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Maximizing the Achievable Sum-Rate of a Busy Spectrum in a Dynamic Licensed Shared Access

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Abstract

During the period when the spectrum is referred to as 'busy' in a dynamic licensed shared access system, there is a notable reduction in the maximum data rate that can be achieved by the licensee's system as a result of the imposition of the incumbent's interference threshold constraint on the licensee's system operation. To solve this problem, a power allocation technique that optimizes the licensee's sum-rate without adversely affecting the incumbent's operation is proposed in this paper. We begin by solving a sum-rate maximization problem subject to the incumbent's interference threshold constraint. Using the Lagrangian method, an optimal power allocation model is derived from the formulated convex optimization problem. When compared to a non-optimized system, results obtained from simulations show a remarkable improvement in the achievable sum-rate of the licensee system under the proposed optimal power allocation model. The results further show that at low transmit power, the proposed optimal power allocation scheme is better for smaller number of users, while the size of the cell radius does not significantly affect the sum-rate gain of the proposed scheme.

Keywords: *Licensed shared access, Achievable sum rate, Convex optimization, Interference threshold*

1. INTRODUCTION

The Licensed Shared Access (LSA) is one of the promising solutions to the well-discussed expected growth of global internet traffic as well as meeting the fifth generation (5G) technology goals. The expected explosive growth of wireless and mobile traffic, which in turn drives the total internet traffic [1] (i.e including fixed traffic), has further compounded the strain on the already scarce spectrum. This trend has been largely driven by the emergence of services/technologies such as Machine- to Machine (M2M) and internet of things (IOT) which demands that virtually "everything is connected" by wireless. The need for real time delivery of richer content in such applications as augmented reality, tactile internet, remote health check/monitoring, safety and lifeline systems, etc, is also contributing its quota to ensure that the trend in global internet traffic becomes even more pronounced in the coming years..

In the light of the expected explosion in global internet data traffic, the design, engineering and configuration of cellular mobile network must be geared towards meeting the reality on ground (spectrum scarcity), the forecasted exponential growth in global IP traffic, and the 5G technology requirement as highlighted in the international mobile telecommunications (IMT) for 2020 and beyond [2]. In this regard, the LSA as an authorised spectrum-sharing scheme, becomes imperative for spectrum access in the resulting ultra-dense network. The LSA ensures cooperative, authorised/licensed and coordinated dynamic sharing of spectrum between an incumbent, (original owner or occupier of the band) and a Licensee, (another user of the LSA band granted licensed tenancy by the incumbent) [3].

One of the key 5G defining applications, the 'automated smart city', further highlights the importance of the LSA scheme. Under the

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current paradigm of fixed spectrum management, the high-density machine type communication of the `smart city' would exacerbates the existing inadequacy in spectrum availability. The LSA scheme offers the fluidity in spectrum management that such applications demand [4]. Similarly, in the case of unanticipated network failure during rescue operations when there is a disaster outbreak, the dynamic and fluid nature of the LSA scheme provides a swift and adaptable alternative for the public safety systems [5]. The several experimentation conducted with live LTE test beds validating the feasibility of dynamic LSA scheme further lends credence to the reputation of LSA as one of the most viable solution to the challenge of inadequate spectrum in the 6 GHz radio frequency and below [6] – [12].

Crucial to the LSA spectrum sharing arrangement are: (i) guaranteed predictable quality of service (QoS) for all stakeholders and more importantly (ii) the protection of the incumbent from excessive interference that could adversely affect reliable operation [13]. Ensuring that the incumbent(s) is/are protected from harmful interference emanating from the licensee’s transmission inspires the creation of protection, restriction, and exclusion zones. Depending on the incumbent’s transmission coverage and system interference requirements, these zones, especially the exclusion zone, could lead to a considerable geographic waste in spectrum utilization [14, 15].

Addressing this spectrum utilization inefficiency requires measures to reduce the geographic restriction of these incumbents’ protecting zones. Inspired by this, in [16], the dynamic form of the LSA, which replaces the static exclusion zone with a dynamic zone, was proposed. In [15], the authors proposed shutting down the licensee's transmission at the exact position and time when the incumbent is active or reducing the licensee’s transmit power to such a level that the interference generated does not exceed the interference threshold of the incumbent system. For example, if the incumbent is an air traffic control system (ATC), and the licensee is a mobile network operator, (MNO), the licensee can only cause interference to the flying aircraft along the flight path when the ATC transmission `radio shadow' crosses the licensee eNodeB coverage area. It is only at this(ese) time interval(s) that the transmit power needs reduction, otherwise the MNO can operate without reducing its transmit power [17]. Obviously, limiting the transmission power results in corresponding decrease in achievable network data rate [18]. This, even though is better than total shut down, is less desirable within the context of existing and envisaged future capacity crunch.

