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Cost Benefit Analysis: Evaluation among the Millimetre Wavebands and SHF Bands of Small Cell 5G Networks

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Abstract**—**This article discusses the benefit cost analysis aspects of millimetre wavebands (mmWaves) and Super High Frequency (SHF). The devaluation along the distance of the carrier-to-noise-plus-interference ratio with the coverage distance is assessed by considering two different path loss models, the two-slope urban micro Line-of-Sight (UMiLoS) for the SHF band and the modified Friis propagation model, for frequencies above 24 GHz. The equivalent supported throughput is estimated at the 5.62, 28, 38, 60 and 73 GHz frequency bands and the influence of carrier-to-noise-plus-interference ratio in the radio and network optimization process is explored. Mostly owing to the lessening caused by the behaviour of the two-slope propagation model for SHF band, the supported throughput at this band is higher than at the millimetre wavebands only for the longest cell lengths. The benefit cost analysis of these pico-cellular networks was analysed for regular cellular topologies, by considering the unlicensed spectrum. For shortest distances, we can distinguish an optimal of the revenue in percentage terms for values of the cell length, R ≈ 10 m for the millimeter wavebands and for longest distances an optimal of the revenue can be observed at R ≈ 550 m for the 5.62 GHz. It is possible to observe that, for the 5.62 GHz band, the profit is slightly inferior than for millimetre wavebands, for the shortest Rs, and starts to increase for cell lengths approximately equal to the ratio between the break-point distance and the co-channel reuse factor, achieving a maximum for values of R approximately equal to 550 m.

Keywords**—**5G, millimetre wavebands, super high-frequency band, SINR, signal-to-interference-plus-noise ratio, cost benefit analysis.

I. Introduction

Cellular planning can be optimized by studying the system's performance concerning its fundamental parameters. This work compares the carrier-to-noise-plus-interference ratio (SINR or CNIR) and the supported throughput for millimetre wavebands (mmWaves) and SHF band within the framework of 5G New Radio (NR) mobile networks while considering the linear and Manhattan grid topologies as in [1], as shown in Fig. 1, where reuse pattern K = 3 is assumed.

In this work, aiming at evaluating the proposed deployments, two propagation models are considered: the two-slope propagation model, for the SHF band [2], and the modified Friis propagation, at mmWaves.

The general description of 5G NR was given by Rel. 15 of the Third Generation Partnership Project (3GPP) and allows for the deployment of a complete commercial network with a service-based architecture employing the concept of modularity [3], with the elements of the architecture, called network functions (NFs), offering their services via a common framework that will allow communications with speeds up to 2 Gbps, in both downlink and uplink directions.

Rel. 15 has also established two sets of frequencies identified as frequency range 1 (FR1) and frequency range 2 (FR2). FR1 comprises the sub-6 GHz frequency range (450-6000 MHz) while FR2 is the mmWaves (24250-52600 MHz). In this work, one considers carrier frequencies in both ranges and a bandwidth of 100 MHz that allows for a total of 270 physical resource blocks (PRBs) with 60 kHz sub-carrier spacing. Besides, in order to map the minimum CNIR, $CNIR_{min}$, into the supported throughput, R_b, we have considered the values for $CNIR_{min}$ from 3GPP [4].

After obtaining the results for the system capacity of small cells, we study the benefit cost analysis aspects. It is possible to classify the system's cost into two parts, i.e., capital costs and operating costs. The first category considers fixed expenses such as spectrum auctions (where costs are null for unlicensed spectrum) and the number of Base Stations (BS) and transceivers per unit of area, while the second class considers the expenses to operate and maintain the system. Revenues depend on the price per MB and on the supported throughput.

The remainder of the paper is organized as follows. Section II starts by presenting a general description non-standalone 5G NR. Section III describes the path loss models for millimetre wavebands and SHF band. In Section IV, the CNIR is analysed. Section V addresses system capacity by studying the variation of CNIR and supported throughput with the cell length. In Section VI, the capacity/cost trade-off is addressed. Finally, conclusions are drawn in Section VII.

