Metrics for Efficiency of Spectrum Sharing in Wireless Networks

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Abstract

With the rapid development of wireless services, the demand for spectrum keeps growing. Spectrum sharing is regarded as a means to achieve more efficient spectrum access. This paper presents a literature review of current metrics for efficiency of spectrum sharing in wireless networks. Considering the perspective of various stakeholders, namely the network operators, the government and the service providers. Two new metrics are introduced to address stakeholder interests: the *Satisfaction Fairness Index* (SFI) and the *User Service Capacity* (USC). Simulations are carried out to give examples of how both metrics can be used for an LTE-LAA and WiFi coexistence scenario. The SFI is proven to be effective for assessing both the fairness and satisfaction of a spectrum sharing network, while the USC can be used to gain insight into the number of users served.

Keywords— metrics, coexistent networks, network operators, governments, service providers, users

1 Introduction

The past decades have shown an increase in wireless devices, yet the future looks towards even more of them to enhance our quality of life. It is estimated that by 2022 there will be about 12 billion mobile devices globally [3]. However, each device requires a portion of the electromagnetic spectrum to be able to communicate with others and unfortunately, the spectrum is a finite resource. Moreover, the division of spectrum into licensed and unlicensed categories has resulted in idle, yet inaccessible frequencies in the licensed region. So, as the demand for spectrum grows, wireless connectivity becomes constrained as a result of its scarcity.

A popular remedy for this is spectrum sharing, which allows users to share the same channel. However, the nature of sharing spectrum brings with it the dilemmas of disruption of communication, fairness of resource distribution, and efficient use of spectrum resources [27]. Apart from this, security is needed to enforce the rules associated with the spectrum resources and to guard against attacks that use the behaviour of a sharing system to strategically strike users [13]. These problems are known to be heightened when networks with dissimilar technologies coexist. This is a barrier to spectrum availability as it can hinder the uptake of spectrum sharing. Therefore, it is important to be able to adequately quantify the performance of such networks to be sure of what can be expected from the system.

Many current metrics for spectrum sharing efficiency are application specific with the goal of a given system in mind [22],[36]. However, for spectrum management and regulatory purposes it is more useful to have generic metrics which are technology and usage neutral [23]. Additionally, the current metrics examined do not mention how they are applicable to the key players in communication systems. The four key players can be identified as government, network operators, service providers and end-users; which all have different interests. First, governments generally work towards spectrum availability for the growth of services to better their nation and have a more social outlook. Second, network operators want to maximize their business value by having access to a diverse range of spectrum and have a more economic perspective. Finally, service providers and end users share the goal of wanting an acceptable quality-of-service (QoS) at reasonable costs [27].

This study aims to develop new metrics to evaluate the performance of spectrum sharing systems in relation to stake holders' interest. These efficiency metrics will cover fairness of resource allocation and efficient use of spectrum resources. The effect of spectrum sharing on security will not be further discussed as, at the time of research, no metrics for security could be found.

The following questions will be examined:

1. What metrics can be established to evaluate a spectrum sharing network in relation to the needs of the stake holders involved?
2. What insights do the developed metrics reveal when analysing a coexistent network?

This thesis is organized as follows. Section 2 overviews the background knowledge while Section 3 presents current spectrum sharing metrics. Section 4 and 5 propose new metrics and describe the methods and results of simulations; respectively. These results are discussed in Section 6. Finally, the conclusions and recommendations of this study are stated in Section 7.

2 Background

2.1 Spectrum Sharing Domains

The European Radio Spectrum Policy Group (RSPG) define spectrum sharing as: "the common utilization of the same frequency resources by more than one user

- at the same time in different geographical locations or
- at the same geographical location in different times or
- at the same time and the same geographical location."

Appendix A shows that signals can be separated in multiple ways for spectrum sharing, namely: time, frequency, code and space.

2.1.1 Time Domain

In this domain, freedom from interference is valued over continuity of transmission. Users are assigned a mutually exclusive

Research conducted at the Design and Analysis of Communication Systems (DACS) group, of the Electrical Engineering, Mathematics & Computer Science Faculty at the University of Twente, under the supervision of Dr. S. Bayhan and Prof.Dr.Ir Geert Heijenk.[July 2021] time slot in which they can transmit on a common channel. The time slot may be fixed or dynamic [24]. Either way all stations must be aware of the beginning and end of their time slots to ensure transmissions do not overlap. The Time Division Multiple Access (TDMA) protocol can be used to implement this kind of sharing.

2.1.2 Frequency Domain

In the case of static networks, channels are preassigned to transmitters and any changes need to be coordinated in advance. As such, receivers know which channel must be used to receive a message from a specific transmitter. This is commonly used in licensed sharing [24].

Contrastingly, for dynamic networks, channel assignment is determined at the time of transmission using a database or sensing to determine which channels are available. Based on the network's demand, one or more users share the same channel for a given period of time. A popular scheme of dynamic access in terms of frequency and time is FDMA [24]. Frequency Division Multiple Access (FDMA) protocol separates one channel into multiple sub-channels such that each user has their own bandwidth that can be used without time constraints [1]. Generally, guard bands are used to separate these sub-channels. Guard bands are narrow idle channels that are used to separate active channels and minimize signal leakage into adjacent bands [27].

2.1.3 Code Domain

Code Division Multiple Access (CDMA) is a protocol that uses the transmitted data to determine which nodes can communicate at the same time. These nodes transmit for as long as needed and use a unique code sequences to differentiate signals. The signal, of each user, can only be decoded by the intended receiver. The bandwidth of the coded data is chosen to enlarge the original data signal and spread the signal across the operating band [1]. This method is most effective when all nodes in a given band use it; provided that all of the codes are distinct so the receivers can tell the signals apart [24]. By increasing the transmission bandwidth, the power spectral density and the susceptibility to interference within the same band is reduced [20].

