Energy Saving Potentials in the Radio Access through Relaying in Future Networks

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Abstract—**The progressive deployment of cell sites in wireless networks to deal with the massive demand of wireless services experienced in the last years has led to a huge increase in energy consumption and associated operational expenditures for wireless network operators. As a result, significant research efforts are being recently devoted towards energy efficient wireless communications. The use of relay nodes that enhance coverage/capacity in wireless systems has been identified as a means to improve energy efficiency thanks to the associated reduction in transmit power. In this context, this paper presents the assessment of the energy savings that can be achieved by means of relaying in a wireless system. As a difference from prior works where the impact of relaying on energy efficiency is obtained as a result of multiple aggregated effects, the analysis performed in this paper will highlight, separately, the role played by each of the key elements influencing on the performance, such as the propagation and shadowing effects, the energy consumption model parameters and the influence of the bit rate and spectral efficiency.**

Keywords—energy consumption; relaying; wireless networks

I. INTRODUCTION

The massive demand of wireless services experienced during the last years with the high penetration of new generation wireless devices such as smartphones among the population has required the progressive deployment of more cell sites as well as new infrastructure equipment with enhanced data capabilities. As a result of this trend, the technological evolution has been accompanied by a huge increase in the associated energy consumption of deployed wireless networks. In [1] it was stated that the energy bill for a mobile operator accounted for roughly 18% of Operational Expenditures in a mature European market and increased up to 32% in other markets such as India. Therefore, techniques able to increase the energy efficiency of wireless systems have not only ecological benefits but can also lead to significant economic benefits [2]. Following this trend, several projects have addressed in the last years the research towards energy efficient wireless communications, such as EARTH [3], OPERA-Net [4], eWIN [5] or the GreenTouch initiative [6].

Moreover, the evolution towards novel 5G technologies will involve the requirement for a substantial increase of data rates in a factor between 10 and 100 [7] that will rely on increased spectrum efficiencies of associated technologies. However, from the perspective of energy consumption there is a trade-off between spectral efficiency (i.e. bit/s/Hz) and energy efficiency (i.e. J/bit) [8]. Therefore any increase in spectral efficiency to achieve larger bit rates has to be carefully balanced with the associated increase in energy consumption. Then, techniques able to provide such bit rates with enhanced energy savings will be of high interest in the development of future wireless systems.

Besides, the use of relay nodes is considered in LTE-A as a means to enhance coverage/capacity in wireless systems [9] and it is envisaged to play a key role in heterogeneous deployments and in future networks. In this respect, the reduction in transmit power resulting from the use of relays has been also identified in some works as a means to improve energy efficiency in wireless networks [10]-[14]. However, the assessment of the actual energy savings that can be achieved by means of these technologies are tightly coupled with the specific characteristics of the propagation conditions in the radio environment and with the consideration of accurate figures and models to assess the real power consumption of the different nodes involved in the network.

Several models exist in the literature to characterize the power consumption of a base station. In [3] the power consumption is modelled as a linear function of the RF transmission power associated to the base station load. It has been used in the analysis of different scenarios including relays [13][14]. In [15] a similar linear model is proposed that has also been used in several papers to evaluate the power consumption in cellular networks with different deployments [16][17]. In both cases, it is obtained that the power devoted to signal processing, circuits, etc. can be of the same order of magnitude, or even higher, than the RF transmit power. However, there exists a lot of disparity in the parameterization of the above models depending on the type of base stations.

Under the above framework, this paper presents the assessment of the energy savings that can be achieved by means of relaying in a wireless system. As a difference from prior works such as [10]-[14] where the impact of relaying on energy efficiency is obtained as a result of the multiple aggregated effects existing in a wireless network, the analysis performed in this paper will intend to highlight, separately, the role played by each of the key elements influencing on the performance, such as the propagation and shadowing effects, the energy consumption model parameters and the influence of the bit rate and spectral efficiency. This type of analysis that, to the authors' best knowledge, cannot be found in any of the previous references in the literature, should contribute to better identifying the specific scenario conditions leading to relevant energy savings when considering relay deployments.

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This paper is organized as follows. Section II presents the considered energy consumption model for a relay communication. Section III details the main elements of the reference scenario considered for the evaluation. Section IV presents the energy saving assessments that can be achieved under different parameters of the scenario, and finally conclusions are summarized in Section V.

