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Research Article

A Practical Perspective on 5G-Ready Highly Dynamic Spectrum Management with LSA

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A diversity of wireless technologies will collaborate to support the fifth-generation (5G) communication networks with their demanding applications and services. Despite decisive progress in many enabling solutions, next-generation cellular deployments may still suffer from a glaring lack of bandwidth due to inefficient utilization of radio spectrum, which calls for immediate action. To this end, several capable frameworks have recently emerged to all help the mobile network operators (MNOs) leverage the abundant frequency bands that are utilized lightly by other incumbents. Along these lines, the recent Licensed Shared Access (LSA) regulatory framework allows for controlled sharing of spectrum between an incumbent and a licensee, such as the MNO, which coexist geographically. This powerful concept has been subject to several early technology demonstrations that confirm its implementation feasibility. However, the full potential of LSA-based spectrum management can only become available if it is empowered to operate *dynamically* and at high space-time-frequency granularity. Complementing the prior efforts, we in this work outline the functionality that is required by the LSA system to achieve the much needed flexible operation as well as report on the results of our respective live trial that employs a full-fledged commercial-grade cellular network deployment. Our practical results become instrumental to facilitate more dynamic bandwidth sharing and thus promise to advance on the degrees of spectrum utilization in future 5G systems without compromising the service quality of their users.

1. Introduction

The fifth-generation (5G) wireless systems aim to decisively advance on the levels of spectral and energy efficiency, user-experienced throughput, as well as communication latency and reliability. They prepare to rely on leveraging extremely high frequency (i.e., mmWave) spectrum bands, employing massive Multiple-Input Multiple-Output (MIMO) techniques, as well as deploying increased numbers of small cells with various sizes and across different frequencies. However, the use of mmWave radios is costly and the key enabling technology is still under standardization, whereas massive MIMO requires complex and expensive coordination that is difficult to achieve in practice. Therefore, the main feasible method to offer larger capacity on existing pre-5G deployments is via extreme network densification.

Today, the mobile network operators (MNOs) are however struggling to deploy a higher density of small cells due to the need of extra investment that is not compensated by the actual revenues [1, 2]. On the other hand, multiple field measurement campaigns strongly evidence that the conventional spectrum below 6 GHz may be substantially underutilized across space, time, and frequency [3]. This is a consequence of the legacy "command-and-control" spectrum management approach that used to create static and overprotective allocations [4]. Hence, as a viable alternative to deploying additional small cells, the MNOs may quickly boost the capacity on their deployments with more *dynamic* and market-friendly spectrum management mechanisms. These should be made available in the emerging 5G systems [5].

With more dynamic spectrum management, the expensive frequency bands could be shared between different stakeholders flexibly, as opposed to exclusive use of licensed spectrum. This may go far beyond opening up unlicensed frequencies for collective uncontrolled use and promises to unlock the much needed additional bandwidth that is currently employed sparsely by its existing incumbents. It can also improve the utilization of presently allocated spectrum across its various dimensions (space, time, frequency), which is essential to support the throughput-hungry 5G applications. To this effect, powerful spectrum sharing technologies emerged recently, such as LTE in unlicensed spectrum (LTE-U), Licensed Assisted Access (LAA), MulteFire, Citizens Broadband Radio Service (CBRS), and Licensed Shared Access (LSA) [6–8].

The latter framework is an evolution of the industry-driven Authorized Shared Access (ASA) technology for controlled spectrum sharing between the incumbent holding the rights to use the frequency bands and the licensee (e.g., the MNO), who is utilizing such spectrum temporarily [9] This concept has been taken forward by the European Commission (EC) to develop a new "individual licensing regime" for authorized spectrum sharing [10]. According to the EC's Radio Spectrum Policy Group (RSPG), the LSA framework enables a limited number of licensees to operate in a frequency band already assigned to one or more incumbents in accordance with well-defined sharing rules. As a result, all of the authorized users, including the incumbents, can maintain their desired Quality of Service (QoS) requirements (see RSPG 13-538).

Ever since its introduction several years ago, the LSA concept has spawned an avalanche of engineering, business, and regulatory work that focused on adapting it promptly for practical applications [11]. This development has been facilitated by the Conference Europeenne des Postes et des Telecommunications (CEPT) as it had established two project teams, PT52 and PT53 (ETSI TS 103 113), to ensure that there are no barriers to the adoption of LSA in 2.3 – 2.4 GHz bands from a regulatory perspective (EC Mandate on MFCN for 2.3–2.4 GHz, 2014) [12]. In parallel, the European Telecommunications Standards Institute (ETSI) has been targeting to outline the LSA system architecture in their respective technical specifications (ETSI TS 103 154 and ETSI TS 103 235). In the US, a Notice of Proposed Rulemaking (NPRM) in 3.5 GHz band was introduced by the FCC [13, 14].

As a result of this concentrated effort, the LSA has soon been ready for practical demonstrations, which took place in Spain (2015), Italy (2016), France (2016), Finland (2016), Czech Republic (2016), and the Netherlands (2017). However, many of these past activities considered near-static LSA operation with longer-term allocations since they primarily addressed the technical feasibility of LSA implementation [15]. Continuing our initial work in [16] and more recent technology groundwork in [17], we here complement these earlier initiatives with a new perspective on highly dynamic spectrum management within the LSA framework. In this paper, we specifically emphasize the QoS aspects and the corresponding service reliability performance as our work unveils the practical limits of dynamic LSA operation based on a real-world trial in a live LTE system.

