Hindawi Publishing Corporation
Mobile Information Systems
Volume 2016, Article ID 4313527, 12 pages
http://dx.doi.org/10.1155/2016/4313527

Research Article

Licensed Shared Access System Possibilities for Public Safety

Kalle Lähetkangas,[1] Harri Saarnisaari,[1] and Ari Hulkkonen[2]

[1] *Centre for Wireless Communications, University of Oulu, 90014 Oulu, Finland*
[2] *Bittium Wireless Ltd., Tutkijantie 7, 90570 Oulu, Finland*

Correspondence should be addressed to Kalle Lähetkangas; kallela@ee.oulu.fi

Received 11 March 2016; Accepted 30 May 2016

Academic Editor: Fernando Casadevall

We investigate the licensed shared access (LSA) concept based spectrum sharing ideas between public safety (PS) and commercial radio systems. While the concept of LSA has been well developed, it has not been thoroughly investigated from the public safety (PS) users' point of view, who have special requirements and also should benefit from the concept. Herein, we discuss the alternatives for spectrum sharing between PS and commercial systems. In particular, we proceed to develop robust solutions for LSA use cases where connections to the LSA system may fail. We simulate the proposed system with different failure models. The results show that the method offers reliable LSA spectrum sharing in various conditions assuming that the system parameters are set properly. The paper gives guidelines to set these parameters.

1. Introduction

The wireless operators should prepare for 1000 times growth in mobile data over the next 10 years [1, 2]. This growth is giving pressure for governmental spectrum users, which rarely utilize their spectrum, to free up their frequencies for commercial use. In the United States, 500 MHz of the spectrum from the federal and nonfederal applications is going to be freed completely or by spectrum sharing for commercial mobile radio systems by the year 2020 [3]. This may be the direction also in Europe. The main interest in the United States for spectrum sharing is the spectrum access system (SAS) [3]. For spectrum sharing in Europe, licensed shared access (LSA) [4–7] has gained interest, since the LSA systems can be made operator-specific. More specifically, the operators of every country can agree on their own spectrum utilization between the possible secondary users. LSA has been proposed as an option for sharing the spectrum with PS in [8].

This work extends our work in [9] and first gives an overview of how special applications such as public safety, shortly PS hereafter, and other governmental users fit into the possibilities of spectrum sharing with LSA and how to prepare for it. The PS has a wide range of different users and applications needing the spectrum. The users are, for example, first responders, police, firefighters, border control, and military, which are vital for the society. One of the critical issues in deploying commercial technology to these kinds of special applications is the ownership of the spectrum. For example, by the PS being an LSA licensee, it can obtain the legal right to utilize additional LSA spectrum resources when they are available. Note that the PS can also be an incumbent of other predetermined frequencies for guaranteed resources. While there are multiple choices for PS to utilize spectrum sharing, it is also a political decision how the spectrum will be shared. Spectrum sharing principles for public safety have been categorized in five different sharing models in [10] and the spectrum sharing has been extensively studied further in [11]. There is also ongoing work on use cases for synergies between commercial, military, and public safety domains in [12]. We examine sharing approaches in the means of owned spectral resources and their advantages and disadvantages. To our knowledge, this issue has not been considered previously although it may be one of those steps that are needed for the release of spectrum with LSA and for system development therein.

After the review of this novel topic, our second contribution is planning a more specific system where the PS is an LSA licensee for LSA spectrum resources. Importantly, if the PS utilizes LSA spectrum resources, the PS requires the sharing process to be robust against connection problems. The fall-back measures for the LSA system are generally presented only on a high level [7] and they are still in the planning phase. While the LSA system has been implemented and demonstrated in the project [4], the trials have not yet included any connection breaks inside the LSA system. Our objective is to plan a system that can be tested in a live environment. More specifically, we design a highly robust LSA system to be implemented with current commercial technology and equipment. By robust it is meant that the proposed system is resilient to connection breaks in the LSA system that may be reality in real life due to electric breaks, and so forth, that is, in the cases where the PS services are often needed.

We validate our proposed spectrum reservation method via simulations. We study the duration of time intervals between connection checks for noticing connection breaks and the effect of doing the resource reservations a predetermined time before the incumbent transmissions. These are the main system design parameters and the aim is to give guidelines for selecting them properly.

The paper is organized as follows. In Section 2, we go through the different spectrum sharing possibilities with commercial domain and PS. In Section 3, we present a system model of an LSA system to be built in a live network for the PS and the key functionalities of the system components to overcome connection breaks. In Section 4, we present validating simulation results of the LSA system. We conclude the paper in Section 5.

2. Spectrum Sharing Possibilities

In this section, we provide an overview of alternatives for the spectrum sharing in the case of PS and a commercial system (CS). The truth is that the PS might not always use their full spectrum and it might remain available most of the time, at least locally. Examples are police patrolling where just a small voice service part of the spectrum needs to be reserved and military users that often, in peace time, need large part of the spectrum only in exercises and in special exercise areas. Naturally, in the case of increased threat they need it in patrolling in the cities, and so forth. The temporally and spatially available spectrum could be used for other purposes at those times unused by the PS assuming it will be released immediately back to the PS when needed. For example, the nonused spectrum can be used to speed up CS transmissions, for example, to ease rush hour data traffic; naturally, this is of interest in areas that have a high mobile traffic and that are not in isolated areas.

In addition, the PS may also need complementary or additional resources for its events and thus it would be beneficial for them to get spectrum from CSs. For example, when there is a large fire in a city, the demands of the PS users can grow dramatically especially if they would like to use new services like live video streaming, connections to data bases to collect information about the area, and social media to alarm people. In that case, the PS requires their full spectrum and possibly even more. With spectrum sharing, the additional spectrum can preferably be obtained from silent commercial devices. The target spectrum bands considered are any bands that can be exploited by the PS, for example, the bands of mobile operators and wireless camera and microphone systems.

In Figure 1, we plot different options for spectrum sharing in the means of owned spectral resources. The different options for allowing the other entity to use the spectrum are depicted with arrows. All the approaches can be grouped as follows. First, the sharing framework is designed so that the CS users are the LSA licensees. This way, incumbent is always allowed to use the spectrum and the CS obtains additional spectrum. Second, the CS is incumbent and complementary spectrum is given to the LSA licensee such as the PS. Third option is that all the users are using the CS. Note that these ideas can also be used in parallel in different situations and areas. We briefly list the above spectrum sharing system possibilities and their advantages and disadvantages as follows.

The PS Owns a Relatively Wide Spectrum (See Figure 1(a))

(1) The incumbent PS allows CS to use all its spectrum. In some areas, where the incumbent does not usually have activity, allowing is more or less naturally permanent. In cities, the incumbent activity can be more frequent and allowing happens on a faster time scale.

(2) The incumbent PS allows CS to use its free spectrum. The incumbent system might not need the entire spectrum but only parts of it. Thus, the remaining available spectrum can be utilized by the CS.

