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Optimizing the Energy Efficiency of Short Term Ultra Reliable Communications in Vehicular Networks

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***Abstract*—We evaluate the use of HARQ schemes in the context of vehicle to infrastructure communications considering ultra reliable communications in the short term from a channel capacity stand point. We show that it is not possible to meet strict latency requirements with very high reliability without some diversity strategy and propose a solution to determining an optimal limit on the maximum allowed number of retransmissions using Chase combining and simple HARQ to increase energy efficiency. Results show that using the proposed optimizations leads to spending 5 times less energy when compared to only one retransmission in the context of a benchmark test case for urban scenario. In addition, we present an approximation that relates most system parameters and can predict whether or not the link can be closed, which is valuable for system design.**

I. INTRODUCTION

The next generation of wireless networks (5G) aims to not only improve link speeds and the number of users, but also to allow for future applications to have stricter constraints whilst spending less energy [1]. For instance, 5G will support ultra reliable communications (URC) [2].

URC is divided into two types, both long term (URC-L) and short term (URC-S) [2]. The former ensures close to 100% reliability with guaranteed data rates for a large number of users, while the latter provides the same reliability with guaranteed latency for short data packets. Both schemes will enable a whole new range of applications that will allow many aspects of modern life to be improved. For instance, having URC-S in vehicular networks can lead to increased traffic safety preventing the loss of human lives [3]. This could be achieved by vehicles regularly exchanging short messages with structures, allowing them to take automated decisions (such as breaking) when a collision is imminent. However, for this to be possible, it is highly important that the messages are delivered within a maximum latency and with very high reliability [3].

Green radio communications, in which energy efficiency is the focus of protocol design, have been widely investigated [4], [5]. In vehicle to infrastructure (V2I) communications, the massive deployment of base stations to form dense networks and meet high coverage demands, urges for energy efficiency to reduce overall consumption for both financial and environmental reasons [6]. Additionally, the use of purely electric or hybrid vehicles - in which available energy is a pressing issue [7] - is expected to grow in the near future [8], making energy efficiency an important research area in vehicular communications. Diversity techniques have been widely used to reduce energy consumption. Hybrid automatic repeat request (HARQ) schemes such as simple HARQ (S-HARQ) [9] and Chase combining HARQ (CC-HARQ) [10] can provide time diversity and are known to improve the energy efficiency of communication systems [5].

In the vehicular communications scenario, spatial diversity through multiple antennas [7] or cooperation [11] has been recently shown to reduce overall consumption. In [12], Zhang *et.al.* proposes a sub-carrier allocation strategy to meet latency requirements whilst increasing energy efficiency. More recently, [13] studied the use of femto access points with LTE backbone to improve delay, throughput and reduce energy consumption in vehicular networks.

In this paper we analyze the energy efficiency of HARQ schemes considering V2I communication in the URC-S scenario described by the METIS Test Case #12 [3]. Since a latency constraint is imposed, we investigate if retransmissions are a viable diversity strategy to improve energy efficiency.We demonstrate that is not possible to meet the required constraints [3] without diversity and that HARQ is a possible choice if the maximum number of transmissions is limited. Furthermore, we show that choosing an optimized number of maximum transmissions can lead to several times less energy consumption when compared to the naive approach of limiting to 1 retransmission, which highlights the importance of our results. Additionally, we derive a link budget relationship, containing most system parameters, useful in practical design.

The remainder of this work is organized as follows. Section II presents the communication and energy consumption models. Section III solves the optimization problem and presents an algorithm to determine the optimal maximum number of transmissions attempts. Section IV presents the numerical

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results while Section V concludes the paper.

II. SYSTEM MODEL

We consider a point to point link between a vehicle and a structure (V2I) in the context of the METIS Test Case #12 [3] from a channel capacity stand point. We analyze the urban scenario proposed in [3], which consists of short term ultra reliable communications (99.999% reliability) with a strict latency constraint (< 5 ms) and medium user speeds (60 km/h). Considering the above, a block fading model is justified because, although the user is moving, the latencies are short, and thus the transmission time is also short. Nakagami-m has been demonstrated to be the most adequate channel model for this type of communication [14] since it includes sub-Rayleigh (*i.e.* when vehicles are on different streets than the structures) to strong line of sight (LOS) conditions [15].