2.1.4 Spatial Domain

Radio wave can be sent in an omnidirectional or directional manner. Omnidirectional antennas radiate a signal in all directions at an equal power, while directional antennas focus their signals towards the receiver. By directing their power, the interference with neighbouring towers is limited and concurrent frequency sharing can be allowed [24]. However, this is only possible when the directional antennas do not send signals in the same direction.

2.2 Types of Spectrum Access

There are five main categories of spectrum access: license exempt, licensed, Licensed Shared Access (LSA), Licensed Assisted Access (LAA) and Dynamic Spectrum Access (DSA). Appendix B, gives a condensed overview of these access methods in terms of their regulatory approach and the priority of users involved. License exempt (or spectrum commons) and licensed access are considered to be the conventional approaches where a clear line is drawn between usage of licensed and unlicensed bands. On the other hand, LSA, LAA and DSA are alternative in the way in which they blur the lines between the two conventional bands [25]. These alternative means of access provide more opportunities for increased spectrum utilization.

2.2.1 Licensed Exempt & Licensed Access

Licensed access gives exclusive rights to spectrum resources and binds the licensee to operational rules which ensure limited interference to nearby operators [25]. Licensed users pay for a guarantee of quality of service. On the other hand, license exempt access shares unlicensed spectrum between unlicensed users with the premise that all users should have equal access to resources. It employs mechanisms to reduce interference like listen before talk but can not guarantee there will be no disturbances (e.g., WiFi) [10].

2.2.2 Dynamic Spectrum Access

Dynamic spectrum access (or licensed exempt shared access) does not require a license. There are two versions of DSA; one is database-assisted and the other is spectrum sensing based. DSA facilitates sharing of licensed spectrum to license exempt users. It finds currently under utilized bands that will cause minimal interference to primary users in the area and stores this information in the database. Users can then choose a channel to operate on from the database. This information can be extracted from a database or spectrum sensing mechanisms [25].

2.2.3 Licensed Shared Access

Licensed Shared Access (LSA) is a two-tiered model whereby incumbents have a formal agreement with a limited number of sub-licensees on how spectrum will be shared between them [31]. It gives licensees access to spectrum that would be otherwise inaccessible while ensuring quality of service to the licensee and incumbent users. The two users share the same spectrum in a TDMA manner such that there is exclusive band use at a given time and place [27]. Spectrum management in this case is done using a database provided by incumbents. This database specifies the availability of spectrum over frequency, time and space which determines if sharing access will be granted [29]. Furthermore, LSA includes sharing between different types of radio systems [15].

2.2.4 Licensed Assisted Access

Licensed Assisted Access (LAA) occurs when a licensed user uses its licensed spectrum as well as additional unlicensed spectrum. These licensed users opportunistically gain access to unlicensed spectrum to boost transmission capacity and speed. A common example of this is LTE in the unlicensed band [32]. In this case, spectrum sharing occurs in the unlicensed domain. This means that the license-exempt users can be viewed as primary user that should not experience service degradation due to the secondary (licensed) user.

2.3 Coexistent Technologies in the Unlicensed Band

Sharing in the licensed exempt band has been a major point of interest in research due to the few restrictions placed on users in these bands. Sharing in these cases typically requires more coordination unlike sharing in the licensed bands; which tend to rely on technical specifications and procedures [23]. This is especially important for spectrum sharing networks that use different wireless technologies [8]. Networks try to meet their own needs, but without adequate coordination they can ignore the needs of their spectrum sharing partners.

The authors of [8] name WiFi as the incumbent of the licensed-exempt regions of spectrum. WiFi is a prominent wireless technology that has existed in the unlicensed band for a long time. It can be seen as an incumbent to emphasise that the performance of current widely implemented systems (like WiFi) should not be degraded when other systems use unlicensed spectrum.

WiFi-LTE coexistent networks are viewed as the main candidate to deal with traffic offload in cellular networks [11]. LTE typically operates using licensed bands to gain channel access. However, recent initiatives have been made to use unlicensed spectrum in addition to its licensed spectrum. In spite of the operational guarantees of licensed access, high prices and limited availability have caused a shift towards using unlicensed spectrum. The main effects of this are a boost in speed and increased capacity at no additional cost. Typically, the unlicensed channel is used to supplement the downlink (base station to device) transmission capacity of the licensed channel [32]. LTE exists in the unlicensed bands as LTE-Unlicensed (LTE-U) or LTE-Licensed Assisted Access (LTE-LAA). LTE-U senses channel utilization and uses this to determine its on/off duty cycle. On the other hand, LTE-LAA, uses a Listen-Before-Talk (LBT) protocol to check if a channel is free before transmitting [32]. Without these regimes, LTE in the unlicensed bands would transmit of its own accord since it is designed for uninterrupted and synchronous operation [17]. Contrastingly, WiFi would wait for the channel to be free [8]. This leads to unfair resource distribution among the networks.

In continuation, ZigBee is a low power and low data rate technology that operates in the 2.4 GHz band just like WiFi [4]. However in this case, WiFi generally does not suffer from the coexistence. Due to ZigBee's low operation power, if the network it coexists with uses a high power level, the ZigBee network will experience strong interference [8]. Additionally, if access points are in close proximity, ZigBee will face interference even when it does not use the same channel. This results from WiFi transmissions sending unwanted signals on the frequencies surrounding its operating channel which can jeopardise ZigBee communication [28].

3 Current Metrics

We categorize the current metrics as economic, social or QoS. These groups derived from the interests of the various stake holders involved in wireless communication systems (see Section 1). An overview of current metrics and their associated categories can be found in Fig. 1.

