The Role of the Total Transmit Power on the Linear Area Spectral Efficiency Gain of Cell-Splitting

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***Abstract*—In cellular wireless networks where the signal attenuation is proportional to a power of the distance, evidence so far shows that cell splitting provides linear area spectral efficiency gain as the density of nodes increases. However, the investigation on cell-splitting has focused mostly on the throughput gain, while little attention has been given to the total transmit power needed for achieving such gain. In this letter, we provide the expression for the minimum transmit power that guarantees linear area spectral efficiency gain while performing cell-splitting. Then we use this expression for the power in order to show that, whenever the path-loss exponent is greater than two, increasing the cell density yields a reduction of the total transmit power in the network while achieving linear gain in terms of area spectral efficiency.**

***Index Terms*—Area Spectral Efficiency, cell-splitting, small cells, transmit power, linear gain, SINR, scaling.**

I. Introduction

THE emerging interest in small-cells has pushed researchers to investigate the performance gain of cell-splitting. In fact, the increase in throughput gained through cell size reduction seems to have great potential. For instance, in dense networks, when the path-loss follows an attenuation proportional to a power of the distance, cell-splitting provides linear area spectral efficiency gain with the density of nodes [1]. Moreover, recent work has proved that this gain can be achieved in both single tier [2] and multi-tier networks [3] where the base station deployment is modeled as Spatial Poisson Point Process (SPPP).

However, to the best of our knowledge, research in small-cells has not focused to-date on how the overall or total transmit power of the network changes as cell-splitting occurs and what transmit power levels are needed to maintain linear gain. To address this we first provide the expression for the minimum transmit power that guarantees linear Area Spectral Efficiency (ASE) gain while performing cell-splitting. Then, by applying this expression for the minimum power, we show that the ***total transmit power*** of the network (i.e., the sum of the transmit power of all the base stations within a finite portion of the network) needed to achieve linear ASE gain by means of cell-splitting is a decreasing function of the node density, meaning that a significant reduction in the total transmit power can be obtained by shrinking the cell size and increasing the node density.

This document is organized as follows. In Section II we present the mathematical formulation of our contribution, while we show the simulation results in Section III. The conclusions are drawn in Section IV.

II. Mathematical formulation

A. Assumptions

In our model, we consider a wireless cellular network and we make the following assumptions:

- Each base station has the same bandwidth B available.
- Each user connects to the base station providing the strongest signal. We refer to the wideband Signal to Interference plus Noise Ratio (SINR) as γ and we assume that the link capacity is a function $c(\gamma)$ of the SINR.
- The path loss can be described by the model [1]:
$$P_{\mathrm{L}}(x) = K^{-1}x^{\beta}, \tag{1}$$
where x is the transmitter-receiver distance, K is a constant and $\beta \in \mathbb{R}$ is the path-loss exponent.
- The network extends up to infinity. However, this assumption is required only for the analytical formulation since, as we will see later in Section III, the simulation results obtained from a bounded network match well the analytical model.

Based on the assumptions stated above, we first provide the expressions of the SINR, of the cell spectral efficiency and of the network Area Spectral Efficiency (ASE). Then, we show how the transmit power needs to be set in order to achieve linear ASE gain by means of cell-splitting.

Some papers have already studied the SINR in cognitive networks with nodes distributed according to SPPP [4] and in cellular networks where the base stations are deployed in single tier [2] or multi-tier [3] based on SPPP. Nonetheless, in this letter we aim to keep our results as general as possible and therefore independent of any specific deployment model. Thus, we assume that the base stations locations can be obtained either from the realization of a stochastic process (e.g. SPPP) or from a deterministic geometric pattern.

B. Signal to Interference plus Noise Ratio

We are interested in computing the SINR $\gamma(\mathbf{z})$ of a given user. The variable $\mathbf{z} = (x, y)$ denotes the position of the user with respect to the serving base station, which is placed at position $\mathbf{p}_0 = (0, 0)$. Let $\mathbf{p}_n$ be the position of the n-th

Manuscript received Month Day, Year; revised Month Day, Year.

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This work was funded by Higher Education Authority under grant HEA/PRTLI Cycle 5 Strand 2 TGI and by Science Foundation Ireland through CTVR CSET grant number 10/CE/I1853.