II. 5G NR

5G is expected to operate in backward compatibility with LTE/LTE-A in the non-standalone phase, considering both technologies, the cells could offer diverse or the same coverage. Within 5G NR deployment scenarios, among other topologies, it is possible to have a LTE/LTE-A eNB (evolved NodeB) as a master node, offering an anchor carrier that can

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be boosted by a NR gNB (Next-generation NodeB), with data flow aggregated by the evolved packet core (EPC) [5].

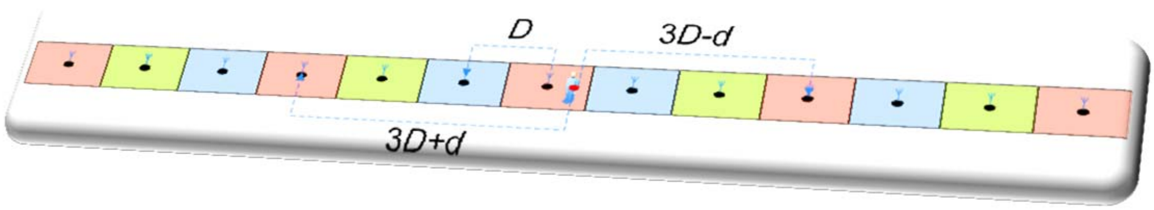

Fig. 1 Linear topology with cigar-shaped cells (downlink) and reuse pattern 3

The physical layer operation of NR is based on Orthogonal Frequency Division Multiplex (OFDM) with cyclic prefix (CP) for both downlink and uplink directions. Uplink communication also supports Discrete Fourier Transform-spread-OFDM (DFT-s-OFDM) and both channels are designed to be bandwidth agnostics [6], with their capacity being determined by the number of allocated PRBs, which is a function of the operating bandwidth and the sub-carrier spacing (SCS). As defined by 3GPP Rel. 15, the sub-frames of NR are composed of slots that comprise 14 OFDM symbols, with lengths of 1 ms and 15 kHz SCS.

III. Propagation Models

To define the behaviour associated to the path loss in Line-of-Sight (LoS), the ITU-R proposes to consider the two-slope propagation model that accounts for two-path fading, which occurs over longer distance, to optimize small cells in UMiLoS environments. Min and Bertoni identified that, as a result of the two-slope behaviour, smaller out-of-cell interference is obtained with the two-slope model, leading to, according to [7], system designs with different optima than are obtained using the single slope model.

The UMiLoS two-slope model is specified in the frequency range from 2 GHz to 6 GHz, as follows, as in [8]:

$$PL_{UMi\,LoS} = 22\cdot\log_{10}(d_{[m]}) + 28.0 + 20\log_{10}(f_{c[Hz]}),\ d < d_{BP} \quad (1)$$

$$PL_{UMi\,LoS} = 40\cdot\log10(d_{[m]}) + 7.8 - 18\log10(h'_{BS}) - 18\cdot\log10(h'_{UT}) + 2\log10(f_{c[Hz]}), d > d_{BP} \quad (2)$$

where h_{BS} = 10 m and street width 20 m, and the average building height 20 m, while $h'_{BS\,[m]} = h_{BS}$ -1 and $h'_{UT\,[m]} = h_{UT}$ -1. The break point distance d_{BP} is determined by:

$$d_{BP} = 4\cdot h'_{BS}\cdot h'_{UT}\cdot f_c/c \quad (3)$$

where f_c is the centre frequency, in hertz, $c = 3.0 \times 10^8$ m/s is the propagation velocity in free space. Consequently, $d_{BP\_UMi\_LoS}$ is 351 m at 5.62 GHz.

The path loss for the millimetre wavebands is defined by [1], [8]-[10]:

$$PL_{LoS\,[dB]}(d) = 20\log_{10}\left(\frac{4\pi}{\lambda}\right) + 10\cdot\bar{n}\cdot\log_{10}(d) + X_\sigma,\ d \geq 1\text{ m} \quad (4)$$

where X_σ is the typical log-normal random variable with 0 dB mean and standard deviation σ, in decibels (i.e., in reality, it is a zero-mean Gaussian distributed variable), that models shadow fading. In the mmWaves, d_{BP} is of the order of kilometers, and is not considered for small cells.