We investigate the use of the following HARQ schemes to achieve time diversity:

- *Simple HARQ (S-HARQ)* [9]: In S-HARQ messages with low instantaneous signal to noise ratio (SNR) are discarded and a non acknowledgment message (NACK) is sent back, requesting a retransmission. The transmitter receives the NACK and attempts a new transmission. This process is repeated until the message is correctly decoded.
- *Chase Combining HARQ (CC-HARQ)* [10]: In CC-HARQ messages with low instantaneous SNR are stored and a NACK is sent back, requesting a retransmission. The transmitter receives the NACK and retransmits the message. The receiver combines it with previous copies using maximum ratio combining (MRC), before decoding. The process is repeated until successful decoding.

Note that, in this work we impose a maximum number of transmission attempts z in order to meet the latency constraint. If the receiver cannot decode the message after z rounds, an outage event occurs. The probability of an outage event ($P_{\text{out},z}$) is what determines the reliability of the communication. Note that even tough payload lengths in the V2I scenario are short (1600 bits [3]), we use the outage probability - which assumes infinite block length - to compute the average error probability. This approximation is tight if the payload length is not too short and the data rates are large enough [16], which holds in this case. Furthermore, we consider a maximum transmit power ($P_{\text{rf,max}}$) of -6 [dB], according to the long term evolution (LTE) uplink regulations [17]. Finally, we highlight that in order to achieve diversity in this block fading scenario, slow frequency hopping is used between retransmissions. In addition, to simplify the model, we assume perfect channel state information (CSI) knowledge at the receiver.

A. Energy Consumption Model

Following the work of Rosas *et. al.* [5], the energy used by the transmitter and the receiver is composed of: *radio startup energy*; *coding energy*; *pre-transmission processing energy*; *feedback processing energy*; and *electromagnetic irradiation energy*. Next we explore each component.

When not communicating, the radios switch to a sleep mode in order to save energy. The *radio startup energy* (ε_{st}) is the consumption involved in taking the radio from low power mode to active state.

The *pre-transmission processing energy* ($\varepsilon_{\text{el,tx}}$) is the consumption of electronic circuits used by the radios in order to power the baseband radio-frequency (RF) electronic components. It depends on the air time of the radio during a forward packet T_{b}, which is given by

$$T_{\text{b}} = \frac{L_{\text{H}} + L_{\text{O}} + L_{\text{P}}}{R_{\text{b}}}, \tag{1}$$

where R_{b} is the bit rate and L_{H}, L_{O} and L_{P} are the header, overhead and payload lengths, in bits, respectively. Hence, considering the power consumption of these circuits as $P_{\text{el,tx}}$, we obtain that

$$\varepsilon_{\text{el,tx}} = P_{\text{el,tx}} T_{\text{b}}. \tag{2}$$

The *feedback processing energy* ($\varepsilon_{\text{el,rx}}$) is that involved in powering the passband receiver elements, which consume $P_{\text{el,rx}}$ [W] and depends on the receive time of the feedback message (T_{fb}), which in turn can be obtained by dividing the feedback packet length L_{F} by the bit rate R_{b}. Therefore, we can write $\varepsilon_{\text{el,rx}}$ as

$$\varepsilon_{\text{el,rx}} = P_{\text{el,rx}} T_{\text{fb}}. \tag{3}$$

The *electromagnetic irradiation energy* (ε_{PA}) is the consumption of the power amplifier (PA) in order to produce the magnetic waves. It can be obtained by multiplying the PA's consumption (P_{PA}) by the transmission duration (T) ($\varepsilon_{\text{PA}} = P_{\text{PA}} T$). Furthermore, as in [5], considering a linear PA, P_{PA} can be written as

$$P_{\text{PA}} = \left[\left(\frac{\xi}{S} \right)^{\beta} \frac{N_0 W N_f M_l A_0}{\eta_{\text{max}}} \right] d^{\alpha} \bar{\gamma}, \tag{4}$$

where β and η_{max} depend on the PA class, ξ is the peak to average power ratio of the modulation[1], and S depends on additional back-off. The noise spectral power density is represented by N_0, W is the bandwidth, N_f is the noise figure at the receiver, M_l is a link margin to account for additional unforeseen losses, A_0 is the path loss at a reference distance, d is the distance between the vehicle and the structure, α is the path loss exponent and $\bar{\gamma}$ is the average SNR.