The rest of this text is organized as follows. In Section 2, an overview of recent activities connected with dynamic spectrum management is offered that refines the requirements for vertical communication use-cases. A discussion on the envisaged dynamic LSA system is also contributed. The principles of our dynamic LSA implementation are discussed in detail in Section 3. We pay particular attention to design targets to ensure that the dynamic LSA framework can achieve the expected degrees of control accuracy. Measurement methodology and results follow in Section 4, while the last Section 5 concludes this work.

2. Dynamic Spectrum Management Overview

Numerous activities and contributions are dedicated to the definition of vertical communication use-cases by refining their requirements and assessing how all of these can be addressed in the 5G specification and standardization process. It is important to note that most of these activities are coming from research, e.g., European FP 7 and H 2020 projects as well as the mobile communications industry community (Next Generation Mobile Consortium (NGMN), 3GPP), while similar initiatives engaging other important vertical industry stakeholders are still rather small-scale [18–20].

With the emerging LSA framework, flexible and more dynamic spectrum sharing may be enabled, which becomes increasingly valuable for demanding 5G applications [21]. The advanced services that can benefit from cross-band spectrum aggregation are those that require massive bandwidths but have difficulty to be supported by the existing MNO deployments (e.g., augmented and virtual reality) [22]. Another category that may take advantage of highly dynamic LSA operation is industrial Internet of Things (IoT) applications across different verticals, especially those requiring reliable operation and dedicated QoS guarantees (e.g., automotive). Finally, LSA can improve a wide range of local broadband services, such as those where the MNOs do not have a possibility of deploying exclusive licensed spectrum (e.g., enterprise) [23, 24].

We thus expect that as LSA technologies mature, an increasing variety of 5G applications and services will be capable of taking advantage of more efficient geographic-temporal spectrum management. In [16], the LSA functionality required to enable truly dynamic spectrum sharing at the timescales of seconds is outlined. Continuing this research, in [25] we addressed a typical cell scenario under the "limit power" policy by capturing the produced interference as a key parameter in the cellular network that employs LSA mechanisms—a summary on our prior system-level evaluations of dynamic LSA operation is available online; see http://winter-group.net/dyn-lsa-sim-res/. In a follow-up research [26], an advanced user satisfaction-aware spectrum management strategy for dynamic LSA management in 5G

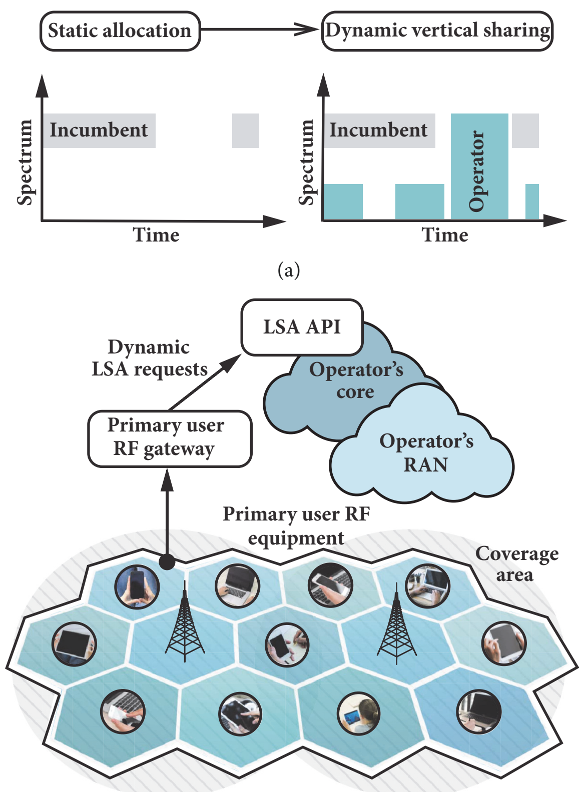


Figure 1: (a) Improved spectrum utilization with dynamic sharing. (b) High-level architecture of dynamic LSA operation.

networks was proposed to balance both the user satisfaction and the MNO utilization. All together, the mentioned capabilities are crucial for the incumbent systems with high-speed mobility (e.g., express trains and airplanes) and may offer much improved performance as compared to rigid and near-static LSA implementations. Given that LSA is an example of vertical sharing (see Figure 1(a)), multiple spectrum users across the same geographical area can operate at different priority tiers. For instance, the LSA licensee (e.g., a commercial LTE network) may avoid causing interference to the LSA incumbent (e.g., an air traffic control system).

2.1. Our Contribution. Our envisaged dynamic LSA system is intended to operate according to the high-level architecture captured in Figure 1(b). The primary user of the spectrum (i.e., the incumbent) identifies its target limitations (across space, time, and frequency), where the wireless interference constraints have to be met by the secondary user (i.e., the LSA licensee, such as the MNO). Further, a corresponding LSA request is issued and transferred to the operator's dedicated Application Programming Interface (API), where it is then converted into specific Radio Access Network (RAN) instructions (e.g., interference estimation, transmit power reduction, frequency band change, and LSA spectrum usage policy). Once these commands are received by the operator's cloud, its RAN executes the required actions as instructed.