- Economic: This class is aimed at network operators. Economic benefits may be in the form of using a licensed band efficiently such that more spectrum is made available. This additional spectrum could be used to increase transmissions without needing to pay for more spectrum access. Additionally, it could be used to generate income through licensed sharing or spectrum leasing. Other means towards economic gain include an increase in quality of service provided to users.
- Social: The social category is targeted at governments. This aspect deals with digital inclusion through coverage and accessibility. Furthermore, aspects like greenness, application case and availability of spectrum also play a role. More available spectrum leaves room for new services and technologies that improve quality of life (e.g., autonomous vehicles).
- QoS: This group targets service providers. QoS takes many forms, for instance, [12] considers improving quality of service to consist of reducing transmission delay, increasing throughput and improving overall network utilization. It is also mentioned that the importance of each of these attributes will vary depending on the application. However, fairness is also required to have a better understanding of the quality of service. Knowing that the quality during service is low is not enough to judge a system's operation. For example, experiencing a low throughput while another network, with the same priority in a sharing scheme, has a high throughput is different to all networks having a low throughput. Fairness is important because it expresses these differences. Consequently, quality of service in this context characterises the quality during use and the level of fairness that networks experience (system level).

The current metrics are analysed from these perspectives; although they may not have been designed with these contexts in mind. Notably, some metrics fall into multiple classes. In these cases, they are placed with the category deemed as most relevant and the other class is mentioned.

3.1 Economic

The *General Area Spectral Efficiency (GASE)* quantifies the spectral usage efficiency while taking into account spatial aspects and greenness of wireless transmissions. Greenness is considered using the power utilization efficiency which makes this metric useful for saving money [35]. It penalises high transmission power regardless of if the increased power results in interference to other networks or not [30]. This metric quantifies both economic and social aspects of a system. Economically it can reduce operational costs by using less power. This improves energy conservation which is considered a social benefit. Moreover, it builds on the Area Spectral Efficiency (ASE) metric in [34] and among other things, generalizes it for use with arbitrary wireless systems [35].

Similarly, there is the *Energy Efficiency* metric which measures the energy consumption with respect to the traffic capacity provided by a network. To this end, a network's efficiency is high when there is efficient transmission and, in the case of no ongoing transmissions, when minimal energy is consumed in an idle state. This metric is made up of two sub-metrics. When there is no data, the *Sleep Ratio* is used but when there is data, the *Average Spectral Efficiency* is used instead [21]. The *Sleep Ratio* is the proportion of unoccupied time resources to the cycle of the control signal. The *Average Spectral Efficiency* is the sum of the throughput of all users divided by the channel bandwidth multiplied by the number of transmission reception points and the time for data to be received [21].

Besides these, there is a broadly defined *Economic Efficiency* metric which is the ratio of value of output to cost of all inputs [16]. Here "value" refers to the significance of the information transmitted and the aim is to optimize a given value criteria using the least amount of input. This broad interpretation allows for application specific and independent versions of the metric.

3.2 Social

Spectral Efficiency is the the ratio of the maximum throughput to the bandwidth. It quantifies the efficiency of a communication system by checking how much data can be transferred using a given bandwidth [7]. From a social perspective, this is important to minimize spectrum wastage and have available spectrum for new services or users. The measure has the units bits/Hz.

The *Bandwidth Density* is the ratio of the theoretical channel capacity per second to area covered [33]. This measures how efficiently a portion of spectrum has been used in a given area. Similarly, the *Area Traffic Capacity* calculates the total throughput in

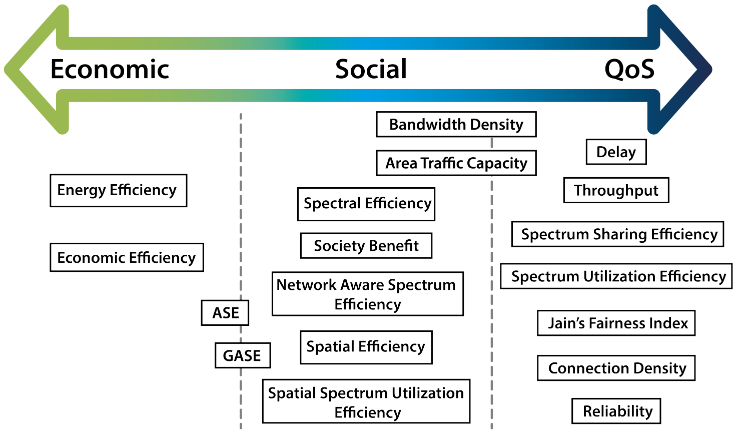


Figure 1: An overview of current metrics in relation to stake holder perspectives (Economic, Social & Quality of Service)

a given area [21]. This metric is more insightful than the Bandwidth Density as it uses the actual amount of data transferred rather than a fixed data capacity. The Area Traffic Capacity can highlight which regions of a country are limited by their network connectivity while the Bandwidth Density reveals which areas have more opportunities for digital inclusion. That being said, they can both also be used as indicators for quality of service.

In continuation, the *Society Benefit* measure refers to a non-technical consideration of the value an application gives to the public [33]. In [33] it is proposed to use Society Benefit along with the Economic Efficiency to create the "ultimate spectrum efficiency measure". For example, bands allocated for safety applications could use the Society Benefit to compensate for low efficiency due to having a low throughput. The main downfall of the Society Benefit is its high level of subjectivity [33].

In a similar fashion, the *Network Aware Spectrum Efficiency* considers priority of users and bits [30]. This priority means that important bits and users are provided with more resources irrespective of degradation to other services. Despite this, the metric considers the changing interference footprint of network users in its calculation. Furthermore, it describes the relationship between transmit power and efficiency in a way that depends on network parameters in dynamic access regimes. This allows for the optimal power of a system to be determined. This metric takes inspiration from the *GASE* but does not consider a greenness factor. As a result increasing transmit power is only penalised by this metric when it causes interference to other users. Furthermore, it is notable to mention that this metric facilitates frequency reuse; which is the sharing of a channel in the spatial domain.

