RAS

Radio Access and Spectrum

A white paper on spectrum sharing

October 2012

What is spectrum sharing ?

The traditional way of handling spectrum for cellular wireless wide area networks is illustrated in Figure 1-a, where two operators own certain parts of the spectrum which is again subdivided into three smaller frequency bands each assigned to one Radio Access Technology (RAT). A trend of more flexible use of spectrum is supported by novel developments in radio technology. The first step to flexible radio spectrum usage for a single operator is intra-operator spectrum sharing which includes the dynamic allocation of RATs within the spectrum blocks of one operator as well as the movement of users between bands (illustrated in Figure 1-b). In a number of European countries the adaptive assignment of RATs to licensed spectrum is allowed by the regulatory bodies [1] enabling the flexible application of Software Defined Radio (SDR) technology.

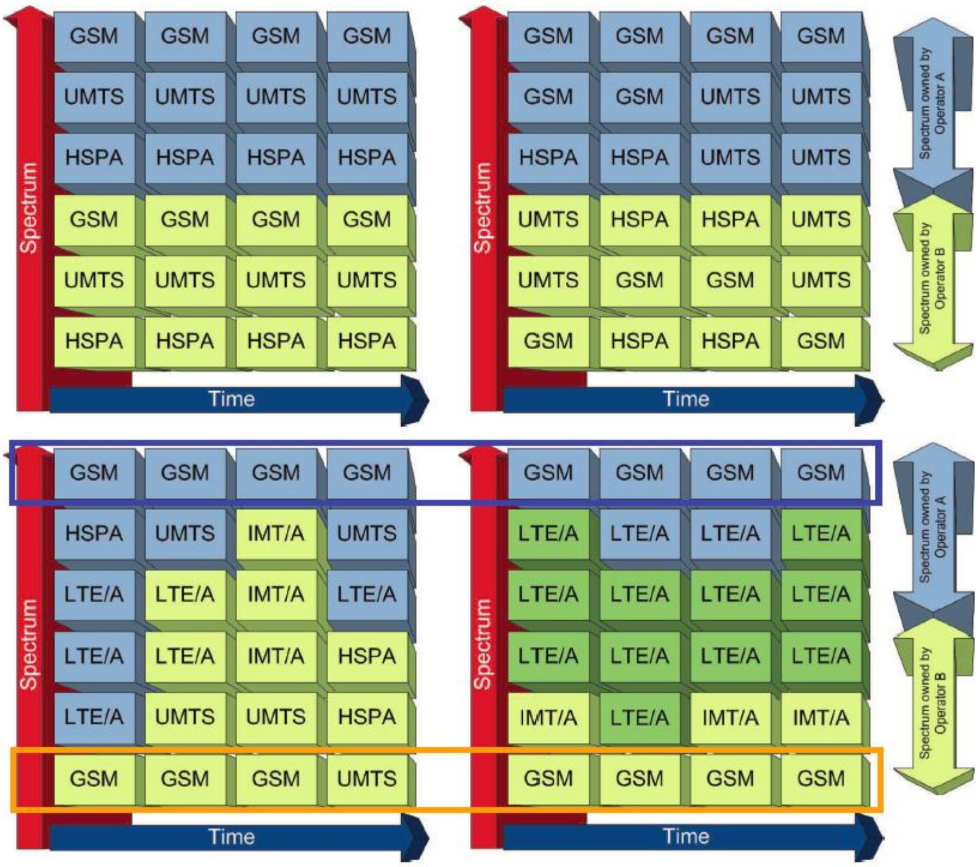

Figure 1. Classification of spectrum sharing methods: a) upper left: no spectrum sharing, b) upper right: intra-operator spectrum sharing, c) lower left: inter-operator orthogonal spectrum sharing, d) lower right: inter-operator non-orthogonal spectrum sharing.

In orthogonal spectrum sharing the users can be moved over the spectrum bands of both operators. However, one spectrum band is still exclusively assigned to one operator. No additional interference is created by orthogonal spectrum sharing as illustrated in Figure 1-c. Both operators keep some part of the spectrum – protected bands: blue and orange boxes in Figure 1-c and Figure 1-d – in order to satisfy their Quality-of-Service (QoS) guarantees for their customers. Gains by orthogonal inter-operator spectrum sharing in terms of spectral efficiency and throughput are reported in [2] and also discussed later in this paper.

Why do we need to share spectrum ?

The role of wireless communications is becoming increasingly important in providing fixed and mobile broadband coverage and capacity. In the fixed sector, wireless can provide broadband connectivity to premises that are too remote to utilise metal pairs or fibre. In the mobile sector, cell sizes are becoming smaller to cope with increasing capacity. Predictions of growth of data rates and in numbers of connected devices are increasing over time; strong growth in the mobile telecommunication data rates towards the year 2020 was reported by the International Telecommunication Union Radiocommunication (ITU-R) sector in 2005 in [3], whereas later predictions for the next decade (2012-2022) in [4] show even stronger growth. Wireless needs to cope with this growth and so far has been achieving this through two mechanisms, namely the shrinking of cell sizes and usage of more spectrum. Whereas these two can be traded to an extent, unavoidably the increasing data rate requirements will lead to increasing spectrum demand [5] [6], which will be challenging under the current spectrum regulatory framework. Another estimate from the Wireless World Research Forum (WWRF) is that 7 trillion devices will serve 7 billion people 24 hours 7 days a week until 2017 [7].

Today’s spectrum usage is largely licensed access, while only a small part of the spectrum uses licence-exempt equipment. With licensed access, operators can acquire spectrum with sole governance over the bands and deploy communication networks to carry a range of services with predictable quality of service (QoS). The amount of licensed spectrum that could be made available for communications in the future is limited by the unavailability of unallocated spectrum, especially below 2GHz. In the license-exempt bands, such as the 2.4 GHz industrial, scientific and medical (ISM) band, the users need to fulfil a set of criteria to facilitate coexistence of different systems on the same band which in practice means limited transmission power levels and hence reduced coverage. Thus, the ability of license-exempt bands to satisfy the growing data rate demand in the future is limited to short range deployments without predictable QoS due to interference from other uncoordinated users.

