Assessment of Energy Savings in Relay-Assisted 5G and Beyond Radio Access Networks

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***Abstract*— Reducing the overall energy consumption in mobile networks is currently an important aspect that drives the evolution towards 5G and beyond systems, both for environmental and economic reasons. In this direction, the use of relay nodes, whose interest is recently revamping through different initiatives such as the Integrated Access and Backhaul, is considered because they can contribute to reducing the overall power consumption thanks to improving the overall coverage conditions in the network. Then, this paper presents an assessment of the energy efficiency improvements and energy savings that can be achieved through the use of relays considering a realistic scenario of a university campus. The paper studies the different aspects that influence on these energy savings, such as the required bit rates and the power consumption model parameters.**

Keywords*— *Beyond 5G, relays, energy efficiency, energy savings.

I. Introduction

Energy consumption is becoming a big concern in mobile communications industry. Mobile networks are estimated to represent about 0.2% of global carbon emissions and about 0.6% of global electricity use [1]. Besides that, running mobile networks has an approximated annual energy cost of 25 billion dollars, and the energy consumption is responsible for 20-40% of the operational expenditure (opex) [1]. The demand on these networks will continue growing as a consequence of the massive wireless traffic increase, with a higher number of users that require larger data rate services such as video sharing, eXtended Reality (XR) and gaming. Furthermore, the evolution towards beyond 5G technologies will also bring higher energy consumption requirements as a result of, among others, the use of higher frequency bands such as mmWaves, which involve a reduction in terms of coverage.

In this context, finding solutions to achieve energy efficient communication systems constitutes a big challenge for Mobile Network Operators (MNOs), both for environmental and economic reasons. This is why the research on this matter is growing, as an attempt to identify and develop technologies and strategies to reduce energy consumption and achieve greener mobile networks. For example, the authors in [2] surveyed energy efficiency enabling technologies available in the framework of 5G Radio Access Networks (RAN), reporting different studies in the references therein. In turn, [3] and references therein explore the application of Artificial Intelligence (AI) techniques to manage networks and improve the energy efficiency towards green 6G. The development of sustainable and green 6G networks is also a subject of research in recent projects such as the BeGREEN project (https://www.sns-begreen.com/), which targets the development of different mechanisms for reducing the power consumption at the RAN, or the 6GREEN project (https://www.6green.eu/), which targets the design of a service-based and holistic ecosystem that enables the reduction of the carbon footprint in 5G and 6G networks and vertical applications.

Additionally, in views of the widespread deployment of 5G and beyond technologies, an opportunity to develop energy efficient networks arises as long as they are consciously planned and operated. In this respect, the usage of relay nodes has been envisioned as a key technique to enhance mobile networks as it allows improving the coverage and capacity of wireless systems in high density areas while also reducing the number of base stations (BSs) that need to be deployed. The location of relays in strategic positions that improve the propagation conditions of the involved links also leads to a reduction of the transmission power, therefore generating notable energy savings. In fact, although relaying technology has been considered in literature as a way to assess these issues for several years (see e.g., [4][5]), the interest for relays has recently reemerged as a result of various Third Generation Partnership Project (3GPP) initiatives such as the Integrated Access and Backhaul (IAB) relaying technology which consists in providing flexible wireless backhauling using 5G new radio (NR) technology [6], or the inclusion of User Equipment (UE)-to-Network Relaying as a connectivity model in 3GPP Release 18 [7].

Several studies have recently shown the potential of relay nodes for enhancing the operation of wireless networks. In [8] the authors propose a digital twin architecture to support the dynamic placement of relay stations with the aim of enhancing coverage in a mmWave service area. Moreover, the authors in [9] study the coverage probability improvement of a mmWave network by means of relay nodes. Furthermore, in [10] the authors planned the optimum location of relay nodes to achieve the best coverage at cell edge with the minimum cost, considering the interference caused by the relays. In turn, the authors in [11] analyze the energy efficiency of UE-to-Network relay-assisted Device-to-Device (D2D) communications, and show the achieved reduction in energy consumption compared to conventional LTE networks. Other studies have addressed different techniques to ensure an energy-efficient operation of a network with relay nodes. For example, the authors in [12] study the optimization of the transmission power and time allocation, while also analyzing the optimal relay position in bidirectional relay communications, in order to improve the system's spectral efficiency and energy efficiency. Moreover, in [13] an artificial neural network is used for resource allocation and relay selection maximizing the tradeoff between energy efficiency and spectral efficiency.

