

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 an economically viable fashion. Our key finding is that secondary spectrum use is not an attractive method for most of the commercially interesting scenarios, from neither 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 currently present a significant barrier in Europe or the United States.

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 WiFi are becoming gradually more congested due to increased interference and demand. Wireless access technology has practically become viral — so that this rapid development will continue also in the foreseeable future. Recent studies predict at least 25- to 30-fold increase in global mobile data traffic in five years. Furthermore, various machine-to-machine (M2M) applications and services have begun to gain footholds.

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 complementary metal oxide semiconductor (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]. A 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 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 gauge the attractiveness of allowing the secondary use from the regulatory perspective.

The recently finalized QUASAR¹ project, a

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>.

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 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 to poor spectral efficiency or unreliable service, one should question the economic viability and common good of such an approach.

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 for both primary and secondary users. The context of spectrum sharing is then defined, and the business description of our scenarios analyzes 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 secondary usage. Information about technical specifications (e.g., interference tolerance and adjacent channel rejection capability) and operational facts (e.g., frequency allotments, locations, and traffic patterns) are needed for 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 the 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

methods, and geolocation 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 secondary systems cannot be made in a 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 also consider particular usage context, for example, 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]:

- Significant demand for (secondary) spectrum
- Primary and secondary systems having complementary spatiotemporal requirements
- The capability to reliably assess reuse opportunities

All of these requirements need careful consideration even in the preliminary assessment. For instance, 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 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 the aeronautical spectrum
- M2M communication in the UHF TV band

TECHNICAL EVALUATION OF SCALABILITY AND FEASIBILITY

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 on the primary system receivers [4, 5]. This includes both *co-channel* and *adjacent channel interference*. In Fig. 1, we illustrate the sources of interference for a primary TV receiver from white space devices (WSDs). The regulatory treatment for the interference estimation and protection is currently different

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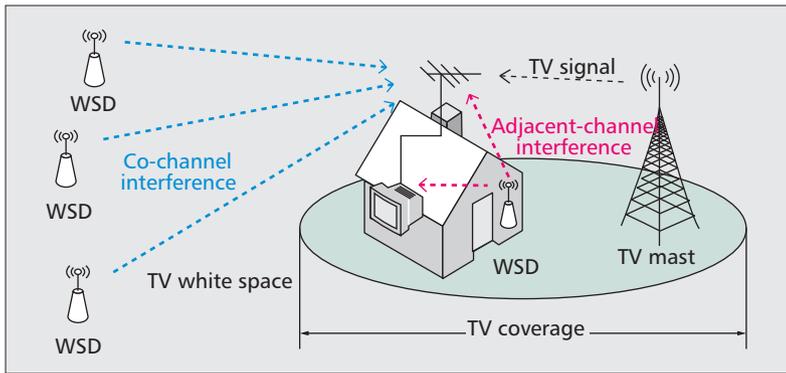


Figure 1. Experienced interference in a TV white space system.

among regulatory agencies, and, for example, the U.S. FCC, U.K. Ofcom, and European CEPT SE43 Working Group have chosen markedly different approaches [6, 7]. One finding of the QUASAR project has been to establish that the total interference from far-away WSDs should also be considered explicitly. This 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 the primary user can still cause significant adjacent channel interference.

Secondary reuse will be prone to errors due to incomplete information. In the DSA literature two main types of problems are listed:

- An opportunity appears to be detected, but secondary use causes excessive interference (*harmful interference*).
- Interference is wrongly estimated to exceed the interference limit, although secondary use would actually be possible (*missed opportunity*).

Thus, robust and good detection of opportunities is a key enabler for efficient reuse of spectrum resources.

Two alternative approaches have been proposed for opportunity detection. Early DSA work focused 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 of building reliable sensing-based approaches for most scenarios of commercial interest. Even in the case of a theoretical perfect primary detector, there remains the problem of unknown primary receiver locations, and those standalone schemes have very limited capabilities to control the aggregate interference.

