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On the Expiration Date of Spectrum Sharing in Mobile Cellular Networks

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Abstract—**Driven by a combination of flat lining revenues and an explosive growth in the mobile data traffic and hence the need for network resources, mobile operators consider infrastructure- and spectrum sharing as a means to reduce operational costs. We develop and apply an assessment approach to quantify the benefits associated with spectrum sharing in an infrastructure-shared environment, and estimate the evolution of the derived 'spectrum sharing dividend' as traffic loads, radio access technologies, spectrum availability and performance targets change over time. The obtained insights can assist operators and regulators in their assessment of the merit of spectrum sharing. Analysis shows that operators with loads that peak at different times continue to benefit significantly by sharing spectrum, despite the diminishing 'trunking gains' of spectrum sharing as individual operator loads and capacities increase over time.**

Keywords—Spectrum sharing, network sharing, mobile networks, performance analysis.

I. INTRODUCTION

The economic benefits of network sharing have been widely recognized, and have led many mobile operators in Europe to implement some form of network and spectrum sharing. The key driver for these forms of sharing is the significant cost savings that can be achieved. For network sharing these savings may range up to 30% in capital investment [1]. Such operational savings are increasingly important for mobile operators, as they are facing challenges of flat lining or even decreasing revenues, while the explosive growth of customer demand for data services demands continuous and significant expansions of their network capacity. This has led mobile operators to consider radical options in reducing the cost for network expansion, including full or partial sharing of the Radio Access Network (RAN).

An important choice in RAN sharing is whether to share only the network infrastructure or also spectrum. A key issue considered in a regulatory assessment preceding the approval of a proposed sharing agreement, is the reduced independence of sharing operators. Regulators may therefore give spectrum sharing proposals additional scrutiny because of concerns for reduced competition in the mobile services market.

RAN sharing occurs in many countries today. Regulators have already analyzed and in many cases approved RAN sharing arrangements without spectrum sharing, while RAN sharing including spectrum sharing has been considered and implemented less frequently by operators. The regulatory status for this sharing arrangement is less clear.

The aim of this paper is to develop and apply an assessment approach to quantify the benefits of spectrum sharing to cellular systems experiencing peak (busy hour) loads, and estimate the evolution of these benefits as e.g. traffic loads and spectrum availability change in future years. The modeling and obtained insights can assist operators and regulators in their assessment of the merit of spectrum sharing. In the followed approach, we consider cases with and without spectrum sharing separately. Using link budget analyses and stochastic performance modeling, we derive per case the maximum allowed inter-site distance (ISD), corresponding with a most cost-effective deployment, that satisfies both coverage and performance requirements during peak load. From this we derive the number of sites needed to serve a given area, and consequently determine the 'spectrum sharing dividend' as the percentage reduction in the number of sites needed when sharing spectrum.

The remainder of the paper is organized as follows. In Section II we give an overview of the considered scenarios. Section III details the system modeling and applied analysis. Numerical results are presented and discussed in Section IV. Section V ends the paper with some concluding remarks.

II. SCENARIOS

The scenarios used to parameterize the developed assessment approach in order to derive realistic estimates of the benefits from spectrum sharing, comprise a number of key ingredients regarding e.g. traffic growth, technology rollouts, spectrum availability and operators' performance targets. In overview, the key change drivers of spectrum sharing dividend as considered in our study are:

- Mobile data traffic increases by 67% each year;
- New radio access technologies (RATs) are characterized by a higher spectral efficiency;
- Over time, more spectrum becomes available for mobile broadband, starting with the 2100 MHz band, and expanding into 900, 1800, 800 and 2600 MHz bands;
- Operators apply higher planning targets for (typically: cell edge) user throughput over the years.

The precise scenario parameter values used in our analysis are given in Table 1, referring the interested reader to [2] for an elaborate motivation behind these scenario choices.

