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Energy Efficient Wireless Communication using Channel Coding

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Abstract: Error correcting coding is one of the technique for reducing the signal-to-noise ratio (SNR) required to attain a given bit error-rate. However, this reduction comes at the cost of extra energy consumption required by the baseband processing for encoding and decoding the data. So to study the complete analysis of the trade-off between baseband consumption and coding gain is prime motive of this paper. In this article the energy-consumption of BCH codes with different code rates over AWGN and fading channels is studied. The results show that codes with low code rate are ideal for performing long-range communications, while is better to use less coding redundancy for shorter transmission distance.

Keyword: Baseband processing, coding gain, AWGN, Rayleigh fading channel, BCH.

I. INTRODUCTION

The development of techniques for decreasing the energy consumption of wireless communications is a main requirement for Wireless Sensor Networks (WSN) to grow into large-scale autonomous networks [1]. The nodes of these networks perform function which include sensing the environment, processing of data and wirelessly communicate it across the network. The latter task dominates the overall energy budget [2] and, therefore, optimizing it has a direct impact on a network's equipment's lifetime [1]. In fact, battery depletion has been identified as one of the main causes of lifetime limitation of these networks [3]. Replacing batteries regularly is not practical solution in networks having many nodes or may even be impossible in hostile environments [4].The communication energy budget depends on the transmission power and packet structure, which have a direct impact on the link's frame error probability. The frame error probability, in turn, affects the number of retransmissions that are necessary and thereby also affects the overall energy required to transmit successfully each bit of information from one node to the next.

Error Control Coding (ECC) is a popular technique to reduce the required transmit power by increasing the link reliability. However, this typically comes at the cost of extra power consumption of the decoder at the receiver. Moreover, while stronger codes offer better error correcting performance, they require more complex decoders which consume much more power than simpler codes.
An analysis from this point of view is performed in [5], where the authors examine the energy efficiency of specific ECC implementations in WSNs. The approach is based on complex iterative codes, like Turbo or Low-Density Party-Check codes (LDPC), and considers only transmissions over the AWGN channel The energy efficiency of coding with automatic repeat request (ARQ) in fading channels is investigated in [6]–[8]. Specifically, a Bluetooth network is analysed in [6], [7], while a more general approach for sensor networks is considered in [8]. Nevertheless, the power consumption of electronic circuits is not taken into account in [6]–[8] and only convolutional codes are employed. On the other hand, the energy efficiency of BCH codes was evaluated for sensor networks in [9], showing that BCH codes can be up to 15% more energy efficient than the best performing convolutional codes. The analysis in [9] focuses on the optimization of the packet length for a fixed code rate. However, the consumption of the circuits is not included in the analysis. This impacts the final results, specially in the case of retransmissions.

In this paper the code rate of BCH codes is optimized to achieve energy efficient communications in a WSN for AWGN and Rayleigh fading channels. The choice of BCH codes is motivated by their simplicity and straightforward implementation, and on the fact that BCH codes are flexible enough to provide a good range of different code rates. However, analysis technique is not restricted to the use of these codes.

Employing the framework for energy consumption analysis presented in [10] as a starting point and extend it to consider the energy cost of baseband processing required for encoding and decoding the data, as well as the effects of retransmissions due to decoding errors which are beyond the correcting capabilities of the code. Results show that, for long transmission distances it is optimal to use a significant amount of coding redundancy, as this allows to attain a low error rate with less irradiated power. On the contrary, for short range transmissions using little redundancy is the best choice. In addition, results also

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show that the transmission distance of a low-power communication device can be significantly increased by choosing an appropriate code rate.

The rest of this article is organized as follows: Section II describes the energy consumption model, Section III uses this model to study the optimal code rate as a function of the link distance, and finally Section IV summarizes our conclusions.

II. ENERGY CONSUMPTION MODEL

The goal is to find the total energy that is necessary for transferring one bit of data successfully, hereafter called a good bit [11], in a point-to-point packet-switched wireless communication. Following [10], the assumption is made that every forward frame is matched by a feedback frame in the reverse direction that recognize correct reception or requests a re-transmission.