Another metric that shares this goal is the *Spatial Efficiency* metric [22]. It consists of the transfer-, space usage- and directivity efficiency of the link. The transfer efficiency used relates the real data transfer rate to a reference transfer rate to quantify spectral efficiency. The space usage efficiency, compares the volume of space the signal occupies during communication to the required volume for successful communication. Finally, the directivity efficiency part measures how well a transmitted signal is focused towards the receiver. This results in a more extensive analysis of spatial sharing than the Network Aware Spectrum Efficiency provides; since transmit power is its main spatial use indicator. With good spatial usage, risk of interference can be reduced and towers could have the potential to transmit further.

Additionally, the *Spatial Spectrum Utilization Efficiency* metric in [5] also regards the spatial domain. It evaluates the efficiency of reusing spectrum for dynamic spectrum sharing scenarios. It considers primary and secondary transmitter towers of different heights, transmission power and gain. High levels of efficiency were found when the primary user's height was significantly larger than the secondary users. Furthermore, efficiency is proportional to the number of secondary users the system can support. Once again, this metric is less insightful that the spatial efficiency mentioned above. This is a result of the fact that only the volume of space used is considered.

3.3 Quality of Service

Delay and *Throughput* are two of these most common QoS metrics for communication systems. *Delay* refers to the amount of time required to send all bits of the packet through the link. It depends on the size of the packet and the link rate [18]. While *Throughput* is the amount of data successfully transferred over a channel per unit of time [14].

Jain's Fairness Index (JFI) is a widely used fairness metric that is mainly for evaluating fairness over long periods of time [19]. Despite this fact, it is still capable of assessing short-term fairness. Jain's fairness index gives an intuitive result of how many users experience a given quality factor fairly such that the percentage fairness is equal to the percentage of users treated fairly. Often, Jain's Fairness Index is associated with assessing the fairness of throughputs among users. However this measure gives no indication of the level of quality experienced. For example, a system will have a 100% fairness of throughput when all users receive 0 bits/s.

The *Connection Density* metric refers to the a number of devices that meet a quality factor per unit area [21]. Instead of considering a quality factor is distributed over users, this metric considers how its quality is spread over space.

The *Spectrum Sharing Efficiency* considers the net spectrum utilization, duty cycle and radio frequency (RF) power density [23]. The net spectrum utilization accounts for the signal to interference ratio. As a result, the Spectrum Sharing Efficiency metric gives insights into how noise, power density and duty cycle affect the extent to which spectrum sharing can be maximized. Trade offs can then be made between sharing efficiency and user satisfaction (in terms of duty cycle and noise). This metric was made for heterogeneous networks in a technology independent manner.

Another similar metric called the *Spectrum Utilization Efficiency* unifies the actual spectrum resource usage (bandwidth, space, time) with the fairness of coexistent systems in terms of throughput [36], to give one value that represents the resource utilization of the entire system. This builds on the *Spectrum Utilization Efficiency* from [9] but provides a technology independent approach. The fairness aspect included is shown to follow the trends of increase and decrease in Jain's Fairness Index for a given system. However there is not an exact correlation. This metric was developed for regulator use therefore it is technology and application neutral.

Finally, *Reliability* measures the probability that a given amount of traffic will be successfully transmitted within a fixed time [21]. More specifically this metric considers the transmission of a layer 2/3 packet and was defined for ultra-reliable and low-latency communications. The predetermined time is given as the duration of delivering a small data packet from a layer 2/3 service date unit ingress point to its corresponding egress point at a certain channel quality.

4 Design of New Metrics

This section presents the proposed metrics along with the requirements and shortcomings of each metric. The proposed metrics are the Satisfaction Fairness Index and User Service Capacity.

4.1 Requirements

The proposed metrics should be applicable for all sharing domains; regardless of technology or use case. This will allow the metric to be applied to a large variety of coexistent systems and allow for these systems to be compared. Furthermore, they should be useful for at least one of the four key players (governments, network operators, service providers and users) by measuring a concept within their scope of interest.

4.2 Satisfaction Fairness Index

The Satisfaction Fairness Index (SFI) combines the level of satisfaction users experience and the fairness with which this satisfaction is distributed. Its goal is to examine a quality of service parameter in terms of equity, by measuring the fairness with which a user's needs are being met. While the fairness of a quality of service parameter is important, it may not always reflect the users experience, because different users have differing needs. These differences may be especially prominent in coexistence scenarios where dissimilar technologies are present. Assume two networks where one requires high throughput whereas the other is network for low-rate applications. Optimizing fairness of throughput would give all users an equal throughput value. However, this value is not representative of the needs of network users because users may not be equally satisfied. SFI improves on this by accounting for users' differing needs.

The SFI is defined as the average user satisfaction of the shared system multiplied by the fairness of satisfaction and is calculated as follows:

$$SFI = \frac{\sum_i s_i}{n} \times JFI(S) \quad ; \quad JFI(S) = \frac{(\sum s_i)^2}{n \sum s_i^2} \tag{1}$$

$$s_i = \begin{cases} \frac{QF_m}{QF_r}{}_i & \text{for } QF_m < QF_r \\ 1 & \text{for } QF_m \geq QF_r \end{cases} \tag{2}$$

S is the set of user satisfaction values, s_i is the satisfaction of i^{th} user, QF_m is the measured quality factor, QF_r is the required quality factor and n is the number of users in spectrum sharing system.