In parallel, the spectral efficiency of wireless systems in terms of achievable throughput per system bandwidth in bits/s/Hz has been improved significantly by the development of IMT-Advanced systems [8]. In the future, there will be less room for improvement in the spectral efficiency due to the natural limits of wireless communications. Another dimension in the spectrum use is the spectrum occupancy which characterises the utilization rate of a frequency band [9]. The spectrum occupancy dimension can offer more room for improvements by facilitating coexistence of different systems on bands where the current spectrum occupancy is low. In fact, several general spectrum

occupancy measurement studies covering a wide range of frequency bands have indicated that there are large portions of frequencies with very little usage. Focused spectrum occupancy studies on selected frequency bands have highlighted this in more detail showing that there indeed is room for more efficient sharing.
In order to meet the growing data rate requirements of the mobile telecommunication market towards 2020, future mobile communication systems will need to find new ways to access spectrum in addition to the current licensed and licence-exempt approaches. A promising approach to respond to the growing traffic predictions is to develop efficient spectrum sharing techniques that could allow fixed and mobile systems to operate on new spectrum bands whose current occupancy is low. Indeed, spectrum sharing can be estimated as being equivalent to the acquisition of extra spectrum, the usage of which yields major economic benefits. It is in general believed that spectrum sharing, in particular when considering wireless broadband, could significantly boost the EU economy and bring additional social benefits to Europe's citizens [10].

In line with the Radio Spectrum Policy Programme (RSPP), the European Commission has published a Communication on 'Promoting the shared use of radio spectrum resources in the EU' in September 2012. It highlights the importance of technologies that can share radio frequencies as well as the need to create incentives and legal certainty for innovators in the internal market [11].

The sharing of spectrum can also offer benefits in terms of energy saving. One way this can be achieved is through sharing a lower frequency part of the spectrum than would otherwise be used in a non line-of-sight situation where the penetration loss is less and therefore lower transmit power is required. Another way is if there is a portion of spectrum that is currently not used, that spectrum could be utilised by another existing system to allow for that system to provide greater capacity per deployed base station. This could allow the system in question to reduce its number of active base stations, enabling power saving modes for some of its base stations thereby saving energy [12]. Of course, such solutions can be considered in tandem with offloading of users between networks in order to enable power saving modes [13]. In the case of licensed spectrum, such possibilities would require an agreement between the licensees of the spectrum bands as well as a reliable mechanism/protocol to be established for the temporary exchange of spectrum access rights. In the case of unlicensed spectrum access, such sharing of course is routine.

Finally, spectrum sharing can also assist realisation of capacity demands. In fact, energy saving potential through spectrum sharing and its potential to increase capacity can be traded-off for one another. Even if similar long-term averages in traffic load persist between networks, statistical fluctuations in the number of users at any one time between networks can be significant. This can allow for spectral reorganisation and sharing of spectrum from the lightly-loaded network to a heavily loaded network, or the offloading of users between the networks. Both have the effect of increasing achievable capacity at given time. This concept can be applied also to the spatial dimension, taking advantage of differences in spatial distributions of traffic. In this sense, it may also be extended to cases such as where some networks or spectrum are newly deployed or recently acquired, and therefore lightly loaded at an initial stage. Much of this spectrum could be shared in order to maximise capacity in collocated networks, or users could be offloaded to these new networks in order to increase capacity. Such ideas concur with the concept of "Authorised Shared Access" (ASA) [14], whereby a spectrum owner may allow opportunistic access to its spectrum that is locally unused, or indeed another form sharing of its unused spectrum, for a fee. This facilitates the spectrum licensee extracting income from the spectrum, even if its network is not yet fully deployed.

Sharing discussed in this paper would apply either to opportunistic secondary spectrum access, or to organised sharing between licensees with an established underlying mechanism and agreement. The use of solutions such as opportunistic secondary spectrum access requires careful guarding against issues such as the potential for mobility and shadowing unpredictability to cause missed detection hence interference to the spectrum licensee.

Challenges in sharing spectrum

Challenges in spectrum sharing are manifold, in the technological, political / regulation and business domains. Our focus in this section will on the technological challenges, although many of these are of relevance to the political and business domains as well. In the technological domain we shall due to space reasons not give a comprehensive review of the topic but focus on challenges that, in our opinion, warrants significant future research.

One fundamental issue in sharing spectrum is to assess the impact that two or more technologies have on each other when operating on the same frequency band or influence each other via adjacent bands. We can discuss this impact either on the level of an individual terminal, or the system as a whole. Existing research literature has had a strong focus on the former case, manifesting in large number of coexistence studies of different nature. Typically in these coexistence studies the focus has been on the influence another transmitter with given power level has on the quality of service of the system of interest in a chosen reference scenario. For example, for the TV white space case there has been a significant amount of interest in how much perceived loss of quality a secondary transmission would cause, often assuming a Wi-Fi like or OFDMA-based physical layer. There is considerable tension between the broadcast industry and the communications industry where the former is arguing for cautious protection margins and that latter is trying to establish confidence for more relaxed margins. A more complicated example of coexistence issues arises when higher layer functions are considered. For example, in Wi-Fi like systems the medium access control mechanism based on contention can result in a significant loss of capacity or even the inability to access the channel at all in the presence of a non-contention-based transmitter. This highlights the importance of a holistic view to coexistence studies, with need to consider not only physical layer characteristics of the system.