The detection of frame errors is assumed to be done by an upper layer protocol. It is also assumed that the radiated power is determined based on knowledge of SNR value at the decision stage of the receiver. Further it is assumed that all frames in both directions are always detected and decoded without error.

A. Forward Transceiver Energy Consumption Components

The energy consumed by transceiver for transmission of forward frames and reception of feedback frames is composed of 6 terms, each one is described next.

1) Start-up Energy Consumption: Transmitter is by default in low power mode or sleep mode is assumed. Hence, it has to be brought online before it can make a transmission. ξ_{st} is denoted as the total start-up energy divided by the number of payload bits that will be transmitted before the transceiver goes into low power mode or sleep mode again.

2) Energy Consumption of Electronic Components due to Pre-transmission Processing: Let's define r = k/n as the code rate, where n is the number of bits per codeword and (n – k) is the number of added redundancy bits. Then, each physical layer forward frame carries H header bits with essential transmission parameters and a payload composed by rL data bits and (1−r)L additional coding bits.

The total duration of a forward frame is shared by T_L seconds for transmitting the L bits of payload (with a suitable modulation), T_H seconds for the transmission of the header and T_O seconds for the transmission of overhead signals for acquisition and tracking which include channel estimation, synchronization, etc. The average air time per data bit in a forward frame is

$$T_b = \frac{T_L + T_H + T_O}{rL} \qquad (1)$$

It is assumed that an M-ary modulation is being used. Each payload symbol therefore carries $\log_2(M)$ bits. If Rs denotes the physical layer symbol-rate, then (1) can be formulated alternatively as

$$T_b = \frac{1}{rR_s}\left(\frac{1}{\log_2 M} + \frac{H+O}{L}\right) \qquad (2)$$

where O is a measure of the total overhead per forward frame, measured in bits.

Following (2), it may be written as the energy per bit per forward frame used for transmit processing as

$$\xi_{el,tx} = P_{el,tx} T_b \qquad (3)$$

where Pel,tx is the power consumption of the baseband and radio-frequency electronic components that perform the forward transmission. It is to be noted that Pel,tx is largely dominated by passband processing components such as filters, mixers and the frequency synthesizer [12], whose consumption is typically orders of magnitude larger than the one of the digital baseband processing modules [1].

3) Energy Consumption due to Electromagnetic Radiation: Each frame is aired with a transmission power Ptx provided by the power amplifier (PA). The PA's power consumption is modeled by

$$P_{tx} = \frac{\eta}{\xi} P_{PA} \qquad (4)$$

where the peak-to-average ratio of the transmitted signal is ξ and η is the drain efficiency of the PA [13]. Thus, the energy per bit per forward frame used for electromagnetic radiation is

$$\xi_{PA} = P_{PA} T_b \qquad (5)$$

where Tb is given by (2).
The PA power consumption is a function of the mean SNR,$\bar{\gamma}$, observed at the decision stage of the receiver. Following the analysis presented in [10], this dependency is modelled as

$$P_{PA}(\bar{\gamma}) = \frac{\xi A_0 \sigma_n^2}{\eta} d^\alpha \bar{\gamma} = A d^\alpha \bar{\gamma} \qquad (6)$$

where parameter that depends on the transmitter and receiver antenna gains and the transmission wavelength is A_0, σ_n^2 is the noise power, the distance between transmitter and receiver is d and α is the path loss exponent [14]. Moreover, the noise power can be expressed as $\sigma_n^2 = N_0 W N_f M_1$ where N0 is the power spectral density of baseband-equivalent AWGN, W is the transmission bandwidth, Nf is the noise figure of the receiver's front end and M_l is a link margin term that represents any other additive noise or interference [13].