Table 1: Scenario parameters

YEAR	'05	'10	'11	'12	'13	'14	'15	'20	'25
Cell edge user throughput target R_j^* (in Mbits/s) per RAT j									
3G	0.15	0.30	0.32	0.34	0.36	0.38	0.40	0.50	
LTE						1.00	1.00	1.20	1.50
Mobile data traffic load ρ_j (in Mbit/s/km^2) per RAT j									
UMTS	0.09								
HSPA		1.20	2.00	3.35	2.79	3.55	5.92		
HSPA+					2.79	3.55	5.92	40.5	
LTE						2.33	3.90	111	
LTE-A								50.6	2104
Spectrum availability S_{fj} (inMHz) per frequency band f and RAT j									
3G/900				8.75					
2100	30							29	
LTE/800						15			
900									17.5
1800						18.75		37.5	
2100								1	30
2600						35			

III. MODELLING AND ANALYSIS

In this section, we present the analysis applied to derive the spectrum sharing dividend for a given scenario, following the approach outlined above, and comprising a coverage- and a capacity-oriented component: per case the maximum allowed ISD is determined, satisfying both coverage and performance requirements, while subsequently the spectrum sharing dividend is derived as the reduction in the number of required sites needed, comparing the scenario with and without spectrum sharing.

A. Coverage analysis

In the coverage analysis, which addresses the *uplink* as the typical coverage bottleneck, we derive the maximum allowed inter-site distance (ISD) from a coverage perspective. For each year in the analyzed period (2005-2025), the desired ISD, denoted $ISD^*_{\text{cov},e}$ for propagation environment e ∊ {urban, suburban}, is derived as follows. First, we derive the *coverage probability curves* $\varphi_{e,f,j}(d)$ that give for environment e, frequency band f ∊ {800,900,1800,2100,2600} MHz and radio access technology (RAT) j ∊ {3G,LTE}, the coverage probability of a given uplink data rate target as a function of the distance d ≥ 0 (in km) from the base station. Given $\varphi_{e,f,j}(d)$ we then obtain the maximum cell range $d^*_{e,f,j}$ such that $d^*_{e,f,j} = \max d$, s.t. $\varphi_{e,f,j}(d) \geq \xi$, with ξ the coverage reliability threshold. Assuming a hexagonal cellular layout, the corresponding ISD is then $ISD^*_{\text{cov},e,f,j} = \frac{3}{2} d^*_{e,f,j}$ (see also Figure 2). Finally, $ISD^*_{\text{cov},e}$ is taken as the maximum of the $ISD^*_{\text{cov},e,f,j}$ over all combinations of j and f deployed in the considered year.

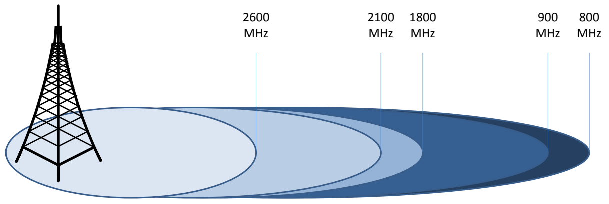

Figure 1: Coverage analysis: illustration of the coverage areas of the different considered frequency bands.

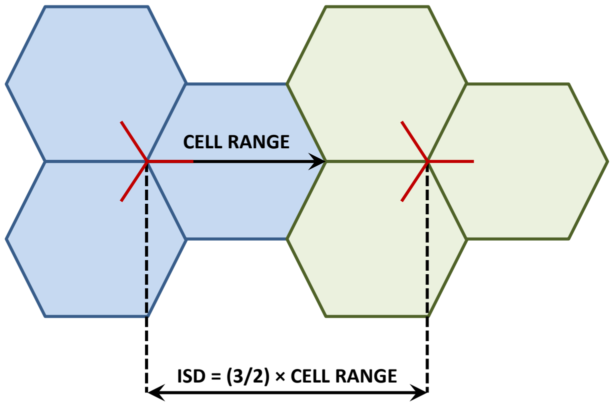

Figure 2: The relation between the cell range and the inter-site distance in a hexagonal network layout. Note that the serving range in the transmission direction exceeds that in the direction of a cell's side lobe.

Before determining $\varphi_{e,f,j}(d)$, we first present typical 3G and LTE link budgets in Table 2 below, which are largely based on [3][4]. The presented link budgets consider the suburban propagation environment in the 1800 MHz band.

Table 2: Uplink link budgets for the suburban propagation environment in the 1800 MHz frequency band.