Further challenges in these classical coexistence studies include the metrics to be used and the models for the workload of the system. These issues have not received much attention in part because coexistence issues have focused on scenarios in which at least one of the technologies involved is of broadcast nature. For audio and video, sophisticated metrics used to characterise the quality of experience (QoE) for the users exist and the continuous nature of the transmission reduces the need to consider temporal dynamics. The situation becomes much more challenging when sharing of spectrum is considered for cases involving packet radios or other types of transceivers with significant temporal dynamics. The ‘utility’ of data traffic is highly varying depending on the application it is associated with, as well as the preferences of the user. Also, there is a complex interplay between the medium access methods and the application layer utilities on impact of spectrum sharing. For example, two CSMA-based systems might coexist gracefully in terms of very low packet error rate, but with significantly increased channel access time, whereas coexistence of TDMA-based systems depends heavily on both the load and the scheduling mechanism used.

When moving from device to system level these problems become more difficult still. First, the system-level utility becomes highly dependent on the considered scenario. For example, in unlicensed bands all the systems involved would typically be treated in a similar manner, so a design objective centred on some kind of utility fairness would typically be chosen. The situation would be highly different in a primary-secondary scenario, in which the key operational parameter would often be the degradation of the primary utility, with (potential) secondary utility playing a role more in the regulatory and business domains. Another major challenge for system level reasoning about the impact of spectrum sharing is the difficulty in developing reference scenarios for evaluation, in a manner used in device-level coexistence studies. In order to capture challenges related to aggregate interference, mobility management, resulting outage probabilities and so on, complex spatial and temporal models of the systems involved are needed. Development of such models is still an open research question.

Besides improving the way we can reason about the impact of spectrum sharing in different contexts, there are also significant opportunities for improving enabling technologies for spectrum sharing. For example, techniques for predicting various aspects of spectrum use can be effectively used to manage interference between systems, as well as mitigate the requirements for spectrum handovers and other similar measures. Existing work in this domain has mainly been focusing on the temporal aspects of the problem, but technologies such as Radio Environment Maps can be used to tackle spatial and spatio-temporal prediction and estimation problems as well.

Another challenge in sharing of spectrum is accurate understanding of temporal traffic variations, enabling assessment of whether spectrum sharing solutions make sense i.e., whether the short-term cost in signalling or spectrum reorganisation of a spectrum sharing action will be higher than the long-term gain due to the duration that it is viable for the spectrum to be shared. It is important to recognise here that many traffic types, particularly software downloads for example, may exhibit a degree of self-similarity, meaning that variations in traffic loads may persist for far longer durations than non-self-similar traffic, despite the (very) long term average being the same [15]. Understanding of such traffic types and therefore making better sharing decisions allows maximal advantage to be gained from sharing.

Cognitive radio is one enabling technology for spectrum sharing and such a device must be able to discover and recognize wireless networks that are present in the surrounding environment. Based on the fact that every wireless technology has its own specific MAC sub-layer behaviour, as defined by a technology standard, network recognition can be achieved by examining the MAC behaviour. From the packet exchange pattern that is peculiar to a single technology, MAC features can be extracted, and can be then used for automatic recognition. The advantage of these MAC 'high-level' features over PHY ones resides in the simplicity of the method: a simple energy detector and low-complexity algorithms are required. This concept is applied in a straightforward manner to automatic recognition of wireless networks operating in the ISM 2.4 GHz band: Bluetooth, Wi-Fi and ZigBee. Furthermore, this idea can be extended to underlay networks such as Ultra Wide Band networks.

Ultra Wide Band (UWB) radio signals are designed to coexist with other radio signals and the problem of possible interference from and onto other communication systems that must be contained within regulated values is thus intrinsic to the UWB radio principle. The next generation of smart UWB devices are able to adapt to the environment, whether this refers to channel or interference patterns, by changing the spectral shape and features of the radiated signals while maintaining compatibility with regulations on emitted radiations. The UWB signal format is capable of being characterized by a high number of tuneable parameters, such as impulse radio (IR) UWB signals formed by pulses that are very short in time. Most important is the flexibility by which the power spectral density (PSD) of such IR-UWB signals can be modified. Signal features may be appropriately tuned by playing with a variety of parameters. These include transmission factors such as the number of pulses representing one bit, coding factors such as periodicity and cardinality of codes, modulation factors related for example to the phase shift, and shape factors related to specific pulse shapes.

Yet another challenge is one of fairness. When multiple secondary users are sharing with primary users, fairness between the secondary users is a challenge to achieve especially when different secondary systems use different databases for spectrum management. The regulators are focussed on primary users protection and are not concerned about this fairness. It requires co-operation between systems and more research here is needed. One other way of achieving such fairness is to use a price-based system such as a broker, but this depends on regulation allowing money to change hands for spectrum usage. The basic premise of this approach is that National Regulatory Authorities (NRAs) should license flexible geographic interleaved awards to primary users which then operate as a 'band manager' or broker. It would have the right, and associated responsibilities, to lease its spectrum to secondary users without recourse to the NRA allowing an automatic spectrum trading process which would be self-regulating.

The final challenge that is mentioned here is in specifying a geo-location database to manage spectrum, to include the unpredictability of unregistered PMSE (wireless microphone) activities, cross-border issues and real-time updating. These challenges deserve further investigation, especially considering the stakeholders involved and the solutions will depend on regulatory policies as well as technological solutions.

Security and trust

The IETF PAWS group is addressing security and trust that are related to protocols for database access for the particular case of TV Whitespace sharing, because of the dependence on this type of system on a geo-location database. However, this topic needs much more work on the wider problems of fairness and trading. TV white spaces are an attractive place to start because they are relatively stable in time and because they allow wireless networks deployments that span for large distances when compared to current cellular and WLANs. This advantage however, brings its own security considerations – even with the limited range of today's cellular and WLANs, it's very common to found open and unsecured networks. Therefore, it is expected that in a spectrum sharing scenario with good propagation conditions, such as TVWS, this number will grow.