4) Energy Consumption of Electronic Components due to the Processing of Feedback Frames: Feedback frames are assumed to last F/Rs seconds, where F is the number of bits that compose the feedback frame and Rs is as defined in Section II-A. During this time, the transceiver consumes Pel,rx Watts, which mainly includes the power required to move to action by passband receiver elements like low-noise amplifiers, filters etc. [12]. Therefore, the energy per forward data bit spent by the transmitter for decoding the respective feedback frame is given by (7)

$$\xi_{fb,rx} = \frac{P_{el,rx}F}{rLR_s} = P_{el,rx}T_{fb} \qquad (7)$$

where Tfb is the feedback time per payload bit.

5) Re-transmission Statistics: A main contributor to the energy consumption is the need for re-transmissions of frames that are delivered & decoded with errors at the receiver end. The number of transmission trials, τ , until a frame is received without error is a random variable, whose mean value given in [8]

$$\tau = 1 + \sum_{j=1}^{\infty} E\{\prod_{i=1}^{j} P_f(i)\} \qquad (8)$$

where E{ · } denotes the expectation operator and Pf(i) is the probability of receiving the frame with error during the i-th transmission trial. In general, the Pf(i) is a random variables that depend on the frame size, modulation type and received SNR during the i-th transmission trial.
For n < L lets define n_c = L/n (n_c ∈ N) as the number of code words per payload. Then, to decode a frame correctly one needs H correct header symbols and n_c code words with at least (n−t) = λ correct symbols, where t is the maximum number of bits that the FEC block code is able to correct per codeword. Hence, by taking into account the various permutations, $\bar{P}_f^*(\bar{\gamma})$ can be written in terms of the bit error rate of the M-ary modulation Pb(γ) and the binary modulation symbol error rate Pbin(γ) as in (9)

$$\bar{P}_f^*(\bar{\gamma}) = [1 - \bar{P}_{bin}(\bar{\gamma})]^H \left[\sum_{j=0}^{t} \binom{n}{j} [1 - \bar{P}_b(\bar{\gamma})]^{n-j} \bar{P}_b(\bar{\gamma})^j\right]^{n_c} \qquad (9)$$

6) Baseband Electronic Consumption: Performing the encoding of each forward frame is the more demanding baseband operation. Each encoding procedure involves K different kinds of arithmetic operations, each operation has an energy consumption component Ek and is performed $n_{enc}^k(r)$ times during the algorithm. Consider that the encoding has to be done once for each frame, and hence it cost is shared among the rL data bits. Therefore, the energy consumption of encoding one frame per data bit,ε_{enc} is given by (10)

$$\varepsilon_{enc} = \frac{1}{rL}\sum_{k=1}^{K} \varepsilon_k \eta_k^{enc}(r) \qquad (10)$$

If the operations are accomplished by an Arithmetic Processing Unit (APU), the energy consumption of the k-th operation can be formulated in (11) as described in [15]

$$\varepsilon_k = V_{dd} I_0 \Delta t_k \qquad (11)$$

where APU’s operating voltage is V_{dd} and I0 is the average current during the completion time of the arithmetic operations. Where I0 depends on Vdd and on the APU’s clocking frequency, f_{APU}. Δt_k is the time needed for executing the k-th operation. It is related to fAPU and to the number of clock cycles required by the operation, C_k, as in (12)

$$\Delta t_k = \frac{C_k}{f_{APU}} \qquad (12)$$

Replacing these terms in (10), the energy required for encoding (or decoding) is given by

$$\varepsilon_{enc} = \frac{V_{dd} I_0}{rL f_{APU}} \sum_{k=1}^{K} c_k \eta_k^{enc}(r) \qquad (13)$$

B. Total Energy per Successfully Transferred Bit
The material presented in Section II-A allows for stating the model of the total energy consumption. Accurately, the energy consumed per goodbit by the transmitter of forward frames, which also decodes feedback frames, is given by

$$\varepsilon_T = \varepsilon_{st} + \varepsilon_{enc} + (\varepsilon_{el,tx} \varepsilon_{PA} \varepsilon_{fb,rx})\tau$$
$$= \varepsilon_{st} + \varepsilon_{enc} + [(P_{el,tx} + P_{PA})T_b + P_{el,rx} T_{fb}]\tau \qquad (14)$$