Finally, the *coding energy* is that involved in the necessary computations for encoding and decoding messages. It is directly linked with the arithmetic processing unit (APU) clock speed, which in turn depends on the bit rate [5]. It is only relevant when data rates are very high and thus we disregard it in our model[2].

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[1] Since we are considering Shannon capacity, we have numerically evaluated this parameter for Gaussian inputs to be around 23.

[2] Although the stringent latency constraint imposes an increase in data rate, since is is proportional to payload lengths, the rates are still not high enough to make the coding energy relevant in the complete model.

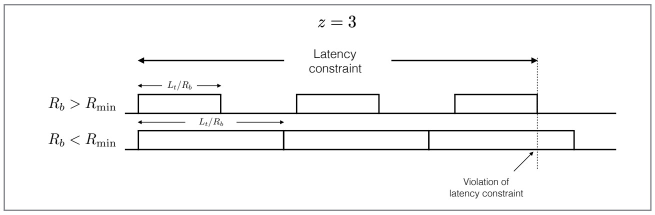

Fig. 1: The latency constraint imposes a minimum bit rate that must be met, depending on the number of transmissions z allowed. In this example, $z = 3$ is considered.

In order to obtain the average energy used per bit in the transmitter and receiver, we must also determine how many transmission rounds will occur on average ($\bar{\tau}$), which is

$$\bar{\tau} = 1 + \sum_{i=1}^{z-2} P_{\text{out},i}. \tag{5}$$

Combining all of the above, the average energies used by the transmitter ($\bar{\varepsilon}_{\text{T}}$) and the receiver ($\bar{\varepsilon}_{\text{R}}$) are expressed as

$$\bar{\varepsilon}_{\text{T}} = \varepsilon_{\text{st,tx}} + \left[(P_{\text{el,tx}} + P_{\text{PA}})T_{\text{b}} + P_{\text{el,tx}}T_{\text{fb}}\right]\bar{\tau} \tag{6}$$

$$\bar{\varepsilon}_{\text{R}} = \varepsilon_{\text{st,rx}} + \left[(P_{\text{el,rx}} + P_{\text{PA}})T_{\text{fb}} + P_{\text{el,rx}}T_{\text{b}}\right]\bar{\tau}. \tag{7}$$

The energy per goodbit ($\bar{\varepsilon}_{\text{b}}$) is represented as

$$\bar{\varepsilon}_{\text{b}} = \frac{\bar{\varepsilon}_{\text{T}} + \bar{\varepsilon}_{\text{R}}}{L_{\text{P}}\left(1 - P_{\text{out},z}\right)}, \tag{8}$$

using (6) and (7) into (8) and rearranging the terms, we obtain

$$\bar{\varepsilon}_{\text{b}} = \frac{\varepsilon_{\text{st}} + \bar{\tau}(T_{\text{b}} + T_{\text{fb}})(P_{\text{el}} + P_{\text{PA}})}{L_{\text{P}}(1 - P_{\text{out},z})}, \tag{9}$$

where $\varepsilon_{\text{st}} = \varepsilon_{\text{st,tx}} + \varepsilon_{\text{st, rx}}$ and $P_{\text{el}} = P_{\text{el,tx}} + P_{\text{el,rx}}$.