(+) The incumbent has all the control for spectrum utilization.

(+) The incumbent has a predictable quality for its applications.

(+) CS obtains additional spectrum.

(−) No guaranteed additional resources for CS.

(−) CS need devices that work using the spectrum of the incumbent.

CS or Other Applications Own the Majority of the Spectrum (See Figures 1(b) and 1(c))

(1) CS gives its available spectrum to the PS (Figure 1(c)).

(2) CS has the obligation to give enough spectrum to the other system using the spectrum during critical operations (Figures 1(b) and 1(c)).

(3) CS has the responsibility to give all its resources, including physical equipment, to PS during critical operations.

(4) Some spectrum can be given for CS by the other system but, as a tradeoff, they can be demanded to give their spectrum to the other system in highly critical situations.

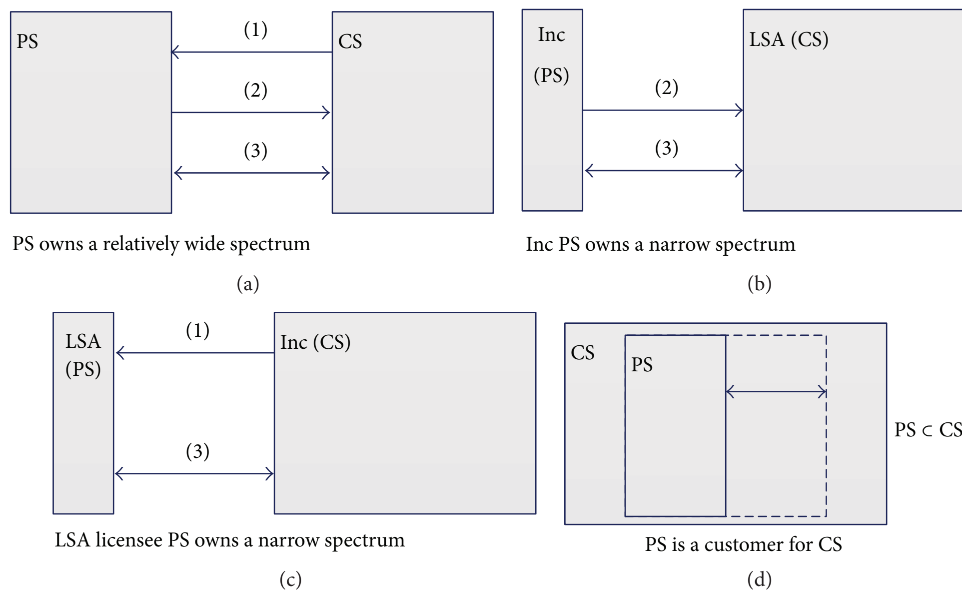

Figure 1: We have different options for spectrum sharing. We use Inc as an abbreviation for the incumbent of the system. (a) The PS owns sufficient number of spectra to support all of its requirements. (b) The incumbent PS has only the critical number of spectra and CS has a wide spectrum. (c) The PS is LSA licensee of CS. After the overview, we concentrate more specifically on this setting where CS allows spectrum use to PS. (d) The incumbent is a roaming user at the CS network. (1) CS allows spectrum use. (2) PS allows spectrum use. (3) CS is allowed to use the spectrum given that CS is obligated to give spectrum when needed.

(+) The LSA licensee obtains additional resources for its applications.

(−) If CS is obligated to give spectrum to the other user, the CS cannot have guaranteed resources.

CS Has a Complete System (See Figure 1(d); Users, Such as PS, Utilize the CS Network)

(1) All of the spectrum users, PS and CS, can be roaming users of the CS network.

(2) The PS can rent/obtain the CS network for their own use.

(+) The PS obtains instant coverage.

(+) The CS is constantly developing its network.

(−) The PS does not have complete control over the CS network.

(−) The system needs a priority protocol, if the incumbent users are PS users.

(−) There is no coverage or support for all the applications at every location. The PS still needs their own service in the areas where the CS network cannot support it.

(−) The PS has to trust CS and their security when being an CS user.

The current state of the affair is that the PS and CS have their own spectrum and they do not cooperate. Here, to obtain similar functionalities as the CS, the PS requires equal amount of spectrum as CS. The first step to this setting is cooperation, as illustrated in Figure 1(a). Naturally, sharing rules have to be agreed on; that is, CS, PS, or both allow their spectrum to be used by the other one. In the following subsections, we go through the options for spectrum sharing in more detail for LSA systems.

2.1. PS Is the Incumbent. In this subsection, we consider options for when the PS is the incumbent in an LSA system as, for example, in Figures 1(a) and 1(b). Here a part of the PS spectrum has been released for CS under the requirement that they must allow the incumbent PS to use that spectrum when and where needed. Obviously, this situation requires a political decision but it is listed here as an opportunity. It is discussed in the US that, in this scenario, the CS and other users can share the spectrum as secondary users [3]. Moreover, in the US, a wide bandwidth of spectrum will be released from governmental users to CSs in the upcoming years. Note that the majority of spectra can still be used by the PS during critical operations.

By being the incumbent, the PS has all the control to support its critical and noncritical applications with a predictable quality. Here the PS can build its network infrastructure and the management system for organizing its network and services. However, the PS might not build a nationwide network for itself. Moreover, the PS might not use its spectrum all the time. This leads to free spectrum which can be utilized by other applications. A possibility is to cooperate with a CS. The additional spectrum could be used as a complementary resource by the CS to unload its data traffic. There are multiple possibilities for cooperation.

First, the PS can allow the CS to use the spectrum at predetermined times and areas. This is applicable when the possible PS spectrum usage is known in advance. This is the case, for example, when the PS has scheduled their operations. In these cases, the PS can have the spectrum for the reserved time and area, even if they are not using it. With this method, the spectrum is free at given times and the individual PS users do not need to worry about the CS transmitting at the same time. This is applicable, for example, in some of the military training scenarios and in border protection as the military is mostly using their spectrum in known areas during peace time.

As a second option, the PS can allow the CS to use the spectrum at all the times when the spectrum is free. This option needs a rapid method for the spectrum reservation. Here the PS should preferably notify the LSA repository a few moments before the transmission, so that the spectrum can be guaranteed to be free for the PS. Another possibility is for the PS to notify the LSA repository when the transmission begins. In this setting, the PS should accept possible interference from the LSA licensee in the beginning of its transmission. Moreover, in the scenarios above, the fall-back measures to handle connection breaks for guaranteeing the possible incumbent transmission should be expeditious.

Third, the PS can allow the CS to use the spectrum at the locations where the spectrum is not currently needed by the PS users. This option can be accomplished by tracking the PS users and by reserving the necessary spectrum for them at their locations. This is applicable for example, with the first responder units, whose locating is important also from the operational perspective.

Fourth, depending on the applications, the PS might not always need all of its frequencies. The PS can allow the CS to use the remaining free frequencies. Here the spectrum band can be divided into multiple smaller bands that can be accessed with the CS according to the need of the PS users.

