

On the Scalability of Cognitive Radio:

Assessing the commercial viability of secondary spectrum access

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Abstract

We report results from the recently finished QUASAR project, which has studied overall system aspects of cognitive radio technologies and has paid attention particularly to the economic viability of different use cases. We find that successful secondary sharing goes far beyond the detection of “spectrum holes”. Large-scale commercial success requires that secondary systems are scalable so that a large number of users can be served in economically viable fashion. Our key finding is that secondary spectrum use is not an attractive method for most of the commercially interesting scenarios, neither from a business nor technical perspective. Perhaps somewhat surprisingly, the likely commercial “sweet spot” for secondary sharing in the lower frequency bands is short-range, indoor communications. We also find that regulation does not present currently a significant barrier neither in Europe nor in the US.

1. Introduction

Wireless communications has become a ubiquitous part of our society and the ever increasing number of services and applications rely on availability of robust and cost-efficient wireless access. The commercial success of mobile and wireless access to the Internet has been monumental. At the same time, customer-installed non-mobile networks such as Wi-Fi are becoming gradually more congested due to increased interference and demand. Wireless access technology has practically become viral, i.e. so compelling that this rapid development will continue also in the foreseeable future. Recent studies predict at least 25- to 30-fold increase in the global mobile data traffic in five years. Furthermore, various machine-to-machine (M2M) applications and services have begun to gain foothold.

However, one of the key requirements for the ongoing development is that both access and device costs are kept low. Providing more radio spectrum for these services is one of the possibilities to achieve this goal. Besides lowering the cost for infrastructure and reducing the energy consumption of wireless devices, abundant and fast access to spectrum fosters rapid innovation in wireless systems and services by lowering entry barriers to the market. Together, this strongly contributes to affordable broadband access and improved services.

Although the progress in microelectronics has made new high frequency bands more affordable to use, the propagation characteristics of millimeter wave bands and the cost efficiency of standard CMOS-technology strongly favor the use of lower frequency bands below 6 GHz. A large number of measurement campaigns worldwide have shown that the spectrum occupation, or duty cycle, of many licensed bands are surprisingly low [1][2]. Spectrum band of particular interest is the one reserved for terrestrial UHF TV-broadcasting. The apparent poor use of lower frequencies has led to proposals to reuse these *white spaces* or *spectrum holes* in an opportunistic fashion. Dynamic spectrum access (DSA), mostly referred to as “cognitive radio technology” has become a thriving research domain, but surprisingly little attention has been paid to comprehensive study of *system aspects* in the context of scalability and economic viability. Most of the existing work has been using relatively simple interference models and has been focusing on specific technologies. Existing experimental trials have not considered aspects of large-scale deployment. However, analyzing the feasibility of widespread and reliable use of secondary access techniques is of paramount importance in order to understand business cases and to gauge the attractiveness of allowing the secondary use from the regulatory perspective.

The recently finalized QUASAR¹ project, a partnership between academia, regulators, and industry, had the objective of bridging the gap between the claims made in early cognitive radio research and likely practice in real deployments and implementations by assessing and quantifying the real-world benefits of opportunistic secondary access to primary spectrum. One of the key goals of the project has been to replace the usual emphasis on *spectrum holes* with a stronger focus on *real-life spectrum reuse opportunities*. The key issue here is that the mere fact that no transmissions can be detected in a certain block of spectrum in a certain area is not a sufficient condition for commercial exploitation. The QUASAR project demonstrates that a real spectrum reuse opportunity must meet a number of additional technical criteria to protect

¹ QUASAR, “Quantitative Assessment of Secondary Spectrum Access”, was a European Union FP7 funded research project, and more information including a full reference list and technical reports can be found at <http://quasarspectrum.eu>.

primary users, as well as criteria for economic viability and applicability to some specific secondary services. One important consequence is that spectrum opportunities are not generic and technology independent, but depend on the intended use and the specifics of the secondary system. The analysis also poses a question of *efficient use of the spectrum*: if the opportunistic use of spectrum were to lead poor spectral efficiency or unreliable service, one should question the economic viability and common good of such approach.

2. Scenarios for Secondary Spectrum Access

Our quantitative assessment strategy is to analyze a number of scenarios, where the technical availability of secondary spectrum is compared to the business demand [3]. In the technical part of the scenario definition, we have considered system characteristics and spectrum usage both for primary and secondary users. The context of spectrum sharing is then defined, and the business description of our scenarios analyses the spectrum demand and reliability requirements of spectrum access.

