On the Impact of HARQ in the Throughput and Energy Efficiency Using a Cross-Layer Analysis

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***Abstract*—This paper studies the potential improvements in terms of energy efficiency and system throughput of a hybrid automatic retransmission request (HARQ) mechanism. The analysis includes both the physical (PHY) and medium access (MAC) layers. We investigate the trade-off provided by HARQ, which demands reduced transmit power for a given target outage probability at the cost of more accesses to the channel. Since the competition for channel access at the MAC layer is very expensive in terms of energy and delay, our results show that HARQ leads to great performance improvements due to the decrease in the number of contending nodes – a consequence of the reduced required transmit power. Counter-intuitively, our analysis leads to the conclusion that retransmissions may decrease the delay, improving the system performance. Finally, we investigate the optimum values for the number of allowed retransmissions in order to maximize either the throughput or the energy efficiency.**

***Index Terms*—Hybrid Automatic Repeat Request, Cross-Layer, Energy Efficiency, IEEE 802.11**

I. Introduction

A more conscious use of energy in the Information and Communication Technologies (ICT) industry is a subject with increasing importance due the growth projections in this sector for the next years. ICT's energy consumption had an annual growth rate of 10% between 2007 and 2011, against 3% of overall electricity consumption [1]. Mobile communication systems alone are expected in 2020 to have carbon emissions three times higher than in 2007 [2]. As a consequence, energy consumption has become a key-factor for future technologies such as 5G, whose expected traffic volume may lead to an inevitable energy crunch if present paradigms are used [3].

The energy consumption of a given network architecture depends on many factors, such as transmit power, circuitry consumption, data rate, transmission scheme, etc, which are usually encompassed into an energy efficiency metric defined by the ratio between the amount of bits correctly transmitted and the energy expenditure [4], [5]. Moreover, energy efficiency also depends on the density of the network, *i.e.*, when many nodes have packets to transmit, the competition for channel access may become very expensive [6], jeopardizing both throughput and energy efficiency. A tradeoff analysis between energy and throughput has been considered by [7], [8] combining physical (PHY) and medium access control (MAC) layers. The PHY layer is modeled assuming Shannon capacity, providing a bit-rate for error-free communications within a relay network. As a result, MAC effects were found to be significant due to the number of nodes contending for channel access, in a setup based on the 802.11 MAC layer, yielding longer transmission delays, and consequently very different conclusions as if the PHY layer is considered alone.

Similarly to relaying, hybrid automatic repeat request (HARQ) mechanisms also demand smaller transmit power for a given target outage probability, but at the cost of more accesses to the channel. As a result, the use of HARQ may present a trade-off in terms of energy efficiency. In the literature, optimal power allocation for HARQ has been considered, *e.g.*, in [9], [10], minimizing the necessary transmit power in block fading scenarios. Moreover, an energy and spectral efficiency trade-off was analyzed in [11] and a closed-form expression for the energy efficiency is provided by [12]. However, contention at the MAC layer was not considered by the above works, which according to [7], [8] is very significant in the energy efficiency and throughput analysis. In addition, [13] recently considers a cross-layer framework in a MIMO network, showing important energy efficiency benefits of multiple antenna schemes. Nevertheless, HARQ mechanisms have not been considered in that scenario as well.

Differently from previous work, we assume single-hop HARQ within a cross-layer PHY/MAC framework. Moreover, we consider quasi-static Rayleigh fading where a target outage probability must be ensured at the receiver, which is common in practice. In addition, we analyze the system performance in terms of two metrics: system throughput and energy efficiency. Then, our results show that, despite the need of more channel accesses, HARQ provides simultaneous benefits on throughput and energy efficiency. The great improvements in the MAC layer are mainly due to the reduced required transmit power, which decreases the communication radius, and thus, the number of contending nodes per area, providing major benefits in terms of throughput and delay. Moreover, we also investigate the optimum number of retransmissions in order to maximize either the system throughput or the energy efficiency.

Next, the system model is described in Section II, while the throughput and energy efficiency formulation are provided in Sections III and IV, respectively. Section V discusses some numerical results, while Section VI concludes the paper.