II. Energy Consumption Model

Let consider a downlink communication in a wireless link intended to provide a mobile service with bit rate R to a certain User Equipment (UE). As depicted in Fig. 1 two possibilities are considered to set-up this communication. The first one is a direct link between the Base Station (BS) and the UE, located at distance d. The second one is the possibility to use a relay node located at distance d_1 from the BS and distance d_2 from the UE. An in-band relay [9] is considered that makes use of the same frequency for both the BS-Relay and the Relay-UE links. It is assumed that the relay devotes half of the time to receive the signal from the BS and half of the time to transmit the signal to the UE. Correspondingly, in order to provide the UE with a total bit rate R, the BS-Relay and the Relay-UE links need to transmit at bit rate $2R$.

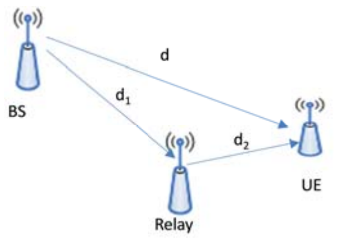

Fig. 1. System Model

Considering first the direct link BS-UE, the required transmit power to provide the bit rate R assuming Shannon bound is given by:

$$P_T = \left(2^{\frac{R}{B}} - 1\right)\frac{L_D(d)\cdot B\cdot I_o}{G_D G_m} \tag{1}$$

where B is the available bandwidth, G_D, G_m are the antenna gains of the BS and the UE, respectively, I_o is the noise and interference power spectral density and $L_D(d)$ is the total propagation loss in the direct link. This can be expressed in general terms as a function of frequency f and distance d as:

$$L_D = k_D f^{\beta_D} d^{\alpha_D} S_D \tag{2}$$

where k_D, β_D, α_D are the constants of the propagation model in the direct link and S_D is a log-normal random variable representing the shadowing with standard deviation σ(dB).

For assessing the energy consumption (J/bit) this paper considers the model proposed in [3][13] that assumes a linear relationship between the energy consumption and the transmit power. Then, for the case of the direct link the energy consumption is given by:

$$E_D = \frac{\Delta_D P_T + P_{o,D}}{R} \tag{3}$$

where $P_{o,D}$ represents the BS power consumption at zero RF output power associated to circuits, signal processing, etc., and Δ_D captures the dependency between the total BS power consumption and the radiated power P_T.

Focusing now on the relay link, the total energy consumption should account for the energy consumption at the BS associated to the BS-Relay link and the energy consumption at the Relay associated to the Relay-UE link. This is given by:

$$E_R = \frac{\Delta_D P_{TD1}}{2R} + \frac{P_{o,D}}{R} + \frac{\Delta_R P_{TR}}{2R} + \frac{P_{o,R}}{R} \tag{4}$$

where $P_{o,R}$, Δ_R are the power consumption parameters of the relay node, and P_{TD1}, P_{TR} are the transmit powers of the BS and the Relay to provide a bit rate $2R$ in the BS-Relay and Relay-UE links, respectively. These are given by:

$$P_{TD1} = \left(2^{\frac{2R}{B}} - 1\right)\frac{L_{D1}(d_1)\cdot B\cdot I_o}{G_D G_{DR}} \tag{5}$$

$$P_{TR} = \left(2^{\frac{2R}{B}} - 1\right)\frac{L_R(d_2)\cdot B\cdot I_o}{G_R G_m} \tag{6}$$

where G_{DR} is the antenna gain of the relay in the BS-Relay link, G_R is the antenna gain of the relay in the Relay-UE link and L_{D1}, L_R are the propagation losses in the BS-Relay and Relay-UE links, respectively, given by:

$$L_{D1} = k_{D1} f^{\beta_{D1}} d_1^{\alpha_{D1}} S_{D1} \tag{7}$$

$$L_R = k_R f^{\beta_R} d_2^{\alpha_R} S_R \tag{8}$$

where k_{D1},β_{D1},α_{D1},k_R,β_R,α_R are the propagation model constants and S_{D1}, S_R represent the shadowing in the two links.

The Energy Saving (ES) achieved by the use of the relay link with respect to the use of the direct link is then given by:

$$ES(\%) = 100\left(1 - \frac{E_R}{E_D}\right) \tag{9}$$

III. Reference Evaluation Scenario

The considered scenario for the evaluation of the energy savings achieved by relaying is a square area of 3 km × 3 km with the BS located at the upper left corner. The area is subdivided into square pixels with granularity 25 m.

