the total length of the OFDM symbol. It means that up to 25% of energy is wasted for repetition of the already transmitted data. Existence of cyclic prefix reduces also the spectral efficiency of the system. In that light more sophisticated solutions could be applied which do not use cyclic prefix, such as Filter Bank based MultiCarrier transmission (FBMC). It seems that the increase of the complexity of the transmitter and receiver structure (and thus energy) do not exceed the gains, however this issue needs further investigation. Nevertheless, cognitive standards should support various transmission techniques, in particular it should keep the door open for more energy efficient modulation techniques, as FBMC tends to be.

E. Ability for Adaptation

It is somehow evident that the cognitive terminal shall be able to adapt its parameters in possibly wide range of various functionalities and values, one can even state that such a feature is a basis of the cognition ability of the mobile terminal. Such an approach is also of high importance from the standpoint of energy efficiency. For example, application of various modulation and coding schemes lead to better utilization of the available resources, and adaptation of the pilot structure based on the current channel characteristic allow to optimize the power split among pilot signal and user data. On the other hand, however, high adaptation possibility is feasible based on the information fed back from the receiver to the transmitter. Cognitive radio standard shall support such solutions that minimize the amount of data sent in the reverse link but ensuring acceptable level of adaptivity.

F. Spectrum sensing - PHY layer perspective

From the PHY layer perspective, one of the most crucial parts of the cognitive cycle is the sensing phase (broader analysis about alternatives to spectrum sensing will be provided later). Sensing procedure has to be reliable (terminal has to be able to detect correctly the primary user (PU) signal at very low SNR level) but not complicated. Moreover, since the sensing procedure has to be repeated every T seconds, the duration of the sensing procedure itself shall be as short as possible. The uncertainty of the received signal can be improved by higher signal sampling, however increase of sampling frequency is equivalent to higher energy consumption. The comprehensive analysis comparing the sensing time, sensing frequency as well as signal frequency sampling from the energy efficiency perspective shall be performed.

G. Architecture

The key aspect of the energy efficiency from the PHY layer point of view is the architecture of the cognitive terminal [5]. Although any standard does not identify the electronic elements, the system designers are obliged to take into account the energy consumption of the proposed architecture. The comparison of the pros and cons of e.g. homodyne or heterodyne structures is out of scope of this document, however it is strongly recommended that the PHY layer researchers take into account technical limitations of the electronic elements - e.g. energy efficiency of the power amplifier, dynamic range and resolutions analog-to-digital converters, presence of local oscillator frequencies, IQ imbalance, harmonic and intermodulation distortion, or power consumption by FPGA, SoC and NoC elements, just to mention few of them. The concept of Dirty RF gains, in fact, continuously more and more attention. The assumption that the cognitive terminal is able to work in very wide range of frequencies implies that either wideband elements will be applied or several RF processing chains will work in parallel. From the other side, the knowledge of the technical limitations may define the shape of the detection algorithms. The awareness of the limitations of the electronic elements should be considered when designing the CR standards; such solutions shall be selected that ensure the assumed quality level of signal reception, transmission or detection, but minimize the power consumption. It seems that the standard should try to define the energy-efficient operation mode of the cognitive terminal.

In this section only few aspects of the energy efficiency in the PHY layer have been presented. A comprehensive analysis should be performed in order to define the PHY layer cost function that will estimate the energy consumption of each specific function or module.

III. Dynamic Spectrum Access and Radio Resource Management

From CR point of view, dynamic spectrum access (DSA) refers to new radio frequency (RF) spectrum management process that consist of three basic components: spectrum opportunity identification, spectrum opportunity exploitation, and regulatory policy [6]. The motivation behind DSA is to provide flexible and efficient use of radio frequency spectrum. There are different methods used to detect or identify spectrum opportunities: spectrum sensing, geo-location databases, beaconing techniques, pilot channel or a combination of spectrum sensing with geo-location database. Unfortunately any one of these methods introduces additional energy consumption to CR devices. However, the amount of this addition energy is insignificant when compared to the potential energy efficient solutions introduced by the CR systems. It is crucial for CR systems implementing DSA to strike a balance between the conflicting goals of minimizing the interference to the PUs without compromising the CR QoS.