B. Latency Constraint

In the context of URC-S, the system is bound by a maximum latency (λ). In other words, the system must be able to fit all the z transmission attempts in less than λ seconds. This in turn can be rewritten as a minimum rate constraint,

$$R_{\text{b}} > z\frac{L_{\text{T}}}{\lambda}, \tag{10}$$

where $L_{\text{T}} = L_{\text{P}} + L_{\text{H}} + L_{\text{O}} + L_{\text{F}}$. Figure 1 illustrates this concept. Note that the model presented in Figure 1 is not the usual in most HARQ systems, because it incorporates the latency constraint. In this work we investigate whether or not using HARQ is still advantageous considering that the stringent latency requirement must be met. This in turn imposes a larger outage probability of each individual attempt due to increased data rates when more retransmissions are allowed.

III. OPTIMIZATION

In this section we present a theoretical analysis of the energy ($\bar{\varepsilon}_{\text{b}}$) to find the optimal maximum number of transmissions ($z^{\star}$) in order to minimize the overall consumption, from a channel capacity point of view. Therefore, we consider a target outage (T_{out}) to account for the reliability required by the system, a minimum bit rate imposed by the latency constraint and a maximum transmit power $P_{\text{rf,max}}$. Formally, the optimization problem is

$$\begin{aligned} \underset{z \in \mathbb{N}^*, \bar{\gamma} \in \mathbb{R}^+}{\text{minimize}} \quad & \bar{\varepsilon}_{\text{b}}(z, \bar{\gamma}) \\ \text{subject to} \quad & P_{\text{out},z} \leq T_{\text{out}}, \\ & P_{\text{rf}} \leq P_{\text{rf,max}}, \\ & R_{\text{b}} \geq z\frac{L_{\text{T}}}{\lambda}. \end{aligned} \tag{11}$$

Where $P_{\text{rf}} = B\bar{\gamma}$ is the required transmit power [5] and $B = N_0 W N_{\text{f}} M_{\text{l}} A_0 d^{\alpha}$.

To tackle the problem analytically, we consider in this section only S-HARQ with a high SNR approximation[3]. The outage probability of S-HARQ is the same as that of selection combining [18]. Since each retransmission is performed in an independent channel, $P_{\text{out},z}$ is found by multiplying the outage probability of each transmission attempt, yielding

$$P_{\text{out},z} \approx \left(\frac{(m\gamma_0/\bar{\gamma})^m}{\Gamma(m+1)}\right)^z, \tag{12}$$

where $\gamma_0 = 2^{R_{\text{b}}/W} - 1$ and $\Gamma(.)$ is the complete gamma function, m is the Nakagami-m distribution parameter, which is related to the amount of LOS.

Since increasing the rate implies in more transmit power to meet the same target outage, and thus increases energy consumption, we set the operating rate to the minimum allowed, so that

$$R_{\text{b}} = zL_{\text{T}}/\lambda. \tag{13}$$

The other two optimization constraints determine whether or not the link is feasible. They can be rewritten in terms of $\bar{\gamma}$ and combined as the inequality

$$\frac{P_{\text{rf,max}}}{N_0 W N_{\text{f}} M_{\text{l}} A_0 d^{\alpha}} \geq \frac{m(2^{\frac{zL_{\text{T}}}{W\lambda}} - 1)}{\left(\Gamma(m+1)T_{\text{out}}^{1/z}\right)^{1/m}}, \tag{14}$$

which predicts if the link can be closed for a given z. Unfortunately (14) has no closed form solution, however it can be tightly approximated by relaxing z and allowing it to assume real values. Moreover, considering high spectral efficiency ($\gamma_0 \approx 2^{R_{\text{b}}/W}$), we have

$$\frac{W\lambda(\Phi - \Delta)}{\ln(4)L_{\text{T}}} < \hat{z} < \frac{W\lambda(\Phi + \Delta)}{\ln(4)L_{\text{T}}}, \tag{15}$$

where $\hat{z}$ is the real relaxation of z,

$$\Delta = \sqrt{\Phi^2 + \frac{\ln(16)\ln(T_{\text{out}})L_{\text{T}}}{mW\lambda}} \tag{16}$$

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[3] Using a high SNR approximation for the outage is well justified due to the reliability constraint imposing a very low target outage of 10^{-5}.

and

$$\Phi = \ln\left(\frac{mP_{\text{rf,max}}}{(\Gamma(m+1))^{1/m}N_0WN_\text{f}M_\text{l}A_0d^\alpha}\right). \tag{17}$$