This metric uses Jain's Fairness Index to find the fairness of satisfaction. A major downfall of JFI is that it considers fairness without any regard for the level of a quality factor. Therefore, maximum fairness (JFI = 1) can be achieved when all users have a throughput of 0. However, in the case of the SFI, this would give the minimum value (SFI = 0). Furthermore, the maximum SFI can only be achieved when there is complete fairness and all users are satisfied. Just like JFI, the SFI is bounded between 0 and 1. This means that the SFI does not favour users having more than their required amount. This reduces biases in the average satisfaction result since users with much more than their required amount will not be able to raise the average satisfaction.

This metric falls into the category of QoS and may be used for any quality. The satisfaction is given as the ratio of measured amount to required amount. This metric can be used by the research and development teams of Service Providers to experimentally investigate which sharing scenarios can meet the service standard they offer to customers. With this knowledge Service Providers can use spectrum sharing systems with less concern for reduced quality and dissatisfied customers. Hence this covers Service Providers' interest in the QoS it can offer to clients. Furthermore, since user satisfaction is fundamental to this metric, the SFI intrinsically promotes the users' interest in receiving an acceptable QoS level. Finally, SFI could be useful for Network Operators in determining how much the service providers of each coexistent network should pay. For example if the SFI is low then it could be decided that the network with high satisfaction should pay more in operation costs.

4.3 User Service Capacity

One of the main reasons for spectrum sharing is to keep up with the growing demand for wireless devices. Moreover, the social perspective pushes for digital inclusion and accessibility. With these goals in mind, the *User Service Capacity* (USC) was designed. This measures how many end-users are served by a given frequency over a period of time. It gives insights on how demands can be met in terms of devices instead of throughput. By doing so, a more social approach is taken where the aim is to maximize the number of devices that can access a channel at a given time.

The USC is defined as the sum of users served in a spectrum sharing system over all sub-channels of each of the networks. The main rationale of this is to ensure that it could be applied to all domain types of spectrum sharing. In fact, the USC favours shared systems, especially those which allow for simultaneous transmissions. It helps to move focus towards dynamic spectrum access regimes and more freely available channels. Formally, the USC is defined as:

$$USC = \sum_{n=1}^{N} \sum_{s=1}^{S_n} d_s \tag{3}$$

N is the number of networks in the system, S_n is the number of sub-channel of network and d_s is the number of users served by a sub-channel in time t.

In terms of use, the USC can be used by governments, in combination with demographic data, to determine the social benefit derived from a given network. This social benefit could be used to incentivize network expansion to less developed regions or underprivileged communities. These areas are important for governments to focus on, since their lack of commercial prowess drives away public sector investment. As such, they tend to fall behind in terms of digital inclusion. However, governments can reduce this gap of inaccessibility by, for example, giving tax rebates to networks that have a relatively high USC in predetermined target areas (eg. less developed regions).

Optimizing a system in terms of USC could potentially lead to different resource allocations. However, since this metric does not contain any indicators of quality of performance, many user requests can be successfully handled without users being satisfied. Other limitations include that comparisons can only be made for networks of comparable size and bandwidth. For networks with immobile devices, size would be in terms of number of connected devices. However, it is more complicated for mobile networks. In this case, size can be considered in terms of area coverage and the networks being compared should also have a similar environment (e.g., both rural) so that the number of potential users is comparable.

5 Simulations

To understand the behaviour of the proposed metrics we simulate a scenario with LTE-LAA and WiFi. This scenario was chosen because it represents an interesting case where licensed-exempt and licensed users should operate essentially as equals, while licensed operators exploit unlicensed channels for economic gain. Without strict rules on operation, these coexistent networks will need to be analysed in a case by case manner to see what impacts sharing have on the networks. Therefore, metrics for this case are important, not only for technical parameters but also for ethical ones like fairness.

The results from these simulations are used to demonstrate how the proposed metrics can be applied to an LTE-LAA and WiFi spectrum sharing setup. In continuation, the metrics considered while establishing the proposed metrics, namely: Delay, Throughput and Jain's Fairness Index, are also calculated. The insights gained from these metrics will be discussed. This aims to determine if the developed metrics add to the understanding of the system's performance, in a way that the existing metrics do not. Additionally, the amount of time each technology uses the channel is measured to help analyse the performance of the system.

The following section explains how simulations were conducted and metrics calculated. Subsequently, the expected outcomes and the results of the simulations are presented.

5.1 Methods of Statistics Collection

The NS-3 network simulator is used to realistically model the network layers and protocols involved in an LTE-WiFi shared system. Due to a low level of familiarity with the NS-3 software and a limited amount of time for this research, these simulations were performed using the open-source code developed by Nicola Baldo [6].

The simulation setting was configured as follows: the system operates at 5.180GHz where LTE has a bandwidth of 18MHz and WiFi 20MHz, 5 LTE User Equipment (UE), 1 LTE eNodeB(eNB), and 1 WiFi Access Point (AP) were deployed. Additionally, the number of WiFi nodes varied between 1 and 21 in steps of 4. All nodes in the simulation carried out transmissions for 30s. The number of steps and transmission duration reduced the overall simulation time and the required data-storage capacity. Moreover, steps of 4 allow for the situation where LTE and WiFi have the same number of users.

Each simulation scenario was run 10 times with randomized traffic generation; all other parameters, including the position of the nodes, were kept constant. The nodes were maximally 10m from their respective towers and the eNB and BS were spaced 30m apart. Other simulation parameters include TCP protocol with a segment size of 1448 bytes, and file size of 512k bytes. The file size is much larger than the segment size to increase channel congestion given the small number of nodes used in the simulation. The file size being larger than the segment size, forces the file to be fragmented and increases the number of packets that must be sent to transfer a single file. Attributes of each transmission were logged using the NS3 flow monitor, capturing the source/destination addresses, transmitted/received bytes, duration and delay. Furthermore, a log of the physical layer from [6] recorded information on the times that each technology used the shared channel.