The maximum RF transmit power of the BS is $P_{Tmax,BS}$=46 dBm and the BS antenna gain is G_D=14 dB. As for the relay, the maximum transmit power is $P_{Tmax,R}$=37 dBm and the antenna gains are G_{DR}=7 dB, G_R=5dB. The antenna gain at the mobile terminal is G_m=0 dB. Other parameters are f=2 GHz, I_o=-164 dBm/Hz.

The required bit rate R, the bandwidth B, the power consumption parameters Δ_D, $P_{o,D}$, Δ_R, $P_{o,R}$ and the parameters of the propagation models of (2)(7)(8) will be modified in the simulations as part of the conducted analysis. 2D spatially correlated shadowing will be considered. The shadowing standard deviation σ (dB) will be varied in different simulations. The decorrelation distance is d_{corr}=100m The generation of 2D spatially correlated shadowing follows the methodology of [18] based on filtering a set of independent shadowing samples using a 2D filter defined from the Fourier transform of the exponential autocorrelation function.

For assessing the ES that can be achieved in the scenario, we place the UE at each pixel and compute for each pixel the energy of the direct link E_D and the energy of the relay link E_R to serve this pixel for all possible locations of the relay node in the scenario. In this way, the ES can be computed for all possible combinations of distances d (BS-UE), d_1 (BS-Relay) and d_2 (Relay-UE) (see Fig. 1). Only the combinations where both the direct link and the relay link are feasible (i.e. the required transmit powers of the relay and the BS do not exceed the corresponding maximum levels $P_{Tmax,R}$ and $P_{Tmax,BS}$) are considered. Note that in the rest of combinations where at least one of the two options (direct link and/or relay link) cannot be established due to power limitations, the ES obtained from (9) does not make sense physically.

Results are presented in terms of the statistical distribution of ES (average, 5-th percentile and 95-th percentile) for different intervals of d and d_1 with granularity 400 m and 100 m, respectively.

IV. Results

A. Impact of Relay position

To gain a first insight on the ES that can be achieved let consider first the reference scenario with the same propagation model parameters for all the links given by $\alpha_D=\alpha_{D1}=\alpha_R=3.76$, $\beta_D=\beta_{D1}=\beta_R=2.1$, $k_D=k_{D1}=k_R=122.1$ dB that corresponds to a typical setting for a urban scenario [19]. With these parameters the propagation model of (2)(7)(8) is computed with f in GHz and d in km. No shadowing is considered initially. The power consumption parameters are taken from [13] as Δ_D=28.4, $P_{o,D}$=156.38 W for the BS and Δ_R=20.4, $P_{o,D}$=13.91 W for the relay. Required bit rate is R=12 Mb/s and bandwidth is B=5 MHz.

Fig. 2 plots the ES distribution for different values of the distances d and d_1 in the reference scenario if no shadowing was considered. Solid lines represent the average values while the upper/lower markers around the solid lines represent the 95-th/5-th percentiles, respectively. It can be observed how the energy saving increases with the distance d between the mobile and UE, but only for large distances (approximately d>2km) positive energy savings can be achieved by means of relaying. On the contrary, for low distances d (i.e., when the UE is close to the BS) no energy saving is obtained because the transmit power constitutes in this case a small contribution to the energy consumption that is limited by the circuit power (i.e., terms $P_{o,D}$, $P_{o,R}$). Then, given that in this case the relay is not saving energy through improved propagation conditions, it is more beneficial to use the direct link and avoid wasting circuit power at the relay node.

It can be also observed in Fig. 2 that for every value of d there is an optimum location of the relay to maximize the ES at around d_1=0.8d. As for the achievable energy savings, considering the case d=3 km, average ES of around 44% can be obtained if the relay is located at this optimum location, while the 95% percentile reaches up to around 49%.