Motivated by the afore-mentioned, this paper investigates improving the achievable sum rate of the LSA licensee when the incumbent is utilizing the spectrum. The authors of [6] – [12], validated the viability of the scheme by carrying out experimental field trials on live LTE test beds. In [18] – [21], the authors modelled the LSA operation using queueing theory and Markov process and analysed the system's performance vis-a-vis, service interruption and blocking probability, average number of connected users, service failure and mean bit rate. In this paper, we optimize the maximum achievable sum rate subject to the incumbent's interference threshold constraint. We then examine the effect of various engineering parameters on the system's achievable sum-rate. Furthermore, we analysed the performance of the proposed power allocation technique using a normalised measure, `the decibel sum- rate gain'.

2. SYSTEM MODEL

We focus on the exclusion/restriction zone of the LSA framework, which could be about 25 km radius for an airport incumbent [15] or an area as large as covering over sixty percent (60%) of the United States population for the Department of Defence (DoD) Naval radar as incumbent[14]. For this work, we consider an airport incumbent and a MNO licensee with multiple eNodeB of coverage radius R in the exclusion zone of the airport (figure 1). The incumbent utilizes the spectrum for communication between the ATC and the aircraft(s). At such period, the spectrum is referred to as ‘busy’ or not available. At other times, the spectrum is free and available, and the licensee can have unrestricted access to it.

2.1 The Interference Model

In this section, we consider the more severe interference that could affect the uplink of the communication path between the ATC

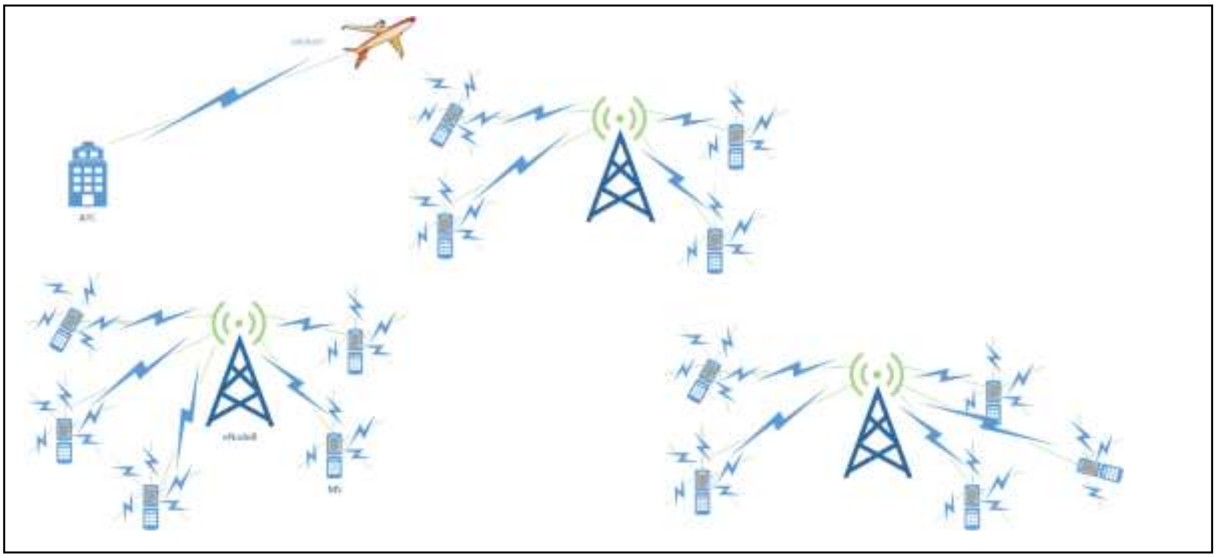

Figure 1. The System Model

transmission and the aircrafts during take-off or landing. This is based on the assumption that the MNO system is configured such that its eNodeB antenna height is lower than ATC tower and that its radiation pattern is directed downwards. Thus, the omni-directional transmissions of the user equipment (UEs) become the main source of the interference received by the incumbent's system [15].

The spatial distribution of the UEs in their respective eNodeB coverage area is modelled as a Poisson point process,

$$\varphi = \{\rho_1, \rho_2, \ \ldots\ldots, \rho_{K.}\} \qquad (1)$$

For a given aircraft receiver located at a location, y, within the coverage of the cellular network, the interference received at that location is given by:

$$I_\varphi(y) = \sum_{\rho\in\varphi} P_k h_k l(\|y - \rho\|), \qquad (2)$$

where, $l(\rho) = l\|\rho\|^{-\alpha}$, l and α are the distance related path-loss and its exponent respectively, h_k represents the fading component, k is the index for the UEs randomly distributed in the eNodeB coverage areas of the LSA licensee and P_k is the UE transmit power.