Similarly, the total energy used by the receiver for demodulating τ forward frames and for transmitting the corresponding τ feedback frames is

$$\varepsilon_R = \varepsilon_{st} + [\varepsilon_{dec} + P_{el,rx} T_b + (P_{el,tx} + P_{PA})T_{fb}]\tau \qquad (15)$$

where ε_{dec} is introduced as the energy consumption of decoding the forward frame, which is defined using (13) with obvious modifications. Note that this term is multiplied by τ because a new decoding algorithm has to be performed for each transmission trial.

Let S = $2\varepsilon_{st}$ as the total start-up energy per bit, Pel = Pel,tx +Pel,rx as the total power consumed by electronic components

$$T_u = r(T_b + T_{fb}) = \frac{1}{R_s}\left(\frac{1}{\log_2 M} + \frac{H+O+F}{L}\right) \qquad (16)$$

as the total time per bit per uncoded transmission trial, i.e. when r = 1. Furthermore, definition of C_{enc} and C_{dec} is $r\varepsilon_{enc}$

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and $r\varepsilon_{dec}$ respectively. Then, the total energy consumption is given by

$$\varepsilon_b = S + \frac{1}{r}\{C_{enc} + [C_{dec}(P_{el} + P_{PA})T_u]\tau\} \quad (17)$$

Because of τ, ε_b is a random variable that depends on the realizations of the channel and of the thermal noise. Using (6) and (8), its mean value is found to be

$$\bar{\varepsilon}_b = S + \frac{1}{r}\left[C_{enc} + \frac{C_{dec} + (P_{el} + Ad^{\alpha}\bar{\gamma})T_u}{\bar{P}_f^*(\bar{\gamma})}\right] \quad (18)$$

With $\bar{P}_f^*(\bar{\gamma})$ given by (9).

III. OPTIMIZING THE CODE RATE AS FUNCTION OF THE TRANSMISSION DISTANCE

The energy-consumption model elaborated in the previous section can be used to compare the performance of different codes, and therefore to optimize the parameters of a coding scheme family.
The focus of the next section is the optimization of the code rate .This work is focused on analysing BCH codes. This coding scheme is chosen for two reasons: they are simple codes with a straightforward implementation, and they are flexible to provide a good range of code rates. The analysis of more sophisticated coding schemes is ongoing work.

A. Costs of Encoding and Decoding Baseband Processing

For calculating the mean energy consumption per good bit $\bar{\varepsilon}_b$ as given in (18), the parameters used are of typical low-power devices which are presented in Table I. The energy required for encoding/decoding the data was calculated as described next.

TABLE I GENERIC LOW-POWER DEVICE PARAMETERS

Parameter	Description	Value
H	Frame header	2 bytes
O	Overhead	5bytes
F	Feedback frame length	11 bytes
W	Bandwidth	10 kHz
R_S	Symbol rate	10 kBaud
ξ_{st}	Start-up energy	0.125 nJ
α	Path loss coefficient	3.2
A_0	Free space path loss	30 dB
η	PA efficiency	35%
$P_{el,tx}$	Tx electronic power consumption	98.2 mW
$P_{el,rx}$	Rx electronic power consumption	112.5 mW
N_0	Noise power density	-174 dBm/Hz
N_f	Reciever noise figure	10 dB
M_1	Link margin	30 dB

The encoding of cyclic codes such as BCH codes can be done using a shift register with feedback connections defined by either the generator polynomial or the parity polynomial [18]. By using the generator polynomial strategy, the k information bits are shifted sequentially into the register, and at each clock cycle at most n − k additions are carried out. The exact number of overall additions depends on the generator polynomial, but in the worst case at most $kn - k_2$ additions are necessary.