Moreover, any combination of the above is also possible. In these systems, however, the spectrum is a complementary resource for the CS when the PS users are silent. To start building the system, the agreements between the incumbent PS and commercial LSA licensees can be first allowed in smaller areas. Then, if the CS is able to develop their applications in such a way that they do not cause intolerable interference to the PS operations, the agreements are easy to expand to wider areas.

The amount of gain obtained by the CS depends on the activity of the PS. For example, if the PS is silent most of the time, the CS obtains the spectrum most of the time. The greatest benefit for the PS by owning the spectrum is the control. It is possible for the PS to freely use the spectrum for its own applications. In addition, it is always possible to decline the spectrum use of the CS or other spectrum users. However, the resources owned by the PS might still not be enough to support all the PS operations. Moreover, the PS might not want to reserve a wide spectrum for its applications. Thus, it may be beneficial for the PS to also obtain additional resources and services from the CS when needed.

2.2. CS Is the Incumbent. In this subsection, we consider options for when the CS is the incumbent in an LSA system as shown in Figure 1(c). The CS has a wide spectrum and is giving spectrum resources to the PS, which only has a small portion of spectrum reserved, for example, to voice communication. Later in this work, we will concentrate only on this scenario in developing an LSA system for the PS. There are multiple possibilities for cooperation, which can all be implemented in parallel depending on the needs by the PS.

First, the resources can be shared with an LSA system. When the incumbent user comes to the area, PS will retreat or change its frequency. This suits the case when the PS is mostly using the spectrum in the area, where the CSs or other incumbent users remain silent. This is applicable if the PS uses spectrum mainly for noncritical applications, such as training, and has the authority to reserve the spectrum completely for itself during critical operations for obtaining spectrum. This is the use case, for example, in military and border control applications, where the PS would require spectrum for their communication during peace time. These PS operators can agree on multiple LSA agreements with multiple incumbents to obtain multiple spectrum bands. Then, they are able to legally utilize the band that is available. With PS being the LSA licensee, the PS users do not necessarily need to inform their location to the LSA repository, and the PS users are not tracked for spectrum information. This type of LSA sharing method brings security in some PS applications, where the location of PS operators should be kept as a secret. Another example of resource sharing like this is a high speed mobile network for the PS at sparsely populated training areas. This kind of high speed networks can also offer a backup mobile infrastructure, for example, in disaster areas and in rescue operations during electrical shortages when a commercial network of the CS is down.

Second, the CS can be obligated to give spectrum to the PS in areas that are not covered by the CS network. Thus, the PS can obtain spectrum for its own use here, that is, for training and for emergency use. This option is applicable in the long term only if the CS is not building its network in these areas, for example, if these areas give no financial benefit. Otherwise, there is no long-term guarantee of interference-free spectrum for the PS.

Third, the CS has the obligation to give required spectrum to the PS during critical operations. Here the PS can have the rights of the incumbent during critical operation. This is a viable option when the PS is mainly a minor user of the spectrum and critical operations happen rarely. The CS can build its network using a wide spectrum. Then, the spectrum is released when the PS users come to the area and need it. This option would require a backdoor for PS to be installed to CS equipment. For example, by using the backdoor, the PS could reserve spectrum or switch off related CS base stations with alarm signals or via central controller. In some PS cases, the spectrum can also be reserved in advance by the basis of the emergency calls, which usually happen via CS base stations and near the locations of the required PS needs.

2.3. PS Utilizes CS Network. One additional option on the above scenarios is the following. As shown in Figure 1, the PS users can be the roaming users of the CS network [13, 14].

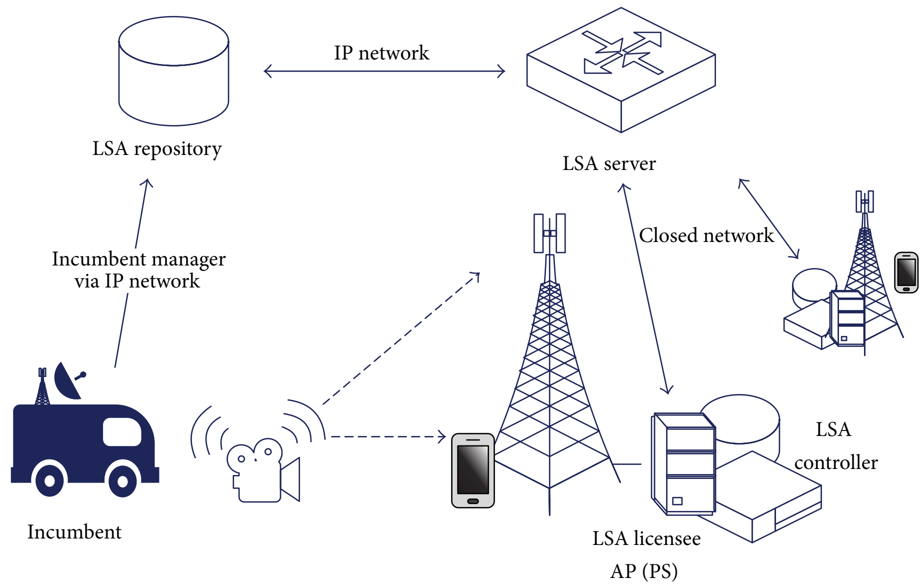

Figure 2: A wireless camera uses the spectrum with LSA licensee that has LSA controllers at every AP.

Here the entire spectrum is owned by CS and it is responsible for building the network. However, in order for the PS to be independent of CS networks, a backup system for the most critical applications and communication is still needed. Note also that this option is not spectrum sharing in the means of LSA, but is listed here as an opportunity.

When the PS users are roaming users at the CS network, they need priority over the CS users. Here the PS should obtain the highest priority for its critical applications. In addition, when the PS users are roaming users at the CS network, the CS operator needs to be able to support PS applications. The benefit of being a roaming user is the instant coverage of the CS network in densely built areas. Another benefit is that the CS develops its spectrum usage to meet the current requirements better because it is competing for users. However, the PS does not have full control over the network which reduces the security. Moreover, there needs to be solid encryption for the PS and the CS network should be built robustly.

3. System Model

Next we concentrate more specifically on developing the LSA system for the PS, which acts as an LSA licencee for accessible LSA spectrum resources as discussed in Section 2.2. The PS use case considered here is only for noncritical applications. The proposed resource allocation method builds on previous LSA work in [15, 16].

We consider an LSA system with an LSA repository, LSA controllers, an LSA licensee, and an incumbent user. These system elements and their connections are shown in Figure 2. The incumbent is the primary user of the LSA spectrum resources. We consider the incumbent to be, for example, employees of programme making and special events services, which are defined in [17, 18]. The LSA repository collects, maintains, and manages up-to-date data on spectrum use. The LSA licensee is a secondary user with a license to utilize the spectrum, when incumbent user is silent. The LSA licensee has multiple access points (APs) that utilize the resources. The LSA licensee has a network that connects the APs together. In contrast to [15] with one LSA controller, every AP of PS has its own distributed LSA controller. Thus, no single device is solely responsible for the spectrum allocations.

