Field Trial of the 3.5 GHz Citizens Broadband Radio Service Governed by a Spectrum Access System (SAS)

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***Abstract*—In this paper, we describe a spectrum access system (SAS) based Citizens Broadband Radio Service (CBRS) field trial using a live LTE network in the 3.5 GHz band. The latest WInnForum specification guided the implementation of the relevant protocols for SAS operation. Here, we evaluate the performance of a CBRS field trial by using one of the most important performance indicators in a spectrum sharing scenario – the evacuation time. It indicates how rapidly the secondary user relinquishes the shared spectrum band to the primary user. Following the applied protocols, we measure and analyze the time scales for the evacuation and frequency change procedures in a field trial environment. Our work shows that the set time limits for the protection of primary users against interference are realistic when using commercially available mobile networks and equipment. Finally, utilizing knowledge of the latest base station models, we propose ways to reduce the evacuation and reconfiguration time by up to 70%.**

I. INTRODUCTION

Spectrum sharing technologies have significantly advanced since Mitola introduced the concept of cognitive radio in [1]. Dynamic spectrum access technologies are already included in multiple standards in different frequency bands, and regulatory processes are being updated to include new forms of licensing [2]. Coordinated spectrum sharing approaches are being developed and proposed between different technologies used in the industrial, scientific and medical (ISM) bands [3]. The idea behind coordinated and licensed sharing access approaches is the ability to provide interference free operation that leads to a better, or even guaranteed, quality of service (QoS) in sharing applications.

One example is the European Licensed Shared Access (LSA) concept, which allows spectrum sharing between incumbent users and LSA licensees, both having exclusive access to a portion of the spectrum at a given location and time [4]. The first application of the concept concerned mobile operators allocating mobile broadband services to new spectrum bands, which already had other types of (incumbent) use. For example, shared use of the 2.3–2.4 GHz band between a mobile network and wireless cameras has been demonstrated in Finnish LSA field trials [5].

In the United States, the prevailing approach to spectrum sharing is the Citizens Broadband Radio Service (CBRS) governed by SAS in the 3550–3700 MHz band [6]. In both sharing concepts, incumbent users have the highest priority in terms of spectrum access and protection against interference from other users at any location and time. While LSA is a two-tier model, SAS has three tiers, including the general authorized access (GAA) tier, to facilitate opportunistic spectrum use. Priority access (PA) users are allocated to exclusive channels and protected from other PA and GAA users. In the GAA tier, multiple users can use a given channel, and thus there is no interference protection.

Compared to LSA, SAS allows a more dynamic and complex sharing model, which is likely to promote competition and foster innovation [7]. SAS is also more likely to provide more efficient spectrum utilization and better support for the deployment of small cells. Small cells with low-power communication enable smaller exclusion zones [8], thus providing more spectrum optimization opportunities than macro sites. A major difference to the LSA concept is the use of spectrum sensing in obtaining information about the current spectrum use. To meet the mission critical requirements of military incumbent users, it is required that sensing is used in and adjacent to the 3.5 GHz band to detect incumbent radar activity in coastal areas and near inland military bases. Confidentiality of the sensitive military incumbent user information is ensured through strict operational security requirements and corresponding certification of the sensing elements, as well as with operator authorization.

Similarly as in LSA, at the core of the SAS concept is a database system. Incumbent users may provide spectrum usage information, such as duration of the use and operational parameters such as transmitter identity, location, antenna height, transmission power, interference tolerance capability and protection contour, to be included in the database [6]. SAS can use either a database or a database-plus-sensing approach to identify the available spectrum opportunities.

Previous studies on the SAS development have focused on the technical and theoretical aspects of the research work. In order to start practical testing and trials of the SAS concept, design and implementation are also important. Recent publications discussing architectural considerations of SAS include [6], [11] and [12]. In addition, a messaging protocol for the SAS operation has been proposed in [12]. Currently, several member companies and research organizations of the Wireless Innovation Forum (WInnForum) are jointly developing interfaces, protocols and messaging formats for SAS. Some of the specified requests enable spectrum inquiries, granting permissions to use spectrum, and spectrum relinquishment [13] between SAS and CBRS devices

(CBSDs).

What is currently missing in the literature is analyses of the dynamics and time domain performance of SAS. Previous work has focused more on spatial and frequency domain considerations. One of the most important performance indicators is *the evacuation time* from the first indication of incumbent use in the same band and location to the time the band is cleared of any interfering secondary systems such as LTE base stations. In the case of an informing incumbent, the evacuation time determines how much in advance the incumbent user needs to declare its intention to use the spectrum at a certain location to avoid interference. In the case of sensing, the evacuation time is directly linked to the detection requirements.

In this paper, we describe a CBRS field trial environment and the related performance measurement results. We use the recent standard specifications from [13]–[15] to study the time domain operation of SAS with a focus on the evacuation and reconfiguration performance. The system is implemented and evacuation and reconfiguration time values are measured and analyzed in a live commercial network environment. It is important to carry out field tests to prove that the relevant SAS requirements can be met using commercial networks and systems. Our measurement results have already contributed to updating the time limits in [9] and [10]. For example, we have found that the configuration command to clear the band can vary in network management systems. Therefore, reserving some additional response time is practical to prepare for worst-case scenarios and large-scale network operations. On the other hand, the industry may also find our measurements on the network reconfiguration time to restore the mobile network operation after the evacuation interesting.