The primary systems investigated include a number of legacy systems: TV broadcasting, radar, and aeronautical navigation. These legacy systems are already in use and must be protected from potential harmful interference generated by the secondary usage. The information about technical specifications (e.g. interference tolerance and adjacent channel rejection capability) and operational facts (e.g. frequency allotments, locations, and traffic patterns) is needed for the secondary systems. The technical assessment criteria we have considered include primary system spectrum occupancy, interference tolerance, regulatory difficulty and global coordination.

Each secondary system has its own spectrum demand in spatial and temporal domains and its individual interference footprint. Hence, the feasibility of a scenario depends not only on the primary system and spectrum availability, but also on the characteristics of the secondary system. Thus, both the primary and secondary systems need to be specified in order to provide detailed feasibility analysis, and the spectrum sharing method between them should be described (e.g. overlay, underlay, and interweave method, and geo-location database vs. sensing-based opportunity finding). It is also important to characterize the interaction between secondary devices and systems in terms of licensing and medium access control schemes. All these requirements show that regulation for the secondary systems cannot be made in purely technologically neutral way, at least not unless large protection margins are provided for primary users and no serious consideration is given for the efficiency of secondary use. When considering the economic viability of the scenario, one has to consider also

particular usage context, e.g. the locations of primary and secondary users, and the propagation characteristics of the geographical areas under investigation.

A large number of potential scenarios were studied by the QUASAR consortium and a preliminary assessment of their potential was done based on [3]: (a) significant demand for (secondary) spectrum; (b) primary and secondary system having complementary spatiotemporal requirements; and (c) the capability to reliably assess reuse opportunities. All of these requirements need a careful consideration even in the preliminary assessment. For instance, a poor primary spectrum utilization, which is often quoted as a prerequisite for successful utilization, is a challenging factor to determine since many legacy systems use large interference margins to compensate for what is today considered to be poor receiver performance. Reliable secondary access for applications that require scalability and high infrastructure cost is mainly achieved when the primary systems exhibit static or predictable activity patterns. Even better results can be achieved when primary receiver locations are known.

The scenarios that we investigated further as potentially the most interesting secondary use cases were:

- Wide-area/local area cellular use of the UHF TV band;
- WiFi-like broadband access in the UHF TV band;
- Secondary spectrum for wireless cellular backhaul;
- WiFi-like use in SHF radar bands;
- Indoor broadband access in aeronautical spectrum; and
- M2M communication in the UHF TV band.

3. Technical Evaluation of Scalability and Feasibility

A. Aggregate interference

The first key part of the assessment in the QUASAR project is to quantify the *aggregate interference* generated by secondary systems, and estimate its effects to the primary system receivers [4][5]. This includes both *co-channel* and *adjacent channel interference*. In Figure 1, we illustrate the sources of interference for a primary TV receiver from white spaces devices (WSD). The regulatory treatment for the interference estimation and protection is currently different among regulatory agencies, and for example FCC, Ofcom and European CEPT SE43 working group have chosen markedly different approaches [6][7]. One finding of QUASAR project has been to establish that the total interference should be considered explicitly also from far-away WSDs. This also implies that there is a need to develop efficient *aggregate interference control mechanisms* [5]. Especially in TV-bands, one of the major obstacles for secondary spectrum access is the poor frequency selectivity of the low-cost, legacy receivers. This

makes most of the existing systems very vulnerable to adjacent channel interference. A WSD using a TV frequency that is not used by primary can still cause significant adjacent channel interference.