5.2 Methods of Processing

The results collected in the NS-3 simulation environment were processed using Matlab. First, the downlink transmissions were filtered out to calculate the USC. Then, the uplink transmissions were filtered to remove duplicate nodes. Unique nodes were identified using the source address data from the flow monitor. Notably, using MAC addresses would be more appropriate to identify devices, however, as all communication in these simulations use the Internet Protocol, IP addresses are adequate to differentiate transmissions. The final USC value for each scenario of WiFi devices was then determined by using the average of the data from the ten repetitions for each unique IP address/device.

The SFI, is evaluated using the throughput per user. First, a required throughput value would need to be determined. For simplicity, all LTE users were assumed to be either browsing the web or using social media applications. Their requirements were estimated to be 4.5 Mbps. Likewise, all WiFi users were assumed to be streaming high resolution videos, so their required throughput was 17 Mbps. Next, the throughput for each user was calculated using the network throughput. Subsequently, the SFI of each simulation was calculated using the set of all user satisfactions (LTE & WiFi) and averaged over the 10 runs.

5.3 Results

5.3.1 Expectations

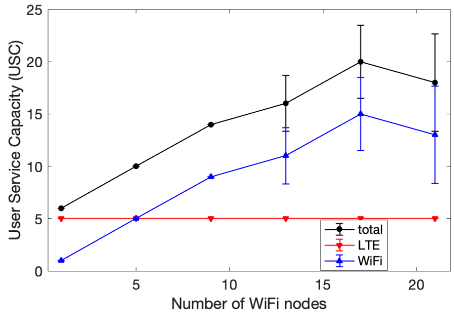
Inspection of the scenario suggests that as the number of WiFi nodes increases, the percentage of time that WiFi uses the medium will increase, because there will be more WiFi requests. The USC is predicted to increase to an upper limit. The total network throughput and spectral efficiency are expected to show similar trends, all of which are limited by the maximum capacity a channel can support. However, while the total throughput increases, the throughput of each user will decrease because the same bandwidth will be split over more devices. This should result in a lower level of SFI for throughput, consequently, the transmission delay will likely increase with the number of WiFi devices. Lastly, the higher the number of WiFi devices, the more likely the shift in fairness of the shared system to resemble the fairness of the WiFi network, since LTE devices will be outnumbered.

5.3.2 User Service Capacity

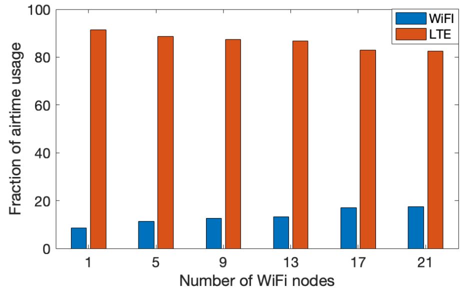
Figure 2a shows that all five of the LTE devices are always served while the number of WiFi nodes served gradually increases to a peak. It can be seen that as more WiFi nodes are present, the variation in number nodes served also increases. Maximally, the network serves 78% of nodes present within 30s. These results align with the previously stated expectations.

5.3.3 Medium Access Time

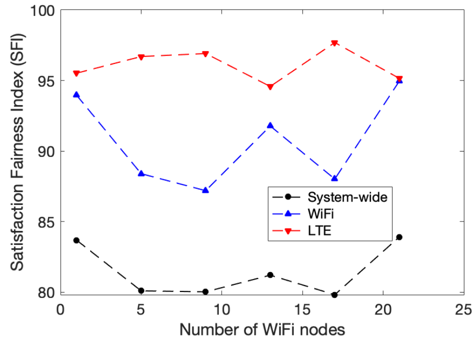
As shown by Fig.2b, LTE occupies the channel over 80% of the time in every case. LTE's occupancy gradually decreases as more WiFi devices are added to the system. Nonetheless, even in the last case when there are 3 times more WiFi devices, LTE has channel access almost 5 times longer than WiFi. In terms of medium access time, the system is unfair.



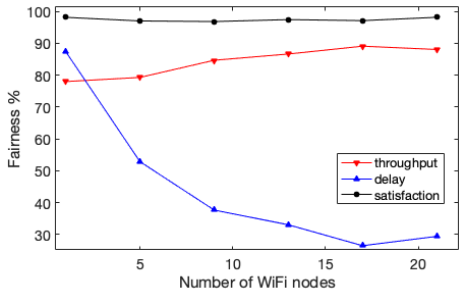
(a) The USC for varying numbers of nodes when LTE nodes = 5



(b) Distribution of medium access time varying numbers of nodes when LTE nodes = 5



(c) Downlink throughput satisfaction for varying numbers of nodes when LTE nodes = 5



(d) Fairness for varying numbers of nodes when LTE nodes = 5

Figure 2: Results of simulations for: (a) USC (b) medium access time (c) SFI of throughput (d) JFI of user throughput, user delay and satisfaction

5.3.4 Satisfaction Fairness Index

Figure 2c depicts the SFI per user based on their application requirements. Overall, users in the system have a high level of satisfaction. Satisfaction fairness in the LTE network varies less than in WiFi. It can also be seen that the SFI of LTE and WiFi are inversely proportional. This shows that within a network, each technology is fair but when comparing the two technologies, there is a lower SFI. The system's SFI is lower than the SFI seen in either of the networks due to the difference between LTE and WiFi's satisfaction levels. This is implied from the SFI WiFi, SFI LTE and fairness of satisfaction values Fig.**??**. Additionally, Appendix C shows the 68% CI of SFI. The variation in the SFI of LTE and WiFi is larger than that of the system; twice the amount in some cases. Therefore the SFI of the shared system is more precise than the other SFI values.