Defining Z as the set of real numbers which satisfy (15) and G as the set of real numbers which satisfy the first and second constraints in (11), the optimization can be rewritten as

$$\underset{\hat{z}\,\in\,Z,\bar{\gamma}\in G}{\text{minimize}} \quad \bar{\varepsilon}_\text{b}(\hat{z},\bar{\gamma}). \tag{18}$$

which can be solved in two steps. First, we find $\bar{\gamma}^\star(\hat{z})$, the optimal SNR as a function of $\hat{z}$, and then use this result to determine $z^\star$. Therefore, we evaluate $\partial\bar{\varepsilon}_\text{b}(\hat{z},\bar{\gamma})/\partial\bar{\gamma} = 0$, yielding

$$\begin{aligned}\lambda m\hat{z}\tau\left(\bar{\gamma}\right)\left(P_\text{el}+P_\text{PA}\right)P_{\text{out},\hat{z}}+ \\ \lambda\bar{\gamma}\left(P_{\text{out},\hat{z}}-1\right)\left(\left(P_\text{el}+P_\text{PA}\right)\partial_{\bar{\gamma}}\bar{\tau}+\frac{P_\text{PA}\bar{\tau}}{\bar{\gamma}}\right)+ \\ m\hat{z}^2\epsilon_\text{st}P_{\text{out},\hat{z}}=0,\end{aligned} \tag{19}$$

which is used to obtain $\bar{\gamma}^\star(z)$. Note that $\partial_{\bar{\gamma}}\bar{\tau}$ is expressed in (20), at the beginning of the next page.

Since (19) does not have a closed form solution, it can be numerically evaluated for every value of z in order to find $\bar{\gamma}^\star$. After that, we determine $\partial\bar{\varepsilon}_\text{b}(\hat{z},\bar{\gamma}^\star)/\partial\hat{z} = 0$, which results in

$$\begin{aligned}P_{\text{out},z}\left(\frac{\lambda\bar{\tau}(z)\left(P_\text{el}+P_\text{PA}\right)}{z}+\epsilon_\text{st}\right)\left(\ln\left(P_{\text{out},1}\right)+\frac{\Omega z}{\gamma_0\lambda W}\right)+ \\ \frac{\lambda\left(P_\text{el}+P_\text{PA}\right)\left(\bar{\tau}(z)-z\partial_{\hat{z}}\bar{\tau}(z)\right)\left(P_{\text{out},z}-1\right)}{z^2}=0,\end{aligned} \tag{22}$$

where $\Omega = m\text{ln}(2)L_\text{T}(1+\gamma_0)$ and $\partial_{\hat{z}}\bar{\tau}$ is expressed in (21), at the beginning of the next page. Although it is not possible to find a closed form solution for (22), it can be evaluated numerically combining with the numerical solutions of $\bar{\gamma}^\star$ in order to determine $z^\star$. Note that in practice the real relaxation of z cannot be used for design, thus $z^\star$ is chosen as the next integer close to the real solution of (18) which yields the least energy per bit. Both the immediate integers larger and smaller than $z^\star$ have to be tested to determine the best.

In order to solve the same problem considering CC-HARQ, the same steps are taken, however $P_\text{out,z}$ is obtained considering the outage probability of MRC ($P_\text{out,z}^{CC}$) instead of SC. At high SNR it is tightly approximated by

$$P_\text{out,z}^{CC} \approx \frac{\left(\frac{m\gamma_0}{\bar{\gamma}}\right)^{mz}}{\Gamma(mz+1)}. \tag{23}$$

Note that $P_\text{out,z} = P_\text{out,z}^{CC}$ has to be considered in both determining Z as well as within $\bar{\varepsilon}_\text{b}$. We have omitted this derivation due to space constraints.

A. Link Budget

Theorem 1. *For the optimization problem described by* (11) *to be feasible, then*

$$mW\lambda ln^2\left(\frac{mP_{rf,max}}{(\Gamma(m+1))^{1/m}B}\right) > |ln(16)ln(T_{out})L_T| \tag{24}$$

must hold.