IV. Carrier-to-Noise-Plus-Interference Ratio

To understand how the service quality degrades while the user roams from the cell centre to the cell edge, it is extremely important to analyse the variation of CNIR in the downlink (DL) as well as throughout the cell for different frequency bands. The implicit formulation from [10] maps the CNIR into the values of the PHY throughput, R_b, at the corresponding MCS. Fig. 2 presents the variation of CNIR with the distance, d ($0 \leq d \leq R$), for R = 400 m. Table I shows the parameters considered in the computations. At the mmWaves, the shadow fading lognormal distribution with the zero mean and the standard deviation, $\sigma_{[dB]}$, is 0.004 at 28 GHz and 4.4 for the 38, 60 and 73 GHz bands (N.B. the latter two go beyond FR2). The propagation exponent for the mmWaves is $\gamma = 2.1$ for the 28 GHz frequency band and $\gamma = 2.3$ for the 38, 60 and 73 GHz bands.

TABLE I
Parameters Considered in the Analysis [3]

Band	mmWaves	SHF
Transmitter Power (DL)	-16.9897 dBW	-0.3047 dBW
Transmitter gain	5 dBi	5 dBi
Receiver gain	0 dBi	0 dBi
Bandwidth	100 MHz	
Noise Figure	7 dB	
Height (**BS**)	9 m	
Height (User Equipment)	1.5 m	

In the SHF band, the UMiLoS two slope model establishes that the propagation exponent is $\gamma = 2.2$ for Rs shorter than d_{BP}, while for Rs longer than d_{BP} the propagation exponent is $\gamma = 4$.

For R = 400 m, the 5.62 GHz band achieves higher CNIR, followed by the 28, 38, 73 and 60 GHz frequency bands. The 60 GHz frequency band shows worst cellular coverage owing to the O_2 absorption excess. For R = 40 m, Fig. 3 shows that the SHF band performance is the worst while at 60 GHz the performance is excellent due to the reduction of interference (O_2 absorption).

V. Supported Throughput and System Capacity

Fig. 4 represents the curves for the supported throughput as a function of the coverage distance (not d), as in [1], [10], obtained for the 5.62 GHz frequency band and for 28, 38, 60 and 73 GHz mmWaves bands, where R varies up to 1000 m.

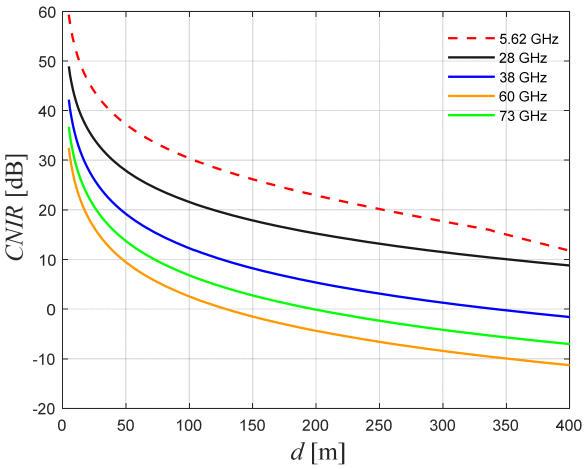

Fig. 2 Variation of the CNIR with the distance d for the 5.62, 28, 38, 60 and 73 GHz frequency bands for R = 400 m

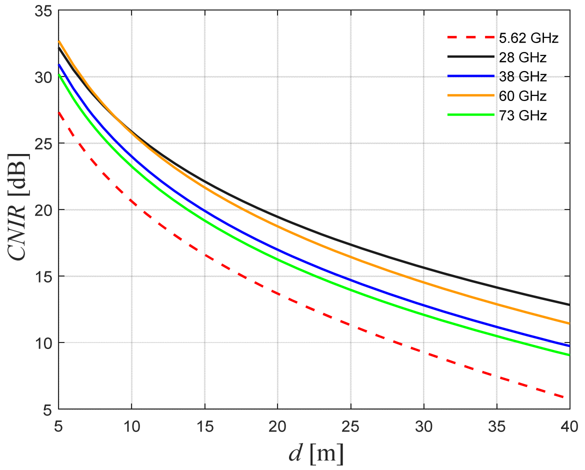

Fig. 3 Variation of the CNIR with the distance d for the 5.62, 28, 38, 60 and 73 GHz frequency bands for R = 40 m