The paper is organized as follows: Section II presents the reference SAS architecture and defines the messaging protocol. The trial environment and the measurement setup are introduced in Section III, and the results are presented in Section IV. Finally, Section V concludes the paper.

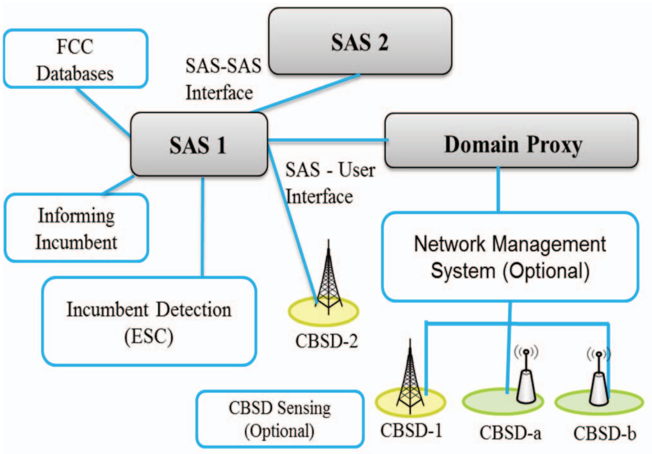

Figure 1. SAS system architecture.

II. HIGH-LEVEL SYSTEM MODEL

A. SAS reference architecture

Fig. 1 illustrates the high-level SAS architecture, which has been mainly defined in the WInnForum [14] and [17]. The reference architecture shows the main components and interfaces needed in defining the messaging protocols. The main component of the reference architecture is SAS 1, which determines the available frequencies and assigns them to different CBSDs and determines the maximum transmission power limits at given locations. It also enforces exclusion and protection zones around incumbent users such as U.S. Department of Defense (DoD) shipborne radars operating in coastal areas and non-federal Fixed Satellite Service (FSS) earth stations.

To protect FSS earth stations, the Federal Communications Commission (FCC) has adopted a rule requiring satellite operators to register their stations annually [9]. In the case of DoD shipborne radars, the SAS uses information from Environment Sensing Capability (ESC) devices to ensure that CBSDs operate in a manner that does not interfere with the incumbent users but still facilitates information exchange between multiple SAS servers.

The protection of federal DoD incumbent users is implemented by utilizing the static exclusion zones (EZ) scattered in a large area of the country. In the second deployment phase, the ESC system enables the rest of the country, including major coastal areas, to become available, as the exclusion zones are converted into protection zones (PZ). An ESC deployment near exclusion zones consists of one or more commercially operated networks of sensing devices that can be used to detect signals from federal radar systems in the vicinity of the exclusion zones. Additionally, a CBSD infrastructure based sensing could be considered under strict operational security requirements. Prospective ESC operators must have their systems approved through a similar process as SAS servers and SAS administrators. An SAS would obtain FCC maintained information about registered or licensed commercial users from FCC databases and exclusion zone information maintained by the National Telecommunications and Information Administration (NTIA).

Where CBSDs are centrally controlled, a Domain Proxy (DP) can act as a managing intermediary for a number of separate CBSDs so that the SAS communicates with the proxy instead of each individual CBSD. The DP selects the channels for use by a specific CBSD, or alternatively notifies the available channels to the Network Management System (NMS) for CBSD channel selection.

There are two types of CBSDs in the CBRS/SAS concept. Category A devices correspond to lower power access points and femtocells, whereas Category B devices correspond to point-to-point and point-to-multipoint types of architecture. Category A devices can operate by using database only or with ESCs, which are dedicated devices to detect incumbent radar activity. Category B operation always requires an ESC. In this paper, we focus on the small cell operation, i.e., Category A CBSDs.

B. Prerequisite procedures for operation

A connection to an SAS is required for CBSDs to access the spectrum. However, there are some prerequisites and a dedicated procedure for opening a connection between an SAS and a CBSD [15]. First, the CBSD or DP initiates SAS discovery to locate a potential SAS to connect to. Then, the CBRS user needs to register with the SAS to obtain a CBRS User ID. PA license (PAL) rights management and PAL ID registration allows the SAS to authenticate the claim to a PA license for privileged users. Device type parameters such as spurious emission mask, entered into the CBSD database, help avoiding corruptions. Installation parameters such as the location of the CBSD and antenna parameters must be entered to the database by certified professional installers to ensure accurate interference and allocation calculations. Finally, a security framework enables trust and identification between the SAS, CBSD and DP components.

There are some time and space domain limits discussed recently regarding the CBRS model. First, CBSDs must be able to determine their geographic coordinates with an accuracy of 50 meters horizontal and 3 meters vertical [6]. Even though there are some technical challenges in achieving indoor location accuracy due to lack of the GPS signal, this is an achievable requirement, particularly because CBSDs are fixed devices [9]. The requirement can be achieved with automatic geolocation algorithms or with input of a professional installer.