This paper analyses the power consumption and energy efficiency improvements that can be obtained through the use of relay stations in 5G and beyond systems. To that end, it analyses the energy saving percentages and energy efficiency improvements by means of simulations that recreate a real scenario corresponding to the UPC Campus Nord in Barcelona and studies the impact that individual variables have on the obtained results, such as the required bit rates or the parameters of the power consumption model. Thus, the main contribution of the paper is to provide a focused quantitative assessment of energy savings in contrast to recent studies like [8][9][10], which put the focus on the use of relays to enhance coverage of wireless networks without considering energy efficiency aspects, [11] that was only focused in D2D communications, or [12] and [13] that elaborate specific optimization problems involving relays.

The paper is organized as follows. Section II describes the considered power and energy consumption model. Section III presents the scenario in which the simulations have been carried out, as well as the obtained energy saving and energy efficiency values. Finally, Section IV summarizes the obtained conclusions and outlines ideas for future work.

II. Power Consumption Model

This section presents the power consumption model considered in the performed studies. First, the required transmitted powers at the BS and the relay to support a given minimum bit rate are formulated, and next, the total power consumption is defined. Finally, the energy efficiency and energy saving metrics are derived.

Let us consider a downlink (DL) communication between a BS and a UE that requires a specific bit rate R. As shown in Figure 1, two possible ways to establish this communication are considered. The first one is the direct link between the BS and the UE, while the second possibility consists in using a relay node to split the connection in two distinct links, one between the BS and the relay and another between the relay and the UE. Out-of-band relaying is assumed [14], which means that the BS-Relay and the Relay-UE links operate in different frequencies.

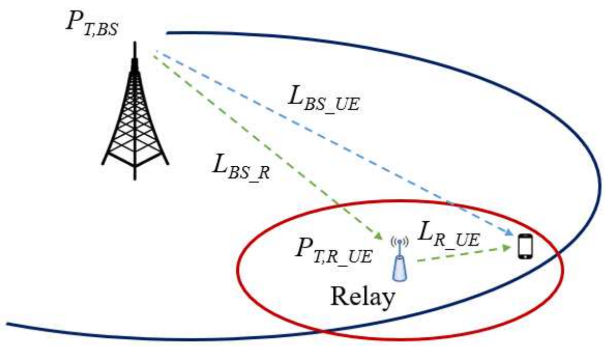

Figure 1. Considered downlink communication scheme.

Focusing first on the direct link between the BS and the UE, the Signal to Noise Ratio (SNR) is defined as:

$$SNR_{BS\_UE} = \frac{P_{T,BS\_UE} G_{BS} G_{UE}}{P_{N,UE} L_{BS\_UE}} \quad (1)$$

where P_{T,BS_UE} refers to the BS transmission power and $P_{N,UE}$ refers to the noise power at the receiver of the UE over a given bandwidth B. G_{BS} and G_{UE} are the antenna gains at the BS and UE, respectively, while L_{BS_UE} is the total propagation loss including path loss and shadowing in the link BS-UE. Interference from other cells is assumed to be mitigated through appropriate interference coordination mechanisms, so it is not considered.

The achievable bit rate is defined by the Shannon formula as follows:

$$R = B \cdot \varepsilon \log_2 (1 + SNR) \quad (2)$$

where ε is a factor 0<ε≤1 that accounts for the overheads associated to cyclic prefix, reference signals, control plane signaling, etc. Then, the needed BS transmission power to guarantee a bit rate R can be derived from (1) and (2) as

$$P_{T,BS\_UE} = \left(2^{\frac{R}{B \cdot \varepsilon}} - 1 \right) \frac{P_{N,UE} L_{BS\_UE}}{G_{BS} G_{UE}} \quad (3)$$

The power consumption is then computed following the model proposed in [15], which assumes that the relation between the BS transmission power and the power consumption of a BS is nearly linear, that is:

$$P_{TOT_D} = a_{BS} P_{T,BS\_UE} + P_{0,BS} \quad (4)$$

where $P_{0,BS}$ represents the BS power consumption at zero RF output power associated to circuits, signal processing, etc., and a_{BS} corresponds to the linear dependency between the total BS power consumption and the radiated power $P_{T,BS}$.