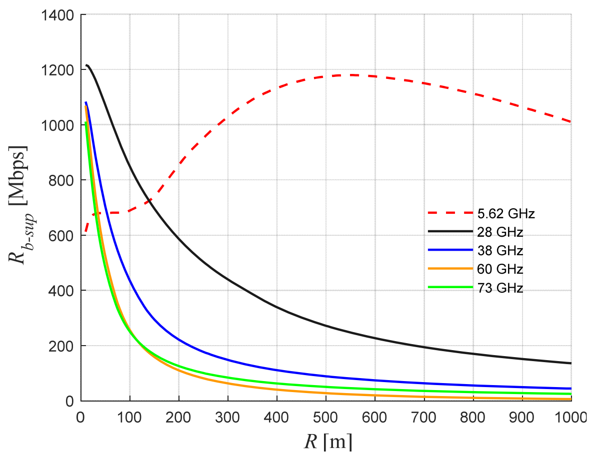

Fig. 4 Variation of the supported throughput for 5.62, 28, 38, 60 and 73 GHz frequency bands and R_{max}=1000 m

It is observed that the supported throughput is higher for the 28, 38, 60 and 73 GHz frequency band compared to the 5.62 GHz frequency band for distances up to approximately 140, 75, 50, 45 m respectively.

VI. Economic Trade-Off

To analyse the cost/revenue trade-off, the models from [11] and [12] have been considered. The revenues per cell, $(R_v)_{cell[€]}$, can be achieved as a function of the throughput per BS $thr_{BS[\text{kbps}]}$, and the revenue of a channel with a data rate $R_{b[\text{kbps}]}$, $R_{rb[€/\text{MB}]}$, and T_{bh} corresponding the equivalent duration of busy hours per day [11], $R_{v\,cell[€]}$ can be obtained by:

$$(R_v)_{cell[€]} = \frac{thr_{BS[\text{kbps}]} \cdot T_{bh} \cdot R_{rb[€/\text{MB}]}}{R_{b[\text{kbps}]}} \quad (5)$$

Revenues are considered in annual basis, where we considered six busy hours per day (saturation conditions), 240 busy days per year [10], and the price of a 144 kbps "channel" per minute (corresponding to the price of ≈ 1 MB), considering $R_{144\ \text{kbps}[€/\text{min}]}$ = 0.005, approximately 5 € per 1 GB. The revenue per cell can be obtained by:

$$(R_v)_{cell[€]} = \frac{thr_{BS[\text{kbps}]} \cdot 60 \cdot 6 \cdot 240 \cdot R_{rb[€/\text{MB}]}}{144_{[\text{kbps}]}} \quad (6)$$

Fig. 5 presents results for the revenue per cell per year, with R_b = 144 kbps, through variation of R for R_{max} = 1000 m. It is clear that 28 GHz band shows the highest revenue per cell of all frequency band for short distances, while the 5.62 GHz frequency band shows higher revenues for long distances, above R = 150 m. At mmWaves revenue decreases as the distance increases for all frequency bands.

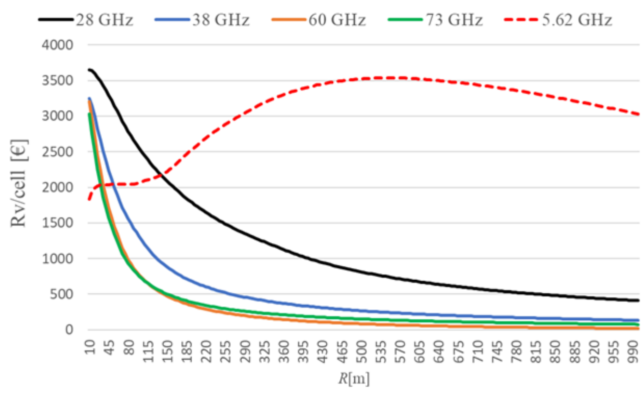

Fig. 5 Revenue per cell with R_b=144 kbps, 10 ≤ R ≤ 1000 m

The overall cost of the network per unit length, per year, $C_{0[€/\text{ul}]}$, can be expressed by:

$$C_{0[€/\text{km}]} = C_{fi[€/\text{km}]} + C_{fb} \cdot N_{c/\text{km}} \quad (7)$$

here C_{fi} is a fixed term cost, which we consider fix null costs. C_{fb} is a cost proportional to the number of BSs, and the number of cells per unit length is given by:

$$N_{C/\text{km}} = \frac{1}{2.R_{[\text{km}]} - \frac{w_{[\text{km}]}}{2}} \quad (8)$$

It is worth to note that the building block dimensions change with R, meanwhile, the side length is ($2R$-w), the variation in the area of the streets does not occur [1]. Nevertheless, the linearized curves of costs and profits of the network are not influenced, since only the street length is considered, instead of the area [11], [12].

We have considered the prices for the BSs operating at 60 and 73 GHz 20% higher than the prices for the ones at 28 GHz and 38 GHz, and 28/38 GHz 20% higher than the prices for the ones at 5.62 GHz due to, e.g., Si-Ge combined with CMOS (SG13C from IHP) technology can be applied for 28 GHz and 38 GHz [13] and will be cheaper.

The revenue per unit area per year, R_v, is obtained multiplying the revenue per cell by the number of cells per unit length, as:

$$R_{v[€/\text{km}]} = N_{c/\text{km}} \cdot (R_v) \cdot cell_{[€]} \quad (9)$$

$$R_{v[€/km]} = \frac{1}{2.R_{[\text{km}]} - \frac{w_{[\text{km}]}}{2}} \cdot \frac{\text{thr}_{BS[\text{kbps}]} \cdot T_{bh} \cdot R_{rb[€/\text{min}]}}{R_{b[\text{kbps}]}} \quad (10)$$

C_{fb} is given by:

$$C_{fb[€]} = \frac{C_{BS} + C_{Inst} + C_{Bh}}{N_{years}} + C_{M\&O} \quad (11)$$

C_{fb} can be obtained by the assumptions present in Table II, for five-year project duration.

Fig. 6 shows the global cost per unit length per year, C_0, and the revenue per unit length per year, considering all the parameters from Table II, and the respective price per minute considered in all calculations.

The revenues are higher than costs for 5.62, 28, and 38 GHz bands, differently from the 60 and 73 GHz bands (for the studied distances), where for the longest distances the cost becomes higher than revenue. One observes higher revenues per unit length for the mmWave bands (28 and 38 GHz) for short distances (up to 140 m in average) and higher revenues per unit length for the 5.62 GHz band for the longest distances.

The profit, P_{ft}, is a metric that needs to be optimized to enhance the network efficiency, and is given by the difference between revenues and costs, in €/km, while the profit in percentage is given by the net revenue normalized by the cost:

$$P_{ft[€/\text{km}]} = ((R_v)_{[€/\text{km}]} - C_{0[€/\text{km}]})/C_{0[€/\text{km}]} \quad (12)$$

TABLE II
ASSUMPTIONS FOR BS COSTS FROM [12] TABLE TYPE STYLES

Parameters	Values [€] mmWaves	Values [€] SHF
Initial costs:		
BS price, C_{BS}	3000 /6000	2500
Installation, C_{Inst}	200	200
Backhaul, C_{Bh}	2000	2000
Annual Cost:		
Fixed, C_{fi}	0	
Op. and maint., $C_{M\&O}$	250	