Furthermore, if we define $\|y - \rho\|$, $\rho \in \varphi$, as $\|r\| \leq D$, the circular area between the two points can then be defined as a ball $b(y, D)$ centred at y with a radius of D. Therefore, the interference point process is defined as $\varphi_I = \varphi \cap b(y, D)$, [22], where the density of $\varphi_{I,}$ and φ are λ_I, and λ respectively. Thus, the interference distribution from the UEs located within distance D to the position of the aircraft is [23], [24]:

$$f_I(i;\beta) = \frac{1}{\pi i}\sum_{k=1}^{\infty}\frac{\Gamma(\beta k+1)}{k!}\left(\frac{\lambda_I \pi \Gamma(1-\beta)}{i^\beta}\right)^k \sin k\pi(1-\beta) \qquad (3)$$

where $\beta = \frac{2}{\alpha}$, $\Gamma(\cdot)$ is the gamma function.

2.2 The Achievable Sum Rate

When the incumbent is not active on the LSA band, the spectrum is said to be free or available. During this period, the licensee is able to operate at its maximum rated power according to the required signal to noise and interference ratio (SINR) as dictated by each UE quality of service (QoS) requirement. The achievable bit rate for each UE is $C = \frac{1}{2}\log_2(1+\gamma)$, where γ is the SINR and is given by:

$$= \frac{P_k\, l_k^{-1}}{N + I_k}. \qquad (4)$$

The total achievable sum rate is therefore given as:

$$C_{sum} = \frac{1}{2}\log_2 \prod_{k=1}^{K} (1+ \gamma) \qquad (5)$$

3. MAXIMIZING THE ACHIEVABLE SUMRATE

When the incumbent is active on the LSA spectrum, the licensee has to limit its transmit power so that the total interference at the incumbent receiver is not above its permitted threshold. In other words, the licensee's operation should not degrade the incumbent's system performance. Mathematically, this implies, the LSA spectrum sharing arrangement between the licensee and incumbent should be configured such that $\mathcal{P}_s(\theta) = \mathbb{P}(SINR > \theta)$ where $\mathcal{P}_s$ is the probability of successful transmission and θ is the benchmark performance threshold. In other words, the outage probability,$(1-\mathcal{P}_s(\theta))$, must be less than or equal to θ. Therefore, the maximization of the license's achievable sum rate is conditioned upon ensuring that the total interference generated does not cause outage in the incumbent system. The sum-rate optimization problem is therefore formulated as:

$$\max_{(P)} \quad \frac{1}{2} log_2 \prod_{k=1}^{K} \left(1 + \frac{P_k\, l_k^{-1}}{N + I_k}\right)$$

$$\text{s.t.} \quad \textstyle\sum_{\rho\in\varphi} P_k h_k l(\|y - \rho\|) \le I_{th},$$

$$P_k > 0, \quad k = 1, \ldots\ldots, K \qquad (6)$$

where I_{th}, is the incumbent's interference threshold.

To solve equation (6), we decouple the sum constraint on the interference power as in [25]. To do this we introduce a new set of variables $[I_{th1}, \ldots\ldots]$ and rewrite the problem as follows.

$$\max_{(P)} \quad \frac{1}{2} log_2 \prod_{k=1}^{K} \left(1 + \frac{P_k\, l_k^{-1}}{N + I_k}\right)$$

$$\text{s.t.} \quad \textstyle\sum_{k=1}^{K} P_k h_k l(\|y - \rho\|) \le \sum_{k=1}^{K} I_{thk},$$

$$P_k > 0, \quad k = 1, \ldots\ldots, K \qquad (7)$$

We then introduce Lagrangian multipliers $\lambda > 0$ and v_k for the interference constraint and the non-negative receiver power constraints respectively

$$\mathcal{L}(P_k, \lambda, v_k = \frac{1}{2} log_2 \prod_{k=1}^{K} \left(1 + \frac{P_k\, l_k^{-1}}{N + I_k}\right) - \lambda\left(\sum_{k=1}^{K} P_k h_k l(\|y - \rho_k\|) - I_{thk}\right) + \sum_{k=1}^{K} v_k P_k. \qquad (8)$$

The Karush Kuhn Tucker (KKT) conditions are given as:

$$\frac{\partial \mathcal{L}}{\partial P_k} = \frac{\frac{l_k^{-1}}{N+I_k}}{2\ln 2(N + I_k)\left(1 + \frac{P_k\, l_k^{-1}}{N+I_k}\right)} - \lambda\left(\frac{l_k^{-1}}{N + I_k}\right) + v_k = 0,$$

$$\lambda\left(I_{thk} - \frac{l_k^{-1}}{N + I_k}\right) = 0,$$

&

$$\sum_{k=1}^{K} v_k P_k, \qquad (9)$$

for the stationarity condition (first equation of (9)) and the complementary slackness conditions (2nd and 3rd equations of (9)) respectively.