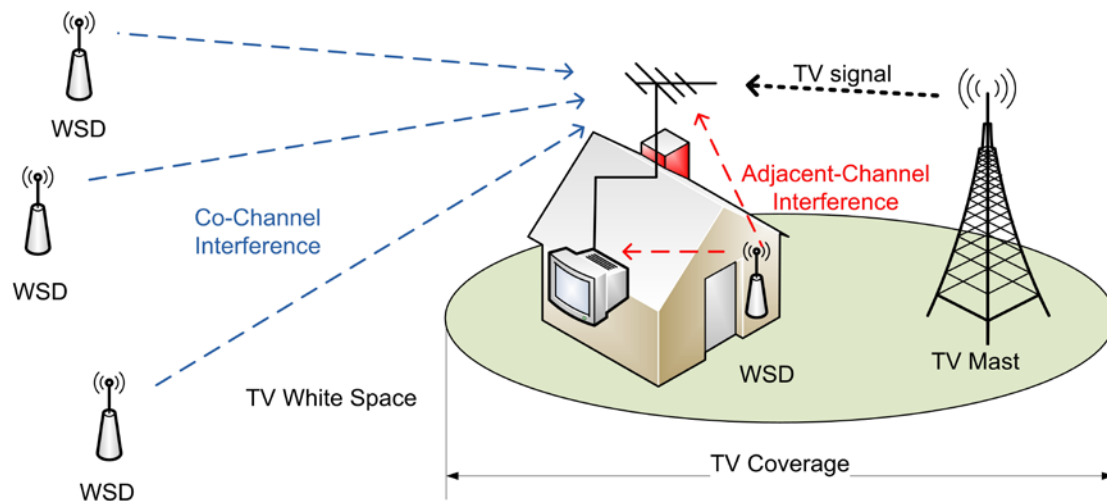


Figure 1: Experienced interference in a TV White Space system.

The secondary reuse will be prone to errors due to incomplete information. In the DSA literature two main types of problems are listed: (a) an opportunity appears to be detected, but secondary use causes excessive interference (*harmful interference*) and (b) interference is wrongly estimated to exceed the interference limit, although the secondary use would actually be possible (*missed opportunity*). Thus a robust and good detection of opportunities is a key enabler for efficient reuse of spectrum resources.

Two alternative approaches have been proposed for the opportunity detection. The early DSA work was focusing primarily on developing standalone and distributed spectrum sensing schemes ("cognitive radio"). The research and regulatory community soon realized that the stringent requirements for spectrum sensing accuracy and sensitivity combined with the inevitable residual errors made this approach technically very challenging to implement. Thus the second, and currently favored, spectrum database approach was introduced. Naturally, hybrid approaches can also be built, in which case typically the operational accuracy of databases is enhanced through different sensing mechanisms. Our analysis confirms the difficulty to build reliable sensing-based approaches for most scenarios of commercial interest. Even in the case of theoretical perfect primary detector, there remains the problem of the unknown primary receiver locations and those stand-alone schemes have very limited capabilities to control the aggregate interference.

In addition, geo-location database systems have to employ conservative interference margins to handle the problem of unknown receiver locations. The

main advantage of the geo-location database solution, however, is that it is capable of limiting the aggregated interference generated by multiple secondary systems. The requirement here is that the potential secondary users will report their positions and request channels from the central database. Responding to the request, the database will assign a channel and a maximum power to be used. This approach requires, however, dynamic control, and thus the system complexity is higher than what truly uncoordinated ISM-band devices have.

B. Primary interference protection

The second step in the assessment of the spectrum reuse is to consider the primary receiver protection requirements. In those cases when there are regulatory decisions already made, the QUASAR project has used these as constraints. In other cases such as secondary use of radar and aeronautical bands, no such constraints yet exist, and reasonable assumption regarding protection criteria had to be made. Whenever regulatory constraints apply, they will strongly affect to the final commercial feasibility and efficiency of secondary systems, and thus they cannot be ignored in the analysis. The main example of such constraints are the ones related to access to TV white spaces. In the US, the FCC has defined a set of specific rules for primarily geo-location based access [7]. In Europe, the ECC has published Report 159 that specifies technical and operational requirements for secondary access to TV white spaces [6]. The ECC requirements were originally designed to protect primary receivers from single co-channel users, but are now, partly influenced by QUASAR results, in the process of amendment to cover both adjacent interferers and aggregate interference.

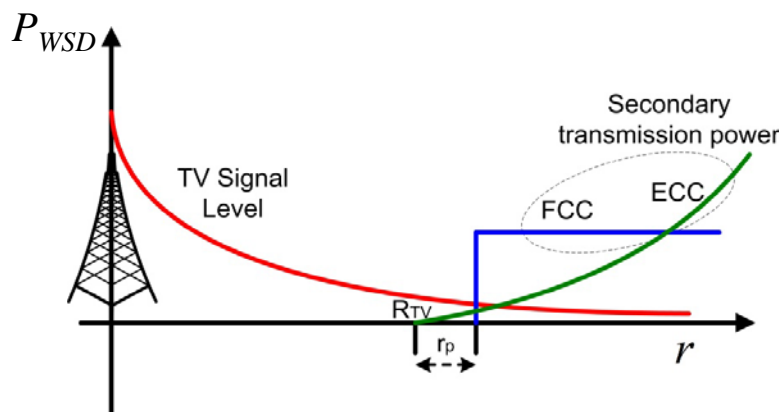


Figure 2: FCC and ECC approaches for allocating power to WSDs. R_{TV} denotes the TV broadcast range and r_p is the protection distance utilized. The primary transmitter signal level is plotted with red color and the WSD power, denoted by P_{WSD} , is shown in blue for the FCC rules and in green for the ECC recommendations.