Digital Object Identifier XXXX.

interferer with respect to the serving base station. We use index 0 for the serving base station, while any interfering base station is indexed by $n > 0$.

Thus, the SINR becomes:

$$\gamma(\mathbf{z}) = \frac{P_{\mathrm{TX},0} K h_0(\mathbf{p}_0, \mathbf{z}) |\mathbf{z}|^{-\beta}}{N_{\mathrm{B}} + I(\mathbf{z})}, \tag{2}$$

where $P_{\mathrm{TX},n}$ is the transmit power of the n-th base station, N_{B} is the noise power at the receiver for a given bandwidth B, $h_n(\mathbf{p}_n, \mathbf{z})$ is the n-th base station antenna gain which depends on the positions $\mathbf{z}$ and $\mathbf{p}_n$ of the user and of the n-th base station, respectively. $I(\mathbf{z})$ is the interference, defined as:

$$I(\mathbf{z}) = \sum_{n=1}^{\infty} P_{\mathrm{TX},n} K h_n(\mathbf{p}_n, \mathbf{z}) |\mathbf{p}_n - \mathbf{z}|^{-\beta}. \tag{3}$$

The series in (3) converges if $\beta > 2$. Let us assume that each base station transmits with power $P_{\mathrm{TX},n}$; for mathematical convenience, we can express each transmit power as $P_{\mathrm{TX},n} = P_{\mathrm{TX}} \alpha_n$, with P_{TX} geometric mean transmit power, $\alpha_n > 0$ and $n \in \mathbb{N}$. From (2) and (3) we obtain:

$$\gamma(\mathbf{z}) = \frac{\alpha_0 h_0(\mathbf{p}_0, \mathbf{z}) |\mathbf{z}|^{-\beta}}{\frac{N_{\mathrm{B}}}{P_{\mathrm{TX}} K} + \sum_{n=1}^{\infty} \alpha_n h_n(\mathbf{p}_n, \mathbf{z}) |\mathbf{p}_n - \mathbf{z}|^{-\beta}}.$$

Now, in our SINR formulation, we want to take the cell density d (i.e., the number of cells per unit area) into account as well as the scaling factor $D \triangleq d^{-1/2}$, which is a measure of the distance between neighbouring base stations in the network.[1] Let us normalize the distances with respect to D, i.e., let us write $\hat{\mathbf{p}}_n = \mathbf{p}_n / D$ and $\mathbf{w} = \mathbf{z}/D$.

We now provide the expression for the geometric mean transmit power that guarantees linear Area Spectral Efficiency gain as the nodes density increases. If we set:

$$P_{\mathrm{TX}} = P_0 D^{\beta}, \tag{4}$$

with $P_0 > 0$ arbitrary power, then, under the assumption that the antenna gain only depends on the azimuth angle,[2] i.e., $h_n(\mathbf{p}_n, \mathbf{z}) = h_n(\angle(\mathbf{p}_n - \mathbf{z}))$, we obtain the following:

$$\gamma(\mathbf{z}) = \gamma(D\mathbf{w}) =$$

$$\frac{D^{-\beta} \alpha_0 h_0(\hat{\mathbf{p}}_0, \mathbf{w}) |\mathbf{w}|^{-\beta}}{\frac{N_{\mathrm{B}}}{P_{\mathrm{TX}} K} + D^{-\beta} \sum_{n=1}^{\infty} \alpha_n h_n(\hat{\mathbf{p}}_n, \mathbf{w}) |\hat{\mathbf{p}}_n - \mathbf{w}|^{-\beta}} =$$

$$\frac{\alpha_0 h_0(\hat{\mathbf{p}}_0, \mathbf{w}) |\mathbf{w}|^{-\beta}}{\frac{N_{\mathrm{B}}}{P_0 K} + \sum_{n=1}^{\infty} \alpha_n h_n(\hat{\mathbf{p}}_n, \mathbf{w}) |\hat{\mathbf{p}}_n - \mathbf{w}|^{-\beta}} \triangleq \hat{\gamma}(\mathbf{w}). \tag{5}$$