Assuming that strict inequality holds in the third equation of (7), (i.e., the non-negative allocated power constraints, $P_k > 0$), then by virtue of the complementary slackness (3rd equation of (8), v_k is equal to zero. Therefore, the optimal power allocation P_K^* is,

$$P_K^* = \frac{1}{l_k^{-1}}\left[\frac{1}{\lambda 2 \ln 2} - N + I_k\right] \quad \forall k \in K \qquad (10)$$

The implication of the non-negative power constraint $P_k > 0$, is that there is a possibility that some transmission channel will have a non-positive receiver power allocation. To find the optimal allocated power P_K^* in such cases, a new set of allocated power $K_P \in K$ is defined so that all the power allocations in the new set are strictly non-negative. The optimal allocated power, P_K^*, in this case is then given as:,

$$P_K^* = \frac{1}{l_k^{-1}}\left[\frac{1}{\lambda 2 \ln 2} - N + I_k\right]$$

$$\forall k \in K_p | P_k > 0 \qquad (11)$$

Table 1: Simulation Parameters

Parameters	Value
eNodeB Radius	100 – 1000(m)
No of UEs	2, 5, 10, 20
Transmit Power	0.2-15.85(w) (or 23-42dBm)
Bandwidth	10MHz
Noise Density	-60dBm

4. Results and Discussion

In this section, simulation results of the LSA system using the parameters shown in Table 1 are presented. Figure 2 shows the achievable sum-rate of our optimized power allocation model and the non-optimized sum-rate under the ATC interference threshold constraint, i.e., when the LSA spectrum is not available. From the graph, we could see a significant improvement in the total capacity of the network using the proposed power allocation model. With the exception of the two user case, we can see that the proposed power allocation scheme achieve approximately twice the normal (i.e when our power allocation model is not applied) sum-rate. In fact at low transmit power, the achieved increase in sum-rate is even slightly higher than twice the normal sum-rate value. Furthermore, the capacity gain increases with increasing number of UEs in the licensee cell. This is better illustrated by figure 3.

Figure 3 shows the linear increase in sum rate and the normalized sum-rate gain in decibel (dB), when comparing the proposed power allocation strategy to a non-optimized system. While the linear sum rate indicates increasing margin with increase in the number of UEs, the normalised sum-rate increase shows approximately equal achieved gain at lower transmit power values but higher gain with increasing user number at higher transmit power. It is worth noting that the sum rate gain decreases with increase in transmit power as indicated by the two graphs in figure. 3 with steeper slope at low transmit power (around the 2w mark) and higher ratio for the linear and decibel graph respectively.