In case that the communication is performed through the relay, the consumed power can be derived in a similar way but now considering two distinct transmission powers, one for the BS-Relay link (P_{T,BS_R}) and another for the Relay-UE link (P_{T,R_UE}). Denoting the relay antenna gain as G_R and the propagation losses in the two links as L_{BS_R} and L_{R_UE} and assuming that the bandwidth in the relay-UE link is B_R, the noise power at the receiver of the relay is $P_{N,R}$ (measured over bandwidth B), the noise power at the receiver of the UE is $P_{N,R,UE}$ (measured over bandwidth B_R), and the efficiency factor is ε_R, the required transmitted powers at BS and relay are, respectively:

$$P_{T,BS\_R} = \left(2^{\frac{R}{B \cdot \varepsilon}} - 1 \right) \frac{P_{N,R} L_{BS\_R}}{G_{BS} G_R} \quad (5)$$

$$P_{T,R\_UE} = \left(2^{\frac{R}{B_R \cdot \varepsilon_R}} - 1 \right) \frac{P_{N,R,UE} L_{R\_UE}}{G_R G_{UE}} \quad (6)$$

Then, the total power consumption in case of the communication through the relay is the aggregate of power consumption at the BS and at the relay, given by:

$$P_{TOT_R} = a_{BS} P_{T,BS\_R} + P_{0,BS} + a_R P_{T,R\_UE} + P_{0,R} \quad (7)$$

where a_R and $P_{0,R}$ are, respectively, the linear coefficient and the power consumption at zero RF power for the relay.

Based on the power consumption expressions, the energy consumption (J/bit) for the direct link (E_D) and for the case of using the relay (E_R) are given by:

$$E_D = \frac{a_{BS} P_{T,BS\_UE} + P_{0,BS}}{R} \quad (8)$$

$$E_R = \frac{a_{BS}P_{T,BS\_R} + P_{0,BS} + a_R P_{T,R\_UE} + P_{0,R}}{R} \quad (9)$$

The energy efficiency measured in bit/J corresponds to the inverse of the energy consumption:

$$EE_D = \frac{1}{E_D} \quad (10)$$

$$EE_R = \frac{1}{E_R} \quad (11)$$

And finally, the energy saving (*ES*) achieved by the use of the relay node with respect to the direct link is given by:

$$ES(\%) = 100 \cdot \left(1 - \frac{E_R}{E_D}\right) \quad (12)$$

III. PERFORMANCE EVALUATION

A. Scenario description

The simulations for this study were carried out by reproducing the scenario of the UPC Campus Nord in Barcelona. This university campus is a rectangular area of 335 m x 125 m (see Figure 2). It comprises 24 buildings of 3 floors. The building names are indicated in Figure 2. The real positions of the 3 closest BSs that provide 5G NR coverage to the campus were used to determine the path loss and shadowing at the different indoor and outdoor locations, with square pixels of 1m. For this purpose, the Urban Macro (UMa) propagation model of [16] was used. The BSs operate at frequency 3.72 GHz in band n78 using Time Division Duplex (TDD). The rest of simulation parameters are given in Table I.

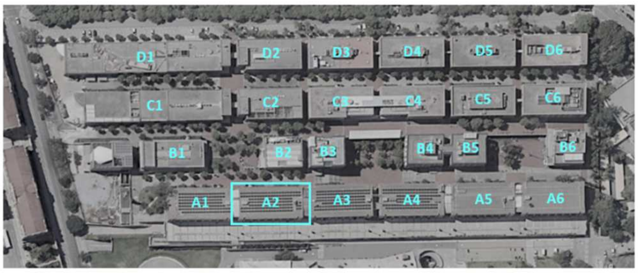

Figure 2. Evaluation scenario at the UPC Campus Nord.

The factor ε is defined as follows:

$$\varepsilon = \frac{14}{15}(1 - OH)\,\alpha_{TDD} \quad (13)$$

where the term 14/15 reflects the ratio between the useful time of the OFDMA symbols in 5G NR with respect to the total time including the cyclic prefix. The term *OH* corresponds to the overhead associated to physical control signals (e.g. reference signals, physical downlink control channels, etc.). For the DL in sub-6 GHz frequencies this term is *OH*=0.14 according to [17]. The term α_{TDD} is the ratio of DL OFDMA symbols in TDD, which equals 52/70 based on the recommended configuration in [18].