FCC and ECC have selected different approaches for protecting the primary systems against the interference from secondary systems as illustrated in Figure

2. The FCC rules specify fixed transmission power and require a protection distance around the TV coverage area both for co-channel and adjacent channel use. ECC recommendation limits the power available for a secondary transmitter based on its distance to the primary system coverage border. Transmission is also allowed on the adjacent channel, but the predefined reference geometry is assumed for determining the distance to the closest TV receiver. However, we have found that the reference geometry approach is not without problems since it assumes that all the adjacent channel transmitters are located in a predefined worst-case position. This leads to overly conservative power allocation. Both approaches work well as long as the number of secondary transmitters is small. In the case of large deployment of secondary networks, both schemes fail to protect the primary system against the aggregate interference from multiple simultaneously transmitting secondary systems [4]. We may also note that the TV signal propagates beyond the service area and negatively affects the quality and usefulness of the secondary opportunity provided by the TV white spaces.

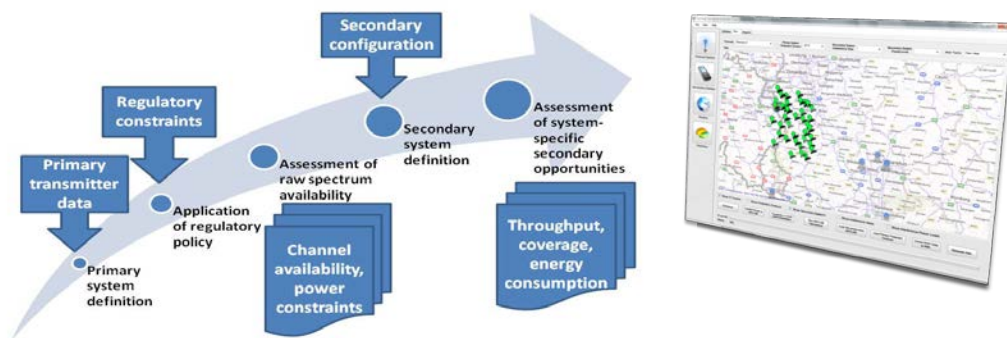


Figure 3: Methodology and the tool developed for assessment of secondary reuse feasibility.

C. A systematic evaluation toolkit

One of the key issues in the assessment of secondary reuse feasibility is that the comparisons between considered systems are done in a systematic manner. Our experience is also that one needs a flexible framework and tool where various technical and regulatory decisions can be tested in an “if-then-what” fashion. In order to enable this, an integrated assessment framework and computerized tool has been designed. The final methodology and aspects inside the assessment tool are outlined in Figure 3 [8]. The tool itself is providing interfaces to exchange data with different business calculation tools so that technical assessment can be combined also with the first level economic feasibility studies. The developed software has been demonstrated in different venues, and the feedback is used to develop it further.

4. Scenario analysis

The developed methodology and tool has been used to study different chosen scenarios, and the most interesting scenarios which have been also suggested in a common DSA literature were analyzed with more details. Here we report the conclusions from those scenarios.

A. Macro cellular use of TV white spaces

Recently there has been interest to consider the use of TV white spaces for macro cellular deployment for traffic offloading or even as standalone networks. In particular, various authors have considered the use of LTE technology in TV white spaces. We observe that the aggregate interference considerably reduces the availability of secondary access opportunities. One can also note that the number of available channels is negatively correlated to the population density – where the capacity is needed the most, the availability is low. In the analysis of macro cellular system, one has to take into account that both up- and down-link of cellular devices must be supported in the operational locations. This requirement makes it harder to find suitable reuse locations. The conclusion is that contiguous cellular coverage in TV white spaces is difficult to achieve. Instead, the use of TV white spaces as a micro-cellular capacity booster in limited local areas is a more plausible approach. However, we note that this kind of secondary use does not capitalize on the favourable propagation characteristics of the UHF bands. It is also demonstrated that current regulatory approaches considered by FCC and ECC are not suitable for multiple cellular-type secondary users. Thus, although macro-cellular (LTE type) systems could use TV white spaces in some countries as an extra offloading capability, this does not seem to be the most attractive approach. The situation in Germany, Finland, and the UK have been considered in more detail in the literature, see e.g. [9].