We also introduce an LSA server to the system. The LSA server is a mediator between the LSA repository and the LSA controllers. By using a mediator, the PS network can be kept closed from the IP network, which provides security. Here, the LSA server is the only device of the PS network that can be connected from the outside. The LSA server reports only the necessary network information from the LSA licensee network to the LSA repository.

The spectrum sharing between the users operates as follows. Incumbent user reserves the spectrum at least a predetermined time before using the spectrum, contrary to the on-demand operation mode for LSA spectrum resource reservation [6]. Thus, during a connection break the most recent information is still valid for the predetermined time. The incumbent reserves the resources by connecting the LSA repository with an incumbent manager. Then, the repository sends notification of the spectrum reservation to the LSA server. After the LSA server obtains spectrum reservation information, it forwards the information to the LSA controllers of affected APs. Finally, the LSA controllers compute the protection criteria of incumbent and control the spectrum usage of the APs.

In Figure 3, we present more precisely how to implement this system in a real Long-Term Evolution (LTE) network. We depict the components and their connections. Here LTE APs (eNodeBs) of PS utilize the spectrum as an LSA licensee. The PS has its own closed LTE network where the backhaul is

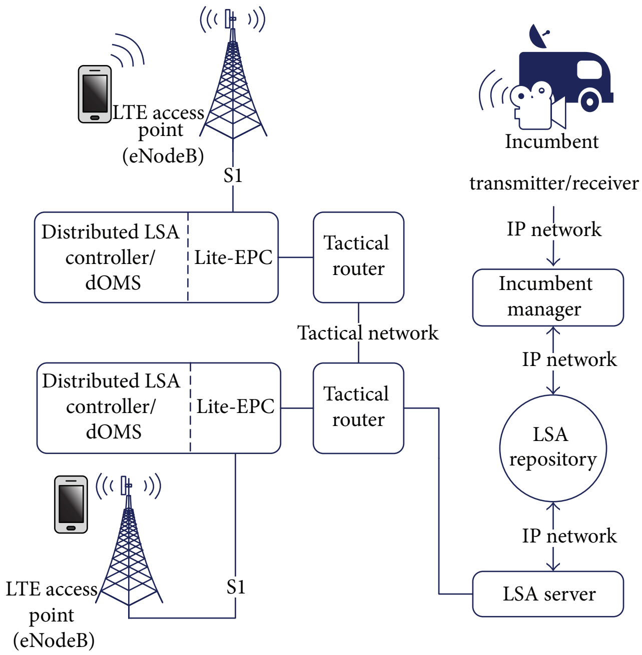

Figure 3: Two LTE access points in LSA licensee network.

built with tactical routers. In addition to wired links, these routers also support radio link connections [19]. They can also automatically reroute any given data from the source to the destination via alternative routes, given that the primary route fails. Every AP is connected to the closed network via a lite-EPC and a tactical router. The lite-EPCs provide LTE hot spots to the network and emulate the evolved packed core functionalities of an LTE network. The access points are connected with S1 interface to the lite-EPC. The computer with the lite-EPC works also as a distributed LSA controller. The LSA system components communicate with each other using http(s) with representational state transfer architechture. The data is formatted using JavaScript objects. We go through the main functions of the main components in the following subsections.

3.1. Incumbent via Incumbent Manager. Incumbents of our system use a http(s)-based incumbent manager to inform the repository of their spectrum access. The reservation message includes "starting" and "ending" time of the incumbents transmission, the reserved frequencies (center frequencies and bandwidths), the location, and the type of the usage. The reservation information is used to calculate the protection zone for incumbent.

The incumbent manager allows reserving the spectrum only for a predetermined time beforehand. More specifically, incumbent has to send a reservation message via incumbent manager to the LSA repository at least a predetermined time T_i before its transmission. This time can vary for different types of users. Additionally, the requirement for reservation of a predetermined time before the incumbent transmission can also be voluntary in some of the systems. Then, if the incumbent does not reserve the spectrum on time, it is obligated to possibly tolerate interference from the LSA licensee for the predetermined time, given that there are connection breaks.

3.2. LSA Repository. The LSA repository keeps a database of up-to-date information about incumbent spectrum reservations and about the conditions for utilizing the spectrum. The LSA repository forwards information about incumbent and its planned use of LSA spectrum resources to the LSA server, when the information becomes available. The information sent from the repository also includes the time when it is sent. The LSA repository can also reply to a request for the incumbent information. This reply includes the information that is new to the requesting device.

Connection checks to the LSA repository happen via heartbeat signals. The devices, which check the connection, request heartbeat signals periodically from the LSA repository. The LSA repository replies to a heartbeat request with a heartbeat signal. If there is no response, the connection is broken. Heartbeat response signals include the time when the heartbeat response signal is sent.

3.3. LSA Server. The LSA server acts as an LSA controller to the LSA repository. It has a strong firewall for separating the PS network from the IP network. After obtaining incumbent information from the LSA repository, the LSA server broadcasts this information to the distributed LSA controllers. The LSA server also saves incumbent information until the information expires. To obtain robustness for connection breaks to this setting, any tactical router could act as an LSA server, given that it has an Internet access and given that it has a programmable interface.

The LSA server sends heartbeat requests to the LSA repository between time intervals of T_{check}. The heartbeat responses are then forwarded to the LSA controllers. The LSA server notices a connection break to the LSA repository if there is no heartbeat signal within time T_{timeout} from the heartbeat request. When this kind of connection break occurs, the LSA server sends heartbeat failure signals to the lite-EPCs periodically between time intervals of T_{check}. These signals provide the LSA controllers information whether the connection break is external or internal.

The LSA server tries to reconnect to the LSA repository during a connection break. The LSA server requests up-to-date incumbent information from the LSA repository when becoming connected to it. The LSA server can also answer to a request for incumbent information and replies with the information that is new to the requesting device.

3.4. LSA Controller in Lite-EPC Computer. The LSA controllers control the spectrum utilization of the PS. They receive the incumbent information from the LSA server when it becomes available. Additionally, an LSA controller requests for up-to-date incumbent information from the LSA server when becoming connected to the PS network. All of the LSA controllers save the received incumbent information until it expires. The main task for an LSA controller is to calculate the protection zone for the incumbent using incumbent information. The calculation is done similarly at every LSA controller using the same algorithms as in the centralized controller developed by the project [4]. However, a lite-EPC controls only the AP that is connected to it.

3.5. Distributed Operations Management System. We have depicted distributed operations management system as (dOMS) in Figure 3. The dOMS are distributed per AP and also work in the same computers as the lite-EPCs. They are responsible for sharing the spectrum between the other APs and include command tool for controlling the AP and the necessary commission plans with a site manager for validating the plans. Each of the individual dOMS sends command messages to their own APs for the frequency allocations and power levels. In other words, every unit of dOMS controls only their own AP but decides the spectrum sharing together with other units of dOMS.