		3G	LTE	
	Data rate	128	128	kbps
	Available bandwidth	3840	1260	kHz
			1	# PRBs
	Frequency band	1800	1800	MHz
	Environment	suburba n	suburba n	
Tx (UE)	Max Tx power	23.0	23.0	dBm
	Tx antenna gain	0.0	0.0	dBi
	Body loss	0.0	0.0	dB
	EIRP	23.0	23.0	dBm
Rx ((e)NodeB)	Noise figure	2.0	2.0	dB
	Thermal noise	-108.1	-121.4	dBm
	Rx noise	-106.1	-119.4	dBm
	SINR	-10.5	3.9	dB
	Rx sensitivity	-116.7	-115.6	dBm

Interference margin[1]		3.0	1.0	dB
Cable loss		3.0	3.0	dB
Rx antenna gain		18.0	18.0	dBi
Fast fading margin		1.8	0.0	dB
Soft handover gain		2.0	-	dB
Coverage reliability		90%	90%	
Shadowing plus penetration loss	mean	10.6	10.6	dB
	sigma	4.5	4.5	dB
	margin	16.4	16.4	dB
Max. allowable path loss		135.5	136.2	dB
Path loss model (COST 231 Hata)	fixed	134.8	134.8	dB
	distance	35.2	35.2	dB
Max. allowable cell range		1.05	1.10	km

The link budget derives, for a given ξ, the maximum allowable path loss, and, subsequently, the maximum allowable cell range $d^*_{e,f,j}$. The only stochastic component in the link budget is the shadowing-plus-penetration loss, denoted *X*, which, expressed in dB, has a Gaussian distribution with an assumed mean of 10.6 dB and a standard deviation (σ) of 4.5 dB, for the considered suburban environment at 1800 MHz. The desired function $\varphi_{e,f,j}(d)$ effectively operates inversely to the link budget equation, i.e. it expresses the probability that the sum of the distance-dependent path loss and the shadowing-plus-penetration loss is too low for the SINR requirement of 3.9 dB (considering LTE) to be satisfied. Using the values listed in the above link budget, this gives

$$\varphi_{\text{suburban,1800 MHz,LTE}}(d) = Pr\{PL(d) + X \leq 136.2 + 16.4\}$$
$$= \Phi_{10.6,4.5}(17.8 - 35.2\log_{10}(d)),$$

where $\Phi_{\mu,\sigma}(\cdot)$ denotes the cumulative distribution function of the Gaussian distribution with mean μ and standard deviation σ. It is readily verified that indeed $\varphi_{\text{suburban,1800 MHz,LTE}}(1.10) = 90\%$. See Table 2 for a detailed specification of the key link budget parameters, the derived $\varphi_{e,f,j}(d)$, $d^*_{e,f,j}$ and the corresponding $ISD^*_{\text{cov},e,f,j}$ for each environment, frequency band and radio access technology. The coverage probability functions for the suburban environment is plotted in Figure 3.

As mentioned above, for a given year, $ISD^*_{\text{cov},e}$ is then taken as the maximum of the $ISD^*_{\text{cov},e,f,j}$ over all applicable combinations of j and f, scenario information that is specified in Section II. The bottom line coverage-oriented inter-site distances, and the associated ('best covering') combinations of RAT and frequency band, are presented in Table 3 below.

B. Capacity analysis

The capacity analysis, which addresses the *downlink* as the typical capacity bottleneck, is based on a stochastic performance evaluation model which effectively maps a number of scenario parameters to an estimation of the cell edge throughput performance. Considering a target cell edge performance level applied in network planning, an optimization shell is used around this performance model, which aims at maximizing the ISD such that the cell edge performance target is still satisfied.

Table 3: Coverage-oriented maximum inter-site distances for the (sub)urban propagation environments.

PERIOD	RAT	FREQ. BAND	$ISD^*_{\text{cov,URBAN}}$	$ISD^*_{\text{cov,SUBURBAN}}$
2005-11	3G	2100 MHz	0.42 km	1.37 km
2012-20	3G	900 MHz	1.08 km	5.57 km
2021-25	LTE	800 MHz	1.43 km	6.23 km