5.3.5 Jain's Fairness Index

Figure 2d displays the fairness of satisfaction, delay and throughput between WiFi and LTE. The fairness of satisfaction between the networks is high while the fairness of delay and throughput are significantly lower. A sharp decrease in fairness of throughput can be seen when the number of active WiFi nodes initially outnumbers LTE nodes. Since JFI uses results from each active node, the network with more active nodes will bias the fairness result. This can be seen by the point at which there is maximal throughput fairness, also being the point where LTE and WiFi throughput has the largest difference (Fig. 3b). Overall, the fairness values do not increase with the number of WiFi nodes as expected.

5.3.6 User Delay

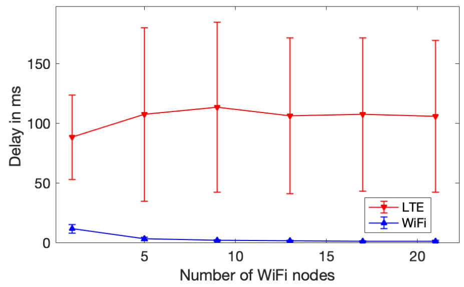
LTE experiences a larger delay per user and variation in delay, than WiFi (Fig. 3a). WiFi's delay decreases and remains relatively constant despite and increase in WiFi devices. LTE's delay increases and gradually reaches a plateau. This increase in delay is likely a result of interference form the near by WiFi nodes. LTE appears to follow the trend of an increase in delay while WiFi does not meet this expectation. This could result from a low level congestion.

5.3.7 User Throughput

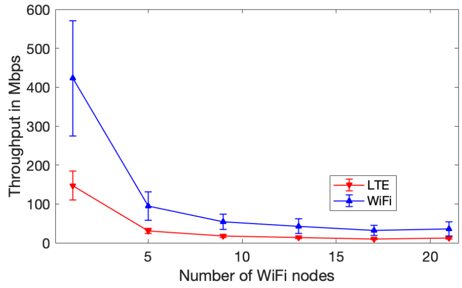
Figure 3b shows that the throughput per user in each network drastically decreases. This aligns with expectations. However, the high initial throughput of WiFi would be expected to correspond to a low delay. However, the delay is seen to be maximum at this point. This could be a result of WiFi waiting for LTE nodes to be served. Since all node's transmissions begin at the same it is difficult to determine which technology will access the medium first. However, given that LTE occupies the medium most and has more nodes in this case, we suspect this indeed to be the reason.

5.3.8 Network Throughput

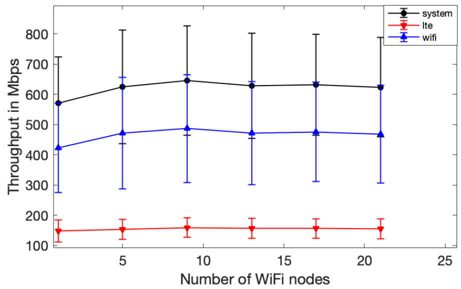
Figure 3c shows the total throughput of the shared system increases to a relatively constant state. A similar trend is seen with WiFi and both have significantly large variations. These are a culmination of variation in per user WiFi throughput and number of active users. Despite these variations and the number of transmitting nodes, the WiFi network has a higher throughput than LTE in every case. Contrastingly, LTE's total throughput remains quite constant with low variations, due to its constant number of active nodes.



(a) Delay per user for varying numbers of nodes when LTE nodes = 5



(b) Throughput per user for varying numbers of nodes when LTE nodes = 5



(c) Network throughput for varying numbers of nodes when LTE nodes = 5

Figure 3: Results of simulations for: (a) user delay (b) user throughput (c) network throughput (d) spectral efficiency

6 Discussion

The uplink SFI is at its maximum value at the beginning and end of the simulation (Fig. 2c). These are the points where the average satisfaction is highest. Initially this is because LTE outnumbers WiFi, which makes the SFI tend to LTE's SFI. In the case of the last point, the system congestion is increasing such that all nodes receive a lower throughput. This causes the throughput of users in the two sub-systems to converge (Fig. 3b).

Overall, the SFI is vague as it could be an indicator of low fairness of satisfaction between networks, a low average satisfaction or both. However, this prevents the misleading results of JFI, which would 100% fairness in the case of all users having no throughput. The SFI gives a high level overview of a system and is useful to determining whether further investigation into the satisfaction or fairness of satisfaction is required. Furthermore, SFI can give insights into the varying needs of users, as they use different application. The results show that despite the decay in throughput, the users of the system are highly satisfied (Fig. 2d). The SFI adds new knowledge about the systems operation.

Although satisfaction could be used in combination with the JFI of satisfaction to derive more precise conclusions than the SFI, this approach increases the amount of data to be examined. Given that there are many metrics which give diverse insights, reducing the number of metrics to be evaluated can be useful for creating a concise overview.

It must be noted that the SFI results reported are unlikely to be seen in practice. This is a result of users of the same technology having the same throughput requirements. In practice, the SFI will likely have more variations than what was simulated.

In continuation, the USC shows that maximally 20 users can be served within the duration of 30s (Fig. 2a). This in turn reveals that the x-axis, of increasing number of WiFi nodes, can be misleading. This axis mainly represents an increase in the congestion of the channel. The USC can therefore be used to identify the number of actively recieving nodes.

Based on the SFI results, service providers and users can conclude that the network setting is suitable for these users' applications while network operators may focus on the difference in the SFI of WiFi and LTE, to determine how to split operation costs. Furthermore, from the USC results the governments would be satisfied with 78% of users being served at a high level of QoS.

The fairness between technologies is important for coexistence, but is difficult to express because it depends on the perspective that is used. As such, the various fairness parameter presented in the results, lead to different conclusions. It can be stated that the shared system is unfair when regarding the channel occupancy. Alternatively, the system appears to be fair when the SFI considered. Therefore, what is considered fair depends on the objective that needs to be met, so no singular fairness metric is best. All of them add to the understanding of the shared system by showing the trade offs involved in optimizing a specific criteria. This concept can be extended to all metrics. In this regard, the proposed metrics are useful but the level of insight gained from them depends on the situation.