B. WiFi-like use of TV white spaces

WiFi-like unlicensed use of secondary spectrum is probably the service that has received the most intense attention so far in DSA community. In this scenario, the requirement to carefully specify the secondary system is crucial for the outcomes. We have demonstrated that WiFi-like secondary system indeed can achieve large coverage with a limited power budget in TV white spaces. Hence, the favourable propagation characteristics are used, as often wished. However, the CSMA/CA medium access control scheme will significantly undermine the performance of the secondary system in the case of *dense deployment of secondary users*. Thus, if the unmodified CSMA/CA access is used due to its easy non-coordinated deployment, we have a dilemma where the results are good for low-density deployments in rural-areas with a lot of doubts on economic

viability due to lower number of customers. In the dense areas, offloading of data traffic would be economically interesting, but the scalability due to the increased interference range raises technical doubts on the scalability and sustainability of the system [11]. However, we have found out that if the WiFi-like use were limited to more indoor scenarios with limited power budget, the situation could become quite interesting, perhaps also with a changed medium access methodology, in particular for M2M communications.

C. Indoor broadband in radar spectrum

We have analysed scenarios, where air traffic control (ATC) radars in 2.7-2.9 GHz frequency band or meteorological radars in the 5 GHz band were considered as the primary system, while low-power devices like LTE home base stations (BSs) acted as secondary users for indoor broadband. The impact of aggregate interference is surprisingly significant in this scenario. Substantial protection margins are required to account for the high density of low-power secondary users. Nevertheless, considerable secondary use outside a separation distance of a few kilometres is feasible in the spectrum overlapping the radar centre frequency. Further exploiting a predictable rotation pattern of a radar antenna provides even higher secondary access availability. However, secondary users in high-rise buildings need more separation from the radar, and in reality the only feasible option is spectrally non-overlapping use of the 2.7-2.9 GHz spectrum. Overall, there are a substantial technical opportunities in the radar bands considering the sparse placement of radars [12][10].

D. Indoor broadband in aeronautical spectrum

Another possibility is to consider the distance measuring equipment (DME) for aeronautical navigation in 960-1215 MHz frequency band as the primary system. We considered the secondary users to be low-power, indoor broadband applications. As in the case of ATC radars, the impact of aggregate interference is significant. In practice, one finds that co-channel access is difficult as a large spatial separation is required between the primary and secondary devices. However, adjacent channel usage is found to be feasible in most of areas in Europe. We have quantified the available amount of spectrum in Germany and Sweden, and found out that DME bands could be used for many applications especially if secondary users have good capabilities for spectrum aggregation (see Figure 4) [13].

For detailed technical results the reader is referred to the public deliverables of the QUASAR project, e.g. [14].