Considering the key mechanisms and constraints in place for dynamic LSA systems, the proposed functionality as discussed below enables the RAN to respond to the received LSA-specific requests issued by the incumbent in near real time. The primary benefit of our approach is in flexible bandwidth segmentation, which is much more fine-grained and adaptive than in previous LSA implementations. With such dynamic and on-demand network configuration, substantial radio resources can be made available to both the incumbent(s) and the LSA licensee(s), since the proposed logic tightly applies to the time domain. Accordingly, the timescale of radio resource utilization has higher granularity than in static LSA approaches. At the time instants when the incumbent does not utilize its bandwidth resources, they are released automatically, without any additional administrative overheads or delays associated with the LSA database updates.

In addition, our approach efficiently leverages the spatial dimension of the shared spectrum resources. That is, the locations where the bandwidth has to be released by the LSA licensee (the MNO) back to the incumbent can be obtained with higher precision than what is possible with the conventional LSA setups, in which the geographical blocks are typically represented as a coarse grid on the map. In the following sections, we continue by providing a systematic perspective on our development efforts to implement a dynamic LSA system. We also highlight the crucial design choices with regard to the communication chain that facilitates near real time LSA operation within a practical LTE network deployment.

3. Principles of Dynamic LSA Implementation

We expect that upcoming LSA implementations will require software and hardware modifications within the existing cellular network infrastructure as well as, potentially, on the side of the user equipment (UE). Despite substantial ongoing efforts to evolve the LTE system as one of the cornerstone 5G technologies, support for highly dynamic LSA operation in practical MNO deployments calls for a dedicated technology development effort. If not reflected comprehensively in further LTE releases, the LSA spectrum sharing mechanisms may be slow to enter the market, where they are much needed at this time. In this section, we address this important demand by exposing the key system functionality required to support highly dynamic LSA in a 3GPP LTE system.

3.1. Proposed Components and Functionality. We recall that wireless technology standardization conventionally begins by defining the functional elements and interfaces between them. Aiming to lay the groundwork for this, we first identify the main functions and interfaces necessary for implementing dynamic LSA mechanisms (see Figure 2). Given that we have recently outlined the core principles behind the dynamic LSA framework as a proof-of-concept study in [17], we build the present system architecture proposal on our rich hands-on experience acquired then. To this end, we

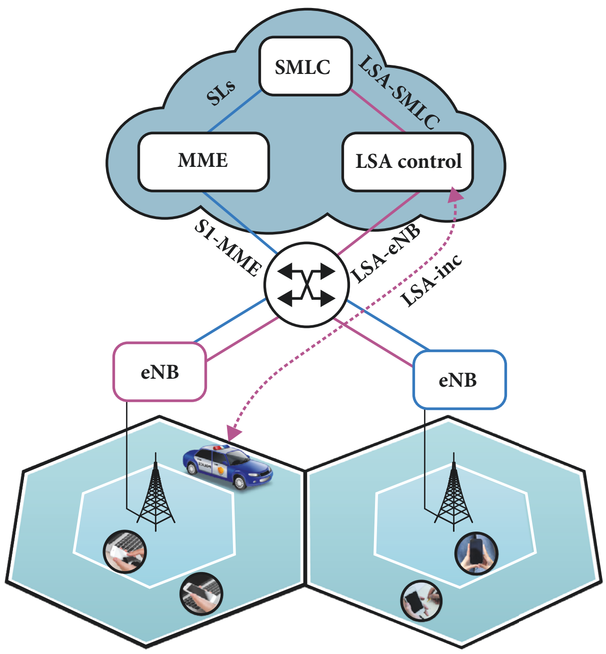


Figure 2: Key elements of proposed dynamic LSA architecture.

rely on a full-fledged cellular system deployment at Brno University of Technology (BUT), Czech Republic, which offers an excellent example of a contemporary 3GPP LTE target system. Therefore, this paper advances on top of our previous works as an enhanced Free Space Path Loss (FSPL) model was constructed to decrease errors of the interference estimation procedure. Also, two representative power allocation policies based on heuristic iterative search were implemented as part of the LSA controller node within the LTE system.

(1) Control is responsible for accepting the incumbent's requests and managing the power allocation across the network. In conventional LSA systems, this function may be performed by the LSA controller, while the LSA repository acts as a proxy. For the intended highly dynamic operation, we utilize a direct interface between the incumbent and the LSA controller to reduce the control-plane latency, since the trial was conducted in a closed environment.

(2) Positioning is used for locating the sources of interference in the network, which is key to efficient power allocation. In cases where the LSA band is utilized for downlink (DL) communication, the positions of all LTE base stations (named eNBs) are typically well known and may thus be programmed into the controller. However, in cases where the LSA is applied to uplink (UL) or TDD bands, it is important to have the position estimates of the UEs as well, since the latter become the main sources of interference. Currently, such information is not available to the LSA controller, but for the current trial we introduced the LSA-SMLC interface, which allows the LSA controller to directly access the LTE positioning data (as calculated based on the cellular signals or reported by the UEs themselves).