First, a global assessment of the spectral efficiency conditions at the different locations of the Campus was conducted assuming a fixed transmitted power of the BSs of 38 dBm and without any relay. The obtained results reflect that there are poor spectral efficiency values (i.e. lower than 1 b/s/Hz) in the ground floor of 18 buildings, the first floor of 15 buildings and the second floor of 11 buildings. Overall and not surprisingly, indoor coverage holes are quite frequent in the Campus, an effect that is exacerbated at ground floor level given that coverage is provided through macrocells on rooftops of buildings in the surroundings of the Campus. To alleviate the problem, the deployment of relays is considered in this paper.

TABLE I. SIMULATION PARAMETERS

Parameter		Value
Propagation Model	BS	UMa [16]
	Relay	InH [16]
Antenna Gain	BS	G_{BS} = 10 dB
	Relay	G_R = 3 dB
	UE	G_{UE} = 3 dB
Bandwidth	BS	B_{BS} = 20 MHz
	Relay	B_R = 20 MHz
Noise Power	BS-UE link	$P_{N,UE}$ = -92 dBm
	BS-Relay link	$P_{N,R}$ = -92 dBm
	Relay-UE link	$P_{N,R,UE}$ = -92 dBm
Efficiency factor (ε)	BS	ε_{BS} = 0.59
	Relay	ε_R = 0.59
Power consumption parameters	BS	a_{BS} = 28.4 [4]
		$P_{0,BS}$ = 156.38W [4]
	Relay	a_R = 20.4 [4]
		$P_{0,R}$ = 13.91W [4]

In order to illustrate the methodology followed to analyse in details the impact of the relay deployment in terms of energy efficiency, a representative example is presented, namely the ground floor of the A2 building highlighted in Figure 2. Figure 3 shows the spectral efficiency map at this floor including the relay position. The pixels in white represent areas with poor spectral efficiency lower than 1 bit/s/Hz. The relay was placed in one of the positions inside the building with sufficiently good spectral efficiency with the BS.

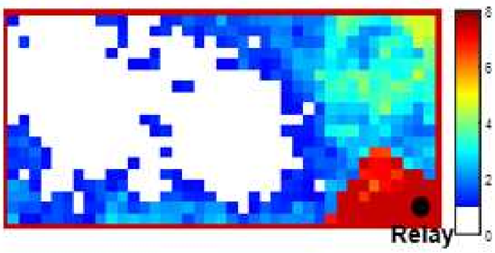

Figure 3. Spectral efficiency map of ground floor of A2 building in bit/s/Hz and position of the considered relay.

Considering now the relay, the power consumption model of Section II has been applied to determine the required transmitted powers at the BS and the relay to serve a UE that could be located in any of the pixels of the ground floor of the building. Then, for each pixel, the total power, the energy consumption and the energy efficiency were computed for the cases that a UE located at that pixel was connected directly to the BS or was connected through the relay. The Indoor Hotspot (InH) propagation model from [16] was applied to compute the propagation losses in the relay-UE link, operating at frequency 3.5 GHz, together with the rest of parameters of Table I. Results are discussed in the following sub-sections.

B. Assessment of energy savings

Figure 4 plots the cumulative distribution function (CDF) of the energy efficiency values obtained by considering all the pixels at the ground floor of the building under study, in the cases that the connection to the BS is done with and without relay and for the particular case where the bit rate required by the UE is $R = 50$ Mbps. As it can be observed, the energy efficiency varies throughout the building when there is no relay, and only about 12% of the positions of the area have an energy efficiency higher than 10^5 bit/J. With the introduction of the relay, however, the energy efficiency increases substantially and most of the positions achieve a value around $2.75 \cdot 10^5$ bit/J. The reason why the energy efficiency is maintained almost the same in all the positions when there is a relay is that the total energy consumption in this case is dominated by the energy used in the BS-Relay link. Instead, the transmission power needed at the Relay-UE link is much lower, and therefore it has little impact on the total energy consumption. Overall the results from Figure 4 show that 95% of the positions achieve an energy efficiency increase with the use of the relay. The remaining 5% of positions are those located close to the relay (i.e. at the lower right part of Figure 3), in which the direct link with the BS already experiences sufficiently good conditions, so UEs there do not need to connect to the relay.