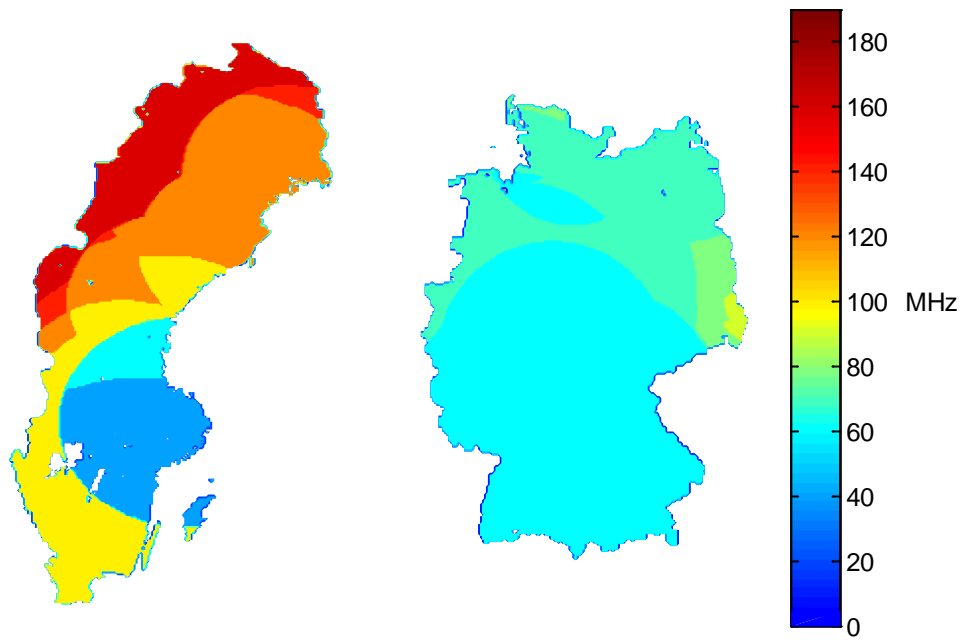


Figure 4: Available number of 1MHz DME channels in Sweden (left) and Germany (right) for the secondary use by setting the secondary user transmission power to 0 dBm/MHz. It is assumed that there are as many secondary devices as the population.

5. Locating the commercial sweet spots - the business cases

The technical analysis shows that the spectrum availability may be somewhat unpredictable and erratic in time or space. However, for the business feasibility, it is not only the total amount and size of spectrum opportunities that matters; critical for success is that the spectrum demand of a specific application matches the availability. A detailed business analysis involves many non-technical aspects, e.g. type of actor that provides the service, and results depend heavily on the working assumptions and the perspective of the analysis. For example, offloading scenarios may be interesting to incumbent operator with increasing traffic and good investment resources, and indoor short-range access might be interesting to new entrants and device manufactures.

Figure 5 summarizes our findings for the most interesting scenarios. In the figure, we map the expected spectrum demand of secondary services (estimated from likely density of devices, bandwidth demand per device and spectrum reusability) against the technical availability of white spaces as discussed in the previous section.

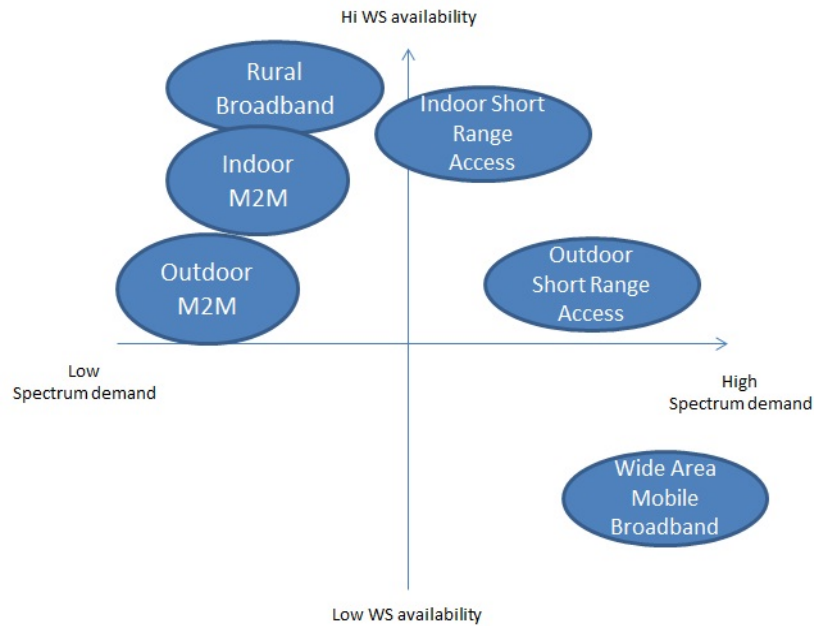


Figure 5: Spectrum demand generated by traffic and business opportunities compared against the availability of white spaces.

The often referred rural broadband services and M2M communication schemes have potentially a lot of secondary spectrum at their disposal, since they either operate in low-population density areas (rural broadband) or require only narrowband channels (huge opportunities to find these in different frequencies). However, the expected demand and customer base is relatively low for these applications. The availability of conventional licensed spectrum does also look promising for these applications. The business case for high-risk investments in “cognitive radio” technology for these applications is therefore limited.

The situation is the opposite for the case of wide-area mobile broadband. There is a tremendous demand for mobile data and new frequencies could be used efficiently. Unfortunately our analysis shows that there is only limited amount of white spaces available for this sort of services. The spectrum usage in this application is very intense, infrastructure costs are high and the techno-economic life-span of the system is at least 10-20 years. The match to the erratic availability in secondary spectrum is therefore poor.