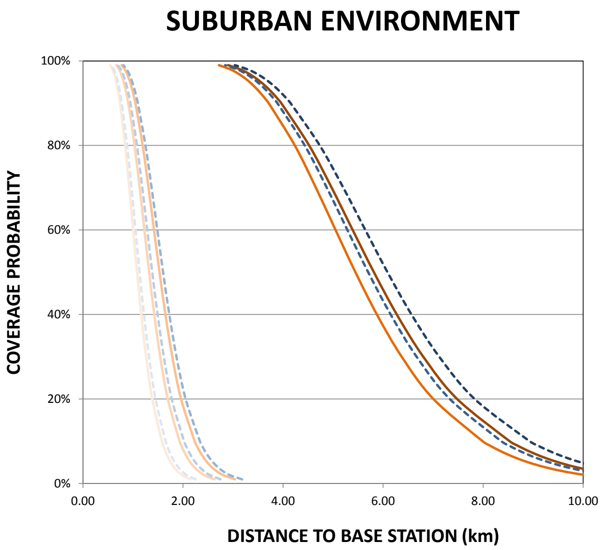

Figure 3: Visualization of coverage probability function $\varphi_{e,f,j}(d)$ for the suburban propagation environment.

Considering the terminals' *multi-RAT capabilities* it cannot be assumed that all terminals in a given year are capable of handling all considered RATs. For analytical tractability of the complex scenario, two distinct approximations are followed to enable an analytical capacity assessment: assuming purely single-RAT (case MRC_I) or purely multi-RAT terminals (case MRC_{II}), given upper and lower bounds for the achievable spectrum sharing gains, respectively [2].

Consider the *spatial spectrum availability*, we note that when cells utilize carriers in different frequency bands, the difference in the coverage of these bands must be acknowledged in the capacity analysis. In our analysis we determine for each zone in the cell (each cell is segmented into a number of equal-area zones; see below) separately the coverage probability for each employed frequency band. The assumed spectrum availability in a given zone is then given by the accordingly weighted sum of the total spectrum availabilities per frequency band [2].

[1] Covering both intra- and inter-cell interference in a 3G network, and inter-cell interference only in an LTE network.