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II. System Model

We consider two communicating nodes, source and destination, separated by a distance d in an area with other nodes competing for channel access. A node density ρ per square meter is considered, as well as a quasi-static Rayleigh fading setup with additive white Gaussian noise (AWGN). Packets transmitted by all nodes are constituted of header and payload, which respectively contain H and I bits, and lead to a total of $Q = H + I$ bits per packet. The received power at the destination is

$$P_{\text{r}} = \frac{P_{\text{t}}\lambda^2}{16\pi^2 d^\alpha}, \tag{1}$$

where P_{t} is the transmit power, α is the path loss exponent and λ the wavelength.

The MAC layer modeling is based on the 802.11 MAC protocol [6] formulation presented by Bianchi in [14], so that all nodes, including source and destination, use the same transmit power P_{t}, have the same reception sensitivity P_{th}, same bandwidth B, and are always ready for transmission. The average signal to noise ratio (SNR) at the destination is

$$\bar{\gamma} = \frac{P_{\text{r}}}{N_0 B}, \tag{2}$$

where N_0 is the unilateral noise power spectral density. Data and control bit rates are constant and identical for all nodes, respectively denoted as R and R_{c}.

A. Physical Layer

In the PHY layer we assume the use of HARQ with Chase combining, in which previous erroneous transmission attempts are not discarded, but rather combined at the receiver [9], [15]. This scheme increases the chance of correct decoding by allowing up to M transmissions of the same packet in case of successive outage. The multiple received packets are merged at the receiver as in maximum-ratio combining in multiple receive antenna setups. Assuming the use of a capacity achieving error correcting code, the system outage probability $\mathcal{O}$ at the PHY layer can be written as [12], [16]

$$\mathcal{O}(M) = 1 - e^{-\gamma_0/\bar{\gamma}} \sum_{k=1}^{M} \frac{(\gamma_0/\bar{\gamma})^{k-1}}{(k-1)!}, \tag{3}$$

where $\gamma_0 = 2^{R/B} - 1$. The transmit power P_{t} is adapted to guarantee a sufficient SNR so that $\mathcal{O}(M) = \mathcal{O}^*$, where $\mathcal{O}^*$ is the target outage probability, for each distance between source and destination. The average number of required transmissions N per data packet then becomes [17]

$$N(M) = \sum_{k=0}^{M-1} \mathcal{O}(k). \tag{4}$$

Moreover, due to the quasi-static fading assumption, for a finite number of allowed transmission attempts the outage probability is non-zero, leading to an average effective data rate that can be shown to be

$$\begin{aligned} \bar{R}(M) &= R \sum_{k=1}^{M} \frac{\mathcal{O}(k-1) - \mathcal{O}(k)}{k} \\ &= R\frac{\bar{\gamma}}{\gamma_0}\left(\mathcal{O}(1) - \mathcal{O}(M+1)\right) < R. \end{aligned} \tag{5}$$

B. MAC Layer

We employ the IEEE 802.11 MAC protocol [6], which is based on a four-way handshake mechanism. When the source has a packet to transmit, it first senses the channel during a time denoted by T_{DIFS} (distributed interframe space). If the channel is idle during that period, it starts a random backoff counter, which is randomly initialized within a contention window, decrementing at every slot time σ. Then, as soon as the backoff counter expires, the source transmits an RTS (request to send) control packet, and if the destination is able to communicate at that moment, it replies with a CTS (clear to send) after a time duration denoted by T_{SIFS} (short interframe space). When the source node receives the CTS, it starts data packet transmission and, if the data packet is successfully received, the destination node replies with an ACK (acknowledgement) message, with time duration T_{ACK}. Otherwise, in the case of transmit errors, the colliding nodes choose a new random backoff value to restart the process, but now with a contention window with twice the previous size.

At the MAC layer, the nodes competing to access the channel are called contending nodes. Assuming isotropic transmission, the source node provides a received power larger than the reception sensitivity P_{th} for all nodes within a circular radius, which contains an amount of contending nodes

$$n = \rho\pi \left(\frac{P_{\text{t}}}{P_{\text{th}}}\frac{\lambda^2}{16\pi^2}\right)^{\frac{2}{\alpha}}. \tag{6}$$

According to [14], the probability p_{tr} of at least one node to be transmitting at a random time, and the probability p_{s} that a transmission occupying the channel is successful (*i.e.*, there is no collision at the MAC layer), are given by

$$p_{\text{tr}} = 1 - (1-\tau)^n, \tag{7}$$

$$p_{\text{s}} = \frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^n}, \tag{8}$$

where τ is the probability that a packet transmission is started by a node and can be determine by [14]

$$\tau = \frac{2(1-2p)}{(1-2p)(W+1) + pW(1-(2p)^m)}, \tag{9}$$

where p, the probability that a transmitted packet collides, is

$$p = 1 - (1-\tau)^{n-1}, \tag{10}$$

W is the contention window minimum size, and m is defined by the maximum contention window size $CW_{\text{max}} = 2^m W$.