Note we obtain (5) because the antenna gain only depends on the azimuth angle and is thus invariant to network scaling (i.e., $h_n(\mathbf{p}_n, \mathbf{z}) = h_n(\hat{\mathbf{p}}_n, \mathbf{w})$), which only affects distances and not angles. Equation (5) shows that, by setting the transmit power according to (4), the SINR does not depend on the network scaling factor D. As long as the assumptions stated in Section II-A are true, the result in (5) is valid for any cell shape, for any path-loss exponent $\beta > 2$, for any antenna gain pattern and for any transmit power $P_0 > 0$. Moreover, despite the fact we did not include any fading effect in the channel model, the equality in (5) still holds if the fading is independent of the scaling factor D, as it usually modeled in the literature [2]–[4]. Note that in (5) the contribution of the noise is not removed from the SINR expression. Although this would be possible in an interference-limited network, by removing the noise and focusing only on the Signal to Interference Ratio we would lose the information on the transmit power. Thus, in order to study the effect of transmit power on the SINR while performing network scaling, we need to keep the noise term in the SINR expression.

[1] If we consider a network with square cells of size $D \times D$ where D is the distance between adjacent base stations, the density of cells is $1/D^2$.

[2] Examples of antennas with such pattern are the omni-directional antenna and the two-dimensional directive antenna for macro-cell sectors [5].

C. Cell spectral efficiency

We define the cell spectral efficiency of a given cell $\mathcal{C} \subset \mathbb{R}^2$ as:

$$C_{\mathrm{cell}}(\mathcal{C}) \triangleq \int_{\mathcal{Q}} c(\gamma(x,y)) \mathbb{1}_{\mathcal{C}}(x,y) l(x,y)\, dxdy, \tag{6}$$

where $c(\cdot)$ can be any function which gives the link capacity as a function of the SINR, $l(x,y)$ is the normalized user-density distribution function describing how users are distributed over space, $\mathcal{Q} = [-\frac{Q}{2}, \frac{Q}{2}] \times [-\frac{Q}{2}, \frac{Q}{2}]$ is the smallest square containing $\mathcal{C}$, while $\mathbb{1}_{\mathcal{C}}(x,y)$ is the indicator function which provides 1 if $\mathbf{z} \in \mathcal{C}$, 0 otherwise. Under the following assumptions:

- Users are uniformly distributed within the cell $\mathcal{C}$, i.e., the normalized user-density distribution function is $l(x,y) = 1/\lambda(\mathcal{C})$, where by $\lambda(\mathcal{C})$ we denote the cell area;
- Full buffer traffic with fully loaded network, where every cell is active and transmits to a non-empty set of users;
- Users within the same cell receive an equal amount of the cell-resources;

the cell spectral efficiency $C_{\mathrm{cell}}(\mathcal{C})$ becomes:

$$C_{\mathrm{cell}}(\mathcal{C}) = \frac{1}{\lambda(\mathcal{C})} \int_{\mathcal{Q}} c(\gamma(x,y)) \mathbb{1}_{\mathcal{C}}(x,y) dxdy. \tag{7}$$

We can now apply a variable substitution, i.e., we set $x = Du$ and $y = Dv$. Let $\hat{\mathcal{C}}$ be the scaled version of $\mathcal{C}$ by a factor D, then $\hat{\mathcal{Q}} = [-\frac{Q}{2D}, \frac{Q}{2D}] \times [-\frac{Q}{2D}, \frac{Q}{2D}]$ is the smallest square containing $\hat{\mathcal{C}}$. Applying integration by substitution to (7), it follows that:

$$C_{\mathrm{cell}}(\mathcal{C}) =$$

$$\frac{1}{\lambda(\mathcal{C})} \int_{\hat{\mathcal{Q}}} c(\gamma(Du, Dv)) \mathbb{1}_{\mathcal{C}}(Du, Dv) x'(u) y'(u) dudv =$$

$$= \frac{D^2}{\lambda(\mathcal{C})} \int_{\hat{\mathcal{Q}}} c(\gamma(Du, Dv)) \mathbb{1}_{\mathcal{C}}(Du, Dv) dudv.$$