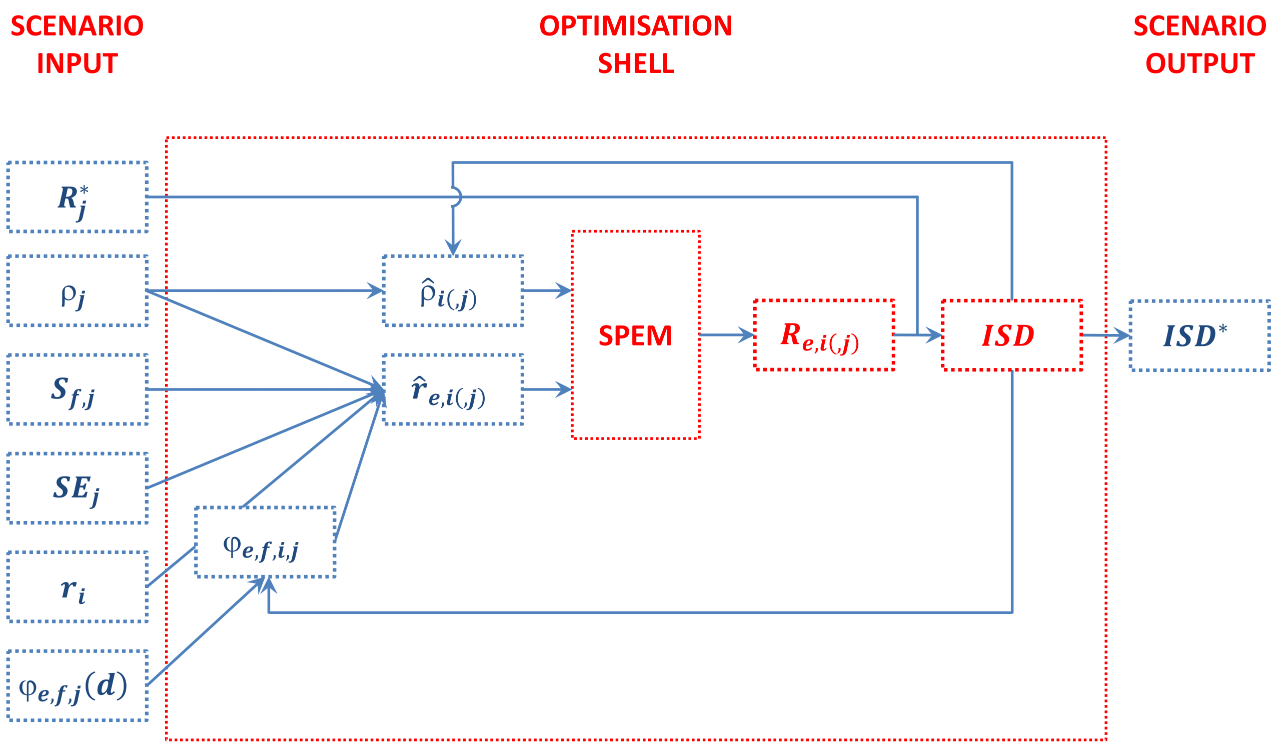

Figure 4: Overview of the capacity analysis: input, optimization shell, performance model and output.

An overview of the scenario parameters, the optimization shell and stochastic performance evaluation model is depicted in Figure 4, and described in more detail below.

The following scenario (input) parameters are provided to the optimization problem, divided in general and time-dependent parameters. The **general parameters** are:

- A RAT-specific *spectrum efficiency* (in bps/Hz), denoted SE_j for RAT j ∈ {UMTS,HSPA,HSPA+, LTE,LTE-A}. We will use SE_{UMTS} = 0.15, SE_{HSPA} = 0.53, SE_{HSPA+} = 1.1, SE_{LTE} = 1.87 and $SE_{LTE\text{-}A}$ = 2.6 bps/Hz [5][6][7].
- *Zone-specific normalized bit rates* for the different zones of a cell, denoted r_i for zone i, i = 1,2, …, I, modeling the effects of link adaptation in modern RATs. We use I = 100, as visualized in [2]. The r_i decrease linearly with distance with a max/min ratio of 5.25 and a (normalized) mean of 1 (based on [8]; this is noted to include the effects of inter-cell interference).
- The *coverage probability curves* $\varphi_{e,f,j}(d)$, which, given a choice of the ISD and consequently the specific segmentation of sectors into zones with their associated boundaries, can be effectively translated to the coverage probability $\varphi_{e,f,i,j}$ for frequency band f in zone i, environment e and for RAT j. For the case of SSA_I we force $\varphi_{e,f,i,j} = 1$ for all e, f, i, j.

The **time-dependent parameters** (see Section II for the specific values of the different parameters for the considered period from 2005-2025) are**:**

- A *cell edge throughput target* R_j^* assumed by the network operators for network planning purposes for RAT j ∈ {3G, LTE} in a given year, assuming that operators increase R_j^* over the years. In the analysis we use an effective cell edge throughput target R^* which is determined as the load-weighted average of the RAT-specific targets:

$$R^* = \sum_j \left(\frac{\rho_j}{\sum_{j'} \rho_{j'}}\right) R_j^*$$

- The *traffic load density* ρ_j (in Mbps/km^2) offered to the network for RAT j ∈ {UMTS, HSPA, HSPA+, LTE, LTE-A} in a given year, denoting the aggregate load density offered to the sharing operators. For scenarios with no spectrum sharing, we assume equal shares.
- The *amount of spectrum* $S_{f,j}$ (in MHz) jointly available for the sharing operators for RAT j in frequency band f in a given year. For scenarios without spectrum sharing, we assume equal shares.

As also depicted in Figure 4, the **optimization shell** takes these scenario parameters, translates them into a suitable input format and then applies the stochastic performance evaluation model to do a performance assessment. More specifically,

- The *effective zone-specific bit rates* $\hat{r}_{e,i(,j)}$ (in Mbps) in zone i, environment e and RAT j (case MRC_I only) are determined as

$$\hat{r}_{e,i(,j)} = \begin{cases} r_i \left(SE_j \sum_f \varphi_{e,f,i,j} S_{f,j} \right) & \text{for } MRC_I, \text{RAT } j \\ r_i \sum_j \left(\frac{\rho_j}{\sum_{j'} \rho_{j'}} \right) \left(SE_j \sum_f \varphi_{e,f,i,j} S_{f,j} \right) & \text{for } MRC_{II} \end{cases}$$

- The *effective load* $\hat{\rho}_{i(,j)}$ (in Mbps) in zone i and RAT j (case MRC_I only) is determined as

$$\hat{\rho}_{i(,j)} = \frac{\frac{1}{6} ISD^2 \sqrt{3}}{I} \cdot \begin{cases} \rho_j & \text{for case } MRC_I \\ \sum_j \rho_j & \text{for case } MRC_{II} \end{cases}$$

  considering a spatially uniform traffic distribution and a total cell area of $\frac{1}{6} ISD^2 \sqrt{3}$ which is uniformly segmented into I zones.