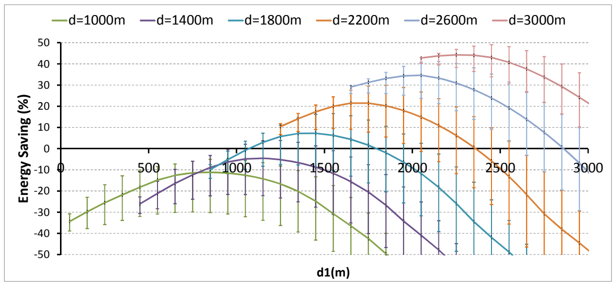

Fig. 2. Energy saving distribution (average, 5-th percentile, 95-th percentile) in the reference scenario without shadowing. Each curve corresponds to the distances d in the interval (d-200 m, d+200 m), and each value of d_1 to an interval (d_1-50 m, d_1+50 m).

B. Impact of Shadowing

Fig. 3 presents the ES distribution in the reference scenario with the same parameters as in previous subsection but including 2D spatially correlated shadowing in the propagation of the different links with σ=6 dB. 50 different realizations of the shadowing have been considered to evaluate the ES statistical distribution. Comparing Fig. 3 with Fig. 2 it can be realized that shadowing leads to a reduction in the average energy saving values for all distances d. However, there is a much larger dispersion in these ES values. To better quantify these two effects, Fig. 4 depicts the particular case for distances d=3 km, d_1=2.35 km, comparing the CDF (Cumulative Distribution Function) and the average values for the cases with and without shadowing. Moreover, different values of σ are included in the analysis. Focusing on the case σ=6dB, it can be observed how the average ES reduces from 44% to 13% when considering shadowing. However, the 95-th percentile increases from 48% to 75%. For larger values of σ the figure shows that the average ES is reduced but the 95-th percentile keeps more or less the same value. The larger deviation of the ES distribution actually reveals the potential of relaying to have large ES gains. In particular, the 95-th percentile reflects the existence of certain strategic relay positions where high ES values can be obtained (e.g. in 5% of the combinations ES values above 75% can be obtained) if the relay deployment takes into consideration the actual shadowing conditions existing in each location. In more practical terms, this means that in the case of e.g., a localized traffic hot-spot area, ES up to 75% might be achieved while providing service in this area through the smart placement of a relay node with improved shadowing conditions with respect to the direct link case.

C. Impact of different propagation conditions in the relay and the direct link

The reference scenario considered in the previous results assumed the same propagation model parameters for both the direct and the relay links. However, by a proper positioning of the relay, it is also possible that the propagation conditions in the BS-Relay link can be significantly better, e.g. in the case that LOS (Line Of Sight) exists between BS and relay nodes. To analyze the impact of this effect Fig. 5 plots the ES distribution in case that the propagation model assumes free space loss in the BS-Relay link, and when no shadowing is considered in the scenario. This corresponds to α_{D1}=2, β_{D1}=2, k_{D1}=92.44 dB. Comparing Fig. 5 with Fig. 2 similar effects are observed but now with much more significant gains (e.g. for the case d=3km achievable energy savings increase up to around 70% as opposite to the 44% of ES in Fig. 2). Similar conclusions are obtained when shadowing is considered, as observed in Fig. 6 that compares the CDF and the average values with shadowing of σ=6dB and without shadowing for the case d=3 km and d_1=2.55 km. In particular, when shadowing is considered the 95-th percentile of the ES reaches 82% (as opposite to the 75% in the reference case of Fig. 4). Similar trends would be obtained for other values of σ.

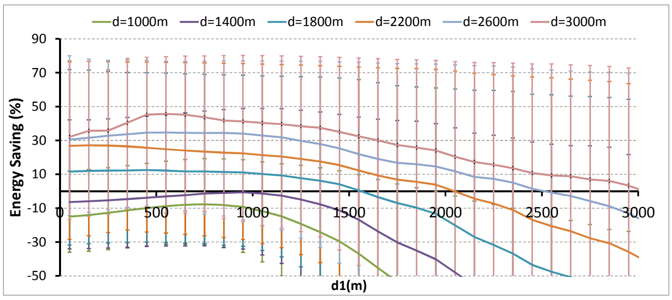

Fig. 3. Energy saving distribution (average, 5-th percentile, 95-th percentile) in the reference scenario with shadowing.

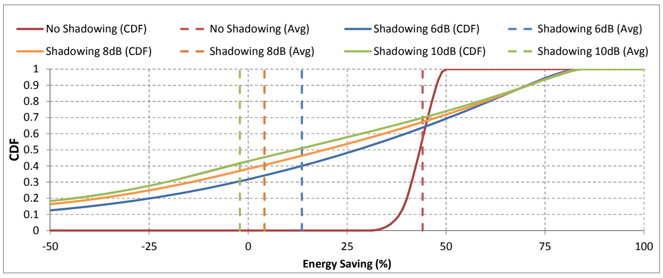

Fig. 4. Comparison between the ES distribution (Average and CDF) for the reference scenario with and without shadowing in the case d=3km, d_1=2.35km.