A. Spectrum Sensing vs. Geo-location Database

The objective of spectrum sensing is to detect the presence of PUs on a given spectrum band. Depending on the network topology, spectrum sensing can either be conducted individually by each CR or multiple CRs in cooperation. Cooperative spectrum sensing combines the detection results of multiple radios to obtain a more detailed information about spectrum availability. Each CR is expected to perform individual spectrum sensing and then forward their decision to the fusion centre (FC) for global decision making. The FC will then broadcast the final decision on which channel to access to all its associated CRs. While this approach (i.e. cooperative spectrum sensing) ensures reliable and efficient spectrum sensing, it introduces energy consumption overhead, especially when the number of cooperating CRs is large [7]. It is therefore important for CR standards to consider energy efficiency when implementing spectrum sensing techniques for both single and cooperative sensing network topologies.

Another method for identifying spectrum opportunities is the use of geo-location database. While not providing real-time information to CRs, geo-location database contains registered PUs that will be interrogated by CR periodically to get the free spectrum. While spectrum sensing still has open issues that need to be addressed to ensure its efficiency and reliability, geo-location database approach is already been considered in early deployments of DSA networks. As future networks move towards intelligent and cognitive systems, the wireless network players (i.e. operators, vendors and regulators) should expect to see large volumes of geo-location database deployments, which in turn will increase the amount energy consumed by the overall wireless networks. For instance, a geo-location database is expected to contain the boundaries of the PUs, and algorithms to calculate the available/free spectrum bands and the powers that can safely be used without causing interference [2]. As a result, these databases are expected to run on faster and high performance processors in order to provide required information (near real-time) when interrogated by multiple

CRs. Such processing will definitely consume more energy and also requires enough cooling systems. There is a need to devise energy efficient databases and also to develop standards for such databases.

B. Core Network and Femtocells

One of the most energy consuming component in the cellular networks is the BS. Macrocell BSs as well as micro and pico cell BSs are heavy equipment deployed by the operator to provide cellular coverage. There are some interesting observations about the way these components are running and the tight link to their energy consumptions. For instance, there are some areas e.g. central business districts with dense population at work hour (between 9am to 6pm) which require a very good coverage during these hours. However at night the overlaying cellular infrastructure is almost idle. But from an energy consumption point of view the main components of the BSs and associated equipment (e.g. cooler system, databases, backhauling component) still have to work almost like in the peak hours. And this is only to cover the few users that may cross this district, sometimes for few minutes or even seconds during handover process. It would be very energy efficient, if a cellular operator was able to turn off a high consuming macrocell BS at night where almost no traffic is generated.

A second interesting observation concerns the coverage of the BSs at regular (or even peak) hour. One of the biggest challenges from a radio planning perspective is to cover the users located at the edge of the cell. These users generally experience poor SINR level due to their almost equal distance to several BSs. The current serving BSs must generally transmit at maximum allowed power level to cover these users. There can be a difference of more than 25% between energy consumption of a BS that has to cover such users and one that does not serve them.

Finally it goes without saying that coverage of indoor users is much more challenging since penetration loss due to walls leads to severe degradation in the SINR level experienced. Also in this case, this is translated in a meaningful amount of energy required from the BSs to successfully cover these users. In the two last cases, we should notice that this leads to excessive energy consumption also from the user device point of view. A user at the edge of the cell or inside a building, hardly covered, will likely have to transmit at its maximum allowed power level in uplink to allow the serving BSs decode its signal successfully.

A potential solution to all mentioned observations relies on femtocell, which is a mini cellular BS [8]. There are two kinds of femtocell, namely indoor and outdoor femtocell. In the former case, as its name indicates this is a plug-and-play cellular home BS (very similar to a Wi-Fi router in size and appearance) deployed by the user. The backhauling of the connection is done through user home connection to the internet. In the latter case, it consists in a device similar to a home femtocell but with an extended transmitter power level capacity and generally deployed by the operator. In this case, backhauling is still through an available internet connection close to the femtocell. The typical coverage radius of outdoor femtocell is about fifth of the macrocell radius in urban environments. However the energy consumption of a femtocell is a couple of watts which has nothing to do with the several hundred watts dissipated for the macrocell BS. Among the multiple reasons for this so green efficient solution are internet backhauling which does not require additional equipment to be located near the BS and also the size of the device which is quite small and do not generate a large amount of heat which would have required a cooler system (well known to be greedy in energy consumption) around. Indoor femtocell clearly solve the challenge of indoor user mentioned earlier, both in downlink and uplink, since it is deployed in the user's home and offer him very good dedicated coverage. To be able to solve the other challenges (edge users, and turning off BS at night) we need some more involved strategies. A strategy referred to as femto-bordered macrocell [9] consist in deploying outdoor femtocell along the border of the macrocell. Therefore, whenever a user experiences a better SINR from the border outdoor femtocell it performs a handover (through CR techniques) from the macrocell coverage to the femtocell one. In this case, we solve again both uplink and downlink challenge of edge located users. Some numerical simulation shows an energy saving of up to 30% with the femto-bordered macrocell strategy. If we would like the operator to turn off the almost unused macrocell at night or other off-peak hours we should guarantee a reliable alternative. This can be done through what we call "‘femto-gridding"’ strategy. Basically, we tessellate the original macrocell coverage with a set of outdoor femtocells. On the one hand we need now much more outdoor femtocell than a single macrocell. But on the other hand the difference in energy consumption between femtocell and macrocell is so huge than this is still green efficient. Actually some performance evaluation shows a benefit of up to 90% energy saving with femto gridding strategy.