These and other factors such as sensing reliability and immunity to mal-use introduce new types of security threats to CR wireless networks that have received little attention to date. To identify such threats and propose solutions for secure and trustworthy communications will be an important aspect of making any cognitive radio based solution a long-term commercially-viable. Eavesdropping should be discouraged by the use of air interface encryption in a manner similar to that on WLANs. One conclusion from the RAS cluster project is that price-based trading is needed and therefore protection is needed against fraud and other mal-use.

Certification

The certification process is the last "hurdle" that cognitive radio systems or reconfigurable radio systems will encounter before they can be deployed in the market as mainstream user devices [16]. This certification usually involves a demonstration of the compliance of the equipment to the applicable regulations and standards, both regional and national. The R&TTE directive specifies this legal process. Historically this process has presumed that the equipment is provided by a single manufacturer and is not altered after its manufacture and sale. The advent of CR systems and SDR upsets this presumption.

With the development of reconfigurable and cognitive radio systems, the compliance will depend on both the manufacturer's equipment and an external geo-location database from another supplier. Furthermore, the equipment may be reconfigured after sale to encompass new operating capabilities, bands and services. The database may also be altered to reflect new spectrum conditions or altered protocols for interaction. No longer is there a single entity responsible for all aspects of the regulatory compliance of the equipment's operation.

A major key to enable the implementation of mainstream CR technology is the development of a dynamic digital mechanism for the declaration of conformity for reconfigurable equipment. A generic method is necessary to handle the dynamic updating of the cognitive radio systems and their associated databases across the full EU common market.

Results from projects

This section presents some example results from projects in the RAS cluster, the topics are orthogonal and non-orthogonal sharing from SAPHYRE, sensing and interference mitigation from COGEU, QoSMOS and WHERE2 and energy modelling from BeFEMTO.

Orthogonal and non-orthogonal sharing

The sharing gain can be extended through a proper resource allocation mechanism in the medium access, up to the higher layers. The evaluation presented in the following refers to an *orthogonal-sharing* case.

It was found interesting to evaluate how multiple operators can coordinate to achieve a better resource usage. We focus on resource sharing by LTE operators covering the same physical area and possibly sharing some of their licensed frequency bands. Each eNodeB of one operator is placed exactly 50 meters apart from the corresponding eNodeB of the other. Both operators can utilize a 10 MHz band in DL, which are adjacent, so the operators can share a portion of their spectrum. In this specific case, a resource sharing of x percent means that 2x resource blocks are orthogonally shared. For the resulting user-generated traffic flows, the operators apply a scheduling policy that aims at maximizing the system throughput, which results in just allocating the user with higher Channel Quality Indicator (CQI) value for each resource block. This model was considering appropriate propagation and channel modelling.

Three different resource allocation schemes are considered to determine how the operators share their common portion of the spectrum:

- *Single operator upper bound*: theoretical upper bound identified by considering the two operators as perfectly collaborating entities, i.e. single decision block that allocates resources, to maximize the total joint throughput. One operator can get exclusive usage of the shared spectrum portion if its users have a better CQI.
- *Quid-pro-quo sharing:* considers same resource allocation that would happen without resource sharing. Both operators are using only their licensed bands. Then, the scheduler checks if a user of a given operator can achieve a higher throughput if allocated on a resource block belonging to the shared pool that is currently allocated to the other operator. Pairwise exchanges are identified, that is, if the resource allocator identifies a symmetrical occurrence of this situation for both operators, i.e. they both have a user that could be allocated on a resource presently allocated to the other, the allocation is switched.
- *Priority sharing*: each operator gets the same number of resource blocks it will get without resource sharing. Every operator is prioritized on its licensed frequency. Both operators select their required number of resource blocks according to CSI dependent greedy criterion. In case of allocation conflict, RB are assigned to the operator that has priority on them. Thus, some of the users are left out from the first allocation round. Then, a second iteration is repeated, by assigning these leftovers. The procedure is repeated again until a convergence is found.

It is important to notice that the two last strategies end up in a Nash equilibrium which is also Pareto efficient for the resource sharing problem. The single operator upper bound instead, which is based on mandatory collaboration between the operators, is not guaranteed to be an equilibrium, and therefore to be achievable in practice in a game theoretic sense, i.e. if the operators are driven by their own profit.

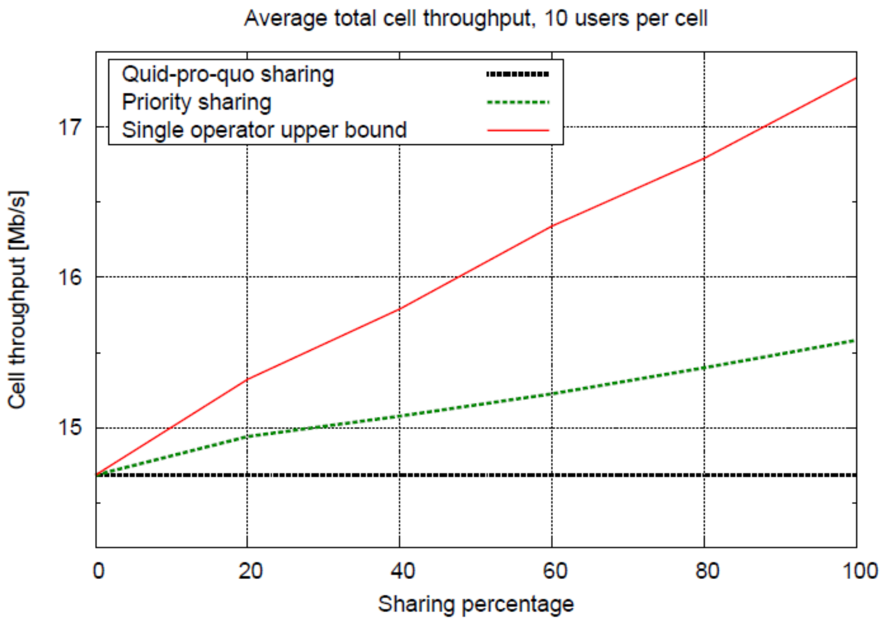

Figure 2. Cell throughput as a function of the sharing percentage, maximal throughput scheduling

Based on the results presented, the overall theoretical sharing gain achievable by purely *orthogonal* sharing is about 12%.