In scenarios requiring large investments (e.g. wide-area cellular), new actors that will use secondary spectrum as the *only* resource will have much higher costs than an existing mobile operator since they have to invest in new infrastructure. The situation is even worse if they need to build up a customer base, customer care and billing platforms. An analysis of prices of licensed spectrum shows that in most countries the cost of acquiring licensed spectrum is dwarfed by these infrastructure costs. It is clear that wideband DSA equipment

has different cost-capacity-energy characteristics than conventional solutions. In addition, new technology is always seen as an additional risk by the operators. The consequence is that the addition of secondary spectrum to existing sites is cost efficient compared to using licensed spectrum only when the spectrum cost is very high or additional spectrum is the only option, e.g. very high density networks [15].

The most obvious sweet spot for secondary use seems to be in the upper right corner of Figure 5: short range and indoor systems with medium to large capacity demands, e.g. WiFi-like systems providing high-capacity hotspot and indoor offloading for mobile cellular data access. In this type of operation, the problems with up- and down-link coincidence and infrastructure costs that were mentioned in Section 4 disfavoring macro cellular deployment are automatically solved by a short link-distance. The infrastructure cost in these systems is not dominated by the radio specific equipment (which is likely to be low cost) but rather by the fixed backhaul, which will be useful even if the wireless access technology is changed later.

For indoor and short-range systems the market entry is easier, and the situation may look more like introducing WiFi-band services. However, the business feasibility depends still on the scalability of the systems as only large markets can drive the costs down and attract sufficient investments. Similarly, the scalability is required to guarantee a reasonable quality of services for many services. One has to be careful that the tragedy of commons does not destroy the market conditions too rapidly.

Finally, our analysis on sweet spots should not be taken as guarantees for success or failure of the different scenarios. However, we provide indications of the overall size of the business, the common good elements to use spectrum, and the attractiveness to enter the market for different stakeholders.

6. Regulator: driver or roadblock?

A regulatory framework for secondary access to TV white spaces is already in place in the USA, and is currently well underway in the UK. On a European level, work within CEPT is being finalized on defining technical and operational requirements for the possible operations. Various countries, such as Finland, Singapore, and Japan, have also provided research-purpose licenses to test opportunistic spectrum access through cognitive radios beyond TV White Spaces. Furthermore, regulators in a number of countries, including Canada, are in the process of putting in place a regulatory framework.

The current “first wave” of regulations has focused on how to offer maximum levels of protection to primary systems against operation of cognitive radios. So far the work has been strongly focused on TV white spaces reuse, and it is not clear if all the results can be applied to other scenarios. Other countries have chosen a more moderate approach to secondary use, e.g. Germany that has simply licensed a part of its “digital dividend”, i.e. channels freed from switching from analogue to digital TV.

In the near future, one would wish that regulators would move from just protecting primary systems to a more balanced approach where more emphasis would be given to enabling profitable wireless services in secondary systems. One of the most interesting debates to emerge is if the capabilities of primary (and secondary) receivers should be regulated too. It is entirely discretion of the regulatory community to decide if it wants to become a driver in new approaches. Already taken steps on considering alternatives show that one can hardly call regulators as roadblocks.

7. Conclusions

We have identified some necessary conditions for successful spectrum sharing in the context of DSA. We have also developed a systematic assessment framework which involves the identification of a number of promising secondary sharing scenarios. The scenarios were exposed to a technical analysis that, in turn, has been the basis of first-level business feasibility studies.

Our work indicates that the most tempting application, i.e. wide-area cellular broadband in the coverage-wise attractive UHF band, is not very well matched to secondary spectrum use. The main technical argument is the poor spatial match between spectrum availability and demand. The very high spectrum utilization of these applications lends itself better for licensed use of spectrum. More importantly, from a business perspective, secondary spectrum usage does not provide real opportunities for either cellular incumbents or new market entrants in the cellular domain. In most industrial countries, the cost for licensed spectrum is today dwarfed by the investments in infrastructure. In short, a “cheap” spectrum is unlikely to induce new market players to enter a high-risk path of opportunistic spectrum access.

In contrast, indoor and short-range access is more attractive, as the radio-related investments are much smaller, and since acquiring the licensed spectrum is not a realistic option. Secondary spectrum access may also significantly lower entrance barriers for new players providing high-capacity hotspot offloading solutions that complement the wide-area cellular systems. This approach is also

attractive as no complex “cognitive radio” technology is required. Relatively simple radio equipment with access to geo-location databases is sufficient to provide services with good protection for primary receivers even in massively popular usage scenarios.