(3) Policy assignment offers the capability to issue commands to the individual cells, which is at the very core of the LSA concept. In our dynamic LSA system, this implies setting transmit power constraints for the corresponding radio interfaces—in the limit up to full cell shutdown. For that purpose, we introduce the LSA-eNB interface that aggregates (i) functions normally accessible via OA&M (set the transmit power, shut the cell down, etc.) as well as (ii) certain instructions issued directly to the UE via the RRC interface (initiate handover to a specific cell, switch the band, etc.).

3.2. Envisioned LSA System Operation. Our proposed system design targets to ensure that the dynamic LSA framework can achieve the desired degrees of control accuracy. To this end, we enable the UEs to know their precise location and make them report it to the SMLC. This information can then be extracted from the SMLC via a proprietary system monitoring interface, which acts as LSA-SMLC. The control interface LSA-inc can be implemented as a socket, over which the current coordinates and the threshold power settings can be reliably reported by each of the incumbent's users, thus defining a constraint in the controller's power allocation algorithm. Unlike in static LSA cases, dynamic reports are transient in nature and time out on their own. Hence, the network reverts to its default operation whenever no more reports are being sent. For our below test measurements, such reports were triggered manually.

Most importantly, to address the increased control granularity in the dynamic LSA system, the LSA-eNB interface needs to be implemented as a combination of the OA&M and the direct UE control. One of our core proposals that are instrumental to the dynamic LSA operation is to reduce the transmit power instead of a complete cell shutdown, which considerably improves the system capacity. While it is relatively easy to lower the UL or DL power limit in a cell instead of shutting it down, actually ensuring it in the UEs that are thus forced outside of the cell's coverage area is much more difficult. In our setup, the DL power control has a few possible settings that match the cell coverage area in the DL with its intended service area in the UL. In a commercial-grade test deployment, it may be cumbersome to send the RRC control signals from the core network side that would enforce the UE handover out of the LSA band (as UEs prefer to handover inside their current band when a cell is shut down). If Multi-access Edge Computing (MEC) infrastructure is available, this issue can be resolved by implementing a service that monitors positions of the incumbent entities and UE devices. Furthermore, computational tasks can be offloaded to the MEC layer, if characteristics of the deployment cause an increase in the computational complexity. For example, if we consider a scenario where the number of UEs is significantly high and they move fast, utilizing MEC services may help distribute the computational load. Hence, responsiveness of the system will increase, which in turn will allow to handle high-speed UEs. However, current ETSI documentation does not list this case as a service scenario [27]. To mimic this functionality, the UEs may employ a user-space program that would shut them down instead, since at the time of the trial we did not have access to MEC-enabled hardware. Further, the UEs that fall out of the service area of a particular cell—but remain capable of receiving its DL signaling—may, according to their protocol, attempt a RACH procedure. These RACH transmissions use power ramping if unsuccessful [28] (and they will be unsuccessful as the cell is instructed not to accept the initiating UEs) and may thus violate the interference constraints. While RACH packets are only short bursts, they may still cause issues in certain cases.

3.3. Important Practical Considerations. Out of the three interfaces identified for the needs of dynamic LSA operation, only two are deployment-ready today. Indeed, reporting the desired interference constraints may be readily achieved with existing IP-based protocols, while connecting the SMLC with the LSA controller is fairly straightforward. On the contrary, ensuring that all of the UEs follow the dynamic power allocation policy in a predictable manner is complicated due to several limitations in the current cellular signaling:

(i) The UEs cannot be forced to handover away from their current serving eNB without a deep integration into the proprietary code inside the MME. While the required functionality may be made available by some of the core network vendors, it is presently not a part of any standard specification. Similarly, UE handovers between the individual cells under the same eNB may not be even reported to the MME, which translates into the need for more proprietary interfaces as of today.

(ii) The service area of a cell with the reduced UL power level may not be easily predicted by the UEs, thus often resulting in futile RACH attempts by the devices that are relatively far away from the cell center (and given the UL power limits). Adding the relevant information elements into the beacon signal could certainly allow to improve on this, but it is neither supported by the current beacon formats nor available in the practical eNBs utilized for testing.

Our LSA controller implementation utilizes all of the needed interfaces together with the relevant power allocation policies that are discussed in the following section. Its current version employs a heuristic iterative search procedure to locate the optimal power assignment across all cells as to match certain performance targets (e.g., maximize the throughput or minimize the number of users that lose service). For the most unsatisfied constraint, a simple algorithm is applied in a loop: a vector of the expected reduction in interference for a 1-dB reduction of power in cell i is computed, and the most impacting cell is chosen. The power in this cell is then reduced by 1 dB and the vector is updated (with its sorted order restored). Once the constraint at hand is no longer the most unsatisfied, another constraint is chosen to proceed further. When all of the constraints are satisfied, the search is complete.

The asymptotic complexity of our proposed algorithm is $O(C \cdot R)$, where C is the number of cells and R is the number of constraints (e.g., incumbent's devices) in the system. The resultant power allocations may then be stored and used to initialize the subsequent runs, thus further reducing the time needed for reaction. This means that our solution can be scaled up to hundreds of cells if desired, without much sacrifice in the response times. To summarize, our proposed system implements all of the dynamic LSA functionality. While some of its components may not be production-ready as of yet (i.e., the LSA-eNB interface) due to the limitations in the underlying LTE subsystems, it clearly confirms that the considered system is not only feasible, but may also be deployed in larger cellular networks with reasonable effort.

Table 1: Main system-level parameters.