The proposed strategies give rise to several important questions. First, which spectrum will be allocated to this second tier composed by femtocells? Second, if femto-gridding is so green efficient why do not simply stop using macrocells? The answer to the first question requires a large development but in a nutshell we can state that the key technology in this case is the use of CR enabled device. Because it is obvious that we cannot allocate a dedicated spectrum to femtocells, CR allows the use of unused frequencies around. This is even more relevant in the case of femtocell, since these latter devices exhibit a low transmitted power level which allows a very efficient frequency reuse. Some other dynamic frequency spectrum sharing scheme have been proposed in [10]. Based on the aforementioned analysis the CR standard shall support the application of those solutions.

IV. Network Layer Analysis

Energy efficiency at the network layer has been a long standing research topic, in particular in the wireless networks community, often in conjunction with energy efficient network organization schemes. Pioneering work explored how network organization [11] and routing [12] can improve network lifetime while guaranteeing acceptable network performance.

Along this line several network organization and routing protocols have been proposed in the literature, exploring different solutions to achieve maximizing energy efficiency, e.g. relying on position information to reduce routing overhead [13].

The specific case of cognitive radio networks poses additional challenges to the achievement of energy efficiency at the network layer, as unpredictable external events such as the appearance/disappearance of primary transmitters may abruptly force changes in the network topology, leading to the need to update routing information in order to preserve energy efficiency. It should be noted that in the case of a cognitive radio network, depending on the application scenario and the behaviour of primary systems, a straightforward minimization of the energy consumption, as proposed in several works on focusing on energy efficient routing in ad hoc and sensor networks (see [14] as one of the first contributions in this direction, and [15], [16] for recent surveys) may not be the optimal solution, as adapting to primary behaviour may lead to improved energy efficiency.

In order to address the above issue, sensing related information can be introduced in the routing strategy, as proposed for example in [17], [18]. A suitable framework for contributing to standardization efforts by taking into account the specific issues of CR systems could be the IETF ROLL Working Group [19], focusing on the design of routing protocols for Low power, Lossy networks, a definition that may fit very well to cognitive networks, in particular in the underlay flavour.

V. Higher layers

Obviously, higher layers and especially application layer, are out of scope of the standardization activities. What is however evident that the future application will be more and more energy consuming, since they will utilize various additional functionalities of the mobile terminals. It has to be also highlighted that the concept of mobile cloud computing or distributing processing influences also the higher layers of the OSI stack. In general, the total energy consumption is determined by every layer and the standardization bodies shall have a broad look at the energy consumption within each layer. This calls however for the definition of a standard representation of such information in a format that can be read and integrated by all functions at network layer and above that may improve their performance by taking advantage of sensing information, concurring to the definition of a cross layer cognitive engine capable of optimizing the whole system including the energy efficiency among its driving design goals.

VI. Conclusions

In this work the analysis of the energy efficiency in the context of cognitive radio systems and networks has been provided. The focus has been put on providing some guidelines for standardization bodies and researchers referring to the need of deliberated energy management in cognitive radios. It is necessary, since cognitive radio can force better energy utilization, but this requires coordinated energy management among and across all OSI layers. It has been showed that there are some modules or functions in the processing chain of each layer which influence the energy consumption. The idea is to have the holistic view on the energy wastage problem and to concentrate on the global solutions, improving in the first stage such solutions that will optimize energy utilization in the most efficient way.

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