TABLE I: Simulation parameters

Reliability	99.999% [3]
Maximum Link Latency (λ)	5 ms [3]
Maximum Transmit Power ($P_\text{rf,max}$)	-6 dB [17]
Bandwidth (W)	500 kHz
Distance (d)	300 m [3]
Header Length (L_H)	16 bits [5]
Overhead Length (L_O)	40 bits [5]
Feedback Packet Length (L_F)	88 bits [5]
Payload Length (L_P)	1600 bits [3]
Radio Startup Energy (ε_st)	0.25 nJ
Peak to Average Ratio (ξ)	25
PA Class	A
η_max	50% [20]
β	1 [20]
Additional Backoff (S)	0 dB [5]
Noise Figure (N_f)	4.4 dB [5]
Link Margin (M_l)	3 dB
Spectral Noise Power Density (N_0)	-204 dB
Attenuation at 1 m (A_0)	30 dB [4]
Path Loss Exponent (α)	3.2 [5]
Electronic Power (P_el)	-15.68 dB [5]

Proof. Comparing both bounds in (15) yields

$$\Delta > 0. \tag{25}$$

Since Φ^2 is always positive and $\text{ln}(T_\text{out}) < 0$, in order for (25) to hold, we must have (24). ☐

Theorem 1 offers interesting insights on how physical system parameters affect the link budget. It shows that the amount of LOS, $P_\text{rf,max}$, bandwidth and a relaxed latency increase the link budget. On the other hand, path loss, L_T and the reliability requirement decrease it. This can be used for system design, for instance if a network operator wishes to guarantee a more strict latency or operate in worse LOS conditions, it must increase other parameters such as available bandwidth. Theorem 1 also shows the degree of influence of each parameter. This offers crucial information. For instance we can observe that having a more strict latency is more impacting than increasing the maximum transmit power or having a worse path loss.

IV. NUMERICAL RESULTS

We have evaluated the energy consumption of a vehicle to structure communication in an urban scenario using parameters from the METIS Test Case #12 [3] and the model presented in Section II. Table I contains the parameters used for all calculations, unless stated otherwise. Note that the bandwidth considered for each user is 500 kHz. We assume a user density of 1000 users/km^2 [3] evenly distributed among structures and 10 structures/km^2, the total bandwidth per structure is 50 MHz, less than the 75 MHz available in IEEE 802.11p [19], a widely accepted standard for vehicular networks.

Figure 2 shows the average energy per goodbit versus the maximum number of transmissions, using both CC-HARQ as well as S-HARQ in Rayleigh fading ($m = 1$). We have simulated every value of z between 1 and 50 and the values which cannot close the link are omitted from the curves. Note

$$\partial_{\bar{\gamma}}\bar{\tau} = -\frac{m\Gamma(m+1)\left(\frac{\gamma_0 m}{\bar{\gamma}}\right)^{-m}\left(\left(\frac{\gamma_0 m}{\bar{\gamma}}\right)^{2m} - (\hat{z}-1)\,\Gamma(m+1)^2 P_{\text{out},\hat{z}} + (\hat{z}-2)\,\Gamma(m+1)^2 P_{\text{out},\hat{z}+1}\right)}{\bar{\gamma}\left(\Gamma(m+1) - \left(\frac{\gamma_0 m}{\bar{\gamma}}\right)^{m}\right)^{2}} \tag{20}$$

$$\partial_{\hat{z}}\bar{\tau} = \frac{P_{\text{out},z-1}\left(\Omega P_{\text{out},1} - \Omega P_{\text{out},z}\right)\left(\gamma_0 \lambda W \ln\left(P_{\text{out},1}\right) + \Omega(z-1)\right)}{\gamma_0 \lambda W\left(P_{\text{out},1} - 1\right)}. \tag{21}$$