Description	Value
3GPP LTE system baseline	Release 10
Division multiplexing	FDD
Number of cells (eNBs)	3
Frequency band	17 (700 MHz)
Bandwidth	5 MHz
Number of resource blocks (RBs)	25
Max. eNB power level	0 dB
Min. eNB power level	-30 dB
Interference threshold	-85 dBm
Noise floor	-100 dBm
Path loss coefficients	5 dBm (concrete) 2 dBm (gypsum)
Path loss model	Enhanced FSPL
Number of terminals (UEs)	4
Transmission data rate	512 kbps
Frequency analyzer	R&S TSMW
Antenna	HL040 log-periodic broadband

4. Our Measurement Methodology and Results

To systematically demonstrate the outlined principles of highly dynamic LSA operation in practice, we conducted a full-scale real-world implementation of our capable LSA-based spectrum sharing system in a commercial-grade 3GPP LTE network deployment. In this unique trial, we focused on the UL LTE channel and evaluated its availability over the LSA frequency bands. The UL system has been preferred due to its significantly higher implementation complexity as compared to the DL LTE channel, which also led to more interesting observations. The primary system-level parameters are summarized in Table 1, while the composition of our trial implementation is detailed in Figure 3.

The UEs under test were continuously communicating with the remote server located on the Internet, which recorded their effective UL and DL bit-rate values over time. Prior to taking measurements, the UEs were configured to target a constant bit-rate (CBR) transmission at 512 kbps, if sufficient UL radio resources were available; otherwise, they utilized all of the remaining UL resources subject to the current transmit power restrictions. The trial focused on analyzing the LSA band and demonstrating its highly dynamic operation. Hence, the UEs were forced to shut down

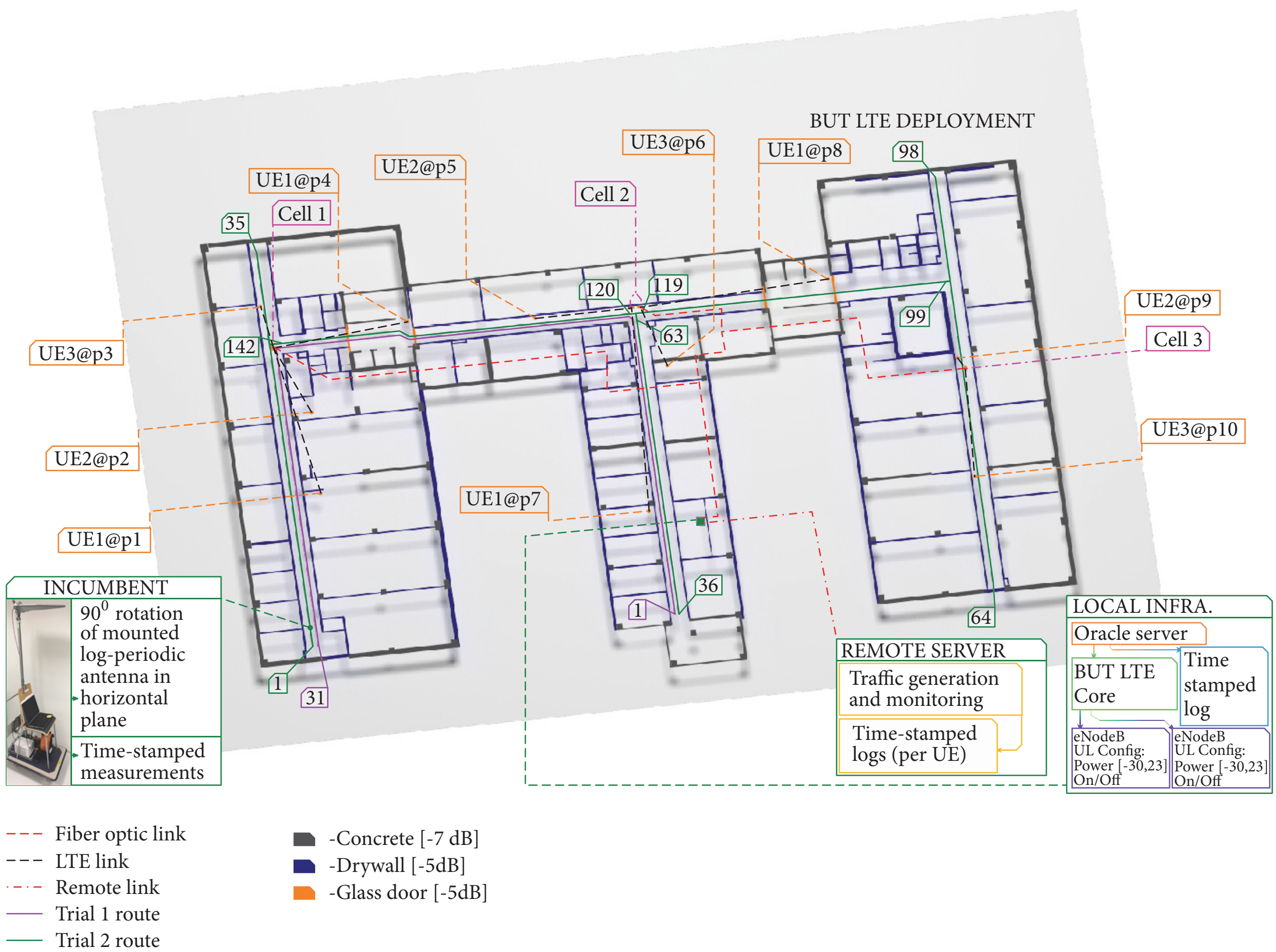


Figure 3: Implemented dynamic LSA setup (architectural components) in our test 3GPP LTE infrastructure.