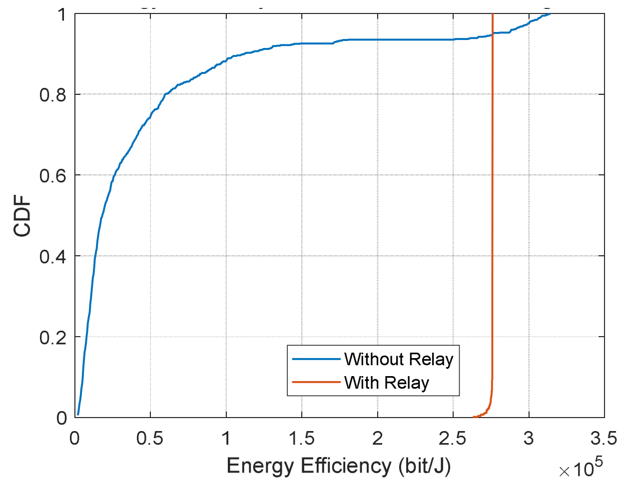

Figure 4. Energy efficiency CDF of the scenario under study for cases with and without relay.

To quantify the energy savings, Figure 5 shows the CDF of the energy saving percentage values obtained in the different pixels. It can be seen that about 93% of the positions achieve energy savings over 40%, and furthermore, savings over 80% are achieved in about 76% of the positions. In fact, only a 5% of the positions of the whole floor do not get any energy saving.

Figure 6 depicts a map with the energy saving percentage of each position. A comparison with the spectral efficiency map shown in Figure 3 allows checking that the highest energy saving percentages are associated to the positions with the lower spectral efficiency values (i.e. the white areas of Figure 3). On the other hand, positions with no energy savings are the ones that already had good spectral efficiency with respect to the BS, which also correspond to the area where the relay is located. In these positions, a suitable connectivity criterion would be to connect the UEs directly to the BS and not through the relay.

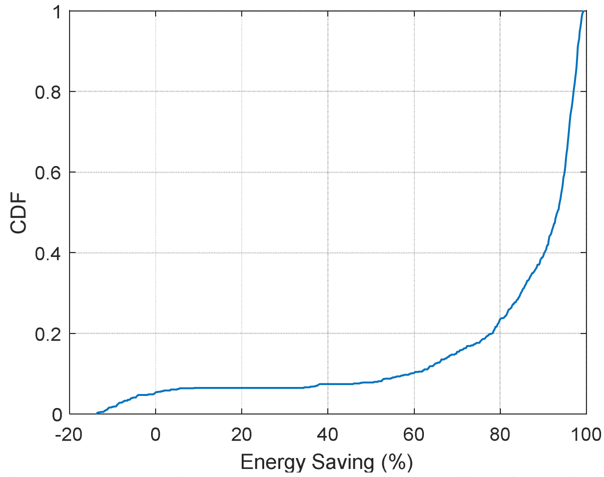

Figure 5. Energy saving percentage CDF at the scenario under study.

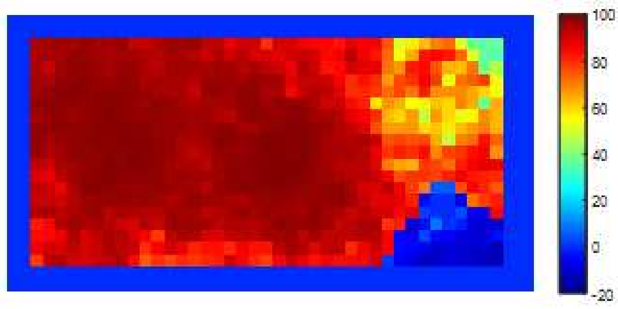

Figure 6. Map of the energy saving (%) in the scenario.

C. Sensitiviy analysis

The results in this section analyse how the energy savings obtained previously vary depending on the required bit rate value and the parameters of the power consumption model (i.e. $P_{0,BS}$, a_{BS}, etc.). Table II indicates the considered combinations of the power consumption parameters for the BS and the relay, selected based on references [4][19][20]. Combination 1 corresponds to the parameters used to obtain the results in section III.B.