The spectrum sharing between APs is done in dOMS that keep a list of APs in the vicinity. To share the LSA spectrum resources, the dOMS utilize signaling methods similar to coprimary spectrum sharing [20]. The difference to [20] is that the spectrum sharing is done between a single PS operator, without the need to compete with other operators. The signaling messages are sent inside the closed PS network.

The dOMS has the task to clear the spectrum, before incumbent utilizes the spectrum and when the spectrum reservation information becomes invalid due to a connection break. Recall that the sending times are included in all of the data originating from the LSA repository. The spectrum reservation information is valid for time T_i after a successful heartbeat signal, or any other data, is sent from the LSA repository.

Let T_{empty} be the time that it takes to empty the spectrum by the AP after a command from the dOMS. If no heartbeat signal or other data arrives from the LSA repository, the LSA spectrum resources are freed after time $T_i - T_{\text{empty}}$ from the sending time of the last successful data from the LSA repository. The spectrum can be emptied immediately or gradually by using graceful shutdown, which gradually lowers the power level of the APs. The dOMS can also order its AP to utilize some available backup frequency. Alternatively, any other fall-back measure [7] can be used.

4. Simulation Setup and Numerical Results

In this section, we present our simulation setup and results for our LSA system. We use simulations to validate the spectrum reservation method setup in the case of connection breaks inside the IP network. We assume that the closed PS network is built reliably. This means that there are no connection breaks inside the PS network. The incumbent is also assumed to utilize the LSA spectrum resources only after a successful reservation. This is a conventional method for incumbents, such as programme making and special events services, which are required to inform their spectrum utilization to a national telecommunications regulator. The connection breaks in the LSA system occurs in the IP network between the LSA repository and LSA controllers. We assume that the APs of PS with the same frequency are at a long distance from each other. We also assume that the APs, which are near each other, utilize different frequencies as usual. Thus, no dynamic spectrum sharing is simulated.

We use spectrum utilization and *valid spectrum knowledge* of the LSA licensee to measure the performance of the LSA system. The latter measure tells us the ratio of time that the spectrum reservation information is valid with respect to the total simulation time. For example, when the value of it is 0.5, the spectrum reservation information is valid for 50% of the time. Recall that the LSA licensee utilizes the free spectrum only when the spectrum knowledge is valid. Thus, the incumbent and the LSA licensee share the LSA resources perfectly only during this time. Therefore, the amount of valid spectrum knowledge reflects the LSA system performance. It also relates directly to the reliability of the LSA system, as the spectrum can be utilized by the LSA licensee during connection breaks if the spectrum knowledge is valid.

We show how our LSA system design parameters, T_{check} and T_i, affect the performance in different network scenarios with different incumbent activity levels. We simulate every scenario over 1000 iterations with different connection breaks and incumbents for average results. In every scenario, we draw the durations of the incumbent transmissions and connection breaks from Poisson distributions. We draw the number of incumbent transmissions and connection breaks from normal distributions, where the negative values are set to zero. The starting times of incumbent user transmissions and connection breaks are uniformly distributed. The rationale for using these simplifying distributions is to obtain first-level insights into our protocol behavior when using different design parameters in different scenarios. The total simulation time is 12 hours. The time to empty spectrum with an order from the dOMS, T_{empty}, is 30 seconds. The delay to transmit data from the LSA repository to the LSA controllers is three seconds when the connection is working.

We model the IP network connection breaks for different scenarios as follows. We model three types of network connections. They are *reliable*, *mediocre,* and *poor* and the parameters to simulate them are shown in Table 1. The last column, *Connection OK*, shows the quality of the connection, that is, the ratio of time that the connection is working between the LSA repository and LSA controllers with respect to the total simulation time. These ratios are also a point of reference for *valid spectrum knowledge* in the currently available LSA systems. More specifically, in the current LSA systems, the spectrum is shared perfectly only when the connection is working. The rationale for simulating low connection reliabilities comes from the fact that the PS should remain functional when the commercial IP networks have serious connection problems.

Similarly, we model the incumbent activity for three types of incumbents. The incumbent types are *rare*, *occasional,* and *active* and the parameters to simulate them are shown in Table 2. The last column, *spectrum utilization*, shows the ratio of time that the incumbent utilizes the spectrum with respect to the total simulation time.

Table 1: The parameters for simulating the connection quality.

	Mean # of connection breaks	Variance	Mean duration of a connection break	Connection OK
Reliable	0	2	5 min	0.99
Mediocre	7	2	20 min	0.73
Poor	15	2	60 min	0.29

Table 2: The parameters for simulating the incumbent activity.

	Mean # of transmissions	Variance	Mean transmission time	Spectrum utilization
Rare	0	2	40 min	0.06
Occasional	5	2	40 min	0.26
Active	12	2	40 min	0.50

In the next simulations, we study the LSA system performance with respect to T_{check}. Recall that the value of T_{check} is the time between heartbeat signal requests.

In Figure 4, the incumbent notifies about itself 15 minutes before its transmission; that is, $T_i = 15$ min. From Figure 4, we observe that the spectrum knowledge for *reliable*, *mediocre,* and *poor* internet qualities is higher than 99%, 73%, and 29%, which are the corresponding percentages of times for internet connection working. Thus, the spectrum can be utilized by the LSA licensee even during some of the connection breaks with our reservation method. Moreover, we see that the quality of the internet connection is important, when the incumbent informs about its spectrum utilization on a short notice.

From Figure 4, we also see that the spectrum knowledge by the LSA licensee is higher when T_{check} is low, that is, when the connection to the LSA repository is checked more often. This is because then it is more likely to get an answer from the repository for validating the connection. Therefore, with an unreliable internet connection, the value of T_{check} should be as low as possible to have the most valid spectrum knowledge. However, from the figure we also see that it is more important to have a good internet connection than to make the value of T_{check} as low as possible.

In Figure 5, the incumbent notifies about itself 60 minutes before its transmission; that is, $T_i = 60$ min. When comparing this figure to Figure 4, we see that the spectrum knowledge is overall better for every type of internet quality for a greater value of T_i. We also can see that setting T_i large is more important in terms of spectrum knowledge than to set T_{check} low. Moreover, we observe that the spectrum is known for over 50% of the time when the internet quality is *poor*, that is, when the internet connection is working 29% of the time. Therefore, the T_i should be large if the internet quality is low. From Figure 5, we see that the *mediocre* internet quality is allowable in this setting; that is, the spectrum can be utilized 100% of the time, when the T_{check} is below 3 minutes. Thus, given that the internet connection to the PS network can be mediocre, the PS should utilize frequencies of incumbents which are able to report their frequencies reliably in advance. Moreover, if the internet connection is poor, the PS requires either additional methods for utilizing all of the free spectrum or an incumbent that reports its spectrum utilization even earlier.