At the receiver side, the decoding of BCH codes has three steps [18]: i.) Syndrome computation; ii.) Finding the error location polynomial; iii.) Computation of error-location numbers and error correction. The number of operations required for the syndrome computation is (n−1)t additions and nt multiplications. Finding the error-location polynomial needs additional $2t^2$ additions and $2t^2$ multiplications, while the computation of error-location numbers and error correction needs more nt additions and nt multiplications. Therefore, a total of $(2n-1)t+2t^2$ additions and $2nt+2t^2$ multiplications are required for decoding.

B. Bit Error Rate Variation

Bit Error Rate (BER) is necessary parameter to calculate which gives us a clear view of the required SNR level at a specific distance. This is done by first generate the random sequence of modulated +1's and -1's then pass them through Ray leigh channel. Then demodulate at received signal and count the number of errors.

This is repeated for different SNR levels. Theoretical formula of probability of error or BER is given by (19) and Fig. shows the graph generated between BER and SNR for Rayleigh Channel and AWGN channel as well. Mathematically this is represented by (19) and the Fig. 1 shows the graph of SNR vs BER.

$$P_b = \frac{1}{2}\operatorname{erfc}\left(\sqrt{\frac{E_b}{N_0}}\right) \quad (19)$$

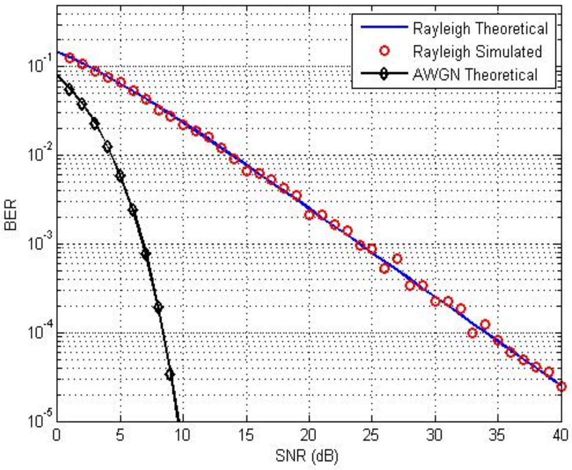

Fig. 1. SNR vs BER plot for BPSK modulation in Rayleigh Channel

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C. Optimizing the SNR

As a first step in the analysis, it is possible to show that the mean energy consumption per goodbit has a convex shape when plotted as function of the SNR. In effect, if the SNR is low then $\overline{\tau} = 1/\overline{P}^*(\overline{\gamma}))$ is large, which reflects the fact that a large number of transmission trials is needed on average to achieve one correctly decoded frame across the transmission link. On the contrary, if the SNR is high then the number of retransmissions is small, but the overall consumption will be large because of an excessive irradiated power. In between these two extreme situations there always exists a single optimal SNR at which the energy consumption is minimized. This insights have been confirmed by numerical evaluations (see Figure 2).

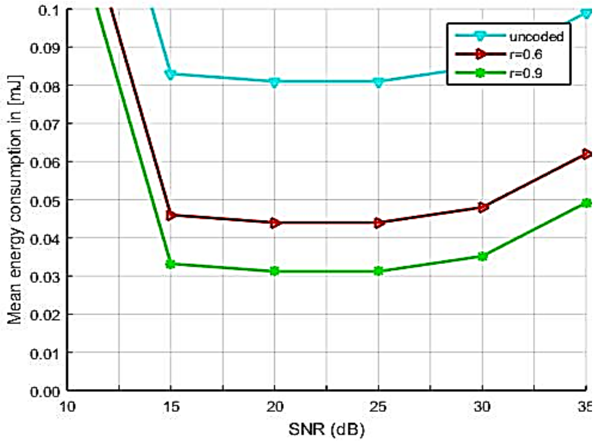

Fig. 2. Mean energy consumption per good bit of BPSK transmissions over a Rayleigh fading channel with a link distance of d = 50 meters. For each value of the code rate r = k/n the consumption is a convex curve, which has an unique minimum value. This minimum gives the optimal irradiation power from the point of view of the energy consumption.