TABLE II. POWER CONSUMPTION PARAMETER COMBINATIONS

	BS		Relay	
Combination	a_{BS}	$P_{0,BS}$ (W)	a_R	$P_{0,R}$ (W)
1	28.4	156.38	20.4	13.91
2			4	6.8
3	4.7	130	20.4	13.91
4			4	6.8
5	2.8	84	20.4	13.91
6			4	6.8
7	2.57	12.85	20.4	13.91
8			4	6.8

Figure 7 shows the resulting average energy savings across all positions of the ground floor in the considered building with the different combinations of power consumption parameters of Table II and for required bit rate values from 5 Mbps to 150 Mbps. It can be observed how the increase of the bit rate required by the user causes the energy saving percentage to grow until reaching a maximum of about 92%. The explanation for this effect is that the higher the bit rate required by the UE the bigger will also be the needed BS transmission power in the direct link, and the increase will be bigger when the UE is placed in locations with poor propagation conditions. However, when the relay is used, the BS transmission power increase is not so significant because the propagation conditions with respect to the relay are good thanks to its strategic location. Therefore, the higher the required bit rate, the bigger is the difference in energy consumption between both cases. Concerning the maximum limit of the energy saving that is observed in Figure 7 at around 92%, it is due to the positions with good spectral efficiency with respect to the BS, which cannot be further improved with the relay even if the required bit rate increases.

It can be also seen in Figure 7 that the chosen energy consumption parameter values impact significantly on the obtained energy savings, especially for lower bit rates. Checking the results for a bit rate of 50 Mbps, for example, the savings range between around 60% and 85% depending on the combination of parameters. In contrast, for a required bitrate of 5 Mbps only combinations 1 and 2 show remarkable energy savings of about 20%. These combinations involve a high scaling factor and circuit power consumption at the BS. Instead, the rest of the combinations show very little gains or even losses. For example, the combinations 7 and 8 that involve the lowest circuit power consumption per antenna (P_0=12.85W) present losses between 10% and 50%. As the required bit rate increases, the difference between the combinations is reduced, and for bit rates higher than 100 Mbps all the combinations result in practically the same savings.

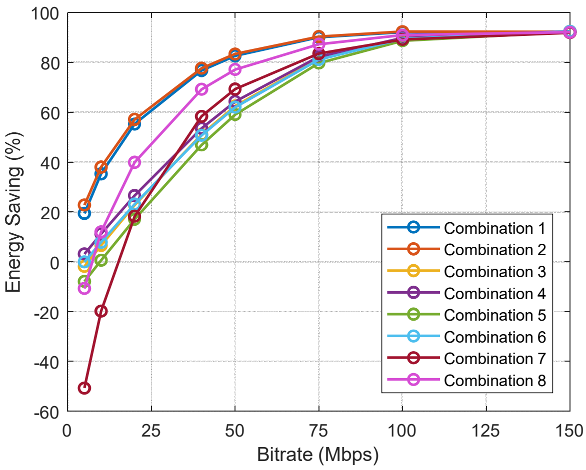

Figure 7. Average energy saving percentages obtained for different power consumption parameter combinations and required bit rates.

D. Analysis for different buildings

In order to draw firmer conclusions, the analysis has also been conducted in other buildings and floors of the campus. Figure 8 plots the energy savings that are obtained for a required bit rate of 50 Mbps with the combinations of power consumption parameters of Table II that provide the best and the worst savings (i.e. combinations 2 and 5, respectively) for a set of 10 different buildings and floors (see Figure 2 for the names of the buildings). Focusing first on the combination 2 that provides the highest energy savings, it is observed in Figure 8 that these range between approximately 70% and 85% depending on the considered building. In general, the buildings/floors with larger gains are those with more areas of poor propagation conditions in the BS-UE link. Regarding the combination 5 that provides the lowest energy savings, Figure 8 reflects that in this case the variation of the savings across buildings is between 43% and 60%, exhibiting a similar variation trend like the combination 2 but now with smaller savings.

Regarding the effect of the bit rate, a similar behaviour like the one observed in Figure 7 for the ground floor of A2 building has been found in the other analysed buildings, noting that the energy savings increase with the required bit rate. Overall, it is found that for bit rates approximately above 25 Mbps, there are positive energy savings for all the power consumption parameter combinations in all the analysed buildings, while for lower bit rates, some combinations can lead to losses. To assess the behaviour when increasing the bit rate, Figure 9 plots the average energy savings for different buildings when considering a required bit rate of 100 Mbps. It is observed that now the differences between buildings and between combinations become smaller than in the case of 50 Mbps of Figure 8. Specifically, for the combination 2, the variation of energy saving across buildings is between 86% and 96%, while for the combination 5 the energy savings vary between 74% and 92%.