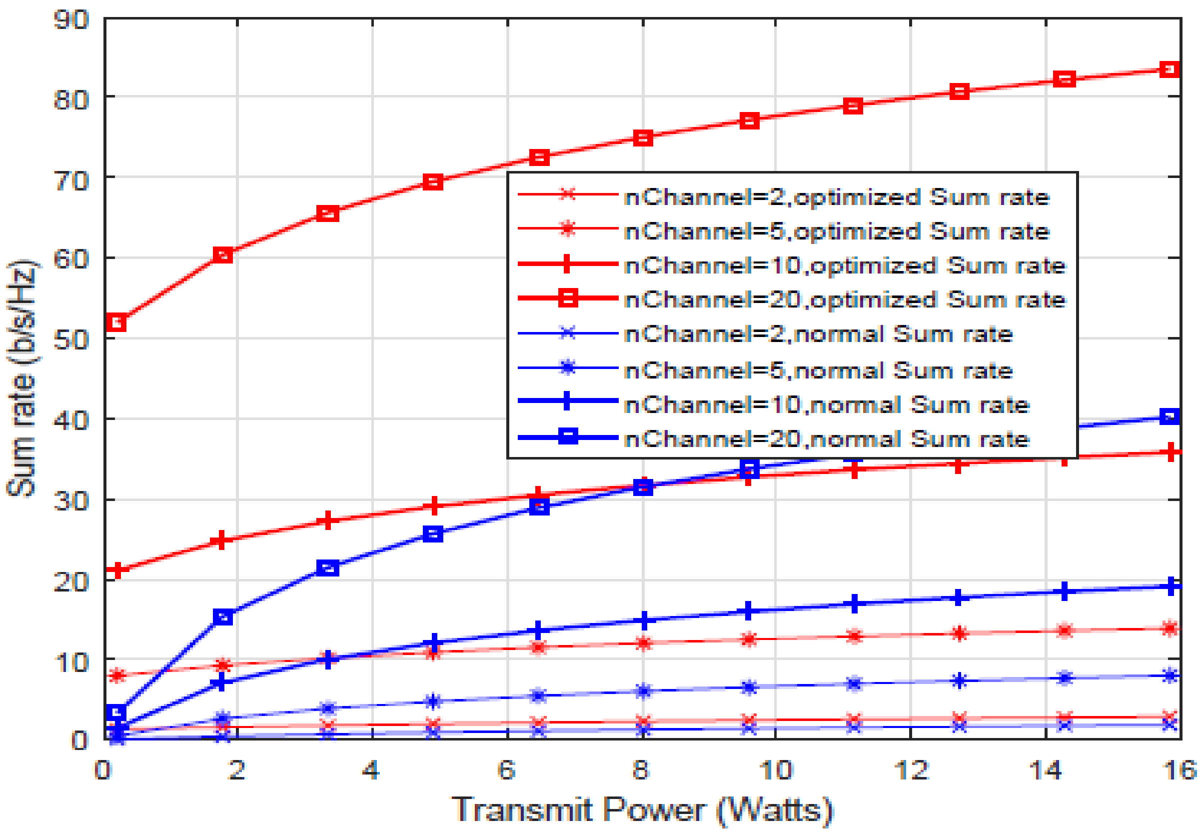

Figure 2. Comparison of the Optimized sum rate and the non-optimized sum rate.

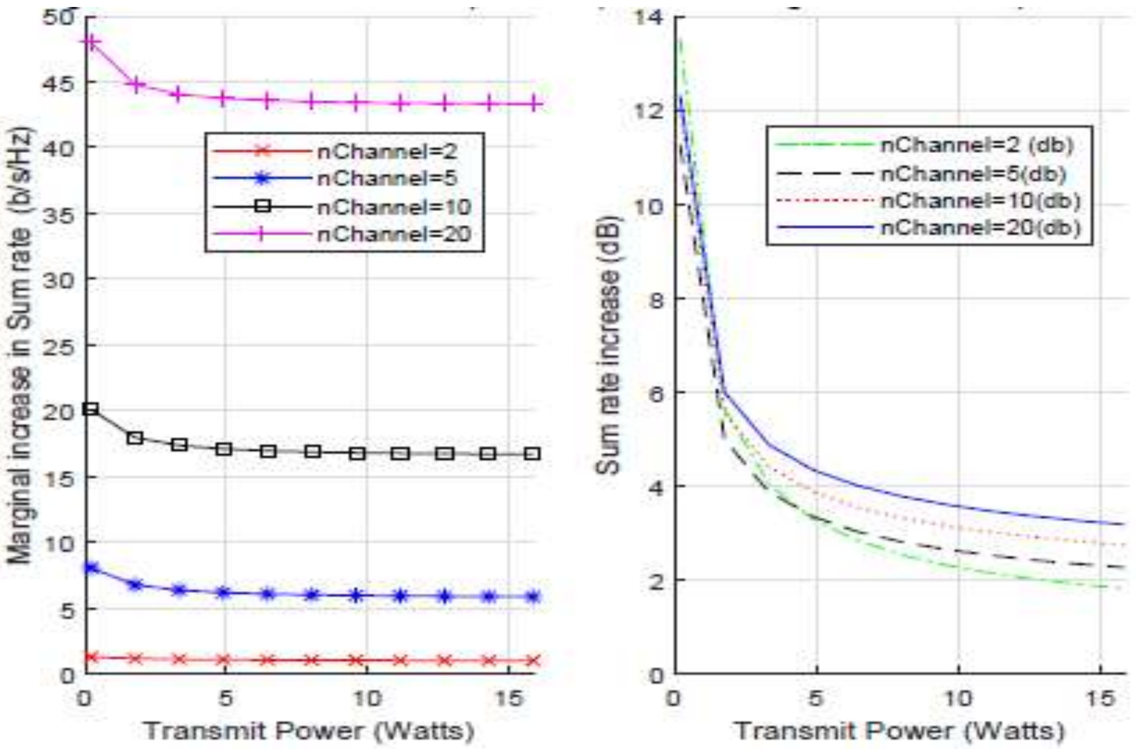

Figure 3. Comparison of Decibel and linear sum rate gain.