whenever they were supposed to switch over to the non-LSA frequencies. An enhanced FSPL model was created to decrease errors of the interference estimation procedure. This step was needed, since no precise radio propagation model of the test environment was available. In order to calculate the path loss, we examined which obstacles signal had to penetrate through, while travelling over the direct path from a transmitter to a receiver. Each of the objects was assigned a specific material with its attenuation value that was added to the total path loss. This model helped us avoid situations where interference was estimated incorrectly because of the fact that the pure FSPL model does not take into account walls and other obstacles.

4.1. Power Allocation Policies. Two representative power allocation policies based on heuristic iterative search were implemented as part of the LSA controller: (i) "Derivative" algorithm and (ii) "Shannon" algorithm. Both methods assign the maximum allowed uplink power across the cells such that the total interference from the network towards the moving measurement cart (which represents the incumbent) does not exceed a given threshold. Our trial scenario utilizes 4 UEs, since we were limited in supply. Despite this, we managed to have a system that is well balanced in terms of complexity and the number of participating UEs. They remain stationary and their positions are known, since the dimensions of the trial required precise positioning, thus making the system more complex. This, in turn, makes the measurement setup more prone to behaving incorrectly, should positioning function inaccurately. The interference from a cell (eNB) can typically be approximated by the maximum interference from all the UEs in this cell. Hence, for the 3 utilized cells (see Figure 3), the total interference on the measurement cart is estimated as a sum of the interference levels produced by the UEs closest to the cart, taken across all cells.

(1) Derivative algorithm: this algorithm maximizes the interference reduction against the total power loss. It lowers the power in the closest cell, thus reducing its interference towards the measurement cart, and when the closest cell is shut down, it moves on to the next closest one. The algorithm for power reduction is as in Algorithm 1.

To increase the power in a cell when the cart has moved away, we use Algorithm 2.

Hence, Derivative algorithm provides us with the most interference reduction by lowering the power in the cells that are the closest to the measurement cart.

(2) Shannon algorithm: this algorithm employs the capacity estimate formula $C = B\log_2(1 + S/N)$ to evaluate the

```
while interference I is higher than the threshold I_0 do
    Find the closest active UE;
    Find cell this UE is associated with;
    Lower the power in that cell;
    if power in cell is reduced below its minimum
      feasible level then
        Shut the cell down;
        Remove cell from the list of active cells;
        Remove UEs associated to the cell from the list
          of active UEs;
    end
end
```

Algorithm 1

```
while interference I is lower than the threshold I_0 and
  list of considered cells is not empty do
    Find the farthest considered cell with less than
      maximal feasible power level;
    Find the UEs associated with this cell;
    Calculate the interference gain dI in case of power
      increase;
    if I + dI < I_0 then
        if cell was shut down then
            Turn the cell on;
            Add cell to the list of active cells;
            Add UEs associated with the cell to the list
              of active UEs;
        else
            Increase the power to I_0;
        end
    else
        Remove the cell from the list of considered cells;
    end
end
Reset the list of considered cells;
```

Algorithm 2

```
for each i from list of considered cells do
    for each j from UEs associated with the cell i do
        calculate the required power level P_ij needed to
          connect to the cell;
    end
end
while interference I is higher than the threshold I_0 do
    if list of considered cells is empty then
        Reset the list of considered cells;
        Reset the list of considered UEs;
        Find the closest UE, which is active;
        Set this UE as inactive;
    end
    Find the closest active UE;
    Find cell this UE is associated with;
    Lower the power in that cell;
    if power in cell i is reduced below its required power
      P_ij needed for the UE j to connect then
        Set power to level P_ij;
        Remove cell from the list of considered cells;
        Remove UEs associated with the cell from the
          list of considered UEs;
    end
end
```

Algorithm 3

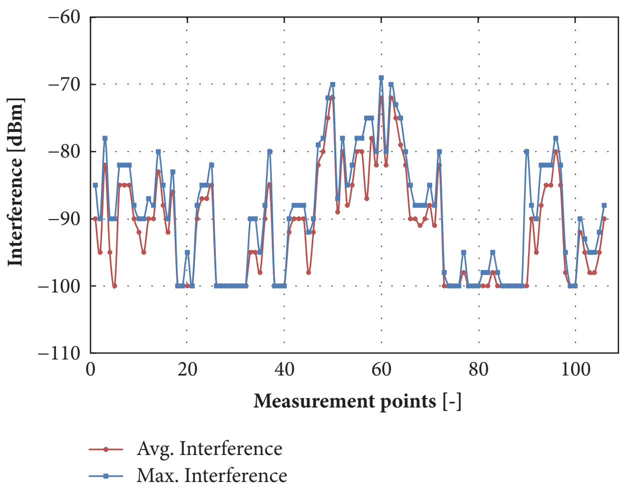
```
while interference I is lower than the threshold I_0 and
  list of considered cells is not empty do
    Lower power in all cells to the closest level P_ij;
    Find the farthest inactive UE j;
    Find cell i this UE is associated with;
    Calculate total interference I' if the power in cell i is
      set to level P_ij;
    if I' ≤ I_0 then
        Set power in cell i to P_ij;
        Set UE j as active;
    else
        Use Derivative power increase algorithm;
    end
end
```