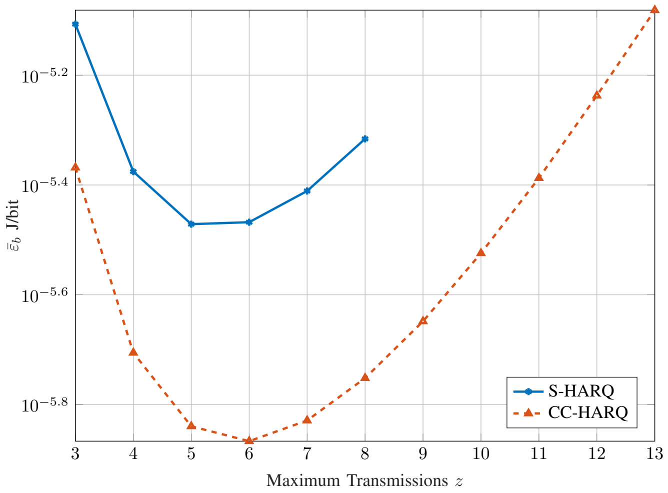

Fig. 2: Average energy per goodbit versus the maximum number of transmissions for S-HARQ and CC-HARQ for Rayleigh fading ($m = 1$).

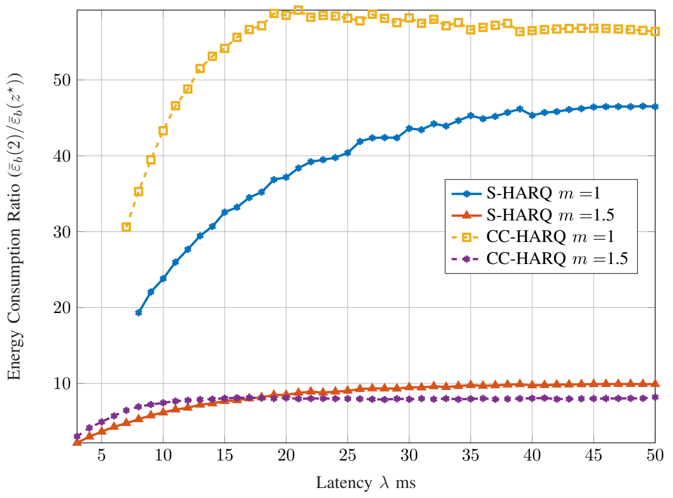

Fig. 3: Energy consumption ratio comparing the optimization with allowing 1 retransmission ($z = 2$).

that when z is small $\bar{\varepsilon}_{\text{b}}$ is large, however as z increases, energy savings are observed due to the increase in diversity up until a point ($z^\star$) where the required transmit powers to meet the latency constraint start to overcome the diversity gains, thus increasing $\bar{\varepsilon}_{\text{b}}$. The importance of optimizing z in terms of energy efficiency is clear in Figure 2. For instance, comparing $z = z^\star$ and $z = 3$ we can observe relative differences in $\bar{\varepsilon}_{\text{b}}$ of around 2.3 and 3.1 times for S-HARQ and CC-HARQ, respectively. Additionally, Figure 2 also shows that CC-HARQ outperforms S-HARQ. The trade-off is an increase in complexity.

Moreover, our results show that having some diversity technique is crucial to close the link in considering this stringent constraints. In the proposed system, it is impossible to close the link without diversity. To show potential savings in energy of using the proposed optimization we have compared $\bar{\varepsilon}_{\text{b}}(z^\star)$ with the case of only up to 1 retransmission ($z = 2$) for different values of λ - ranging from 1 to 50 ms - and for $m = 1, 1.5$. The results are presented in Figure 3 in the form of the ratio $\bar{\varepsilon}_{\text{b}}(2)/\bar{\varepsilon}_{\text{b}}(z^\star)$. Without LOS (Rayleigh, $m = 1$) and with $\lambda = 10$ ms, the difference is on the order of 23 times using S-HARQ and 42 times using CC-HARQ. With some LOS, the savings are still considerable. We can observe consumptions around 5 and 6 times smaller (for $\lambda = 5$ ms [3]) in S-HARQ and CC-HARQ, respectively. The complexity is not increased by much as both cases use retransmissions and the gains are substantial. Figure 3 also demonstrates the high impact of LOS in the energy efficiency of the system.