III. System Throughput

The system throughput is directly linked to the transmission delay, which consists of two parts: *i.)* the delay at the PHY layer, for packet transmission; and *ii.)* the delay at the MAC layer, for channel access and control packet transmissions.

A. Physical Layer Delay

At the physical layer, the transmission delay $\mathcal{D}_{\text{PHY}}$ depends on the average effective data rate $\bar{R}$ and on the overall number of bits Q per packet, so that

$$\mathcal{D}_{\text{PHY}}(M) = \frac{Q}{\bar{R}(M)}. \tag{11}$$

B. MAC Layer Delay

At the MAC layer, we build upon [7], [8], [14], which model the MAC average delay $\mathcal{D}_{\text{MAC}}$ as the sum of the time spent on backoff count, the time consumed by collisions, and the protocol overhead. As in [7], $\mathcal{D}_{\text{MAC}}$ can be written as

$$\mathcal{D}_{\text{MAC}} = E[X]E[L] + \frac{pT_c}{1-p} + T_{\text{MAC}}, \tag{12}$$

where $E[X]$ is the average number of backoff counts needed for successful channel access, $E[L]$ is the average time for the backoff counter to decrement, T_{c} is time the medium is sensed busy by nearby nodes in case of collisions, and T_{MAC} is the overhead of the MAC protocol given by

$$T_{\text{MAC}} = T_{\text{RTS}} + T_{\text{CTS}} + 4\delta + T_{\text{ACK}} + 3T_{\text{SIFS}} + T_{\text{DIFS}}, \tag{13}$$

with T_{RTS} and T_{CTS} being the time consumed by RTS and CTS messages, respectively, and δ is the propagation delay (the ratio between distance and speed of light).

The time spent on backoff count depends on τ and p in (9)-(10), and according to [18] can be calculated by

$$E[X] = \frac{(1-2p)(W+1) + pW(1-(2p)^m)}{2(1-2p)(1-p)}, \tag{14}$$

$$E[L] = (1-p_{\text{tr}})\sigma + p_{\text{tr}}p_{\text{s}}T_{\text{s}} + p_{\text{tr}}(1-p_{\text{s}})T_{\text{c}}, \tag{15}$$

where the amount of time the medium is sensed busy by nearby nodes in case of a successful transmission (T_s) and in case of collision (T_c) are respectively evaluated by [7]

$$T_{\text{s}} = T_H + T_D + T_{\text{MAC}}, \tag{16}$$

$$T_c = T_{\text{RTS}} + \delta + T_{\text{DIFS}}, \tag{17}$$

where $T_H = H/\bar{R}$ and $T_D = I/\bar{R}$ are the time consumed by the header and data packets transmission, respectively.

C. Cross-Layer Delay and Throughput

When both PHY and MAC layer delays are combined, we notice that $\mathcal{D}_{\text{PHY}}$ is independent of $\mathcal{D}_{\text{MAC}}$, since it is a direct function of the average number of transmission attempts N per packet. Nevertheless, the delay at the MAC layer also depends on N, since every retransmission restarts the process for channel access. Therefore, we can write the total delay as

$$\mathcal{D}_{\text{total}}(M) = \mathcal{D}_{\text{PHY}}(M) + N(M) \cdot \mathcal{D}_{\text{MAC}}. \tag{18}$$

Since the overall number of bits Q per packet and of allowed retransmissions M are constant over distance, if the transmit power is adapted to keep a fixed outage probability at the destination, then $\mathcal{D}_{\text{PHY}}$ is constant over distance as well. However, in the same conditions, $\mathcal{D}_{\text{MAC}}$ is monotonically decreasing over distance because as the transmit power increases, so does the delay due to the increase in the number of contending nodes. This causes $\mathcal{D}_{\text{total}}$ to eventually get very dependent on $\mathcal{D}_{\text{MAC}}$ as the distance increases.