The derived effective zone-specific bit rates $\hat{r}_{e,i(,j)}$ and the effective loads $\hat{\rho}_{i(,j)}$ are offered to the applied **stochastic performance evaluation model** ('SPEM'), a generalized multi-class M/G/1 processor sharing model [9] for which the (insensitive) equilibrium probability distribution can be analytically derived. The expected throughput in zone i, environment e and RAT j (case MRC_I only) is given by

$$R_{e,i(,j)} = \hat{r}_{e,i(,j)} \cdot \left(1 - \sum_i \frac{\hat{\rho}_{i(,j)}}{\hat{r}_{e,i(,j)}} \right)$$

for i = 1, 2, …, I, and hence, in particular, the expected cell edge throughput is equal to $R_{e,I(,j)}$.

The **optimization shell** then applies a straightforward bisection search to find the solution to the optimization problem: $\max ISD$, subject to $R_{e,I(,j)} \geq R^*$. The outcome of the capacity-oriented analysis for a given scenario is then given by $ISD^*_{\text{cap},e(,j)}$ i.e. the maximum allowed ISD (from a downlink performance perspective) that still allows the target cell edge throughput to be achieved in environment e and for RAT j (case MRC_I only). Considering case MRC_I, we take the minimum of the obtained RAT-specific ISDs as the bottom line result of the capacity analysis, i.e. $ISD^*_{\text{cap},e} = \min_j ISD^*_{\text{cap},e,j}$.

C. Spectrum sharing dividend

Considering environment e, from the coverage and capacity analyses, respectively, we have obtained

- the maximum allowed ISD $ISD^*_{\text{cov},e}$ that still satisfies the coverage probability target (90%) for the lowest deployed frequency band; and
- the maximum allowed ISD $ISD^*_{\text{cap},e}$ that still allows the target cell edge throughput to be achieved,

from which we derive $ISD^*_e = min\{ISD^*_{\text{cap},e}, ISD^*_{\text{cov},e}\}$ as the bottom-line outcome of the scenario evaluation, giving the maximum allowed ISD that satisfies coverage *and* performance requirements in environment e.

If $ISD^*_{e,\text{NSH}}$ and $ISD^*_{e,\text{SH}}$ denote the optimized ISD for the cases of non-sharing and sharing, respectively, then the *spectrum sharing dividend* SSD^*_e achieved is given by

$$SSD^*_e = \frac{N^*_{e,\text{NSH}} - N^*_{e,\text{SH}}}{N^*_{e,\text{NSH}}} = \frac{\left(\frac{1}{ISD^*_{e,\text{NSH}}}\right)^2 - \left(\frac{1}{ISD^*_{e,\text{SH}}}\right)^2}{\left(\frac{1}{ISD^*_{e,\text{NSH}}}\right)^2},$$

for environment *e*, where $N^*_{e,\text{(N)SH}} = \frac{2}{3} A\sqrt{3} / \left(ISD^*_{e,\text{(N)SH}}\right)^2$ denotes the number of sites required to serve a given service area of size A if the ISD is equal $ISD^*_{e,\text{(N)SH}}$.

The mutual symmetry of cellular operators' load profiles over the day is important in determining the benefit of spectrum sharing. If the peak loads of two operators occur at different times then spectrum sharing will be beneficial, because the operator at peak load can effectively exploit the 'surplus' spectrum of the other (off-peak) operator. To model asymmetry in operator peak loads we define the Load Symmetry Ratio (*LSR*) as the peak combined load of the sharing operators divided by the sum of the individual peak loads of the sharing operators. If the operator loads peak simultaneously then *LSR = 1*, otherwise *LSR < 1*.

Note that spectrum sharing dividend (SSD) is a metric that represents the benefit to operators of sharing spectrum under peak load (namely, 'busy hour') conditions. At other (off-peak) times of the day there are also benefits to sharing spectrum (e.g. [10]) but these do not determine the number of sites required to satisfy peak load conditions.