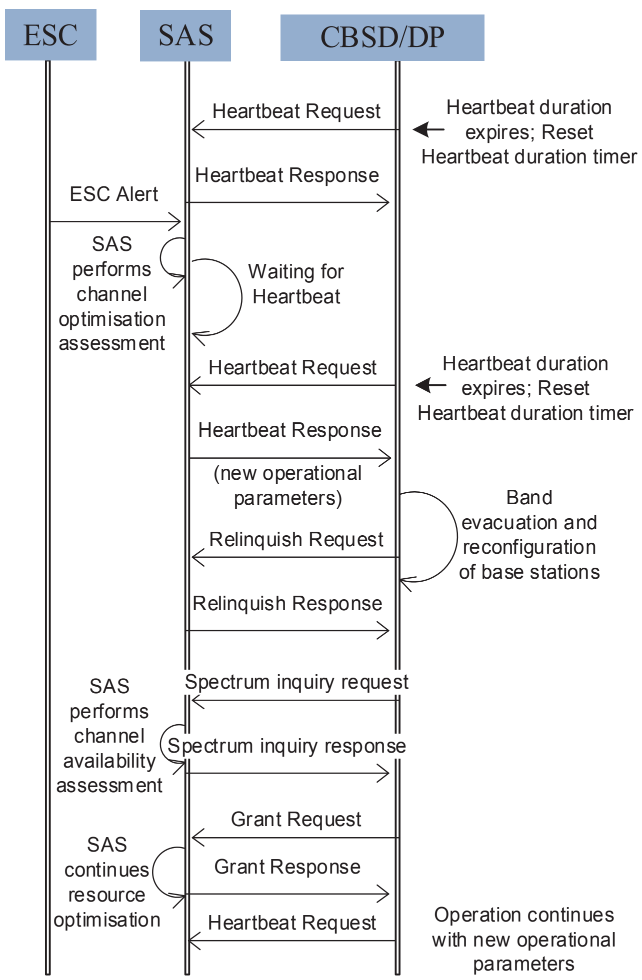

Figure 2. CBSD reconfiguration process after receiving an ESC Alert. Optional spectrum inquiry included.

C. Messaging protocol

The SAS to CBSD signaling protocol has been defined in [13]–[15]. The protocol specifies the messages and their content and sequences needed to register a device to an SAS, obtain permission to transmit, and to stop using allocated resources. The reconfiguration process includes the evacuation of the granted channels and configuring the associated CBSDs to another frequency band. The communication between ESC, SAS and DP/CBSD components related to the reconfiguration process is depicted in Fig. 2. The messages are defined as follows:

An ESC alert informs the SAS of the appearance of an incumbent user. There is a time limit from an ESC alert to the SAS to confirm that the interfering CBSDs have vacated the spectrum. The CBSDs must cease transmission and move to another frequency range or change their power level within the time limit following instructions provided by the SAS [9], [10] [14]. The initial 60-second evacuation time requirement has been increased to 300 seconds, partly due to the work done in our field trials. Our tests have shown that the 60-second limit cannot be achieved for large networks, not even under ideal circumstances.

A heartbeat request from a CBSD informs that the CBSD begins or continues using the allocated spectrum. If the SAS does not receive a heartbeat within a certain period, it will assume that the CBSD is no longer operating in the granted spectrum. Similarly, CBSDs require a heartbeat response to be able to operate in the allocated spectrum.

A heartbeat response allows the SAS to confirm, modify, suspend or terminate a grant and to change the heartbeat interval. A CBSD is authorized to use the spectrum during the time interval defined in the latest heartbeat response message. A grant may be suspended if an incumbent user such as a naval radar arrives in the neighborhood. If an incumbent user such as an FSS station moves into neighborhood to stay, the grant may be permanently denied.

A CBSD can request spectrum from the SAS at any time by sending a **grant request**. CBSDs may also initiate a **spectrum inquiry** procedure to check from the SAS spectrum availability for one or more frequency ranges. A spectrum inquiry does not guarantee channel availability but provides a good indication of that. However, this information is useful to be included in a **grant request** in order to enhance the resource allocation optimization. CBSDs may also request

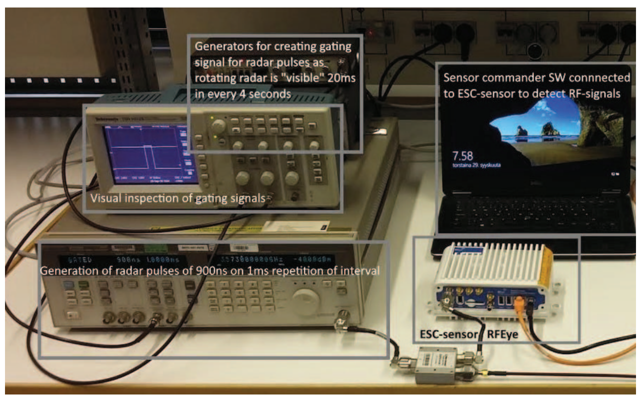

Figure 3. Radar sensing system.

access to a specific channel based on network planning. After receiving a grant request, the SAS then performs a channel interference assessment to determine if the requested frequency range is acceptable.

A **relinquish request** can be sent to notify the SAS that the CBSD no longer uses the allocated spectrum. The SAS answers with a relinquish response, and the freed spectrum can be reused.

D. The evacuation process

In this study, we measured the time intervals of the operations needed to evacuate the channel when the SAS denies an existing grant. The evacuation procedure fulfilling the specifications is depicted in Fig. 2. First, the CBSD is in the *Authorized* state, transmitting on the granted spectrum. The SAS receives an ESC Alert, which means that the sensor system has detected an incumbent use, and then determines which channels are affected by the incumbent use. The SAS then delivers all the CBSDs transmitting on those channels a heartbeat response, denying the use of those channels. The DP/CBSDs then switch off the radio transmissions accordingly. The CBSDs go in a *Registered* state in which they connected to the SAS but cannot use the radio without the allocated spectrum. Each DP/CBSD may send a new grant request to the SAS to gain access to an alternative frequency.