In addition, geolocation database systems have to employ conservative interference margins to handle the problem of unknown receiver locations. The main advantage of the geolocation 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. However, this approach requires dynamic control, and thus the system complexity is higher than that of truly uncoordinated industrial, scientific, and medical (ISM) band devices.

PRIMARY INTERFERENCE PROTECTION

The second step in the assessment of spectrum reuse is to consider the primary receiver's 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 assumptions regarding protection criteria had to be made. Whenever regulatory constraints apply, they will strongly affect 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 United States, the FCC has defined a set of specific rules for primarily geolocation-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.

The FCC and ECC have selected different approaches to protecting primary systems against interference from secondary systems, as illustrated in Fig 2. The FCC rules specify fixed transmission power and require a protection distance around the TV coverage area for both co-channel and adjacent channel use. The ECC recommendation limits the power available for a secondary transmitter based on its distance from 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 at 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 a 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 use-

fulness of the secondary opportunity provided by TV white space.

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 Fig. 3 [8]. The tool itself provides interfaces to exchange data with different business calculation tools so that technical assessment can be combined with first-level economic feasibility studies. The developed software has been demonstrated in different venues, and the feedback is used to develop it further.

SCENARIO ANALYSIS

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

MACROCELLULAR USE OF TV WHITE SPACE

Recently there has been interest to consider the use of TV white space for macrocellular deployment for traffic offloading or even as standalone networks. In particular, various authors have considered the use of Long Term Evolution (LTE) technology in TV white space. 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 a macrocellular system, one has to take into account that both up- and downlink 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 space as a microcellular 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 favorable propagation characteristics of the UHF bands. It is also demonstrated that current regulatory approaches considered by the FCC and ECC are not suitable for multiple cellular-type secondary users. Thus, although macrocellular (LTE type) systems could use TV white space 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 United Kingdom have been considered in more detail in the literature [9].

WiFi-LIKE USE OF TV WHITE SPACES

WiFi-like unlicensed use of secondary spectrum is probably the service that has received the

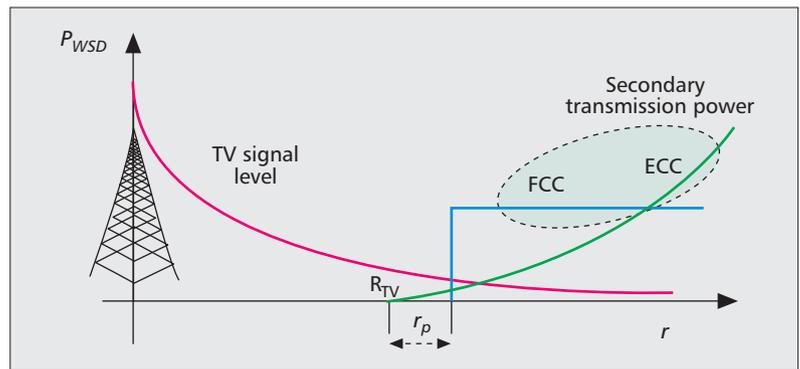


Figure 2. FCC and ECC approaches to allocating power to WSDs. R_{TV} denotes the TV broadcast range and r_p is the protection distance utilized. The primary transmitter signal level is plotted in red, and the WSD power, denoted by P_{WSD} , is shown in blue for the FCC rules and green for the ECC recommendations.

most intense attention so far in the DSA community. In this scenario, the requirement to carefully specify the secondary system is crucial for the outcomes. We have demonstrated that a WiFi-like secondary system indeed can achieve large coverage with a limited power budget in TV white space. Hence, the favorable propagation characteristics are used, as often wished. However, the carrier sense multiple access with collision avoidance (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 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 would become quite interesting, perhaps also with a changed medium access methodology, particularly for M2M communications.