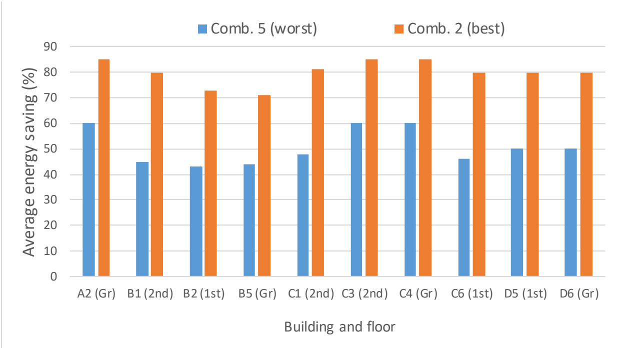

Figure 8. Average energy saving percentages for required bit rate 50 Mbps and different buildings.

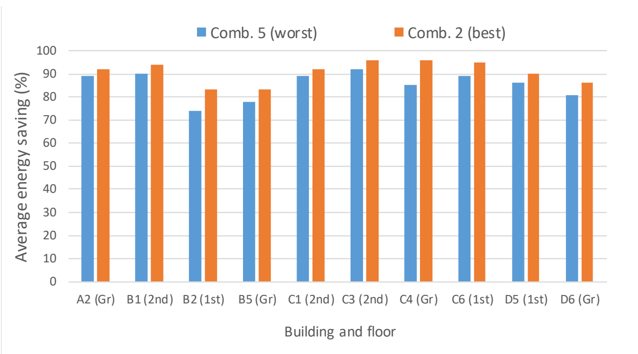

Figure 9. Average energy saving percentages for required bit rate 100 Mbps and different buildings.

IV. Conclusions and Future Work

The interest in using relays to enhance mobile networks is recently re-emerging as a result of recent initiatives such as the IAB and the UE-to-Network relaying. While the relay nodes have been traditionally considered as a tool to enhance the coverage conditions, they can also contribute to reduce the energy consumption in the network. In this direction, this paper has provided an evaluation of the energy savings and energy efficiency improvements achievable through the usage of relay nodes. The results have been obtained by means of simulations recreating a realistic scenario corresponding to the university campus of UPC in Barcelona, considering the real positions of the 5G NR base stations that cover the campus.

The performed analysis has demonstrated that, by properly placing relays in floors of buildings with poor indoor coverage conditions, significant energy savings can be found with respect to the case of not using a relay. These savings increase with the required bit rate and become relevant for bit rates approximately above 25 Mbps. Specifically, in global terms, considering different buildings and floors of the campus as well as different power consumption model parameters, the results have shown that, for a bit rate of 50 Mbps, average energy savings between 70% and 85% depending on the building have been found. In turn, when increasing the bit rate to 100 Mbps the savings range between 86% and 96%. The impact of the power consumption model parameters, namely the linear coefficient of the transmitted power and the power consumption at zero RF power, has also been studied. For the configuration with the parameters that provide the lowest improvements, energy savings for a bit rate of 50 Mbps vary between 43% and 60% depending on the building. This increases to a range between 74% and 92% for a bit rate of 100 Mbps.

Future research directions and challenges deriving from this work include the formulation and optimization of a connectivity criteria to decide in which conditions a UE has to be served by a base station or by a relay. Moreover, the energy savings achieved through relays can also be studied considering the impact of technological features at the base station such as massive MIMO. Besides that, energy savings and coverage enhancements achieved through relays can also be compared against those achieved with other similar technologies, such as the Reconfigurable Intelligent Surfaces.

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REFERENCES

[1] Ericsson. "Breaking the energy curve", 2022. Accessed: January, 2024. Available: https://www.ericsson.com/4aa14d/assets/local/about-ericsson/sustainability-and-corporateresponsibility/documents/2022/ breaking-the-energy-curve-report.pdf

[2] D. López-Pérez *et al.*, "A Survey on 5G Radio Access Network Energy Efficiency: Massive MIMO, Lean Carrier Design, Sleep Modes, and Machine Learning," in *IEEE Communications Surveys & Tutorials*, vol. 24, no. 1, First quarter 2022, pp. 653-697.