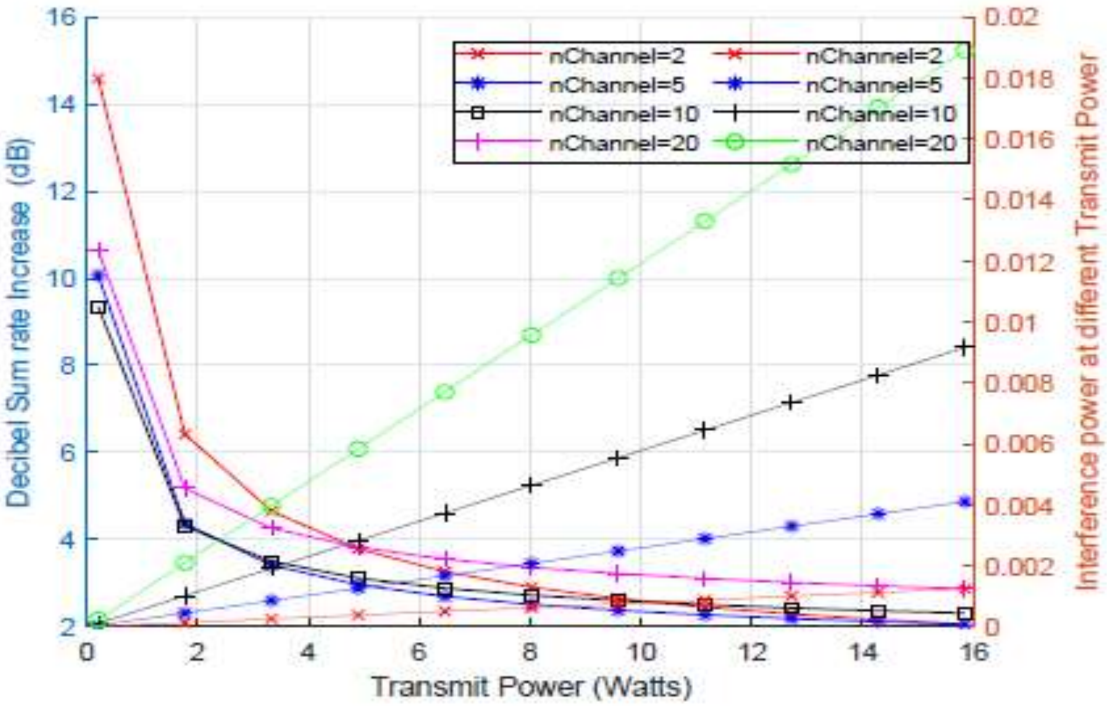

Figure 4. Trade-off between sum rate gain and interference power.

From the foregoing, we can deduce that there is an inverse relationship between the linear or actual gain in sum-rate and transmit power and expectedly a direct relationship with the number of users. However, the effective gain expressed as a decibel ratio is approximately the same for different number of users at low transmit power. The decrease in effective gain with increasing transmission power can be attributed to increase in interference power, which effectively necessitates reduction in the allocated power to prevent the licensee from exceeding the interference threshold and hence adversely affecting the incumbent's operation. This relationship is further buttressed in figure 4 which shows that as transmission power increases, the sum-rate gain decreases with increasing interference power. This fact explains the sum rate gain curve for the different number of users, which has the highest sum rate decibel gain for the smallest number of users at low transmit power while the gain becomes higher with increase in number of users as the transmission power increases.

A combination of small number of users and low transmission power, results in considerable low interference power, hence there is a loosening (or minimizing of the effect) of the interference threshold constraint on the system's performance. In other words, the very low interference of the smallest number of users makes it possible for the LSA to operate closer to its maximum transmission power, hence spectrum gain than larger number of users, which generates more interference. The slight reversal of this trend at higher transmit power can be attributed to a double effect of the cumulative effect of more users and the increase in rate with increasing transmission power.

Generally, we can conclude that at low transmit power, the system's decibel gain is inversely proportional to the number of users. This we can see from the fact that the decibel sum rate gain of 2 users is higher than 5 users which in turn is higher than 10 users. However the decibel sum rate gain for when the number of users is 20 is higher than the when the number of users are 5 and 10 but still lower than when the number of users is 2. This can be explained by the fact that higher number of users increases sum rate and more than compensates for the negative effect of higher interference power relative to when the number of users are 5 and 10. However in comparison with when the number of user is 2, the cumulative effect of increased sum rate due to the large number of users fell short of compensating for the beneficial effect of the low interference power generated by two users on the system. This, thus, leads us to the conclusion that, at low transmit power, the proposed optimal power allocation scheme is better for smaller number of users.