D. Optimizing the Code Rate

Consider now a family of BCH codes with fixed codeword length n and varying information content k, where each code can be parameterized by its code rate r = k/n. Let's denote the set of all the BCH codes for a given value of n as Rn. Then, for a given codeword length n and link distance d, the optimal code rate is given by (22)

$$r_n^*(d) = \underset{r \in R_n}{\operatorname{argmin}}\ \varepsilon_b(r, d, \overline{\gamma}^*_{r,d,}) \qquad (20)$$

Note that in the above definition the performance of each coding scheme is evaluated when using its own optimal mean SNR

$r_n^*(d)$ is numerically calculated for BPSK transmissions using one code-block per frame (i.e. n_c = 1, see (10)) by comparing the performance of all the BCH codes with n = 1023. It is found that the optimal BCH code rate $r_n^*(d)$ increases as the transmission distance decreases (see Figure 3). Although the rate of change depends on the channel fading statistics, the qualitative scenario is always the same: for long transmission distances it is optimal to use a significant amount of coding (small r), while for short distances it is best to use almost no coding at all (large r). For long range communications the most important source of energy consumption is the irradiated power, so it is very useful to use coding in order to reduce the SNR requirements to for attaining a given bit error rate. On the contrary, in short-range transmissions the electronic power is larger than the power consumed by the PA, and therefore is better to use less coding in order to reduce the total time per bit.

The savings that are achieved using the optimal code rate depend on the channel fading statistics (see Figure 3). Note that the curves of energy consumption of uncoded systems have a steep slope around a critical distance (100 meters for the AWGN channel and 30 meters for the Rayleigh channel), which is a consequence of the irradiation power limit [10]. This critical distance governs a "maximum uncoded-transmission range" of the device, which is represented as d_c. For the case of the AWGN channel, if the link distance is smaller than d_c then uncoded communications are the optimal choice

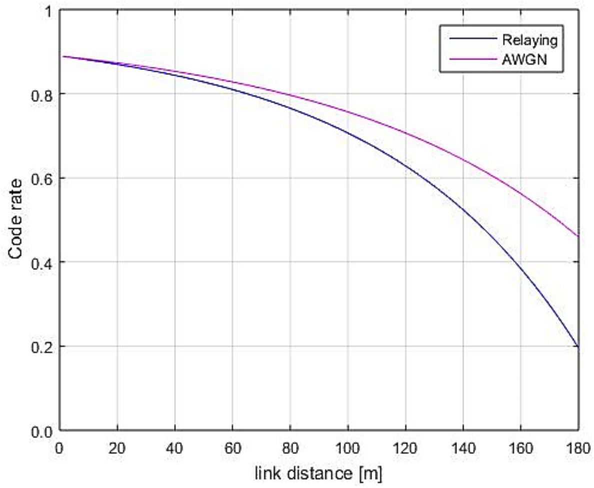

Fig. 3. Code rate of transmission on AWGN and Rayleigh channel

IV. CONCLUSION

For a given modulation scheme, the mean energy consumed per bit for transmission over a fading channel as function of the SNR has a unique minimum value. It is found that the optimal energy consumption per bit and the optimal SNR at which this occurs take larger values for channels with less favourable error statistics. Also it is found that for long transmission length low bandwidth efficiency modulations (eg. BPSK) are optimal in the energy consumption sense. As the transmission length shortens, the optimal modulation size grows. In short range communications, the power required by electronic components governs the irradiated power, and dominates also over the energy consumption of the power amplifier. Under these conditions, the mean air time spent per data

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bit becomes a parameter of interest in the total energy budget. The research work based on this report is concentrated on the implementation of optimized code rate for energy efficient transmission in BPSK modulation over fading channel by improving the SNR, transmission link distance while considering the cost and energy consumption in encoding and decoding process of baseband signal.

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