Algorithm 4

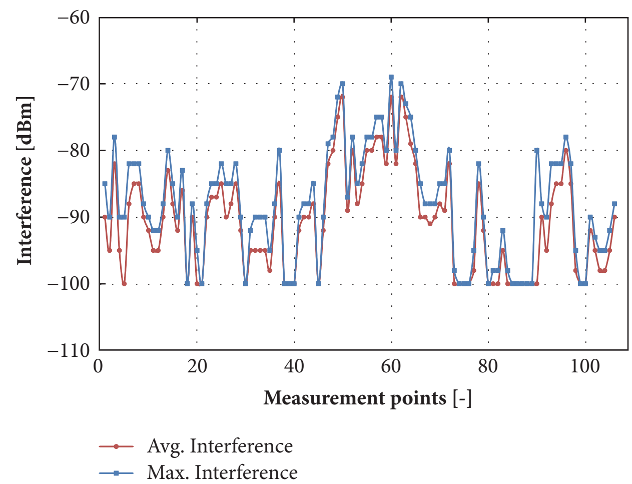
changes in the user's effective transmission rate. Importantly, if the user's required bit-rate is below its capacity (subject to the current power restriction), there is no change in the effective transmission rate. The algorithm selects a cell for the power decrease procedure as to maximize the interference reduction subject to the minimal loss in the total effective transmission rate of its users.

Algorithm 3 aims to maintain the UE connectivity to the cells instead of providing them with the highest reliability service. Therefore, it prioritizes keeping the users connected. A user j is considered to be connected to cell i if its UL transmit power level is above P_{ij} and allows it to maintain rate above a certain threshold. The power increasing algorithm works as in Algorithm 4.

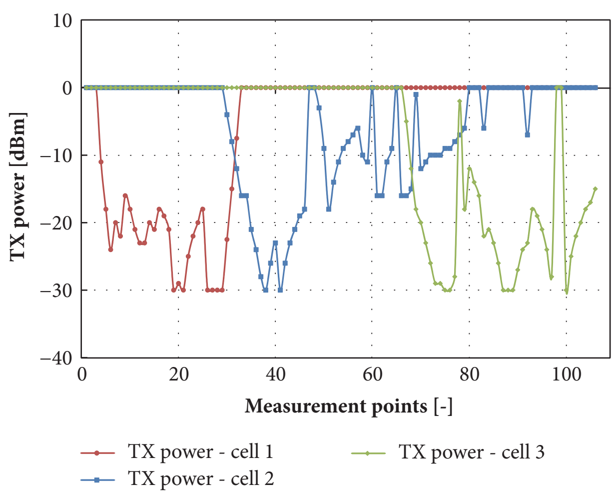
Similar to Derivative algorithm, Shannon algorithm first lowers the power in the closest cell, thus reducing its interference towards the measurement cart, but only until the lowest transmission rate in this cell reaches the threshold. While the interference threshold is still not reached, the algorithm moves on to the next closest cell. If the power level is such that the bit-rate of the "worst" UE has reached the threshold, but the interference still remains above the target value, the algorithm returns to the first closest cell, drops the "worst" user, and lowers the power in a similar manner again by comparing the second "worst" user's bit-rate against the threshold. Varying the transmission rate threshold P_{ij}, one can control the minimal guaranteed bit-rate. On the other hand, setting the threshold too high can cause more user drops from the network, since a UE is considered dropped when it cannot maintain its threshold transmission



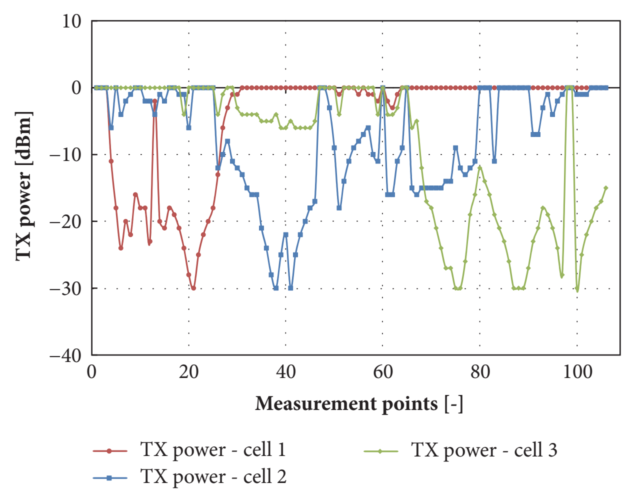
(a) Average/maximum interference for Derivative algorithm



(b) Average/maximum interference for Shannon algorithm



(c) Transmit power allocation for each cell according to Derivative algorithm



(d) Transmit power allocation for each cell according to Shannon algorithm

FIGURE 4: Measurement-based results produced in the conducted dynamic LSA trial.

rate. Therefore, a sensible solution would be to set the QoS-guaranteed bit-rate equal to the threshold transmission rate.