III. TRIAL ENVIRONMENT AND THE MEASUREMENT SETUP

The Finnish live CBRS trial environment is depicted in Fig. 4. The key building blocks are developed and governed by multiple partners of the CORE++ project [16]. The Finnish CBRS trial environment has been demonstrated with new features on multiple occasions [19], [20]. The building blocks of the trial are as follows:

A. Radar sensing system

The used radar sensing system, depicted in Fig. 3, consists of a radar signal simulator (RSS), a spectrum-sensing receiver (SSR) and a sensing software algorithm called Sensor Commander. To avoid the need to have real naval or maritime radars operating in the area, the RSS is used to generate radar signals based on R2-ESC-01 in [17]:

- Pulse repetition frequency 1 kHz
- Pulse width 0.9 µs
- Antenna scan rate 15 RPM
- Antenna beam width 1.8 degrees

The RFeye spectrum sensing device is used to sense the radar signals. The power level values (dBm) are recorded with a frequency resolution of 19.531 kHz over the 20 MHz bandwidth in the SAS band. The occupancy scan is performed every 45 seconds. The developed ESC software processes the occupancy data by detecting and recording power levels higher than -90 dBm. The bandwidth, power level and center frequency of the findings are stored.

B. LTE 3.5 GHz network

The CBRS trial environment consists of three 3GPP Release 10 LTE-Advanced compliant base stations, a radio access network, a management system and a core network. Commercially available Flexi Multiradio time-division (TD)-LTE 3.5 GHz base station at 3GPP spectrum band 42 (3.4–3.6 GHz) are used and equipped as Category A low-power access points for indoor usage. The radios are located inside an office building, as shown in Fig. 5. Two of the CBSDs are connected to a commercial Network Management System

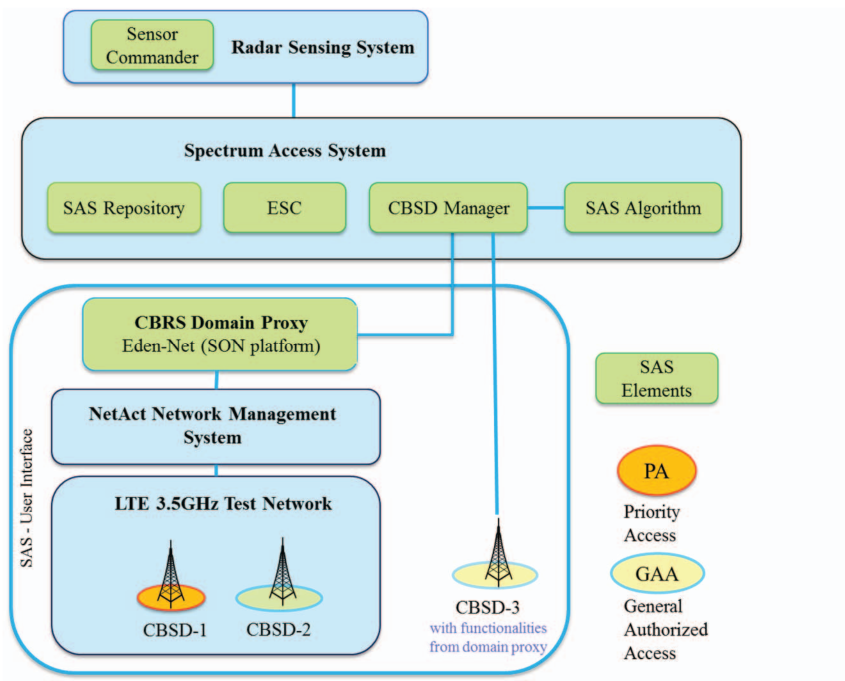

Figure 4. SAS field trial environment.

(NMS) and are managed by a DP. One CBSD is equipped as a standalone CBSD, having the core network functionalities required to operate (Lite-EPC) and control (SAS-controller/BTS_tools) locally.

The authorities have granted an indoor trial license to use the 3.51–3.59 GHz band for field trial purposes.

C. *Spectrum Access System*

The SAS combines multiple functions to provide the SAS capability for the field trial. The SAS component is implemented on a Java Spark server on Linux with HTTPS REST API for DPs and CBSDs. The SAS algorithm, Spark server, ESC, LTE base stations, LTE network and DP are located around Finland. They communicate using CORE++ tools, i.e., in practice by using publish/subscribe message-passing communication [16].

The most important functions the SAS provides in the field trial are as follows:

1) SAS Repository

The SAS repository is a database that gathers data about the spectrum use in the area of interest, including CBSDs' operational parameters such as identification, location, antenna parameters, transmission power, and used channels. The SAS repository stores all the information required by other key components for channel allocations and interference management in the network.

2) Environmental Sensing Capability

The ESC consists of networks of sensors that detect the presence of signals from incumbent systems in the band and communicate that information to the SAS to facilitate protection of operations in the band. The ESC module used in the field trial combines information from the sensing system and sends ESC alerts to alert the SAS to start an evacuation process.

3) CBSD manager

The CBSD manager follows the protocols defined in the SAS-CBSD protocol [13] specification for DPs and CBSDs to access the SAS. It handles SAS requests, creates responses and updates the SAS repository. In the field trial, the SAS implementation also supports the development of alternative SAS algorithms in order to test different channel allocation methods.