Moreover, the system throughput $\mathcal{T}$ is defined as the ratio between the number of payload bits and the time taken for their transmission, yielding

$$\mathcal{T}(M) = \frac{I}{\mathcal{D}_{\text{total}}(M)}. \tag{19}$$

Finally, as our goal is to analyze the possible benefits of using retransmissions, we define a throughput gain denoted by $G_{\mathcal{T}}(M)$, which consists on the ratio between a scenario allowing M transmission trials per packet and a scenario with only one transmission trial ($M = 1$), as

$$G_{\mathcal{T}}(M) = 10\log_{10}\left(\frac{\mathcal{T}(M)}{\mathcal{T}(1)}\right). \tag{20}$$

IV. Energy Consumption

Similarly to the system throughput, the energy consumption is also linked to the transmission delay so that we split the following analysis to tackle each layer separately. But first, let us define the total transmit power consumption P_{tx} as [7]

$$P_{\text{tx}} = \frac{P_{\text{t}}}{\mu} + P_{\text{sp}}, \tag{21}$$

where μ is the transmitter power efficiency and P_{sp} denotes the power consumed by signal processing baseband operations. Moreover, at the receiver the power consumption is fixed and we denote it by P_{rx}.

A. Physical Layer Energy Consumption

The energy consumption at the physical layer mainly depends on the delay for data transmission, which takes into account the bits transmitted during the successful channel access attempts. Thus,

$$\mathcal{E}_{\text{PHY}}(M) = (P_{\text{tx}} + P_{\text{rx}})\,\mathcal{D}_{\text{PHY}}(M), \tag{22}$$

which already encompasses the retransmission attempts due to possible outages.

B. MAC Layer Energy Consumption

At the MAC layer, the energy consumption must take into account the fraction of time spent waiting for the backoff counter to expire, and the fraction of time spent attempting to access the channel. Thus, $\mathcal{E}_{\text{MAC}}$ can be written as

$$\mathcal{E}_{\text{MAC}} = \mathcal{E}_{\text{wait}} + \mathcal{E}_{\text{access}}. \tag{23}$$

While waiting for the backoff counter to expire, three different scenarios are possible for the neighboring nodes: successful, unsuccessful and no transmission, yielding [7]

$$\mathcal{E}_{\text{wait}} = P_{\text{rx}}E[X]\,(p_{\text{tr}}T_{\text{RTS}} + (1-p_{\text{tr}})\,\sigma). \tag{24}$$

TABLE I
SIMULATION PARAMETERS

Parameter	Value
Payload (I) / Header (H)	2000 / 36 bytes
RTS / CTS / ACK	20 / 16 / 15 bytes
Slot time (σ) / DIFS / SIFS	20 / 50 / 10 μs
$CW_{\min}$ / $CW_{\max}$	32 / 1024 slots
α (Path loss exponent)	4
R_c / R	6 Mbps / 48 Mbps
ρ (Node Density)	0.00001 nodes/m^2
μ (RF power efficiency)	50%
P_{sp} / P_{rx} / P_{th}	140 mW / 150 mW / -110 dBm
Frequency (f) / Bandwidth (B)	2.4 GHz / 20 MHz
Propagation Speed (c)	3.10^8 m/s
Target Outage Probability ($\mathcal{O}^*$)	10^{-3}

On the other hand, if there is no packet collision and channel access was successful, MAC energy is spent only on flow control. Otherwise, energy is spent on RTS collision and retrial attempts, leading to [7]

$$\mathcal{E}_{\text{access}} = \frac{p}{1-p} P_{\text{tx}} T_{\text{RTS}} + (P_{\text{tx}} + P_{\text{rx}})(T_{\text{RTS}} + T_{\text{CTS}} + T_{\text{ACK}}). \quad (25)$$

C. Cross-Layer Energy Efficiency

The total energy consumption combines (22) and (23) as

$$\mathcal{E}_{\text{total}}(M) = \mathcal{E}_{\text{PHY}}(M) + N(M) \cdot \mathcal{E}_{\text{MAC}}, \quad (26)$$

while the energy efficiency is defined as the ratio

$$\eta(M) = \frac{I}{\mathcal{E}_{\text{total}}(M)}, \quad (27)$$

representing the amount of bits successfully transmitted per Joule of energy. Finally, we define the energy efficiency gain in a way similar to the throughput gain as

$$G_\eta(M) = 10 \log_{10} \left(\frac{\eta(M)}{\eta(1)} \right). \quad (28)$$

V. NUMERICAL RESULTS

In this section results for throughput and energy, with different numbers of transmission trials M in the PHY layer, are explored according to the numerical parameters in Table I, based on [7], [8]. The node density ρ is relatively small, but we consider that nodes are always ready for transmission, and therefore competition for channel access is high even with small ρ. The target outage probability, $\mathcal{O}^*$, is the same for all scenarios, what demands different average SNRs at the destination for different M according to (3).