7 Conclusion

This study proposes two metrics that are aimed at the key players in communication system. The USC gives insights into the number of users served by a shared network and can be used by governments to monitor and promote digital inclusion. The SFI, is a satisfaction fairness measure that includes the magnitude satisfaction. It is useful in cases where both high fairness and satisfaction are needed and indicates when either of these values is low. Service provider and users can use this to evaluate the QoS a system provides. Alternatively, network operators can use this to determine how operation costs should be divided between the networks.

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A Spectrum Sharing Domains

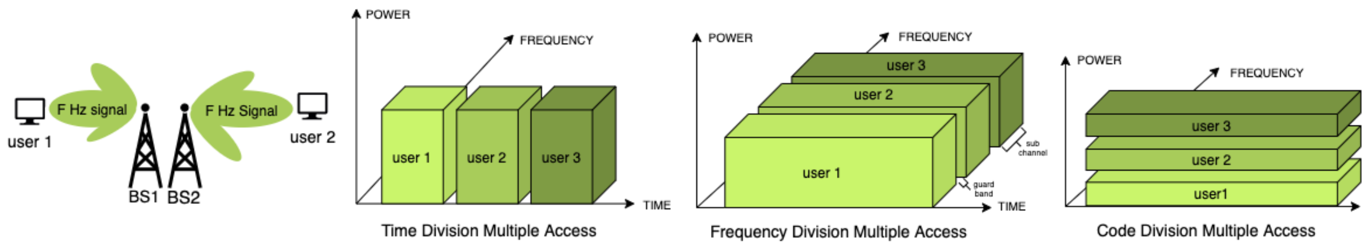

Figure 4: Visualization of spectrum sharing domains -Adapted from [2].

B Types of Spectrum Access

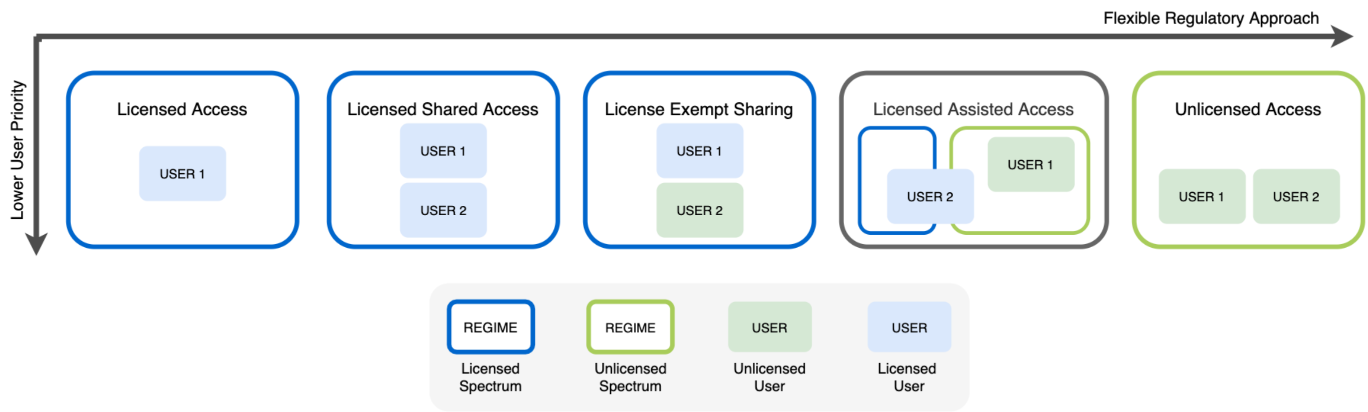

Figure 5: Overview of types of spectrum access and users involved, -Adapted from [26].

C Confidence Intervals for SFI

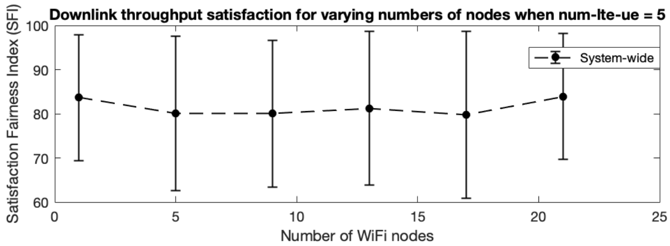

Figure 6: SFI of throughput for system with 68% CI

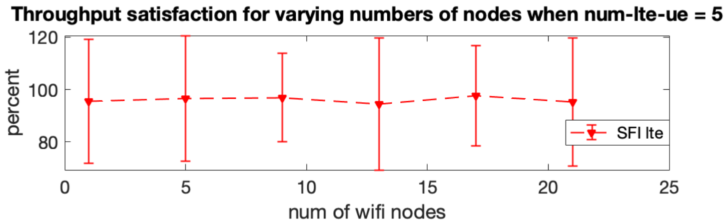

Figure 7: SFI of throughput for LTE with 68% CI

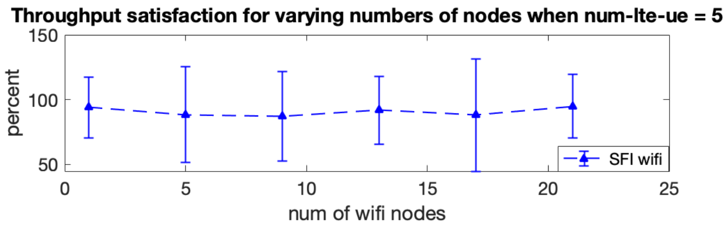

Figure 8: SFI of throughput for WiFi with 68% CI