4) SAS algorithm: Intelligence of the SAS

Frequency channel allocation is a challenging task due to the stringent channel usage priority requirements and a potentially large number of CBSDs. The CBSD manager initiates the SAS algorithm processing in several cases, for example, when incumbent activity is detected or ceases, a CBSD is requesting a grant or relinquishing an existing grant, or a CBSD has not sent a heartbeat within the set interval. The CBSD manager generates an activity report based on the data collected on activities such as channel allocations and on the current state of CBSDs, pending grant requests, and the sensed arrival and departure of incumbent users in or from a specific band. The SAS algorithm uses the activity report as an input to generate series of commands to the SAS to deny, change or allocate CBSD grants. In a single run, the SAS algorithm can carry out at most one state change for each CBSD. For example, spectrum can be granted for multiple CBSDs requesting at the same time. The SAS algorithm was specifically developed to support the research and development of the field trial. Thus, the measured SAS

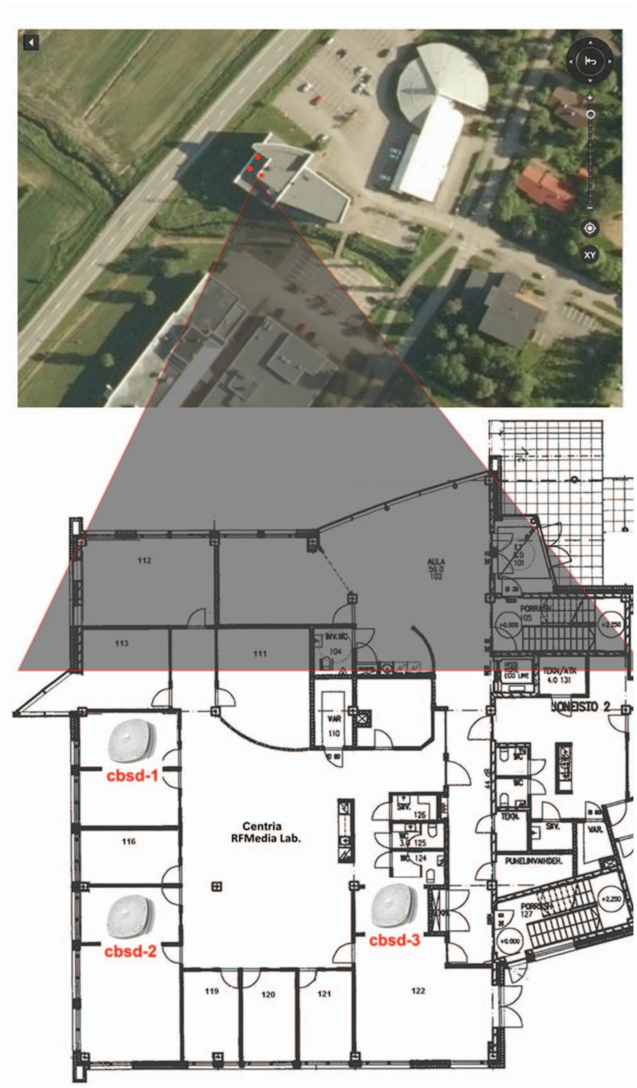

Figure 5. LTE CBSD's in field trial network.

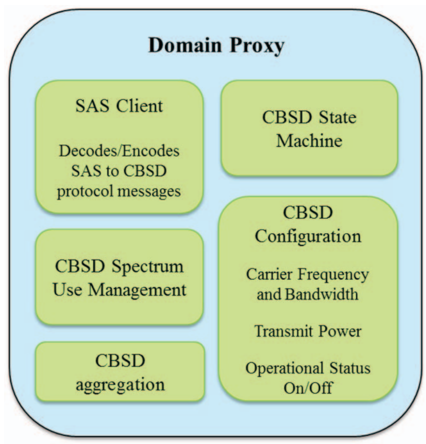

Figure 6. Domain Proxy architecture components.

algorithm is not using any advanced radio propagation or interference minimization calculations that are possible to perform by using radio, antenna, power and other information stored in the SAS system.

The basic idea of the algorithm is to control interference, minimize the number of channel changes and use the SAS band efficiently. First, the algorithm checks the activity report for existence of incumbent users. If incumbent use is detected, the algorithm then denies the grants of any overlapping CBSDs. Second, the algorithm allocates the available free channels to CBSDs in the order they send their grant requests. If all channels are occupied, a requesting GAA user is put on a shared GAA channel or a PAL channel with an existing GAA user. Any requesting PA user is put on a PAL channel that was previously being used by one or more GAAs, and the GAAs' grants are denied. Third, the algorithm checks the possibility to distribute GAA users sharing a channel to other available free channels.

D. Domain Proxy

In a typical Mobile Network Operator (MNO) deployment scenario, a CBSD is a base station in a managed radio network comprising other base stations (BSs), DPs, core network, and the NMS functionality. The DP acts as a managing intermediary component between the SAS and several CBSDs, enabling SAS usage for base stations that do not have interface to an SAS. The two main functions of DPs are: (1) communicating directly with the SAS by using the SAS-CBSD protocol [13] and (2) configuring a number of CBSDs by instructing the NMS to change the frequency, bandwidth, transmit power and operational state of the impacted CBSDs. The DP is able to report certain CBSD measurement data to the SAS based on the SAS's instructions.