IV. Numerical Results

Using the parameters presented in Tables 1-3, the spectrum sharing dividend expected in a suburban propagation environment, $SSD^*_{suburban}$, is plotted in Figure 4. It has been assumed that two operators are sharing spectrum and that their peak loads are equal and occur simultaneously (i.e. their loads are symmetric and *LSR = 1*). Two curves are shown, one for the assumption that all terminals are multi-RAT, and the other curve for the assumption that all terminals single-RAT. A multi-RAT terminal can operate on both 3G and 4G systems, while a single-RAT terminal is either exclusively 3G or exclusively 4G and can only use the spectrum assigned to that generation of technology. In practice there is likely to be a mix of multi-RAT and single-RAT terminals in use and, consequently, the multi-RAT terminals assumption leads to an overestimate of the overall network performance, while the single-RAT terminals assumption results in underestimation. For the year 2025 it is assumed that 3G technology no longer operates, so the multi-RAT and single-RAT curves converge i.e. all terminals will operate on the same technology.

In Figure 4, the *SSD* is effectively zero until 2012 because network planning is mostly coverage-oriented and, in order to provide coverage to (nearly) all terminals at 2100 MHz, operators can be assumed to build more (smaller) cells than are required in a strictly capacity limited system. In 2012 the introduction of UMTS 900 results in much improved cell coverage. The cell size (and number) is now dictated by the required capacity (i.e. cell edge throughput) and the *SSD* peaks. Over time, individual operator loads and capacities increase substantially and the 'trunking gain' benefits of sharing spectrum with another operator diminish. By 2025 these have reduced the *SSD* to 1.3%. (Note that, for brevity, the *SSD* results for urban propagation have not been plotted. Coverage is more difficult to achieve in urban conditions and it would be 2025 before cell densities would be dictated by capacity rather than coverage. SSD^*_{urban} in 2025 would equal $SSD^*_{suburban}$ for that year.)

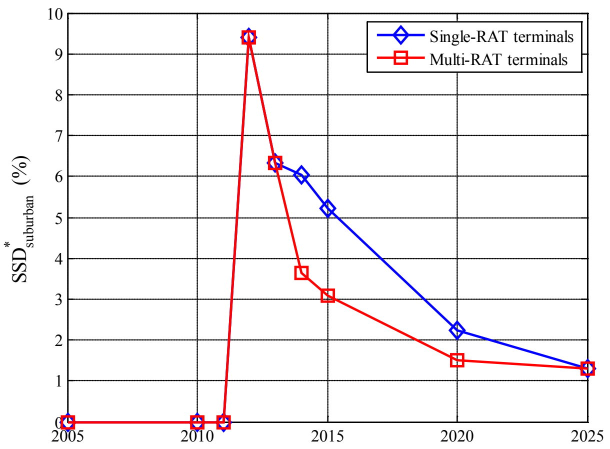

Figure 4: Spectrum sharing dividends for multi- and single-RAT terminals in a suburban propagation environment, assuming symmetric operator loads.

The predicted value of *SSD* is sensitive to the assumptions concerning the availability of spectrum, spectral efficiency and the required cell edge throughput. Table 4 shows the *SSD*'s sensitivity to these factors using the 2025/4G/suburban scenario as a reference. It is noted that in the table, load, spectrum and throughput target values are expressed relative to the 2025/4G/suburban reference scenario.

Note that the 2025 scenario is almost entirely capacity-limited, i.e. the cells are sufficiently small that coverage is no longer as issue. Doubling the assumed available spectrum (or the assumed spectral efficiency) results in a doubling of cell processing capacity and the *SSD* is halved (because there is less 'trunking gain' to be achieved by sharing spectrum. Halving the spectrum or spectral efficiency doubles the *SSD*. Similarly, doubling the assumed cell edge throughput target results in a doubling of the *SSD*. Halving the throughput requirement halves the *SSD*. The effects on *SSD* of spectrum (spectral efficiency) expectations and throughput requirements are seen (in the final two rows of Table 4) to compound.