Figure 4 shows the impact of increasing z towards each component of the energy consumption model, $\varepsilon_{\text{el,tx}}$, $\varepsilon_{\text{el,rx}}$ and ε_{PA}. The startup energy (ε_{st}) was omitted because it does not vary with z. We have calculated the average values ($\bar{\varepsilon}_{\text{el,tx}}$, $\bar{\varepsilon}_{\text{el,rx}}$ and $\bar{\varepsilon}_{\text{PA}}$) multiplying each of the components by $\bar{\tau}$. Furthermore, SNR is fixed at the one which yields the target outage and Rayleigh fading ($m = 1$) is considered. We can observe that $\bar{\varepsilon}_{\text{PA}}$ is the dominant component and the most influenced by variations in z, reinforcing the need for optimizing the number of allowed transmissions.

Lastly, we present the minimum bandwidth required to close the link for values of λ ranging from 2 to 20 ms. Figure 5 contains values obtained using Theorem 1 and via numerical simulation for S-HARQ scheme with different LOS conditions. We can observe that the simulated values agree well with Theorem 1 and that the predictions made regarding requirements in bandwidth for smaller maximum latencies or worse LOS conditions are correct.

V. CONCLUSION

Using retransmission schemes in future wireless networks can be vital to meet the strict demands of future applications, such as vehicular networks. Not only can it significantly improve energy efficiency, it may also mean being able to close the link whilst meeting the stringent constraints of

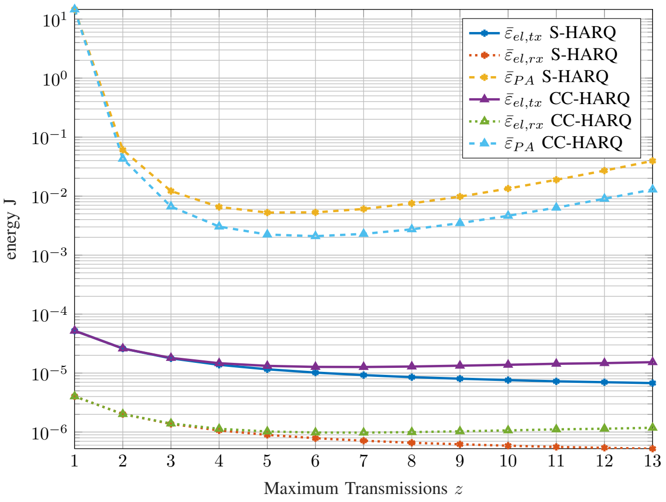

Fig. 4: Different components of $\bar{\varepsilon}_{\mathrm{b}}$.

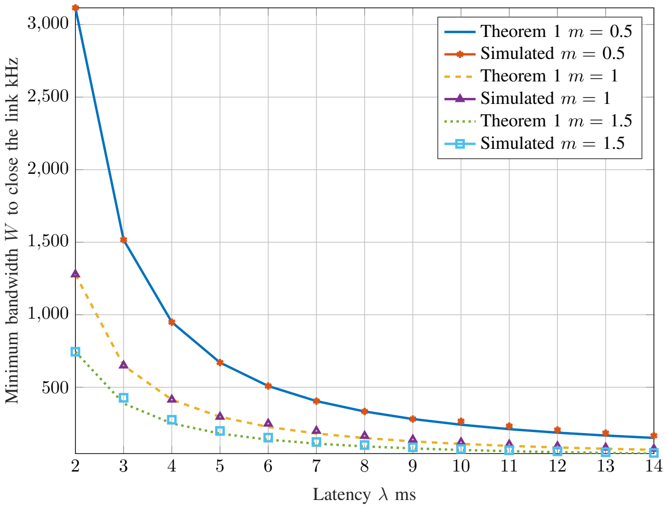

Fig. 5: Minimum bandwidth needed for different values of latency and LOS conditions.

latency and reliability of ultra reliable communications. As we have shown, by carefully tuning the protocol and choosing an optimal limit on the number of transmission attempts it is possible to greatly reduce energy consumption. We have also presented a useful approximation relating most system parameters to predict if the link can be closed, which is valuable for system design.

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