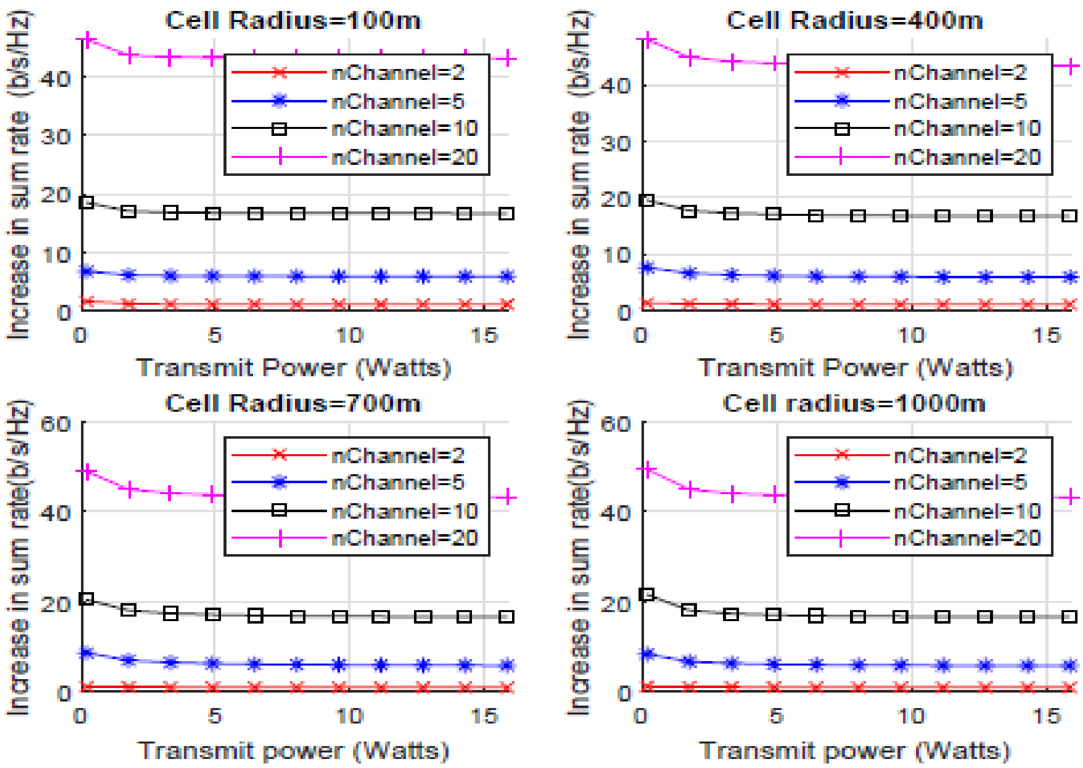

Figure 5. Graph of linear increase in sum rate at different cell radius

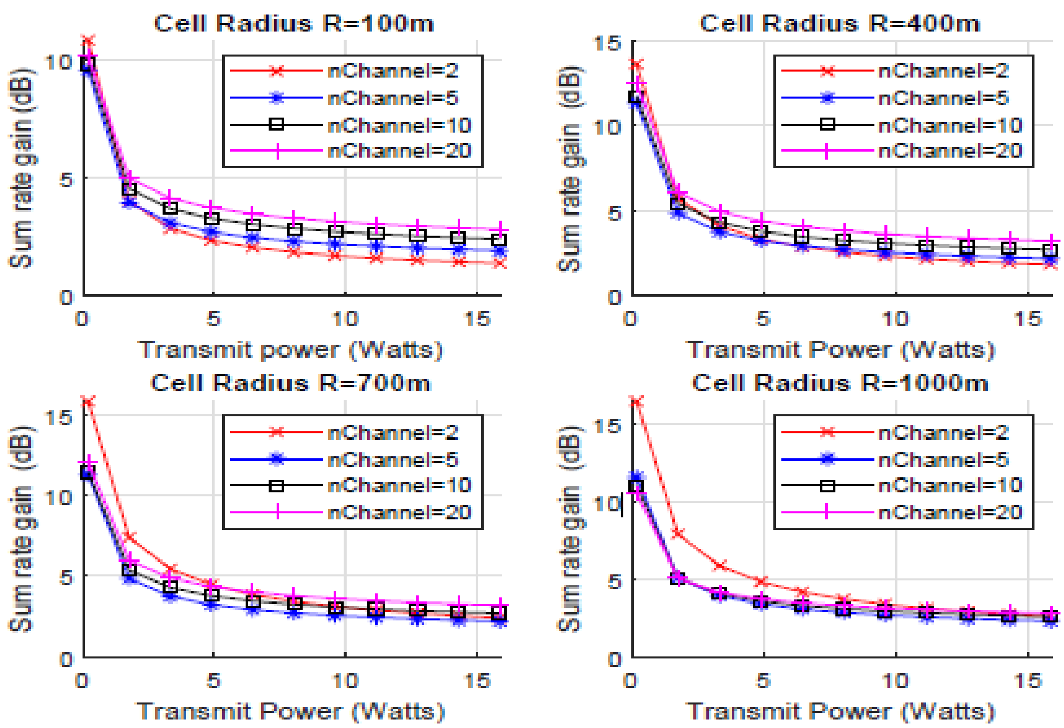

Figure 6. Graph of decibel sum -rate gain at different cell radius

Figures 5 and 6 show the linear and decibel improvement in achievable sum rate for different cell radius using the power allocation scheme proposed in this work. The actual gains is the same irrespective of the cell radius, while the normalised (decibel) gain shows slight increase with increasing cell radius. Also noteworthy is the dichotomy in the relationship between the sum rate gain for different number of users at different cell radius. At low transmission power and smaller cell radius, the sum rate gain for different number of users is approximately equal (in actual sense the sum rate gain for two users is higher than the others) while the sum rate gain shows some distinctive difference at high transmission power.