A standalone GAA CBSD can be controlled directly via the CBSD manager. Wi-Fi was originally thought to be the most potential individual GAA customer. For MNOs, a valid option is an unlicensed LTE in SAS band. For example, a MulteFire system can be installed and operated in the same way as a Wi-Fi access point. Right now, CBRS Alliance is establishing an effective product certification program for LTE equipment in the U.S. 3.5 GHz band to ensure multi-vendor interoperability.

In the trial, the DP was implemented as a self-organizing network (SON) module on top of the Eden-NET SON platform [18] and Eden-NET configuration interface towards NetAct, having the following functions (see Fig. 6):

- Decoding/encoding SAS protocol messages
- Maintaining the CBSD state and channel assigned by the SAS
- Aggregation of CBSD information for the SAS
- Management of spectrum usage of the CBSD through the heartbeat and relinquishment procedures.

The DP may also contain advanced functionalities, such as flexible self-control and interference optimization. In addition to larger MNO operated networks, the DP enables, for example, combining small cells of a shopping mall or sports venue to a single virtual base station entity that covers the entire venue.

E. Evacuation procedure:

We made a performance analysis of the CBSD evacuation and subsequent frequency change procedure in a live LTE test network. The purpose was to find out the total evacuation time in the field trial and record the processing times in each component, so we divided the overall procedure into several steps based on field trial key component boundaries. The steps

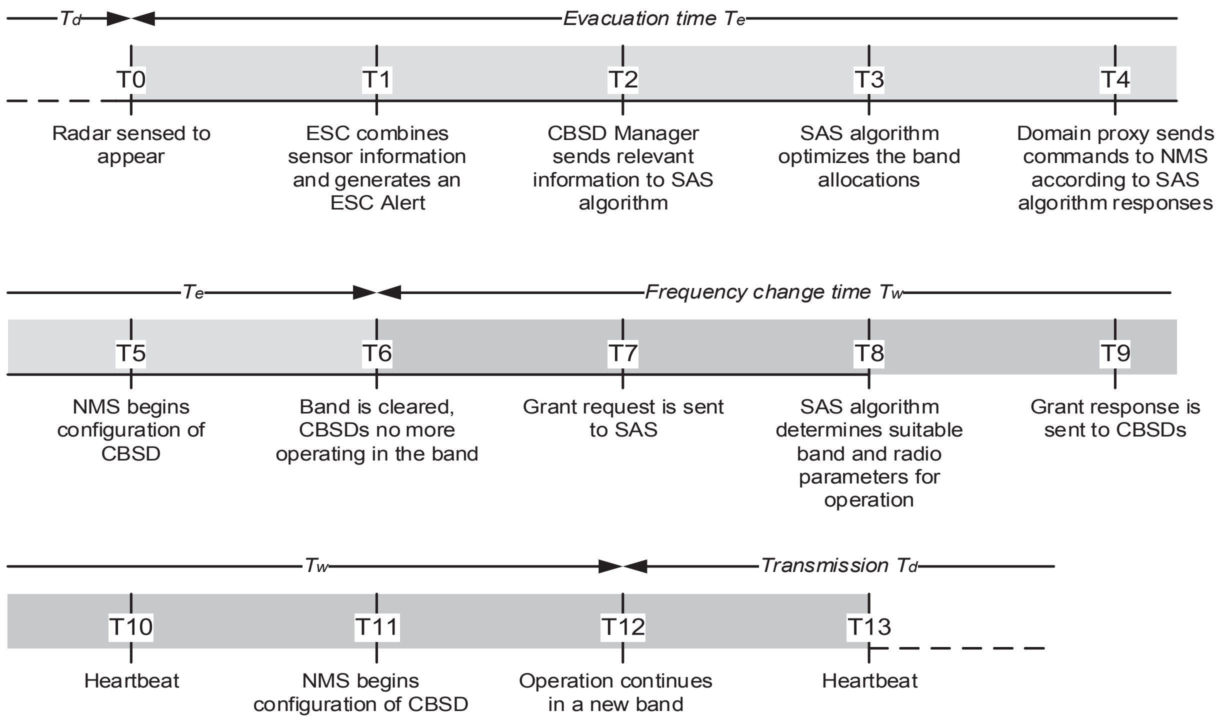

Figure 7. Timeline of the evacuation and frequency change process

are shown in the timeline in Fig. 7, and the details of each step are provided below.

(1) In the beginning, the network is operating on SAS band under SAS control and CBSDs are transmitting using allocated 10 MHz channels. The evacuation begin, when an ESC communicates to the CBSD Manager that it has detected a signal (possibly from a radar) at time instant T0, including information such as sensor location and sensed received power, bandwidth and frequency. Based on the received sensor information and current spectrum usage, the CBSD Manager generates an ESC alert at time instant T1, if the spectrum state has been changed and spectrum management is needed

(2) At time instant T2, the CBSD manager sends an activity report to the SAS algorithm. The activity report includes information about the SAS spectrum range and channel division, ESC alert (incumbent use), and state of each CBSD (*Grant Request*, *Granted* or *Authorized*), band usage, radio information and priority of CBSDs (GAA/PA).

(3) The SAS algorithm optimizes the band allocations based on the sensed incumbent use and existing GAA/PA users, licenses and radio types at time instant T3. The changes made to channel allocations are communicated back to the SAS.