From (5), we can see then that the SINR is independent of the scaling factor D, i.e., $\gamma(D\mathbf{w}) = \hat{\gamma}(\mathbf{w})$. Furthermore, it is possible to verify that $\mathbb{1}_{\mathcal{C}}(Du, Dv) = \mathbb{1}_{\hat{\mathcal{C}}}(u,v)$ and that $\frac{D^2}{\lambda(\mathcal{C})} = \frac{1}{\lambda(\hat{\mathcal{C}})} = A$ is a constant which only depends on the cell shape and is thus independent of D. Hence, we deduce that the cell spectral efficiency is independent of the scaling factor D as well, i.e.,

$$C_{\text{cell}}(\mathcal{C}) = \frac{1}{\lambda(\hat{\mathcal{C}})} \int_{\hat{\mathcal{Q}}} c\left(\hat{\gamma}\left(u,v\right)\right) \mathbb{1}_{\hat{\mathcal{C}}}(u,v) du dv = C_{\text{cell}}(\hat{\mathcal{C}}). \tag{8}$$

Remark When computing the integrals, the integration set should be $(-Q/2, Q/2) \times (-Q/2, Q/2) \setminus \mathrm{B}(Q\epsilon, \mathbf{p_0})$, where $\mathrm{B}(Q\epsilon, \mathbf{p_0})$, with $\epsilon > 0$, is the ball of radius $Q\epsilon$ centred at the serving base station location. $Q\epsilon$ defines the minimum distance at which the propagation model given by (1) is valid. However, for sake of readability, we skipped this part in the formulation above. Motivated by the fact that users are almost never too close to the base station, we assume that $\mathrm{B}(Q\epsilon, \mathbf{p_0})$ is much smaller compared to $(-Q/2, Q/2) \times (-Q/2, Q/2)$ so that the results presented above are still valid.

D. Area Spectral Efficiency

The Area Spectral Efficiency ASE of the network over a square $L \times L$ is $\text{ASE} = \frac{\sum_{k=0}^{N-1} \text{TH}(\mathcal{C}_k)}{B \cdot L^2}$, where N is the number of cells within the $L \times L$ square, while $\text{TH}(\mathcal{C}_k) = B \cdot C_{\text{cell}}(\mathcal{C}_k)$ is the throughput of cell $\mathcal{C}_k$, B is the bandwidth. If we scale the network, considering that the cell spectral efficiency is independent of the scaling factor (see (8)), we obtain that $\text{TH}_{\text{tot}} = \sum_{k=0}^{N-1} \text{TH}(\mathcal{C}_k) = B \cdot \sum_{k=0}^{N-1} C_{\text{cell}}(\mathcal{C}_k) = B \cdot N \cdot \overline{C_{\text{cell}}}$, where $\overline{C_{\text{cell}}}$ is the average cell capacity. Recalling that $\frac{N}{L^2}$ is approximately the cell density, i.e., $\frac{N}{L^2} \approx d = D^{-2}$, we obtain the Area Spectral Efficiency as:

$$\text{ASE} = \frac{N \cdot B \cdot \overline{C_{\text{cell}}}}{L^2 \cdot B} \approx \frac{1}{D^2} . \overline{C_{\text{cell}}} = d \cdot \overline{C_{\text{cell}}}. \tag{9}$$

Equation (9) shows that, when we perform network scaling, the Area Spectral Efficiency is proportional to the cell density.

E. Transmit power

1) Minimum power for guaranteeing linear throughput gain:

Theorem 1. *Under the assumptions stated in Section II-A and II-C,* (4) *yields the minimum geometric mean transmit power that guarantees Area Spectral Efficiency (ASE) linear gain when performing network scaling.*

Proof: Let us suppose we have a network and we perform network scaling $D_1 \to D_2$ by shrinking the scaling factor from an initial value D_1 to D_2, with $D_1 > D_2$. Moreover, let us suppose we reduce the cell transmit power from $P_{\text{TX},1} = P_0 D_1^{\beta}$ to $P_{\text{TX},2} < P_0 D_2^{\beta}$ when performing network scaling $D_1 \to D_2$. We prove Theorem 1 by contradiction as follows. Let us assume that, with such power setting, we obtain ASE gain of $\left(\frac{D_1}{D_2}\right)^2 = \frac{d_2}{d_1}$, i.e., we achieve linear ASE gain. If we compute the SINRs $\gamma\left(D_1 \mathbf{w}\right)$ and $\gamma\left(D_2 \mathbf{w}\right)$ similarly to (5), we obtain that $\gamma\left(D_1 \mathbf{w}\right) > \gamma\left(D_2 \mathbf{w}\right)$, as $P_{\text{TX},2} < P_0 D_2^{\beta}$. Thus, by integrating $\gamma\left(D_1 \mathbf{w}\right)$ and $\gamma\left(D_2 \mathbf{w}\right)$ over the cell, it follows that network scaling $D_1 \to D_2$ reduces the cell capacity. Since having cell capacity invariant to network scaling is the condition for obtaining linear throughput gain of $\left(\frac{D_1}{D_2}\right)^2 = \frac{d_2}{d_1}$ (see (8) and Section II-D), reducing the power from $P_{\text{TX},1} = P_0 D_1^{\beta}$ to $P_{\text{TX},2} < P_0 D_2^{\beta}$ yields an ASE gain smaller than $\frac{d_2}{d_1}$, which contradicts our initial assumption. Thus, this proves that (4) gives the minimum transmit power that guarantees linear ASE gain as the node density increases. ■