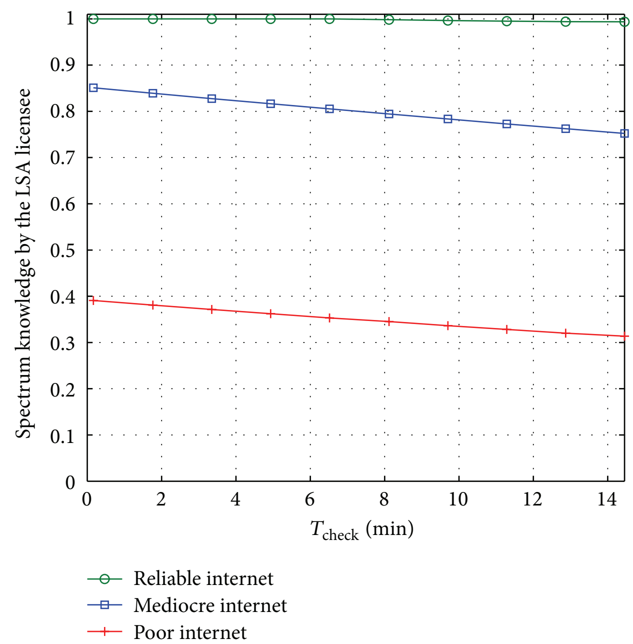

Figure 4: The spectrum knowledge of the channel as a function of T_{check} while $T_i = 15$ min with different qualities of internet connection. The incumbent is *rare*; that is, it utilizes the channel approximately 6% of the time.

In the next simulations, we study the LSA system performance with respect to T_i, with different types of incumbents and internet qualities. Recall that the value of T_i indicates the predetermined time before which the incumbent is required to send its spectrum reservation to the LSA repository.

In Figure 6, the incumbent is *rare* and the T_{check} is set to be 15 minutes. From Figure 6, we see a rise of the spectrum knowledge as a function of T_i. This implies that when the internet quality is poor, the incumbent should reserve the spectrum as early as possible. This is applicable for incumbents that know their spectrum needs beforehand or rarely change their frequency allocations and have a static

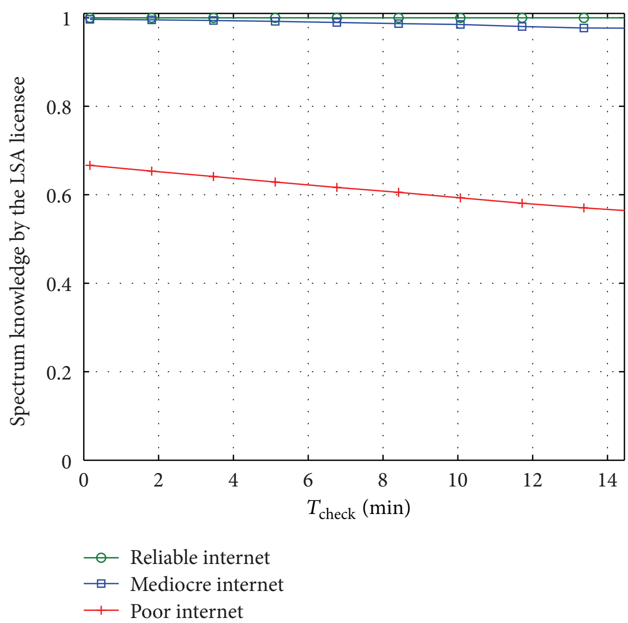

Figure 5: The spectrum knowledge of the channel as a function of T_{check} while $T_i = 60$ min. The incumbent is *rare*.

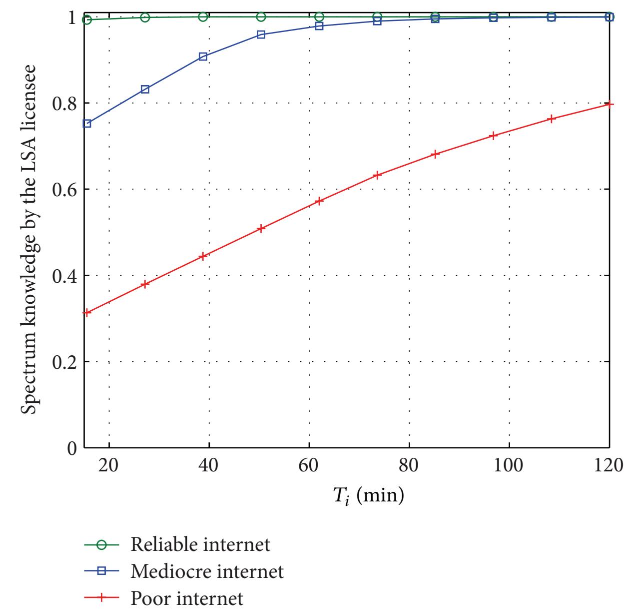

Figure 6: The spectrum knowledge of the channel as a function of T_i while $T_{\text{check}} = 15$ min. The incumbent is *rare*.

operation. An example of this kind of incumbent is an organizer of programme making special events.

In Figure 7, we study how different activity levels of the incumbent affect the LSA system performance. We observe from the results that the spectrum knowledge is higher when the incumbent is more active. This is because then the incumbent reserves the spectrum more often, and the reservations include the spectrum knowledge. However, if the incumbent is very active, it might be hard for all incumbent applications to report the plans at a predetermined time before utilizing the spectrum. Thus, the PS with a poor internet connection should utilize different methods, such as sensing, to obtain the LSA resources with an active incumbent.

In Figure 8, we plot the spectrum utilization of the LSA licensee. In this figure, we compare the spectrum utilization by the LSA licensee by using two measures. First, we plot the utilized spectrum resources divided by *all the resources*. Second, we plot the utilized spectrum resources divided by the *available resources*, that is, the LSA resources that are available at the times when the incumbent does not transmit. From the figure, we see that the LSA licensee can utilize the spectrum less often when the incumbent is more active, while the available spectrum for the LSA licensee is utilized relatively better. Therefore, as natural, it is always preferable for the LSA licensee that the incumbent does not transmit. Moreover, the overall spectrum is utilized more effectively when there are more incumbents.