(4) The DP is responsible for configuring the base stations according to SAS algorithm responses. At time instant T4, the DP receives the changes to the existing grants in the response of heartbeat request of the CBSD.

(5) The NMS begins the configuration of the base station at time instant T5 to switch off the radio of the base station to change power or frequency.

(6) During the configuration, the actual band becomes cleared during the configuration process as the radio is switched off at time instant T6, which ends the evacuation.

F. Frequency change procedure

(7) After the configuration command has ended, the DP sends new grant requests to the SAS to gain access to new frequencies for the base stations that were switched off. This starts the frequency change procedure at time instant T7.

(8) The SAS algorithm allocates bands and radio parameters to CBSDs during the grant request at time instant T8. At this point, the new PA user allocations can also trigger switching off/reconfiguration of some GAA radios on the PAL channels.

(9) At time instant T9, DP/CBSDs receive grant responses. This changes their state to *Granted*. The configuration of base stations to a new frequency may begin at time instant T9, provided that the radios remain off-air.

(10) Each DP/CBSD sends a single heartbeat request to check their grant status at time instant T10. The heartbeat response changes the state to *Authorized*/*Transmission*.

(11) The configuration of base station to switch them back on-air begins at time instant T11 based on the algorithm's decision.

(12) Similarly, the base station switch back on-air using a new channel at some point during the configuration command. This ends the frequency change procedure.

(13) Once the base stations are back on-air, their operation with regular heartbeat requests continues as per usual.

IV. Delay analysis and measurement results

A. Evacuation and frequency change times

We performed ten consecutive measurements using the above-described setup to define the time needed to perform each step in the process composed of the evacuation phase and the frequency change procedure. The following results were obtained with the SAS algorithm described in Section III D. The heartbeat interval was set to 20 seconds. We had two base stations online behind a DP, and we measured the duration of the evacuation and reconfiguration process using a single base station. The evacuation and frequency change measurement points are presented in Tables I and II, respectively.

Table I. Evacuation measurement points, time in seconds.

Event	Avg	Max	Min
T1 ESC Alert	0	0	0
T2 SAS Algorithm begin	0.054	0.074	0.051
T3 SAS Algorithm ready	10.1	10.1	10.1
T4 Heartbeat denies grant	22.3	29.2	12.0
T5 NMS conf. begin	22.5	29.3	12.3
T6 Channel is clear	88	103	78
NMS conf. complete	103	115	94

As can be seen from Table I on the evacuation procedure, the most time-consuming part of the procedure is deactivating the base station by the NMS. This step takes on average around one minute and 20 seconds after the base station has lost the grant. Until the channel is freed, the evacuation takes 88 seconds on average. Time instant T6 was monitored by using a spectrum analyzer.

The total evacuation time is 103 seconds on average; this also covers the completion of the NMS configuration command with additional checks to validate the configuration success or failure overall. At this point, the NMS can confim the band is evacuated.

Table II. Reconfiguration, frequency change time in seconds.

Event	Avg	Max	Min
T7 Grant request	0	0	0
T8 SAS Algorithm	-	-	-
T9 Grant response	4.7	5.0	4.0
T10 Heartbeat, T11	24.8	25.2	24.1
T12 On Air	98	103	93
T13 Heartbeat	105	112	98

Time instant T3 shows that the SAS algorithm delay is on average 10 seconds, which is too large for the algorithm run. This delay includes additional four seconds spent on synchronization, networking and queuing delays due to a slow message passing protocol, and the algorithm is actually run once for both grant requests. The algorithm delay could be optimized to 1–2 seconds by running the algorithm locally and processing the grant requests in a single algorithm run.

Time instant T4 also includes at most the heartbeat interval until the SAS can communicate the grant denial to the DP in the next response. The SAS can alter the heartbeat interval, but here it was fixed to 20 seconds.

The reconfiguration and frequency change of the base station begins right after the evacuation once the DP sends the grant request. Time instant T9 includes running the SAS algorithm to select a new frequency for the base station. T10 includes the first heartbeat request and response after a successful grant response and before the CBSD can turn on the radio. The T11 configuration command starts at the same time and continues on average for 80 seconds after the heartbeat response. Time instant T12 was inspected on-air by using a channel analyzer at the site. T13 indicates the time when the DP communicates to the SAS that the base station is transmitting. Most time in reconfiguring the CBRS system (Table II) to operate in new bands is spent on unlocking the base station. Based on our measurements, it takes from an ESC alert until the frequency change process is completed on average around three minutes and 30 seconds, and less than four minutes in the slowest case.

It should be noted that actual NMS command delays depend on the base station manufacturer and model, selected evacuation type, and load of the NMS during the measurement. Manufacturers have their own LTE access, management and core network systems with different characteristics. In this case, the NMS provides three potential means to evacuate the channel based on the urgency of the request and the type of the used base stations, as depicted in Fig. 8. The fast evacuation type was used in the present measurements, and it is needed, e.g., in the case of ESC alerts. In fast evacuation, the CBSD locks the affected cells, and the terminals will automatically start the cell reselection procedure. In the case of informing incumbents, graceful shutdown can be used when the MNO knows well beforehand the need for evacuation. Graceful shutdown lowers the RX power in the base station in small steps, and the terminals initiate handover to a neighbor cell based on the handover trigger levels. The latest versions of base stations provide an option to change frequency "on the fly" with radio on. In this case the terminal will start the cell reselection automatically.