[3] B. Mao, F. Tang, Y. Kawamoto and N. Kato, "AI Models for Green Communications Towards 6G," in *IEEE Communications Surveys & Tutorials*, vol. 24, no. 1, First quarter 2022, pp. 210-247.

[4] R. Fantini, D. Sabella, M. Caretti, "An E3F based assessment of energy efficiency of Relay Nodes in LTE-Advanced networks", PIMRC, 2011.

[5] J. Pérez-Romero, O. Sallent, R. Agustí, "Energy Saving Potentials in the Radio Access through Relaying in Future Networks", European Conference on Networks and Communications (EuCNC), June, 2014.

[6] 3GPP TS 38.300 v18.0.0, "NR; NR and NG-RAN Overall Description; Stage 2 (Release 18)", December, 2023

[7] 3GPP TS 22.261 v19.5.0, "Service requirements for 5G system; Stage 1 (Release 19)", December, 2023.

[8] K. Tokugawa et al., "Design of mmW Digital Twin platform toward B5G/6G – High-Precision Measurement System and Relay Station Deployment–," 2022 IEEE 33rd Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), Kyoto, Japan, 2022, pp. 813-818.

[9] Belbase, K., Zhang, Z., Jiang, H., and Tellambura, C., "Coverage Analysis of Millimeter Wave Decode-and-Forward Networks With Best Relay Selection", IEEE Access, vol. 6, 2018, pp. 22670–22683.

[10] R. M. Mokhtar, H. M. Abdel-Atty and K. R. Mahmoud, "Optimization of the Deployment of Relay Nodes in Cellular Networks," in *IEEE Access*, vol. 8, 2020, pp. 136605-136616.

[11] A. F. E. Mohammed, M. H. Altayeb and N. I. Osman, "Evaluating the Energy Efficiency of UE-to-Network Relay Assisted Device-to-Device Communication," 2020 International Conference on Computer, Control, Electrical, and Electronics Engineering (ICCCEEE), Khartoum, Sudan, 2021.

[12] C. Cai, R. Qiu and X. -Q. Jiang, "Optimal Resources Allocation of Bidirectional Relay Communication," *2020 International Conference on Artificial Intelligence in Information and Communication (ICAIIC)*, Fukuoka, Japan, 2020, pp. 16-20.

[13] B. S. Khan, S. Jangsher, N. Hussain and M. A. Arafah, "Artificial Neural Network-Based Joint Mobile Relay Selection and Resource Allocation for Cooperative Communication in Heterogeneous Network," in IEEE Systems Journal, vol. 16, no. 4, Dec. 2022 pp. 5809-5820.

[14] 3GPP TR 36.912 v17.0.0 "Feasibility Study for Further Advancements for E-UTRA (LTE-Advanced) (Release 17)", March, 2022.

[15] EARTH project, "D2.3 - Energy efficiency analysis of the reference systems, areas of improvements and target breakdown", January, 2012, Accessed: May, 2024. Available: https://cordis.europa.eu/docs/projects/cnect/3/247733/080/deliverables/001-EARTHWP2D23v2.pdf

[16] 3GPP TR 38.901 17.0.0 "Study on channel model for frequencies from 0.5 to 100 GHz (Release 17)", March, 2022.

[17] 3GPP TS 38.306 v17.1.0, "NR; User Equipment (UE) radio access capabilities (Release 17)", June, 2022

[18] "5G TDD Synchronisation. Guidelines and Recommendations for the Coexistence of TDD Networks in the 3.5 GHz Range", GSMA, White Paper, Apr. 2020, Accessed: January, 2024. Available: https://www.gsma.com/spectrum/wp-content/uploads/2020/04/3.5-GHz-5G-TDD-Synchronisation.pdf

[19] E. Björnson, M. Kountouris and M. Debbah, "Massive MIMO and small cells: Improving energy efficiency by optimal soft-cell coordination," ICT 2013, Casablanca, Morocco, 2013.

[20] G. Auer et al., "How much energy is needed to run a wireless network?", in IEEE Wireless Communications, vol. 18, no. 5, October 2011, pp. 40-49.