A. Throughput Analysis

As distance increases, each layer contributes differently to $\mathcal{D}_{\text{total}}$ as shown in Fig. 1. The average PHY throughput for a given fixed target outage probability $\mathcal{O}^*$, as given in (5), is a decreasing function of M, but constant over distance. For a fixed M, with the increase in distance and consequent increase in the required transmit power to meet the target outage probability, so does the number of contending nodes (6), negatively affecting the throughput at the MAC layer.

However, differently from the PHY layer, in the MAC layer the throughput does not necessarily decreases with M. That is because when retransmissions are allowed the required transmit power to meet a given target outage probability is reduced, and therefore the number of contending nodes is also reduced, as illustrated in Fig. 2. As the delay in the MAC layer is heavily dependent on the number of contending nodes, allowing for retransmissions in the PHY layer has a very positive impact in the MAC layer throughput. Moreover, as with the increase in distance – and therefore in the required transmit power – the delay in the MAC layer dominates over the delay in the PHY layer, and therefore improving the performance of the MAC layer significantly affects the overall system throughput as shown in Fig. 1. For very short

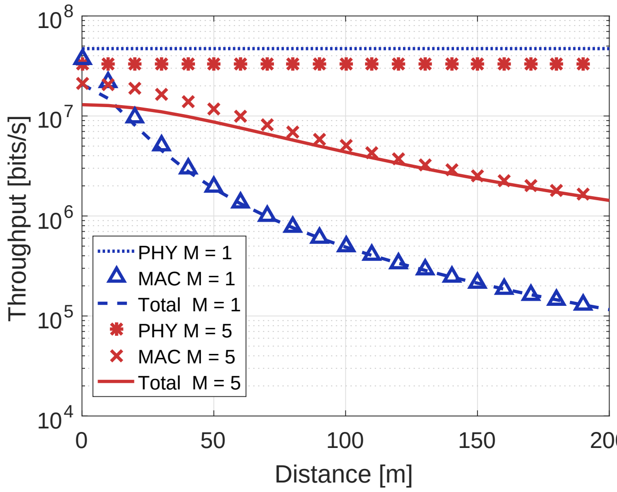

Fig. 1. Throughput in the PHY and MAC layers, as well as the total throughput, as a function of the distance for $M = 1$ and 5.

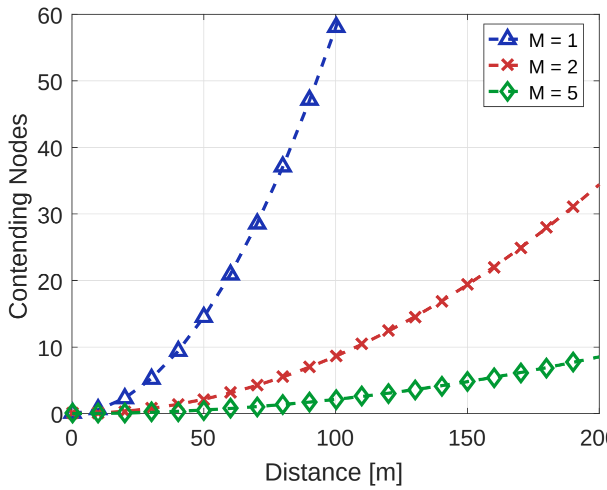

Fig. 2. Number of nodes contending for channel access as a function of the distance for $M = 1$, 2 and 5.