As can be seen from the results, the duration of the configuration command time varies between 78 and 103 seconds (Table I). This is mainly due to the overall load of the shared operational NMS used in the field trial.

B. *Relation to FCC limits*

How do these results relate to the FCC time limits? The FCC rules allow up to 300 seconds after the ESC communicates that it has detected a federal incumbent user for the SAS to confirm suspension of any CBSD in the band. The FCC has not specified how the 300 seconds can be divided for the SAS to process messages, communicate with CBSDs, etc. That is up to each implementation. Furthermore, according to the standard, the SAS cannot start the communication with the CBSD since the standard allows the CBSD to open an IP port for communication only when it sends a heartbeat request. Thus, the SAS must wait for the next heartbeat request to be able to communicate back to the CBSD.

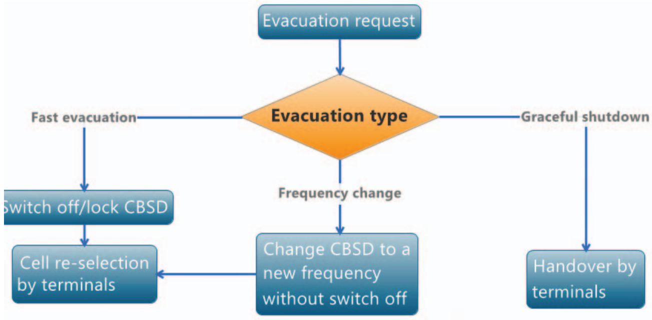

Figure 8. Evacuation types on base station.

The current requirement is that CBSDs must comply with SAS commands within 60 seconds. The SAS can notify the CBSD of incumbent use or needs only in the next heartbeat response. From that, the CBSD has 60 seconds to process the message before responding back. This may increase the response time of the SAS, which must be able to confirm within five minutes that the CBSD has vacated the relevant spectrum.

Based on our measurements, we can confirm that the field trial operates well and fulfills the above requirements. The achieved evacuation time totals around 90 seconds when using the base station locking procedure, which means that the band is cleared well before the required five-minute time limit. The total reconfiguration time, including the frequency change and continuing operation in a new channel, takes at most four minutes based on our measurements.

Our measurements were performed using a small-scale commercial LTE system but with NMS being in shared use. For large-scale networks with densified small cell installation, the SAS scalability could be an issue, for example, when the entire network needs to evacuate. In MNO use today, NMS is operating very large networks and is capable of performing parallel operations on several base stations at the same time. Another possible solution for controlling large-scale evacuations is an emergency evacuation type of operation in NMS, where the evacuation takes place according to a pre-defined emergency plan, which shuts down mobile networks in two to three minutes. By defining a similar emergency plan for a network in an SAS band, the DP could utilize this feature to evacuate all CBSDs, if needed.

C. *Techniques to reduce latency*

There are a couple of methods that could be used to reduce delays in the evacuation and frequency change process compared to the field trial, which fulfils the current specification requirements [13]–[15]. Since the SAS must wait for a heartbeat message before it can initiate the evacuation process, there is an initial waiting time totaling on average half of the heartbeat interval t_h. If the SAS could initiate the procedure immediately after receiving an ESC alert, $t_h/2$ seconds would be saved in the process. For example, if t_h is 10 seconds, the time saved in the evacuation would be 5 seconds.

Another, and more remarkable, improvement could be achieved in the frequency change process by enabling frequency change "on the fly" without a need to turn off base stations when the band is cleared. This could be done if other channels were available. That would mean that at time instant T5, the CBSDs would immediately send their grant request. Then, after receiving a heartbeat response, the DP could switch the frequency on-air to the base station. This would shave off more than a minute from both the evacuation and the frequency change procedure. The total time reduction would roughly amount to two minutes, which means an almost 70% reduction in the reconfiguration time.

V. Conclusions

A key to the success of 5G, potentially implemented across multiple industry verticals, lies in forward-looking spectrum policies and unlocking new spectrum assets. In this paper, we have concentrated on the 3.5 GHz band by implementing a CBRS concept governed by an SAS in a live network using standardized messages and protocols. This is the first work to analyze time domain operation in a practical SAS based CBRS system, focusing especially on the evacuation time, which is one of the most important indicators of the feasibility and dynamicity of the sharing system.

The trial highlights certain concerns regarding the ability to meet the FCC's 60-second requirement concerning the SAS power down directive, when driven through the NMS and SON. We analyzed how much time is needed for each process phase and what are the most time-consuming phases in the evacuation and frequency change process. The results show that most time is spent on configuring the base stations by the network management system. The standard process could be improved by enabling frequency change "on the fly" without a need to lock the base stations during the evacuation process. This would reduce the total reconfiguration time to less than half of the original.

To enable faster and more dynamic frequency change, the base stations should be optimized to support fast on-air frequency changes. Time scales, aggregate interference studies and allocation algorithms could be studied further in large-scale trials including, for example, hundreds of base stations and advanced allocation algorithms.

VI. Acknowledgments

The CORE++ research project [4] is funded by the 5thGear program of the Finnish Funding Agency for Technology and Innovation (Tekes) and the project consortium: VTT Technical Research Centre of Finland, University of Oulu, Centria University of Applied Sciences, Fairspectrum, Turku University of Applied Sciences, Nokia, PehuTec, Bittium, KeySight, Finnish Defence Forces. The project is also supported by the Finnish Communications Regulatory Authority.

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