D. Impact of the bit rate and spectral efficiency

One of the key parameters influencing on the energy saving is the required bit rate R since it determines the required transmit power in each of the considered links. The bit rate R is related with the bandwidth B by means of the spectral efficiency as R/B (bit/s/Hz). In this respect, Fig. 7 depicts the average energy saving that can be achieved in the reference scenario for different values of the spectral efficiency obtained by varying the bit rate R with bandwidth B=5 MHz and with bandwidth B=100 MHz. The rest of parameters are those of Section IV.A. Results are presented for some specific distances d and d_1 where the relay and direct link are feasible for all considered bit rates. In particular, note that the distances considered for B=100 MHz are shorter than those for B=5 MHz because, for a given spectral efficiency R/B, the transmit power requirements increase with B as seen in (1)(5)(6). Therefore, the feasible distances decrease with B.

Looking at Fig. 7, a similar trend is observed in all the cases. In particular, for low values of R/B the impact of the constant power consumption term over the energy is larger than that of the RF transmit power. This leads to low energy savings because the relay mainly contributes to reducing the energy associated to the transmit power. Then, when increasing R/B the impact of the RF transmit power becomes more significant, so larger energy savings can be achieved, as observed in Fig. 7. For example, in the case d=2.6 km with B=5 MHz the ES increases from 6% for R/B=0.8 bit/s/Hz up to 35% for R/B=2.4 bit/s/Hz, and a similar behavior is observed for B=100 MHz with d=1.4 km where the ES increases from 18% for R/B=0.8 bit/s/Hz up to 41% for R/B=2.4 b/s/Hz. However, if R/B is too large, the energy saving starts to decrease because the increase of the transmit power with the spectral efficiency is faster for the relay link, which increases with $2^{2R/B}$ as seen in (5)(6), than for the direct link, which increases with $2^{R/B}$ as seen in (1). As a result, there is an optimum value of spectral efficiency R/B that allows maximizing the achievable ES. For the considered distances in Fig. 7, this optimum is at around 2.4 - 2.8 bit/s/Hz, and this applies for both B=5 MHz and B=100 MHz. Consequently, the performance in terms of energy savings for the considered scenario and the assumed energy consumption model is mainly dependent on the spectral efficiency R/B rather than on the specific values of R and B.

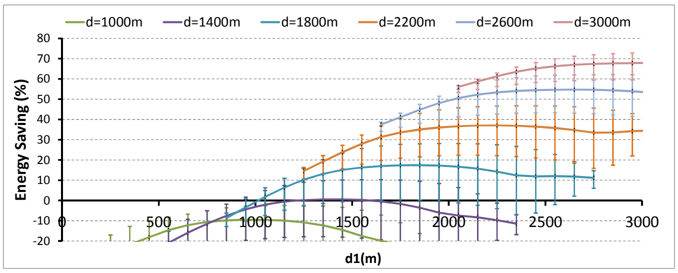

Fig. 5. Energy saving distribution (average, 5-th percentile, 95-th percentile) if there is LOS between BS and Relay without shadowing.

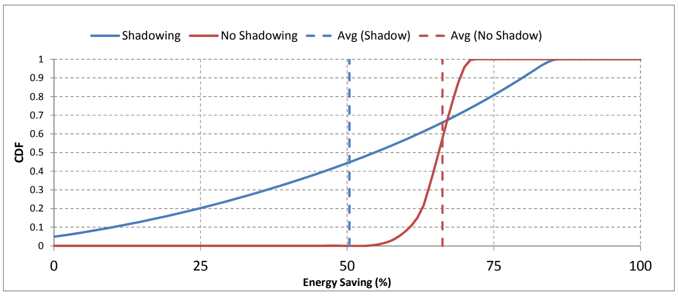

Fig. 6. Comparison between the ES distribution (Average and CDF) for the scenario when there is LOS in the link between the BS and the Relay, with and without shadowing in the case d=3km, d_1=2.55km.