INDOOR BROADBAND IN RADAR SPECTRUM

We have analyzed scenarios where air traffic control (ATC) radars in the 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 kilometers is feasible in the spectrum overlapping the radar center frequency. Further exploiting a predictable rotation pattern of a radar antenna provides even higher secondary access availability. However, secondary users in

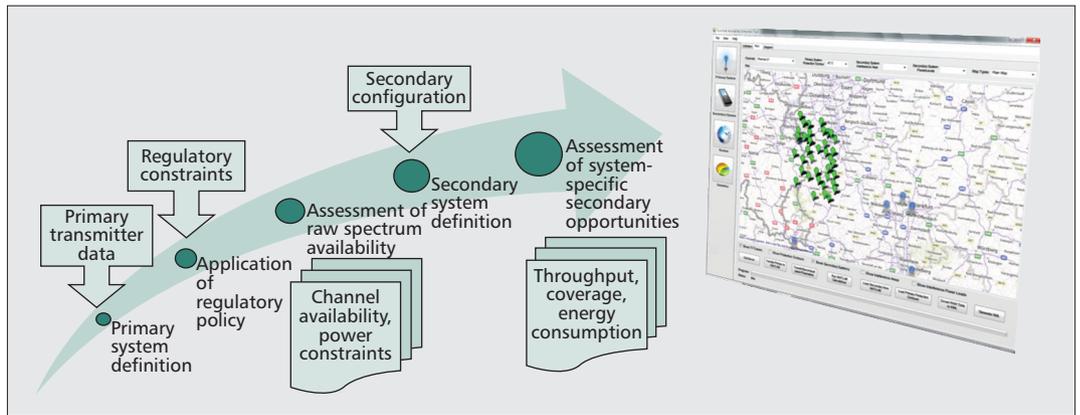


Figure 3. Methodology and the tool developed for assessment of secondary reuse feasibility.

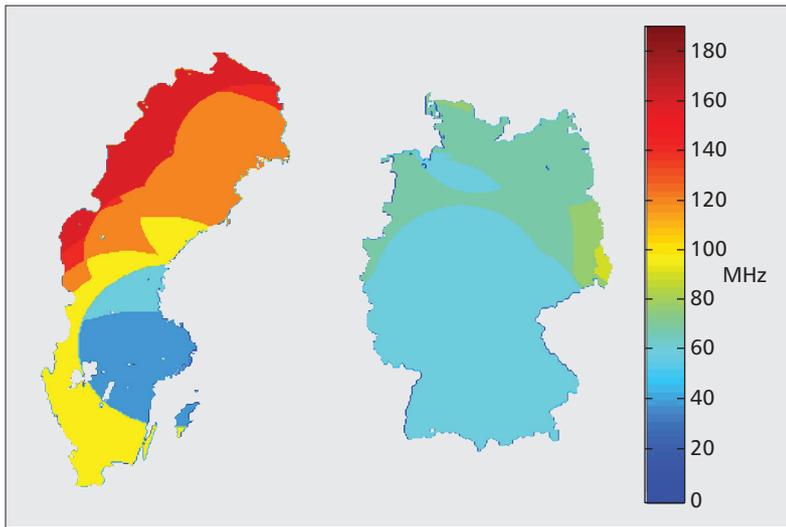


Figure 4. Available number of 1 MHz DME channels in Sweden (left) and Germany (right) for the secondary use by setting the secondary user transmission power to 0 dBm/MHz. It is assumed that there are as many secondary devices as members of the population.

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 substantial technical opportunities in the radar bands considering the sparse placement of radars [12, 10].

INDOOR BROADBAND IN AERONAUTICAL SPECTRUM

Another possibility is to consider the distance measuring equipment (DME) for aeronautical navigation in the 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 that DME

bands could be used for many applications, especially if secondary users have good capabilities for spectrum aggregation (Fig. 4) [13].