Interestingly, changing the load per square kilometer has no effect on *SSD* in a capacity limited cellular environment. This is because the required cell areas are adjusted in inverse proportion to the load/km^2 so that the load in each cell remains constant and the throughput requirements are (just) met i.e. the number of cells required for the sharing and non-sharing systems scale by the same factor and the *SSD* is unchanged.

The results presented in Figure 4 and Table 4 assume that the operators sharing spectrum have symmetric loads i.e. their peak loads occur at the same time; and hence the peak combined load of the sharing operators is the sum of the operator peak loads (*LSR* = *1*). In practice the operator peak loads may not coincide and the Load Symmetry Ratio will be less than 1. Figure 5 illustrates the importance of the *LSR* by showing *SSD* curves for four different *LSR* values (1, 0.9, 0.8, 0.7) for the multi-RAT scenario plotted (for *LSR* = 1) in Figure 4. In the year 2025 the cellular systems will be almost entirely capacity limited and the number of cells required by a solo operator of a cellular system will be proportional to the operator's peak system load. Similarly, the number of cells required by operators sharing spectrum will be proportional to their peak combined load. Given the definition of *LSR*, it is easy to show that,

$$SSD = (1 - LSR) + LSR \times SSD_{sym},$$

With SSD_{sym} the SSD that would result if *LSR* = *1*. Although SSD_{sym} is low in 2025 (i.e. 1.3%), spectrum sharing remains beneficial for operators with loads that peak at different times. For these operators the *SSD* will be greater than *1* - *LSR*.

Table 4: Sensitivity of *SSD* to load, spectrum availability (~ spectral efficiency), and cell edge throughput target.

LOAD	SPECTRUM	R_j^*	SSD	COMMENT
1	1	1	1.3%	reference case
0.5	1	1	1.3%	half load
2	1	1	1.3%	double load
1	0.5	1	2.7%	half spectrum
1	2	1	0.7%	double spectrum
1	1	0.5	0.7%	half throughput
1	1	2	2.7%	double throughput
1	2	0.5	0.3%	worst SSD
1	0.5	2	5.5%	best SSD

V. CONCLUDING REMARKS

In this paper we have presented and applied an assessment approach to quantify the benefits in terms of reduced deployment costs associated with spectrum sharing in an infrastructure-shared environment. Considering realistic scenarios, we have estimated the evolution of the derived 'spectrum sharing dividend' as traffic loads, radio access technologies, spectrum availability and performance targets change over time.

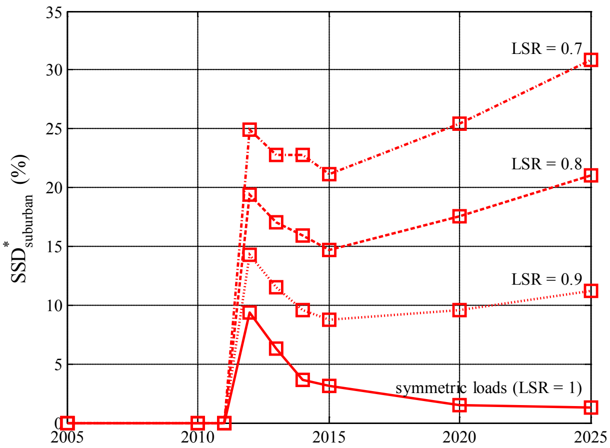

Figure 5: The effect of the operator load symmetry ratio on the spectrum sharing dividends assuming multi-RAT terminals and a suburban environment.

In case a cellular network deployment is 'coverage-limited' the number of cells required in the system is essentially determined by the propagation range of the frequency bands used, and there are no significant spectrum sharing dividends. When traffic densities increase sufficiently, a cellular system will become 'capacity-limited' and there will be a benefit in sharing spectrum with another operator. If the operators traffic loads are symmetric (i.e. peak simultaneously) then the benefit of sharing spectrum diminishes as operator loads and service capacities continue to grow. However, when operators' loads peak at different times they will always benefit from sharing spectrum and spectrum sharing dividends can be sizeable.

These insights can assist operators and regulators in their assessment of the merit of spectrum sharing. In this light, we have recently been allowed to present these findings at the ECC's (Electronic Communications Committee) 'Working Group Frequency Management' (WG FM), is responsible for developing strategies, plans and implementation advice for the management of the radio spectrum in Europe.

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