Future cellular networks will achieve higher spectral efficiency if the operators decide to share parts of the spectrum that has hitherto been exclusively licensed to them. It is expected when the operators share the spectrum *non-orthogonally*, i.e. they concurrently use the same frequency bands in the same geographical location. The major impairment, that has so far prevented such a development, is the interference caused by co-channel transmissions.

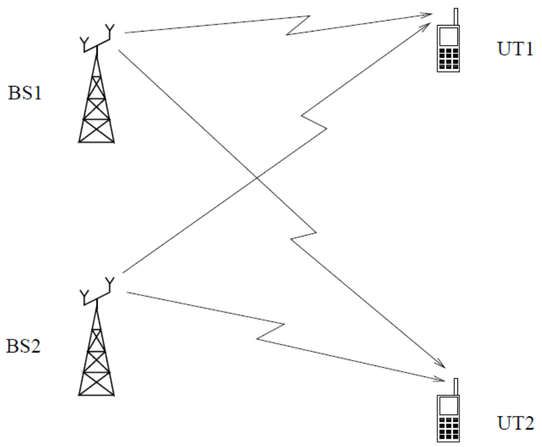

Figure 3. Two-user MISO interference channel

Figure 3 depicts the simplest setup for the DL mode of the non-orthogonal spectrum sharing scenario: two neighbouring base stations BS1 and BS2 of different operators transmit towards their user terminals UT1 and UT2 respectively and the UTs receive a combination of the transmissions.

SAPHYRE advocates that reliable and fast communication can be achieved in both links by applying advanced signal processing techniques to mitigate the interference caused by sharing.

The most prominent of these techniques is called *transmit beamforming* and it is enabled by the availability of multiple antennas at modern BS. By applying appropriate scaling of the transmitted signal in each antenna, the overall effect is to steer the transmission power towards the intended UT and away from the other UT. The interference is managed by effectively separating the transmissions in space. Transmit beamforming techniques have been well-studied in the context of single cell DL scenario, which is modelled by the MISO broadcast channel. Extending these techniques to the scenario interest in Figure 4, the so-called MISO interference channel (IC), is non-trivial. The capacity region of the MISO IC is yet unknown in general. However, it is possible to compute practically-relevant achievable rate regions.

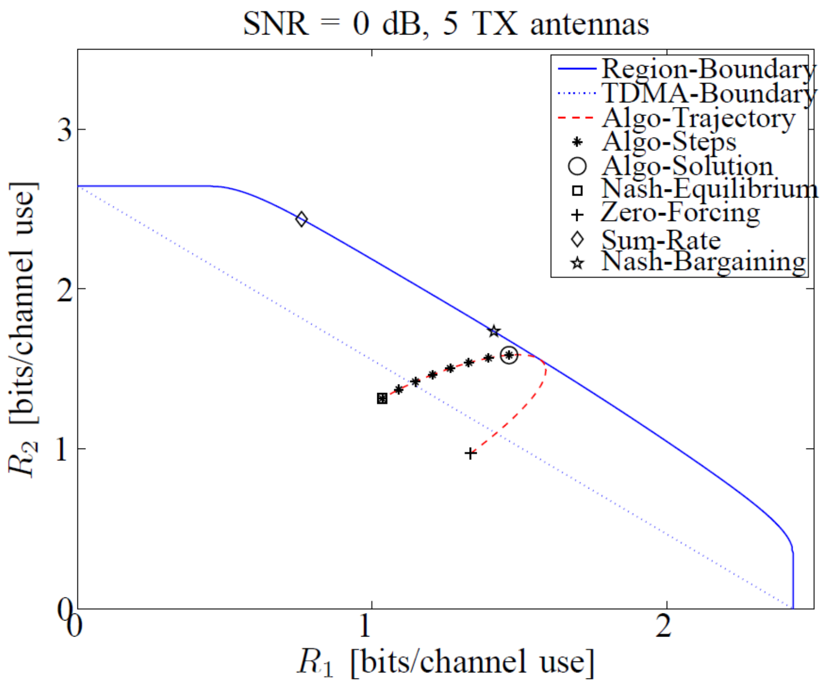

Figure 4. Exemplary achievable rate region and important operating points

Figure 4 illustrates such an achievable rate region for an arbitrary instance of Rayleigh-fading channels, assuming that they are perfectly known at the BS' and that the UTs treat the interference as additive noise. The triangular region achieved by orthogonal sharing (TDMA) is also depicted and it is evidenced that it lies inside the non-orthogonal sharing region. Hence, there is a multitude of operating points that yield high-rate to both links, which can only be achieved by non-orthogonal spectrum sharing.

This spectrum sharing scenario resembles the problem of intercell interference management in modern cellular networks with aggressive frequency reuse, but there are some important distinctions. First, the interference level can be significant, since the cells of different networks overlap each other and the BSs might even be co-located, especially in dense urban environments where the need of sharing is more prominent. Second, since the BSs belong to different operators, they do not share the user data and hence cannot use CoMP techniques to turn intercell interference into an advantage. What they need to share, via an appropriate inter-operator backbone interface, is only CSI. Third, the objectives of the operators are conflicting since they want to optimize the communication experience of different UTs using the same resources. This calls for decentralized designs that can be motivated by fundamental game-theoretic concepts. One extreme approach is that the BSs selfishly maximize the rate of their own UT disregarding the interference caused to the other UT: the other extreme is to altruistically maximize own rate while ensuring that no interference is caused to the other UT. The former approach leads to the so-called Nash equilibrium and the latter to the so-called zero-forcing operating point. As evidenced in Figure 4 both of them are in general inefficient, since the lie far inside the rate region. SAPHYRE claims that both operators can achieve more gain by equally sharing their spectrum and by cooperating in the design of their transmissions. Further details can be obtained from the SAPHYRE project report [17].