The capacity available for secondary system is fundamentally limited by the interference tolerance of the primary receivers. If primary and secondary systems would collaborate, then it would be possible to increase the interference tolerance or avoid the interference at the primary receivers altogether using, e.g. interference alignment methods. However, the co-operation implies coordination and even standardization between systems, warranting further research. Any future work in this field should consider more specifically hardware constraints more carefully. Many of our conclusions would have been different if we had abstracted away performance characteristics of radio devices and propagation constraints. Designing low-cost, high-performance equipment to operate over a wide frequency range is certainly a non-trivial task.

Acknowledgement

This work has been in part funded through EU FP7 QUASAR-project (Grant no. INFSO-ICT-248303). The authors would like to acknowledge the contributions of their colleagues from Aalto University, British Telecom plc, Ericsson AB, KTH Royal Institute of Technology, RWTH Aachen University, University of St Cyril and Methodius (UKIM), and Yonsei University. The valuable input from the regulator partners of the project BNetzA (D), FICORA (FI), Ofcom (UK), and PTS (SE) is also gratefully acknowledged.

References

- [1] M. A. McHenry, P. A. Tenhula, D. McCloskey, D. A. Roberson, and C. S. Hood, “Chicago Spectrum Occupancy Measurements & Analysis and a Long-term Studies Proposal,” in Proc. Workshop on Technology and Policy for Accessing Spectrum (TAPAS), Boston, USA, 2006.
- [2] M. Wellens and P. Mähönen, “Lessons Learned from an Extensive Spectrum Occupancy Measurement Campaign and a Stochastic Duty Cycle Model,” *Mobile Networks and Applications*, Vol. 15, No. 3, 2010, pp. 461-474.
- [3] Y. Hwang, K. W. Sung, S.-L. Kim, and J. Zander, “Scenario Making for Assessment of Secondary Spectrum Access,” *IEEE Wireless Communications*, Vol. 19, No. 4, August 2012.
- [4] K. Ruttik, “Secondary spectrum usage in TV white space,” Ph.D. Thesis, Aalto University, (Chapter 6), December 2011. [available at <http://lib.tkk.fi/Diss/>]
- [5] K. Woyach, P. Grover, A. Sahai, “Near vs. Far Field: Interference Aggregation in TV White Spaces,” *Global Telecommunications Conference, GLOBECOM*, December 2011.
- [6] CEPT WG SE43, “Technical and operational requirements for the possible operation of cognitive radio systems in the “white spaces” of the frequency band 470-790 MHz,” ECC Report 159, February 2011. [available at <http://www.ero.dk>]

- [7] FCC, "In the Matter of Unlicensed Operation in the TV Broadcast Bands: Second Memorandum Opinion and Order," FCC-10-174, September 2010.
- [8] A. Achtzehn, L. Simic, M. Petrova, P. Mähönen, P. Latkoski, V. Atanasovski, and L. Gavrilovska, "A Generic Software Tool For Assessing Secondary System Opportunities," in Proc. IEEE DySPAN 2012, Bellevue, USA, October 2012.
- [9] A. Achtzehn, M. Petrova, and P. Mähönen, "On the performance of Cellular Network Deployments in TV Whitespaces," in Proc. IEEE ICC 2012, Ottawa, Canada, June 2012.
- [10] R. Saruthirathanaworakun, J. Peha, L. M. Correia, "Opportunistic Sharing Between Rotating Radar and Cellular", IEEE Journal on Selected Areas in Communications, vol. 30, No. 10, pp. 1900-1910, November 2012.
- [11] L. Simic, M. Petrova, and P. Mähönen, "Wi-Fi, but not on Steroids: Performance Analysis of a Wi-Fi like Network Operating in TVWS under Realistic Conditions," in Proc. IEEE ICC 2012, Ottawa, Canada, June 2012.
- [12] M. Tercero, K. W. Sung, and J. Zander, "Exploiting Temporal Secondary Access Opportunities in Radar Spectrum," to appear in Wireless Personal Communications.
- [13] E. Obregon, K. W. Sung, and J. Zander, "Availability Assessment of Secondary Usage in Aeronautical Spectrum," to appear at IEEE WCNC 2013, Shanghai, China, April 2013.
- [14] K. W. Sung (editor), "Methods and tools for estimating spectrum availability: case of multiple secondary users," QUASAR deliverable D5.3, March 2012. [available at <http://quasarspectrum.eu>]
- [15] J. Markendahl and S.-L. Kim (editors), "Business impact assessment," QUASAR deliverable D1.3, June 2012. [available at <http://quasarspectrum.eu>]