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

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 business feasibility, it is not only the total amount and size of spectrum opportunities that matter; 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., the 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 an incumbent operator with increasing traffic and good investment resources, and indoor short-range access might be interesting to new entrants and device manufacturers.

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 space as discussed in the previous section.

The often referred to 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 also looks 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 tremen-

dous demand for mobile data, and new frequencies could be used efficiently. Unfortunately, our analysis shows that there is only a limited amount of white space 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 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 Fig. 5: short-range and indoor systems with medium-to large-capacity demands, for example, WiFi-like systems providing high-capacity hotspots and indoor offloading for mobile cellular data access. In this type of operation, the problems with up- and downlink coincidence and infrastructure costs that were mentioned earlier disfavoring macrocellular deployment are automatically solved by a short link distance. The infrastructure cost in these systems is not dominated by 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 market entry is easier, and the situation may look more like introducing WiFi-band services. However, the business feasibility still depends 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 reasonable QoS 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.

REGULATOR: DRIVER OR ROADBLOCK?

A regulatory framework for secondary access to TV white spaces is already in place in the United States, and is currently well underway in the

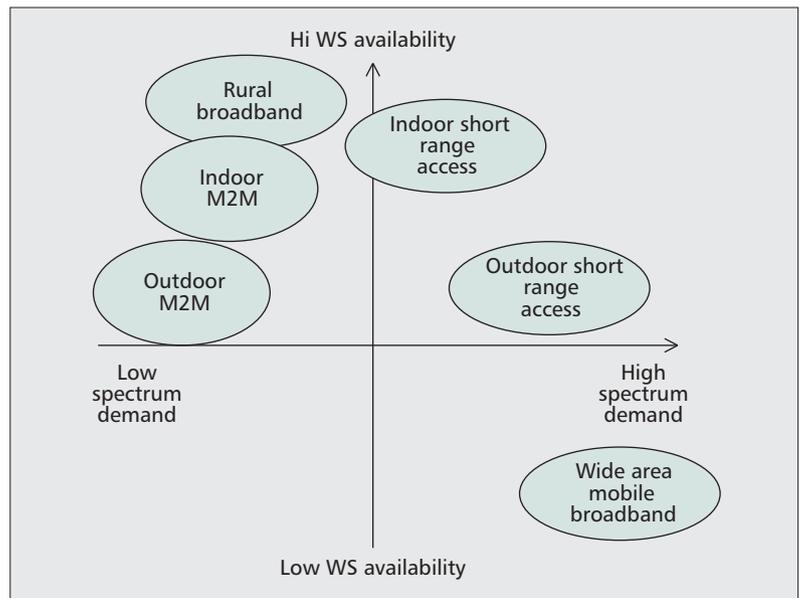


Figure 5. Spectrum demand generated by traffic and business opportunities compared against the availability of white spaces.

United Kingdom. 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 space. 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 space 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; for example, Germany has simply licensed a part of its digital dividend (i.e., channels freed by switching from analog 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 whether the capabilities of primary (and secondary) receivers should be regulated too. It is entirely at the discretion of the regulatory community to decide if it wants to become a driver in new approaches. Steps already taken on considering alternatives show that one can hardly call regulators roadblocks.

CONCLUSIONS

We have identified some necessary conditions for successful spectrum sharing in the context of DSA. We have also developed a systematic assessment framework that involves the identification of a number of promising secondary shar-

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 nontrivial task.

ing 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, 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 to licensed use of spectrum. More important 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 acquiring 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 geolocation databases is sufficient to provide services with good protection for primary receivers even in massively popular usage scenarios.

The capacity available for secondary systems is fundamentally limited by the interference tolerance of the primary receivers. If primary and secondary systems were to collaborate, it would be possible to increase the interference tolerance or avoid interference at the primary receivers altogether using, say, interference alignment methods. However, cooperation implies coordination and even standardization between systems, warranting further research. Any future work in this field should specifically consider 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 nontrivial task.

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