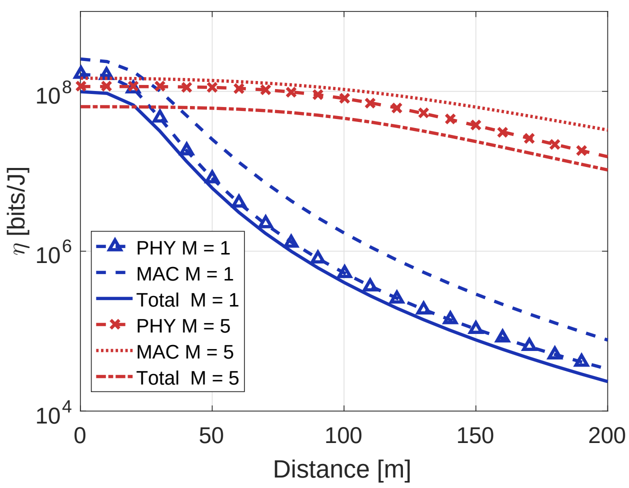

Fig. 3. Energy efficiency in the PHY and MAC layers as a function of the distance for $M = 1$ and 5.

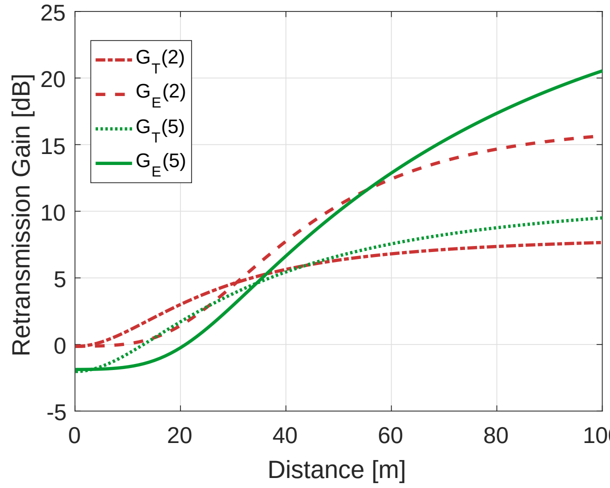

Fig. 4. Throughput and energy efficiency gains, $G_{\mathcal{T}}$ and G_{η}, as a function of the distance for $M = 2$ and $M = 5$.

distances retransmissions at the PHY layer do not provide sufficiently low power to overcome the increased number of average transmissions, but for sufficiently large distances the advantages in terms of throughput are very clear.

B. Energy Efficiency Analysis

The energy efficiency of the PHY and MAC layers is shown in Fig. 3 as a function of the distance for different M. Clearly, η is a decreasing function with d in both layers. In the PHY layer, we observe that the energy consumption in (22) depends on transmit and receive powers, as well as on the PHY delay. Thus, an increasing transmit power is needed to maintain the SNR constant at the receiver with the increase of distance, in order to meet the target outage probability $\mathcal{O}^*$. Therefore, η decreases with d due to the higher required transmit power, but increases with M since then the required transmit power is reduced. At the MAC layer the effects are very similar, with η decreasing with the increase of the transmit power, but increasing with the number of allowed transmission trials M.

Moreover, Fig. 3 shows an interesting behavior at very small distances. In that case, the fixed power consumption related to $P_{\rm rx}$ and $P_{\rm sp}$ becomes very relevant in the energy consumption, as can be observed in (22), (24) and (25). Therefore, at small transmit ranges (smaller than 25 m in this particular example), Fig. 3 also shows that it is better to avoid retransmissions (imposing $M = 1$), slightly increasing $P_{\rm t}$ to meet the outage probability target, achieving better energy efficiency.

C. Combined Energy and Throughput Analysis

Fig. 4 plots the throughput and energy efficiency gains, $G_{\mathcal{T}}(M)$ and $G_{\eta}(M)$, respectively, for $M = 2$ and $M = 5$ as a function of the distance between source and destination. Notice that gains above 0 dB imply in an improvement when compared to the case without retransmissions ($M = 1$). As we can observe from Fig. 4, there are no throughput improvements for very low distances, as $G_{\mathcal{T}}(M)$ and $G_{\eta}(M)$

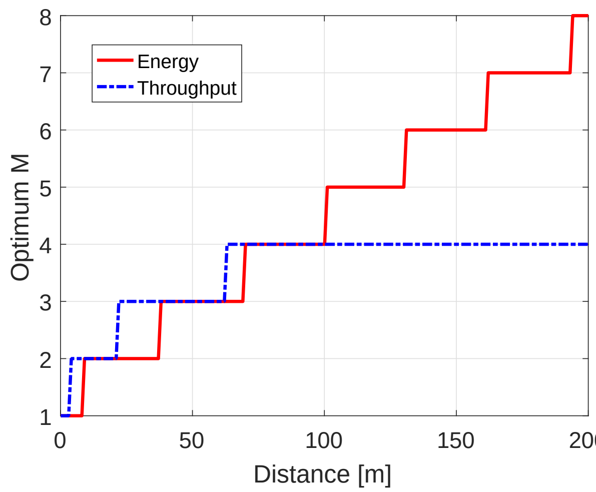

Fig. 5. Optimal number of allowed transmission trials (M), that maximizes either the throughput or the energy efficiency, as a function of the distance.