In Figure 9, we study the spectrum utilization of the complete LSA system. This is the utilization of the spectrum by either the LSA licensee or the incumbent. We plot the utilized spectrum resources divided by the total spectrum resources. We see that the spectrum utilization is inline with the spectrum knowledge by the LSA licensee shown in Figure 7. The spectrum is utilized approximately 100% of the

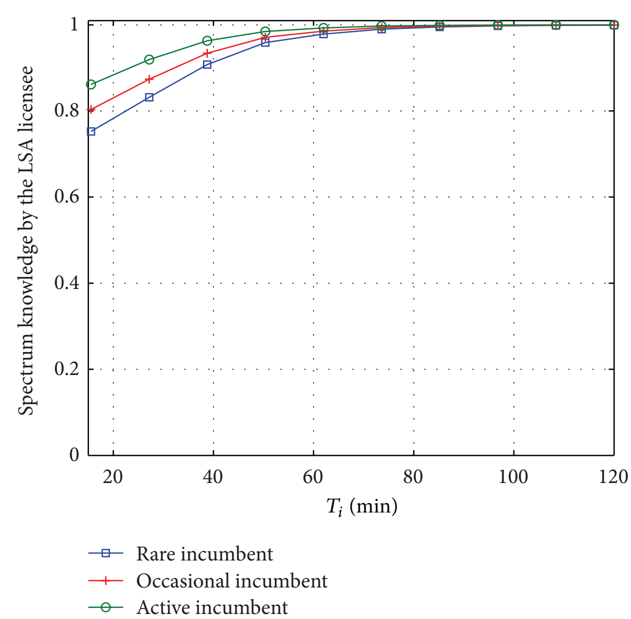

Figure 7: The spectrum knowledge of the channel as a function of T_i while $T_{\text{check}} = 15$ min with different incumbent activity levels. The internet connection is *mediocre*.

time when the T_i is over 80. We can see that the proposed LSA system with *mediocre* internet connection to the LSA licensee is ideal for sharing the spectrum with incumbents, such as mobile operators, if they can reliably estimate their spectrum needs 80 minutes beforehand.

In Figure 10, we plot the utilized spectrum resources divided by the total spectrum resources for different values of T_{check} with an *occasional* incumbent and *mediocre* internet. Note that the value of T_{check} affects only spectrum utilization

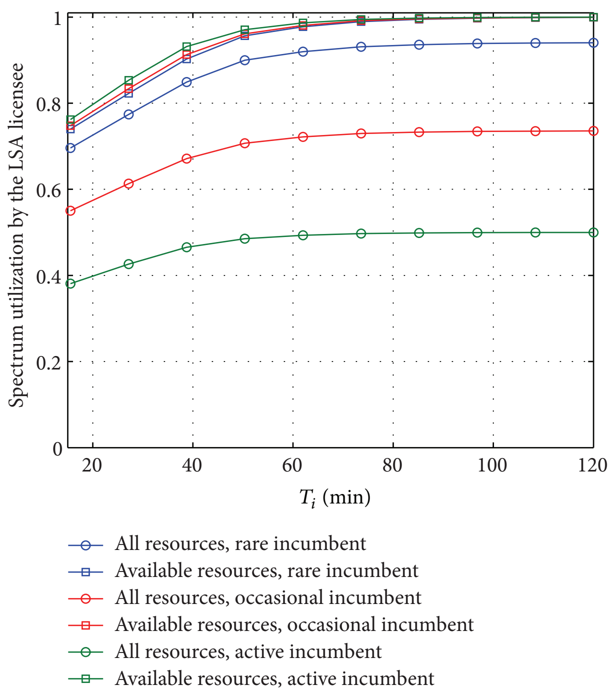

FIGURE 8: LSA resource utilization by the LSA licensee as a function of T_i while $T_{\text{check}} = 15$ min in a *mediocre* channel.

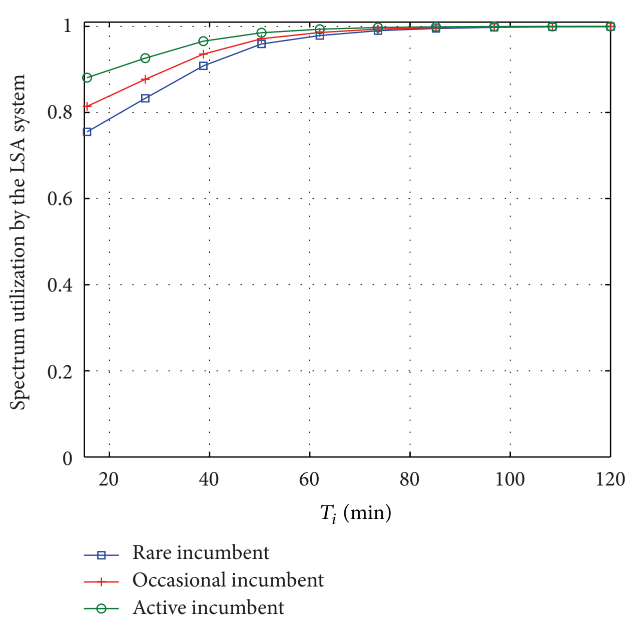

FIGURE 9: LSA resource utilization by the LSA system as a function of T_i while $T_{\text{check}} = 15$ min in a *mediocre* channel.

of the LSA licensee. Thus, from Figure 10, we notice that the LSA licensee receives more resources with smaller values of T_{check}. This is because the LSA licensee knows more valid spectrum information when it checks the connection more often. However, the amount of valid spectrum information does not grow significantly, when the T_{check} becomes smaller than 15 seconds. From the figure, we also see that the valid

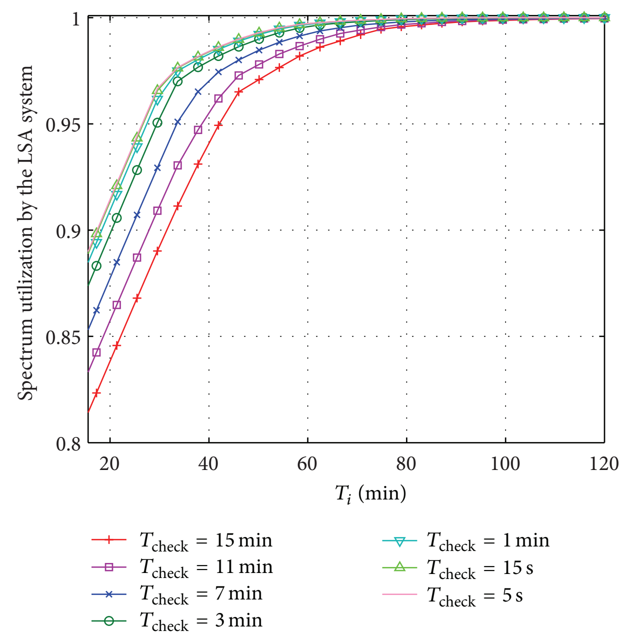

FIGURE 10: LSA spectrum resource utilization as a function of T_i with *occasional* incumbent in a *mediocre* channel.

information does not vary significantly for different values of T_{check} if the T_i is over 80 minutes. Thus, the value of T_{check} can be set adaptively according to the value of T_i, that is, according to the predetermined time before which the incumbent sends its spectrum reservation to the LSA repository.