4.2. Main Hands-On Observations. Our primary objectives in the conducted dynamic LSA trial were to (i) compare the above power allocation policies and (ii) verify whether the corresponding algorithms operate as intended; i.e., they do not breach the interference threshold while meeting their respective optimization targets. The results were collected on a predetermined set of the measurement cart locations placed along the route for the second trial; see green path in Figure 3, where two evaluation scenarios are illustrated: (i) the purple path indicates the measurements for the purposes of QoS assessment (completed in our previous trial [17]), while (ii) the green path stands for the overall testing of the implemented heuristic iterative search logic (conducted in the current trial). As it was mentioned above, measurement points were placed along the route. Their numbering is given in Figure 3 as index of the first and the last measurement point on each segment of the route. Distance between the neighboring points was equal to 1.5 meters. All indexes of the points in this trial refer to points along the green line in Figure 3. Note that the system was notified on the movement of the measurement cart, while at every instant of time the interference was recorded. All of the relevant data were continuously logged for further analysis. Accordingly, Figures 4(a) and 4(b) report on the average (red line) and the maximum (blue line) interference levels received by the measurement cart at each position for both algorithms. It is also important to clarify that since we only had 4 physical UEs, we devised an approach to increase their number in a trial by reusing physical devices at different positions. Hence, the label "UE3@p3" means that the third physical UE was placed at position 3 in our trial. Relocation of the UE was performed only when any interference from it was negligible at the measurement cart, in order to minimize the effect of this procedure.

Comparing Figures 4(c) and 4(d) that illustrate the power allocated according to Derivative and Shannon algorithms, one can observe that when the cart is located in the first cell the Derivative algorithm only alters the power allocation there, while the Shannon algorithm adjusts all three cells in order to raise power and transmission rate in the closest cell. Hence, it can be concluded that Shannon algorithm operates more flexibly over the entire network, while Derivative algorithm mostly concentrates on the nearest cells. From Figures 4(a) and 4(b), where the average and the maximum interference levels received by the measurement cart across the check points are reported, we learn that unlike the Derivative algorithm the Shannon algorithm not only lowers the average interference, but also attempts to maintain it as close to the threshold as possible, so as to increase power and transmission rate in the network. In both plots, however, we can observe an interference threshold breach with the peak value of 10 dBm. This breach spans from point 50 to 70, and it can be seen that at these points the measurement cart was close to the UEs. This can be explained by imperfections in the path loss model, which was used to estimate the interference and calculate the penalties for the UL.

5. Conclusions

This work accentuates the importance of highly dynamic spectrum sharing to leverage additional bandwidth that may be lightly used by its original incumbents. To further improve upon spectrum utilization in demanding 5G systems, we focus on the emerging LSA framework for vertical sharing, where the incumbent(s) and the licensee(s) operate over the same geographical area by utilizing common frequencies in a carefully controlled manner. This concept has been coined in 2013 and since then rapidly took off with many hands-on demonstrations across Europe, primarily in 2016. Supported by visible research initiatives, such as ADEL [3] and CORE++ [6, 11, 13], the LSA functionality has been tested in a number of countries with the emphasis on the feasibility of its early implementation.

Complementing these important efforts, the present study relies on our rigorous past research (please refer to a summary on our prior system-level evaluations of dynamic LSA operation here: http://winter-group.net/dyn-lsa-sim-res/) to advance the state of the art on LSA by outlining its additional functionality required for highly dynamic operation. We therefore elaborate the key principles of system implementation as well as contribute our unique practical methodology based on a live cellular network deployment. The obtained measurements corroborate the rich capabilities of highly dynamic LSA operation in a commercial-grade network as well as report on the crucial performance indicators related to QoS and service-level reliability.

After completing the trial and analyzing the results, we therefore conclude that application of power control policies is viable. Moreover, to a certain extent it is possible to use the considered policies indoors in cases where precise signal propagation model is available. The only locations where the cell was powered off are those near the UE positions. However, since there was no precise model available, and the scale of the deployment was relatively small, some discrepancies were experienced.

As a result, we can state that when applying power control policies in indoor scenarios, there are certain prerequisites. One of them is a precise path loss model. Another one is the capability of pinpointing the locations of the UE devices in case of uplink LSA application. MEC may aid further in this regard in case the UE mobility is present. For example, supplementary sensor information can be collected from the UEs to estimate their movement in a more accurate manner. Moreover, if the UE devices or the incumbents travel at high speeds, we need to update the UL power limits with higher periodicity in order to keep up with the current situation. Pushing the threshold calculation tasks as close as possible and increasing the compute power will help grow the update frequency as well as the maximum number of UE devices in the network.

Going further, we believe that our results will become instrumental to comprehensively reap the benefits of LSA-based highly dynamic spectrum management scenarios, whether in 2.3 – 2.4 GHz frequency bands or at alternative frequencies, such as 3.4 – 3.8 GHz and possibly up to 4.2 GHz in perspective. This will require further demonstration efforts that may rely on our methodology proposed in this work, which could also be useful for other spectrum sharing initiatives across the globe, including CBRS in the US as well as dynamic spectrum utilization at mmWave frequencies.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Disclosure

The partial presentation of the manuscript was done as part of the successfully defended doctoral thesis of the first author "Heterogeneous Connectivity of Mobile Devices in 5G Wireless Systems" [29].

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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