are below the 0 dB margin in this range, what is in accordance with Fig. 1. However, $M = 2$ quickly surpasses the 0 dB margin. As M increases the starting gain decreases due to the increased average number of transmission trials, however, the reduced amount of contending nodes provides a larger gain with M over distance. As for throughput, energy efficiency also benefits from the decreased number of contending nodes that is a consequence of allowing multiple transmission trials and reducing the required transmit power. The starting gain in terms of energy efficiency is mainly defined by the fixed energy consumption of some components, such as $P_{\rm rx}$ and $P_{\rm sp}$ pondered by the average number of transmissions, resulting in a successive decrease with M.

It is interesting to notice in Fig. 4 that optimum values of M for energy efficiency and throughput are not necessarily the same, due to the difference on switching points (change

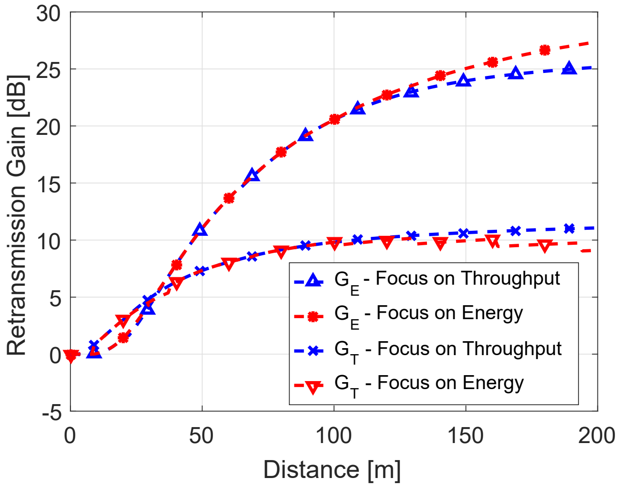

Fig. 6. Throughput and energy efficiency gains, $G_{\mathcal{T}}$ and G_{η}, when the optimal M for either throughput or energy efficiency is applied.

of optimal M) for energy and delay. Fig. 5 presents the optimum M for the considered scenario, illustrating that the difference on switching points for energy and throughput leads to different optimum M, and also that this value changes with distance due to different starting gains and growth rates for each M, as illustrated in Fig. 4.

Two possible optimization scenarios with respect to M arise from Fig. 4, one which focuses on energy efficiency, and the other focused on throughput. Fig. 6 presents the behavior of $G_{\eta}(M)$ and $G_{\mathcal{T}}(M)$ for both scenarios. It can be noticed that for up to a distance the performance is very similar for both energy efficiency and throughput scenarios, because the optimum M is very similar in both cases. However, as the distance increases, the difference on the optimum M for each case starts to grow. When considering an optimization focused on throughput, the energy gain ever grows with distance, even though at a decreasing rate. On the other hand, if the optimization is focused on energy efficiency, the throughput gain starts to decrease over distance because the optimum M for energy efficiency is larger than that for throughput, excessively penalizing the PHY layer delay. Therefore, for maximum energy efficiency it may be not possible to achieve the best performance in terms of data throughput.

VI. Conclusions

In this work, a PHY/MAC cross-layer analysis was applied to a scenario considering multiple transmission trials in the PHY layer, under the effect of quasi-static Rayleigh fading. The main conclusions of this work can be summarized as follows: *i.*) Retransmissions improve the data delay, and therefore the throughput, except for very short distances; *ii.*) Retransmissions may provide simultaneous energy efficiency and throughput improvements; *iii.*) There are different optimum numbers of maximum transmission trials for energy efficiency or throughput. Despite the need of more channel access attempts, retransmissions may provide higher throughput due to the decreased MAC delay caused by a smaller required transmit power, leading to a reduced probability of collision during channel access. As future work, relay nodes and multiple antennas may be integrated into this framework, expanding the analysis.

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