Sensing

Sensing of the wireless environment is an essential function in spectrum sharing as an input to the decision-making process about which spectrum to transmit within and about what power to use. Depending upon the spectrum and environments in question, sensing can either be used as a stand-alone function or used in conjunction with a data-base. Sensing can be used to detect the presence of secondary spectrum users of which the database is unaware, such as other sharing systems or wireless microphones in the case of TVWS. Energy sensing is the simplest but does not yield the high sensitivity and low probability of false detection that is required in the TVWS bands to be used as the sole input to the decision-making, where the sensitivity needed has been calculated by Ofcom UK to be -126dBm. Sensing relying on some known auto-correlation features of the signal (repetitive frames) and the Teager-Kaiser method for analogue signals are shown compared to energy sensing in Figure 5, from the QoSMOS project. Correlation detection and frequency domain energy sensing are shown to meet the requirement.

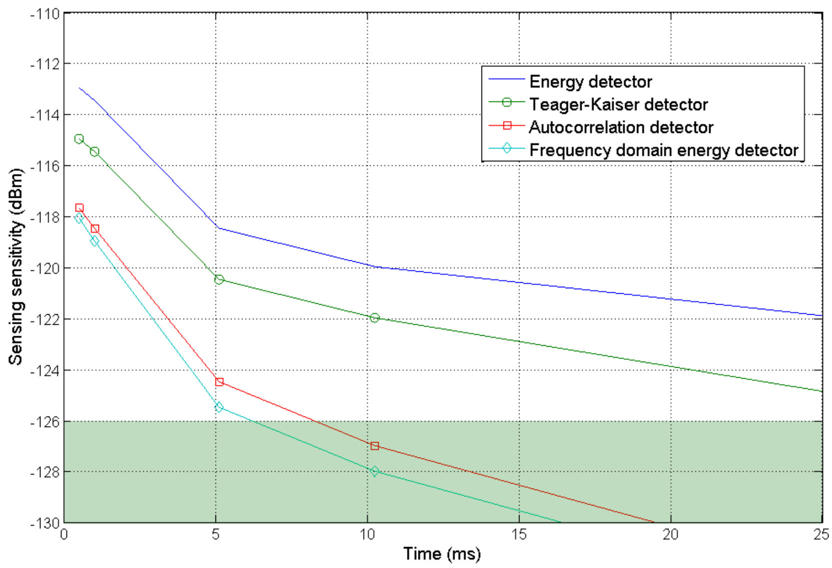

Figure 5. Comparison of energy, auto-correlation and Teager-Kaiser sensing

Further information on sensing from the QoSMOS project can be obtained here [18].

From the CogEU project, an experimental test-bed has been built that combines wireless microphone sensors with a web-based DVB-T geo-location database and PMSE spectrum-booking platform. Test trials, in a real scenario, have shown that the platform was able to gather information from a DVB-T geo-location database and a PMSE spectrum-booking platform, and update the list of vacant channels with local sensing techniques. The proposed method has shown capabilities to protect primary users of interferences from secondary users of the TV spectrum. Simulations have been performed of sensing of PMSE and DVB-T using distributed and feature-based sensing and made use of other secondary users to facilitate mechanisms for managing fairness. For TVWS, a cognitive radio system that uses only sensing to make decisions on which channels to occupy requires a reliable and very sensitive sensing system that has proved too challenging, so that all practical spectrum managers in TVWS use a combination of sensing and database.

The Where2 project has been addressing this problem mainly through generating innovative ideas in the scope of statistical signal processing. A novel technique named differential energy detection has been recently reported in [19] that fulfil the requirements of spectrum sensing assuming knowledge of bandwidth and the system employing Fourier-based waveforms. When the geo-location information of a wireless device is assumed to be available, Where2 is identifying a promising way of translating the location information into key parameters such as bandwidth and pattern of waveforms in the local area. Moreover, the differential energy detection technique is of great interests also to the Exalted project with specific to the application in LTE-M systems. The ongoing activity is to further reduce the signal processing complexity of spectrum sensing so that it is affordable for low-cost devices [20]. Finally, it is worth noticing that how to devise a promising spectrum sensing technique for generic waveforms still remains an interesting problem to be investigated.

Interference mitigation

Interference is minimised if the air interface used in one channel does not spill significant energy into the adjacent channels. Orthogonal frequency division multiplexing (OFDM) based CR systems suffer from high adjacent channel leakage, depending upon the side-lobes of the filter frequency responses and also upon any non-linearities in the analogue stages of the transceivers. The insertion of the cyclic prefix (CP) in each OFDM symbol adds overhead and hence decreases the system capacity. These defects are overcome by the use of Filter bank multicarrier (FBMC) systems in at least two projects, by employing offset quadrature amplitude modulation (OQAM). This achieves smaller intersymbol interference (ISI) and intercarrier interference (ICI) and removes the need for a CP by utilizing well designed pulse shapes that satisfy the perfect reconstruction conditions. The problem of spectral leakage can be solved by minimizing the side lobes of each subcarrier which leads to high efficiency (in terms of spectrum and interference) [21] [22]. Figure 6 shows a comparison between OFDM and FBMC.