2) Total transmit power: Given a finite network portion bounded by a square of area L^2 and containing N base stations, we define the total transmit power as:

$$P_{\text{TX},tot} = \sum_{k=0}^{N-1} P_{\text{TX},k}. \tag{10}$$

In general, when performing network scaling, N, i.e. the number of the cells within the square L^2, varies and then the arithmetic mean $\overline{P}_{\text{TX}} = \frac{1}{N} \sum_{k=0}^{N-1} P_{\text{TX,k}}$ might change. Let us assume that the arithmetic mean $\overline{P}_{\text{TX}}$ does not change when performing the network scaling, i.e, $\overline{P}_{\text{TX}} = P_0 D^{\beta} \frac{1}{N} \sum_{k=0}^{N-1} \alpha_k = P_0 D^{\beta} \overline{\alpha}$ and $\overline{\alpha} = \frac{1}{N} \sum_{k=0}^{N-1} \alpha_k$ is independent of the number of cells N. For instance, this is verified when all the base stations transmit at the same power or when we choose a square $L \times L$ big enough so that increasing N does not change $\overline{P}_{\text{TX}}$. Supposing the power is set according to (4), from the eq. $\frac{N}{L^2} \simeq D^{-2}$, the total transmit power becomes:

$$P_{\text{TX,tot}} = P_0 D^{\beta} N \overline{\alpha} = P_0 D^{\beta - 2} \overline{\alpha} L^2. \tag{11}$$

We notice that, if $\beta > 2$ like in most of the path-loss models used for cellular scenarios [6], by setting the power according to (11), network scaling yields an overall power reduction while guaranteeing linear growth of the ASE.

III. Simulation Results

In order to validate the results provided in Section II, we run simulations and compare the numerical results with the analytical ones. Since the formulation provided in Section II is valid for any kind of base stations spatial distribution model, we could test any model in our simulations. We chose two particular models. The first one consists of a regular shaped grid, where the cells are square shaped and are placed according to a square grid pattern. The second one is the so-called Spatial Poisson Point Process (SPPP) [2]–[4]. Once the base stations locations are determined according to the SPPP, the cell boundaries are determined by Voronoi sets.

In order to limit the simulation computational complexity, we have restricted the area of investigation to a square surface of 1 km^2. The users, which are randomly deployed over this area, are attached to the base station from which the strongest signal is received. The path loss model (see Table I) is amongst the ones suggested by [7] for pico-cell scenarios. Once the user is deployed and attached to the serving base station, we compute its wideband SINR and its throughput as a function of the SINR. Finally, the cell throughput is computed as the sum of the users throughput per cell. The most relevant simulation parameters are provided in Table I. In Fig. 1 and 2 we show the results regarding ASE and total transmit power for the square grid and the SPPP distribution models, respectively.

As we can see from Fig. 1 and 2, by setting the transmit power of each cell according to (4), the area spectral efficiency grows linearly as the cell density increases, while we observe a

TABLE I: Simulation parameters

Parameter	Value
Scenarios	i) Base stations placed in a $1000\,\mathrm{m} \times 1000\,\mathrm{m}$ square grid.
	ii) SPPP over a $1000\,\mathrm{m} \times 1000\,\mathrm{m}$ square.
Number of snapshots	50
Path Loss	$P_{\mathrm{L}}(d_{\mathrm{km}}) = 140.7 + 36.7\log(d_{\mathrm{km}})$ [7]
Shadow fading	Log-normal, 8 dB standard deviation [7]
Penetration loss	20 dB [7]
Bandwidth	10 MHz centered at 2 GHz.
Noise	Additive White Gaussian Noise with -174 dBm/Hz Power Spectral Density.
Noise Figure	9 dB
Capacity function	$c(\gamma) = \max\left(0.75\log_2\left(1 + \frac{\gamma}{1.33}\right), 5.55\right)$ [8]
Transmit power per base station	Set according according to (4), e.g. 30 dBm per cell for a density of 100 cells/km^2. All base stations transmit at the same power.
Antenna at BS and UE	Omni-directional with 0 dBi gain.