5. Conclusion

We gave an overview of spectrum sharing possibilities between PS and CS since there may be a possibility to find more spectrum for their users in the future. While there are multiple choices for PS to utilize spectrum sharing, it is also a political decision how the spectrum will be shared. Therefore, PS should be ready for every scenario. If PS owns the spectrum, it can rent the free spectrum to CS via an LSA/SAS system. Another option for providing high quality PS performance is the following. We reserve only a small portion of the spectrum for voice service to PS. We let CS networks utilize the remaining spectrum with the condition that CS is obligated to release spectrum to PS when needed for critical applications. We gave multiple options to automatically reserve CS resources for PS use. In addition, the PS can be a roaming user at CS network. Furthermore, PS can be an LSA licensee of the incumbent CS.

Moreover, if LSA sharing arrangement is used, there needs to be a reliable method for spectrum allocation to PS during connection breaks. We developed a specific LSA system for robustness to overcome short-term connection breaks. In this system, the PS is the LSA licensee and the CS is the incumbent, which can be, for example, when the PS requires additional resources with LSA. In our system, the incumbent reserves the spectrum for a predetermined time beforehand and is not transmitting during this predetermined time. We validated the reservation system and studied how to select suitable durations for the predetermined times and for time intervals between connection checks. The time intervals between connection checks can be selected adaptively based on the network quality and on the time before which the incumbent sends its spectrum reservations. The simulations show that the proposed system is able to reduce the impact of possible connection breaks inside the LSA system.

However, this method is not alone sufficient for utilizing all the LSA spectrum resources during all connection breaks. There might be a long connection break and no possibility for an internet connection. In addition, the incumbent might not always have an internet connection but can still utilize the spectrum. Therefore, if the PS is an LSA licensee and requires available LSA spectrum resources, it needs to develop other methods to guarantee its own error-free transmission and incumbent protection.

To protect the incumbent without internet connection, there can be additional signals that tell about a connection break and that the incumbent is using the spectrum, such as errors accumulating to the LSA licensees, human intervention at the base stations, local reservation signals with separate control channels, and sensing methods. In the upcoming work, we will develop the LSA system to coexist with the already available sensing methods and enable spectrum sharing and utilization also during major connection breaks.

Competing Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

The authors would like to acknowledge CORE++ project consortium: VTT, University of Oulu, Centria University of Applied Sciences, Turku University of Applied Sciences, Nokia, PehuTec, Bittium, Anite, Finnish Defence Forces, FICORA, and Tekes.

References

[1] Cisco, "Cisco visual networking index: global mobile data traffic forecast update, 2015–2020," Cisco White Paper, 2014, http://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/mobile-white-paper-c11-520862.pdf.

[2] "The 1000x mobile data challenge," Qualcomm Presentation, 2013, http://www.qualcomm.com/media/documents/files/1000x-mobile-data-challenge.pdf.

[3] The White House, "Realizing the full potential of government-held spectrum to spur economic growth," Presidents Council of Advisors on Science and Technology, 2012, https://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast_spectrum_report_final_july_20_2012.pdf.

[4] Core++ project web page, June 2016, http://core.willab.fi.

[5] The Electronic Communications Committee, "Licensed shared access (LSA)," ECC Report 205, The Electronic Communications Committee, Copenhagen, Denmark, 2014, http://www.erodocdb.dk/Docs/doc98/official/pdf/ECCREP205.PDF.

[6] ETSI, "Reconfigurable radio systems (RRS); System requirements for operation of mobile broadband systems in the 2300 MHz—2 400 MHz band under licensed shared access (LSA)," ETSI TS 103 154 V1.1.1, October 2014, http://www.etsi.org/deliver/etsi_ts/103200_103299/103235/01.01.01_60/ts_103235v010101p.pdf.

[7] ETSI, "Reconfigurable radio systems (RRS); system architecture and high level procedures for operation of licensed shared access (LSA) in the 2 300 MHz–2 400 MHz band," ETSI TS 103 235 V1.1.1, October 2015, http://www.etsi.org/deliver/etsi_ts/103200_103299/103235/01.01.01_60/ts_103235v010101p.pdf.

[8] ETSI, "Reconfigurable radio systems (RRS); use cases for spectrum and network usage among public safety, commercial and military domains," Article ID 102900, ETSI TR 102 970 V1.1.1, 2013, http://www.etsi.org/deliver/etsi_tr/102900_102999/102970/01.01.01_60/tr_102970v010101p.pdf.

[9] K. Lähetkangas, H. Saarnisaari, and A. Hulkkonen, "Licensed shared access system development for public safety," in *Proceedings of the European Wireless Conference*, Oulu, Finland, May 2016.

[10] R. Ferrús, O. Sallent, G. Baldini, and L. Goratti, "Public safety communications: enhancement through cognitive radio and spectrum sharing principles," *IEEE Vehicular Technology Magazine*, vol. 7, no. 2, pp. 54–61, 2012.

[11] R. Ferrús and O. Sallent, *Mobile Broadband Communications for Public Safety: The Road Ahead Through LTE Technology*, John Wiley & Sons, New York, NY, USA, 2015.

[12] ETSI, "Reconfigurable radio systems (RRS); Feasibility study on inter-domains synergies; synergies between civil security, military and commercial domains," ETSI TR 103 217, June 2016, https://portal.etsi.org/webapp/workProgram/Report_WorkItem.asp?wki_id=43285.

[13] "Ukkoverkot commercial service," June 2016, http://www.ukkoverkot.fi/.

[14] R. Hallahan and J. M. Peha, "Enabling public safety priority use of commercial wireless networks," *Homeland Security Affairs*, vol. 9, article 13, 2013, http://www.hsaj.org/articles/250.

[15] M. Palola, T. Rautio, M. Matinmikko et al., "Licensed Shared Access (LSA) trial demonstration using real LTE network," in *Proceedings of the 9th International Conference on Cognitive Radio Oriented Wireless Networks (CROWNCOM '14)*, pp. 498–502, June 2014.

[16] M. Palola, M. Matinmikko, J. Prokkola et al., "Live field trial of Licensed Shared Access (LSA) concept using LTE network in 2.3 GHz band," in *Proceedings of the IEEE International Symposium on Dynamic Spectrum Access Networks (DYSPAN '14)*, pp. 38–47, McLean, Va, USA, April 2014.

[17] Electronic Communications Committee, "Broadband wireless systems usage in 2300–2400 MHz," ECC Report 172, 2012, http://www.erodocdb.dk/docs/doc98/official/pdf/ECCRep172.pdf.

[18] European Radiocommunications Committee, "Handbook on radio equipment and systems videolinks for ENG/OB use," ERC Report 38, 1995, http://www.erodocdb.dk/docs/doc98/official/pdf/REP038.pdf.

[19] Elektrobit, "Enhancing the link network performance with EB tactical wireless IP network (TAC WIN)," EB Defense Newsletter, December 2014, http://www.bittium.com/file.php?fid=785.

[20] M. Jokinen, M. Mäkeläinen, and T. Hänninen, "Demo: co-primary spectrum sharing with inter-operator D2D trial," in *Proceedings of the 20th Annual International Conference on Mobile Computing and Networking*, pp. 291–294, September 2014.