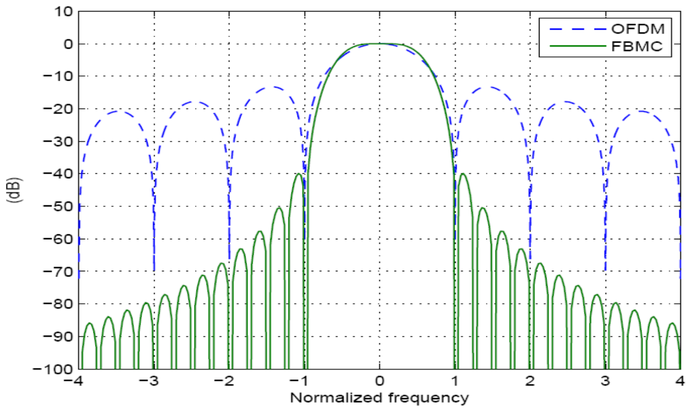

Figure 6: Subcarrier PSD's of the OFDM and FBMC systems.

The cleaner PSD of FBMC results in an increase in system capacity. There are some mild disadvantages, such as the absence of a CP that prevents initial symbol synchronisation and also equalisation is more complex. QoSMOS has IP in these areas and has built a prototype to demonstrate an end to end FBMC link.

The BeFemto project has shown that femtocell networks have recently gained attention as a technical solution to offer uniform broadband wireless service in indoor environment [23]. Compared to macro users (M-UEs), femto users (F-UEs) likely experience larger coverage, high quality link, and prolonged battery life. These advantages are mainly due to three reasons:

- the reduced distance between the user terminal and the femtocell access point (FAP),
- the limited number of F-UEs served by a single FAP
- a reduced interference level due to penetration and propagation losses.

Moreover, cellular network offloading by femtocell deployment may enable a notable reduction of the OPEX at mobile operators.

Such a novel architecture sets new challenges to interference mitigation techniques and RRM schemes. In fact, macrocells and femtocells likely share the same spectrum in a given geographic region. Thus, M-UEs located nearby FAPs can experience harmful femto-to-macro interference that can drastically corrupt the reliability of communication. Similarly, neighboring femtocells belonging to the same operator may also interfere with each other thus creating femto-to-femto interference. Moreover, closed access femtocell deployment introduces new challenges with respect to classic cellular network. Indeed, in that case, only a limited set of users, the so-called Closed Subscriber Group (CSG), is allowed to access the FAP. A user not belonging to the CSG and located in the vicinity of such an FAP is thus forced to connect to the Macro-base station or to a distant open access FAP. This situation might create a strong interference between this user and the closed FAP. However, in 3GPP release 10, there is neither X2 interface between CSG FAPs and Open Access FAPs nor between FAPs and Macro-BSs. Hence, ICIC through direct cooperation amongst interfering FAP and neighbouring BSs cannot take place. Therefore, femtocells need to be autonomous and self-adaptive to limit the undesired effects of interference at neighbouring cells.

Presented here is a simple and effective method that improves the performance of macro and F-UEs in co-channel deployment. Advantage is taken of the fact that only a small number of users (typically < 4) share the FAP spectral resources. Techniques are applied based on modulation and coding scheme (MCS) scaling to trade-off energy for frequency resources [24]. In a nutshell, these techniques exploit the wide available amount of spectrum per user by allotting each user more spectrum than the minimum necessary to ensure his requested QoS when the transmission power takes a nominal value. This larger spectrum can then be used with both lower transmission power and lower MCS. In this way, we can reliably implement the underlay paradigm proposed in classic cognitive radio networks [25] and subsequently decrease the overall generated interference. This simple approach coined "Ghost" can be implemented in both cooperative ($Ghost_{NF}$) and stand-alone ($Ghost_{SAF}$) femtocell scenarios [26] [27] and lead to improved performance for both femto and macro users. Eventually, we show in Figure 7 the macrocell performance as transmission cost Γ^M, the ratio between the transmission power and the cell throughput [J/bit] versus the power budget Pmax at each FAP with respect to a traditional approach (RRM_{SOA}). In fact, RRM_{SOA} scheme implements neither MCS scaling nor power control. Results indicate that $Ghost_{NF}$ and $Ghost_{SAF}$ limit the impact of the femto-to-macro interference in all considered scenarios (up to 22% of gain in terms of reduced transmission cost). δ_L, δ_M, and δ_H, indicate respectively the low femtocell density scenario, the medium femtocell density scenario, and the high femtocell density scenario. Improvements only come from the femtocell behavior; in fact, the M-BS uses a fixed RF power in each allotted resource block.

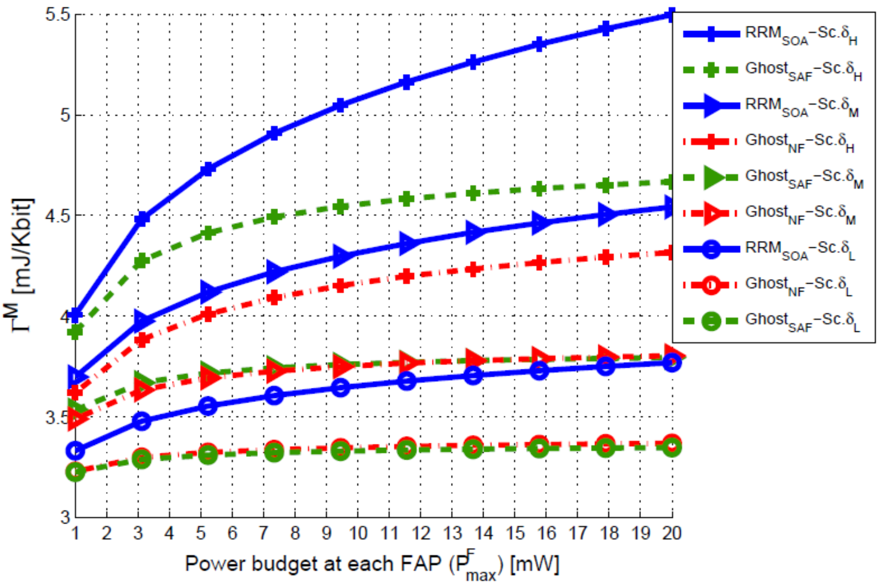

Figure 7. Macrocell performance against power budget

Discussion

Increasingly smart spectrum sharing is a potential solution to meeting increasing demand for connectivity and capacity. An implication is the disruption of the licensed / unlicensed regime, and considerable push-back can be expected from organisations whose business models are threatened. The RAS projects should continue to develop enabling technologies but also continue to focus upon the other ingredients that an operator needs in place before considering investment in large-scale platforms. These ingredients are interest from large vendors, a uniform regulatory position in Europe enabling a large market, and well-developed standards. This can come about by increasing the involvement of industry in projects and increasing interaction with regulation and standards bodies.