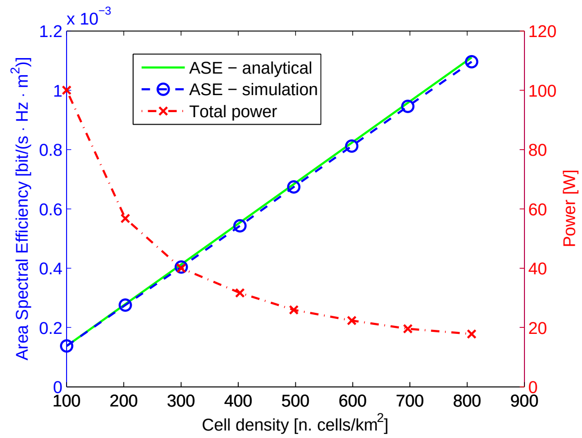

Fig. 2: ASE and total transmit power for Scenario (ii).

reduction in the total transmit power. Given that the path-loss exponent $\beta = 3.67$ is greater than 2, the simulation results confirm that increasing the nodes density yields a reduction of the transmit power and a linear ASE gain.

Note from Fig. 1 and 2 that the ASE curves obtained from simulation show a small deviation from the analytical curves. This is due to the fact that we have simulated a bounded network, while the analytical results consider an unbounded network. In fact, the users placed at the network boundaries will experience lower interference and subsequently higher throughput compared to the inner users. As we increase the cell density, the percentage of network-edge cells will reduce, meaning that users will experience higher interference at higher densities. This will reflect in a smaller throughput gain compared to the case of an infinite network.

Moreover, if we compare the ASE curves in Fig. 1 with the ones in Fig. 2, we observe that a network with base stations deployed in a regular lattice yields higher performance than a network with SPPP based deployment. This result is in agreement with that previously pointed out in [2].

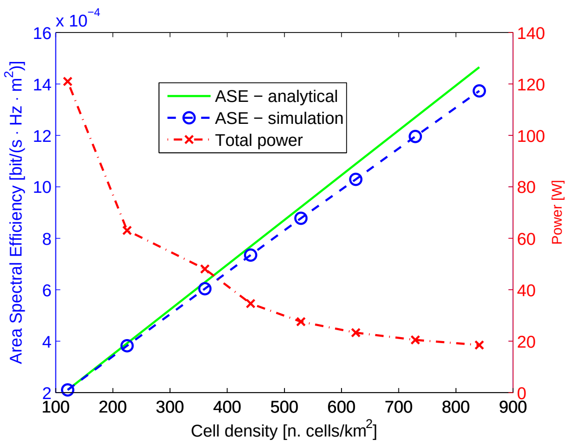

Fig. 1: ASE and total transmit power for Scenario (i).

IV. Conclusions

In this letter, we provided the expression for the minimum transmit power that yields linear Area Spectral Efficiency (ASE) gain when performing cell-splitting. In addition, we showed that the total transmit power of the network necessary to achieve linear ASE gain by means of cell-splitting is a decreasing function of the node density, meaning that shrinking the cell dimension and increasing the node density can lead a significant reduction of the total transmit power of the network, depending on the channel attenuation. Our results can be interpreted as a proof that this linear ASE gain is in fact due to a better reuse of the spatial resources of the network made possible by cell-splitting rather than as a result of an overall transmit power increase.

The overall transmit power reduction achievable by setting the transmit power according to our study may have positive implications in reducing the aggregate interference experienced by an incumbent willing to share spectrum with a secondary system of small cells. This may be particularly useful in future scenarios involving Licensed Shared Access or Authorised Shared Access schemes in which small cell networks exploit new spectrum sharing opportunities.

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