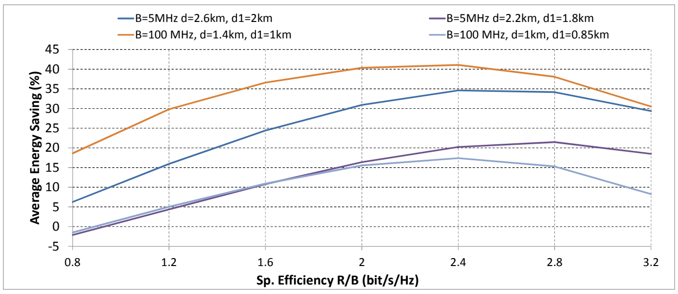

Fig. 7. Average energy saving as a function of the spectral efficiency for two different bandwidths B and different sets of distances.

E. *Impact of the power consumption model*

To assess the sensitivity of the achieved energy savings to the power consumption model, Fig. 8 plots the average energy saving that can be achieved in the reference scenario with the parameters of Section IV.A for different values of the constant term of the power consumption model $P_{o,R}$ of the relay in relation to the corresponding term of the BS, $P_{o,D}$. The reference case taken from [13] corresponds to approximately $P_{o,R}$=0.09$P_{o,D}$. Results indicate that the ES is very sensitive to this parameter, and in fact the ES can be highly reduced when $P_{o,R}$ increases (e.g. from around 44% in the reference case down to 17% in the extreme case in which $P_{o,R}$=$P_{o,D}$). Consequently, this reveals the importance of having accurate and realistic power consumption models of the different components of the wireless network in order to properly capture the energy gains achieved by means of relaying.

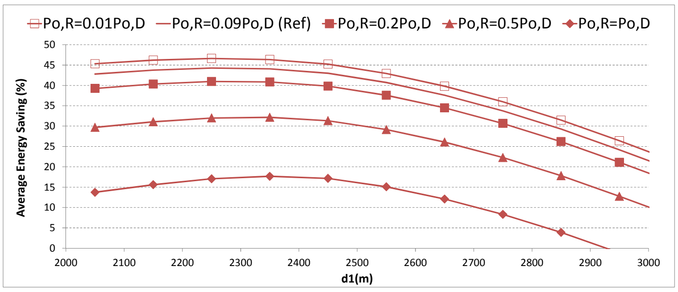

Fig. 8. Average energy saving for different values of the constant term of the power consumption model in the relay for the case *d*=3000 m.

V. CONCLUSIONS

This paper has provided an assessment of the energy savings that can be achieved by means of relaying in a wireless system through analyzing the role played by the different radio parameters that influence on the performance. The first analysis has revealed that achievable energy savings by means of relaying are positive when the UE is located at a large distance from the BS, while for shorter distances the average energy savings become negative. For example, in the considered scenario with maximum distance 3 km for the direct link average energy savings up to around 44% are achieved when the UE is located at distances above 2 km if no shadowing is considered. The inclusion of shadowing reduces the average energy saving gains that can be achieved when considering all the possible combinations of relay position and UE terminal, but it significantly increases the dispersion and the 95-th percentile of this gain. This reflects the existence of certain strategic relay positions where high ES values can be obtained (e.g. larger than 75% in the analyzed scenario for the usual values of the shadowing standard deviation σ).

Regarding the influence of the propagation model in the different links, the paper has shown that, by selecting the relay position such that the BS-Relay link has better propagation conditions (e.g. LOS), important energy savings enhancements can be achieved, up to 70% on average terms with respect to 44% in the same case without LOS conditions.

The paper has also analyzed the impact of the bit rate and spectral efficiency in terms of energy savings. In the considered scenario it has been obtained that the performance is mainly dependent on the spectral efficiency *R/B* rather than on the specific values of bit rate *R* and bandwidth *B*. In this respect, it has been shown that there exists an optimum spectral efficiency that maximizes the achievable energy savings. In the considered scenario, this optimum is at around 2.4-2.8 bit/s/Hz with associated energy savings of around 20-40 %.

Finally, given that very different models of power consumption parameters can be found in the literature, the importance of having accurate power consumption figures and models when trying to assess the achievable energy gain has been highlighted. In particular, this gain is very sensitive to the value of the constant power consumption term in the relay, and energy saving differences ranging from 17% up to 44% have been observed in the analyzed ranges of this parameter.

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