However as radius increases, the distinction in sum rate gain for different number of users at higher transmission power gradually gets eroded while the distinction seem to shift to the low transmission power end of the curve. This is better depicted in figure 7 that shows the sum rate gain for different number of users at cell radius 100 and 1000m, the two extremes of the range considered.

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From figure 7 we could see that at low transmit power and small cell radius, there is no distinctive difference between the sum rate gain for the different user number (again the sum rate gain for two users is slightly higher then the others). This is depicted in the upper sub plot of figure 7. However, with increasing transmission power, the sum rate gain is marginally better for higher number of users. At large cell radius, (the lower sub plot of figure 7) there is actually no significant difference between the sum rate gain of different number of users at high transmit power while the better performance of the 2 user case is more evidenced at low transmit power. Even though, there seems to be parity for the other different number of users, there is however a case to be made for the earlier observation that the proposed optimal power allocation is better for smaller number of users

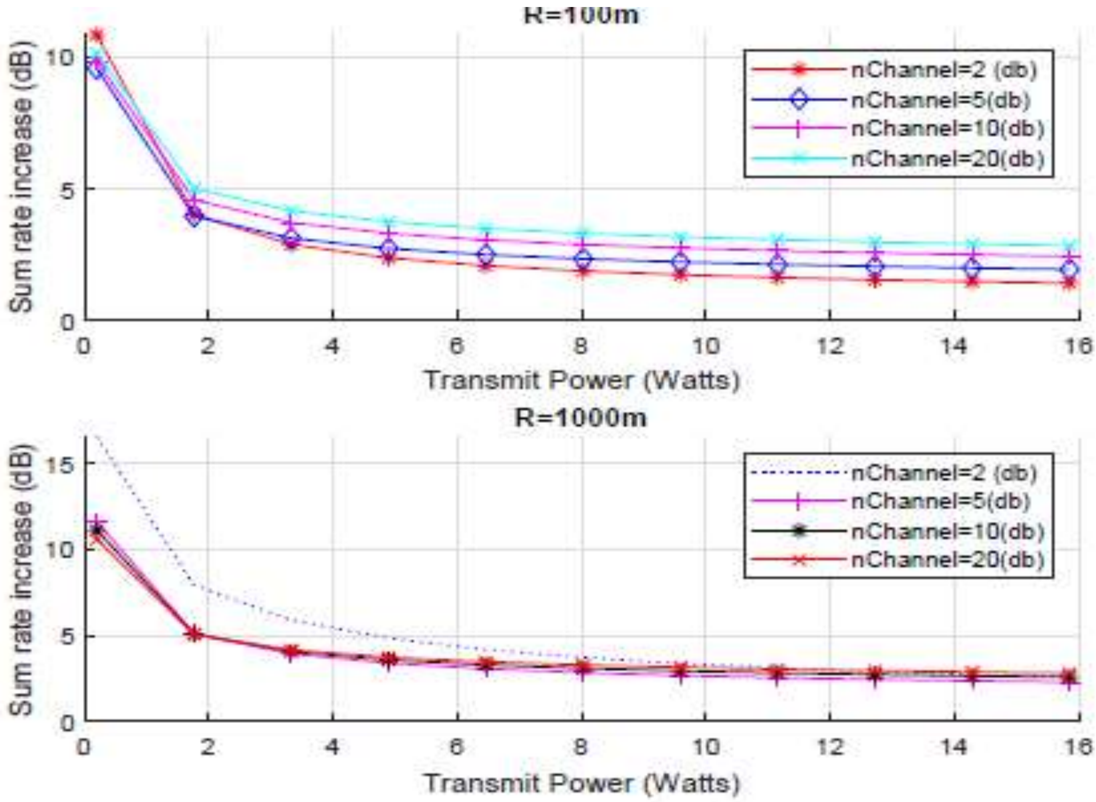

Figure 7: Capacity gain comparison for different number of users at different cell radius.

5. CONCLUSION

In this paper, an optimal power allocation scheme was proposed to address the challenge of data rate degradation of the LSA licensee when the incumbent is utilizing the LSA spectrum. We begin by solving a sum-rate maximization problem subject to interference constraint using the Lagrangian method. We then derived an optimal power allocation model from the resulting convex optimization problem. The performance of the proposed optimal allocation was analysed vis-à-vis system parameters such as, the number of users in the network, the transmit power and the coverage radius of the eNodeB.

A comparison of the proposed scheme shows a remarkable increase in the achievable sum-rate over when the licensee system is not optimized. Furthermore, a decibel measure was introduced to quantify the performance improvement obtained from the proposed power allocation scheme and to analyse the effect of the system parameters on the sum-rate gain obtained from the optimal power allocation scheme. The results showed that at low transmit power, the proposed optimal power allocation scheme is better for smaller number of users, while the size of the cell radius does not significantly affect the sum-rate gain of the proposed scheme.

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