In terms of technology, it seems that spectrum occupancy decisions based upon sensing alone is currently not practical due the hidden terminal problem but work should continue on distributed sensing and data fusion. An example of geo-location database access combined with local sensing to enhance the information is being used in TV Whitespace trials to protect incumbents services such as DVB-T and PMSE applications.

An area of technology that requires still some activity is with radio design, the ability of a software-defined transceiver to tune flexibly across a wide range of frequencies and waveforms and yet maintain good performance is limited at present with current methods of antennas and analogue design. New materials and techniques are urgently needed, to avoid having multiple analogue front-ends fitted to every terminal, as is the case now with cellular handsets.

The availability of shared spectrum depends on the location and the protection requirements of other users. To reach consensus on availability, regulators have to fix protection parameters and define the methodology and the reference scenarios. Above all a European standardized data format is indispensable for practical reasons.

For the geo-location database, it will be desirable to have European standardised protocols/languages to access the database and format of data within it. The first part of this is being fulfilled by the IETF PAWS working group for TV Whitespace. All devices and entities that are to use the geo-location database need to be accredited by an authority, ensuring that, protocols and restraints/constraints are implemented and are available on any whitespace device, to complying with the database instructions and limitations. The preliminary structures of the geo-location database have to be refined to consider significant improvements in the accuracy and latency to gather geo-location information especially indoors [28].

The need for concertation and a common approach to protect incumbents in cross border areas should be matter of special interest. Cross-border issues have to be considered in the specification of the database. These policies will have to take account of existing EU data protection and privacy directives. It is not thought feasible to have a European central database, because of differences in the methods and policies by the member countries. However, co-ordination and co-operation are essential.

Market based spectrum usage and spectrum commons (license exempt) usage complement each other in the TV white spaces. Both can be used to deliver wireless access services with different QoS provisioning strategies: best-effort services fit under the commons, while services requiring QoS guarantee fit under the secondary spectrum trading regime. An example is the free and paid usage of the TV white spaces that form different business models as proposed by COGEU, implementation of different technologies will require different regulatory policies.

Different propagation conditions impact the spectrum sharing availability. As an example, TV whitespaces databases are currently populated considering line-of-sight conditions, indoor M2M applications operating in the same spectrum may enjoy extra protection due the walls propagation losses. Ongoing research shows the lack of proper indoor channel models and accurate and mature indoor geo-location information. Therefore, the protection of indoor M2M applications was not considered so far in any database deployment.

The initial TV whitespace example has served as a catalyst for change in spectrum management. The concept of spectrum sharing has been expanded to consider other frequency ranges. In Europe, the L-band (1452-1492 MHz) remains largely unused. In other areas, notably in North America, the take-up of DAB from terrestrial sources using the L-band has been very small, and the satellite services, while deployed, have relatively small numbers of subscribers. Internet distribution of broadcast audio programming is now common (as it is also for broadcast video) and this has altered the commercial landscape for digital audio broadcast both terrestrial and via satellite. A number of countries have therefore been investigating the future use of the L-band. In Canada, Industry Canada's 'Consultation on the Spectrum Allocations and Spectrum Utilization Policies for the Frequency Range 1435-1525 MHz (L-Band) [29] considered that 'with the convergence of fixed, broadcasting and mobile services over digital wireless platforms, a regulatory approach promoting flexible use of spectrum is increasingly important.' One option currently being considered is the re-assignment of unused DAB portions to other services such as commercial mobile and M2M communications. In Europe, the CEPT ECC launched recently a major review of the L-band with a view to making more effective use of this spectrum [30].

M2M is expected to grow rapidly over the next five years, becoming a large commercial market. Some of the factors driving this growth are the desire for increased efficiency and decreased costs, timely information, increased safety, a desire to carry out proactive maintenance rather than repair, minimizing environmental impact, increased national security, and increased operator revenue.

In order to avoid choke-points in market growth due to an inability to support scalability on a massive scale and to maximize the operating lifetimes of battery-powered M2M devices, a new technology approach is needed that achieves the targets of low cost and ability to scale on the order of hundreds of thousands of devices per base station.

M2M communications aren't as demanding as humans in terms of delay and are more predictable in nature allowing for machine learning and cognitive Radio Resource Management (RRM) techniques that takes advantage of traffic patterns/demands for spectrum in a clever way. Due to favourable propagation characteristics, TV white spaces is regarded by COGEU consortium as a very practical commercial opportunity for future M2M wireless connectivity. This suitability of the spectrum in turn will focus support for the development of an international low-cost M2M standard over TVWS. This vision is aligned with the Weightless™ SIG, a special interest group set up within Cambridge Wireless [31] in the autumn of 2011 with the purpose of developing a standard specifically for M2M communications in the TV white spaces spectrum. The Weightless™ standard is aimed entirely at M2M requirements: low bandwidth, extremely low power terminals and many thousands of devices per base station.

As a closing remark, much of the work on use-cases, architecture and management techniques for spectrum sharing has been completed, with remaining challenges of sensing, good radio designs, and development of regulation and standards to encourage industry to adopt it.

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