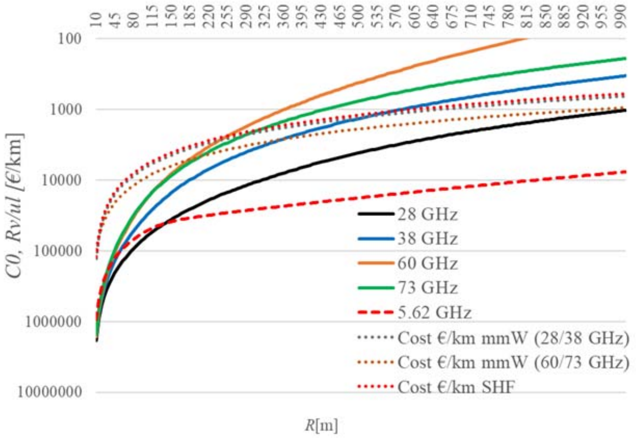

Fig. 6 Network revenue/cost per unit length per year as a function of R, with R_{max} = 1000 m

Fig. 7 shows the profit in percentage, instead of the absolute profit, because this is a more relevant metric for operators and service providers [12]. If $R_{v[€/\text{km}]}$-$C_{0[€/\text{km}]}$ is positive, there will be a positive profit.

For the studied distances, only 5.62 frequency band is entirely profitable, whereas, for 28, 38, 60 and 73 GHz frequency bands, for distances longer than 300, 90, 33, 28 meters, respectively, the system becomes unprofitable (negative profit).

At 28 GHz, for distances up to 45 m, the profit is higher than 150%. For the 60 and 73 GHz frequency bands, the average profit is similar, while for distances longer than 115 m, the profit for the 73 GHz band is higher due to the highest system capacity (as the extra O_2 absorption additionally affects coverage at the 60 GHz frequency band), even though 60 and 73 GHz show less profit due to higher BS costs. For 5.62 GHz band, the 5G system is going to sustain its profitability for longer distances.

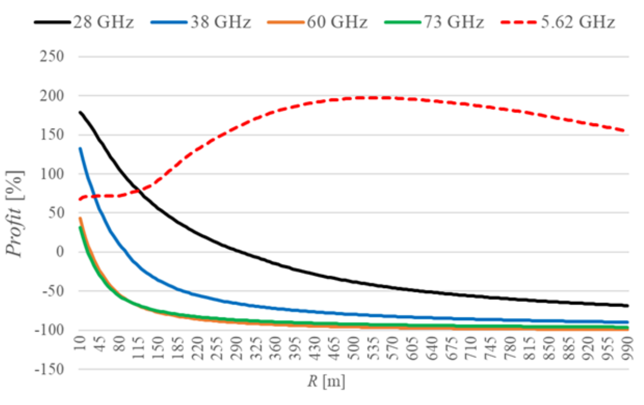

Fig. 7 Profit per unit length per year, R_{max} = 1000 m

The results are a key point for operators and service providers to enhance their incomes whilst improving the system for coverage distances up to 45 m for mmWaves, and longer than 150 m for 5.62 GHz frequency bands, aiming at increasing the profit in percentage.

VII. Conclusion

In this work, we compare the benefit cost analysis aspects between the millimetre wavebands and SHF band for mobile 5G NR cellular networks. 5G technical specifications are considered to perform the mapping between carrier-to-noise-plus-interference and modulation code schemes to obtain the supported throughput for both bands.

By considering reuse pattern K = 3 and a linear topology as in [14], results for the SHF band show that the supported throughput increases for the longest distances, while for the millimetre wave bands, the supported throughput decreases for the longest radii, up to the maximum considered value of 1000 m, with the highest values being obtained at the 28 GHz frequency band. The 60 GHz frequency band only performs better than the 73 GHz band for Rs up to approximately 115 m, mainly due to the O_2 absorption excess. Regarding the economic trade-off, for the mmWaves, the 5G network shows a decreasing behaviour of the profit along with the distance. At the 5.62 GHz frequency band, the profit is very low for the shortest Rs and starts to increase at a distance equal to the ratio between the break-point distance and the co-channel reuse factor, achieving maxima for R equal to circa 550 m.

Computations show that, in the future, it is possible to install these types of structure when costs of installation and maintenance of the network decrease, enabling higher system capacity while reducing prices.

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