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# Error Control in Wireless Sensor Networks

A Process Control Perspective

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## Abstract

# **Error Control in Wireless Sensor Networks: A Process Control Perspective**

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*Oskar Eriksson*

The use of wireless technology in the process industry is becoming increasingly important to obtain fast deployment at low cost. However, poor channel quality often leads to retransmissions, which are governed by Automatic Repeat Request (ARQ) schemes. While ARQ is a simple and useful tool to alleviate packet errors, it has considerable disadvantages: retransmissions lead to an increase in energy expenditure and latency. The use of Forward Error Correction (FEC) however offers several advantages. We consider a Hybrid-ARQ-Adaptive-FEC scheme (HAF) based on BCH codes and Channel State Information. This scheme is evaluated on AWGN and fading channels. It is shown that HAF offers significantly improved performance both in terms of energy efficiency and latency, as compared to ARQ.

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# 1 Introduction

## 1.1 Background

The use of wireless sensor networks (WSNs) for process control has attracted a lot of interest in recent years, see e.g. (Gungor & Hancke, 2009), (Song, Han, & Mok, 2008), (De Biasi, Snickars, Landernäs, & Isaksson, 2008), (Saifullah, Xu, Lu, & Chen, 2010). The primary reasons are that WSNs can be deployed easily and effectively, sensors can be placed where wires cannot go, and the cost of wires and installations can be significantly decreased. However, implementing wireless control with small battery driven sensor nodes require extreme energy efficiency. In the process industry, plants frequently have thousands of control loops. As an example, consider an industrial plant with four thousand battery driven sensor nodes. If the node lifetime is uniformly distributed between one and two years, then in steady state one will, on average, have to exchange battery on about ten nodes a day. Clearly this is not an option in most situations. Therefore, it is not at present clear whether the use of battery powered sensor nodes is feasible for process control.

To attain long lifetime, it is necessary to put the sensor node radios to sleep as much as possible. However this will be in conflict with the requirement of small delays in the network and the use of excessively fast sampling, frequently occurring in the process industry. Therefore, it becomes increasingly important to use the radios' on-time efficiently, and to choose sampling intervals and transmission techniques judiciously. Here, the design of energy- and latency efficient error control schemes play an important role. Error control can generally be realized by Automatic Repeat Request (ARQ), Forward Error Correction (FEC), or a combination of the two: Hybrid-ARQ (HARQ) (Akyildiz & Vuran, 2010). Today, ARQ, which is purely based on retransmissions, is the implemented technique in process control networks (HART Communication Foundation, 2007). Even though retransmissions, caused by packet losses, improve the throughput, they also introduce latency and excessive energy expenditure, which may be unacceptable, particularly in time-critical control applications.

## 1.2 Problem Description

FEC introduces redundant bits, which due to increased packet lengths increases both energy expenditure and latency. On the other hand it reduces retransmissions, which works in the opposite direction. Hence, there is a trade-off between code rate and retransmissions. How this trade-off should be made in industrial scenarios will be investigated in this thesis. Furthermore, we will investigate the pros and cons of ARQ and HARQ in terms of energy efficiency and latency. The HARQ scheme is based on FEC with BCH codes. Such schemes have been used previously in the literature, see e.g. (Vuran & Akyildiz, 2009), (Howard, Schlegel, & Iniewski, 2006), (Kleinschmidt, Borelli, & Pellenz, 2007), (Balakrishnan, Yang, Jiang, & Kim, 2007). Here we will use a Hybrid-ARQ-Adaptive-FEC scheme<sup>1</sup>.

Performance of Hybrid-ARQ-Adaptive-FEC in terms of energy consumption, latency, and packet loss will be investigated and compared to ARQ. The investigation performed here is based on insights gathered from a radio channel measurement campaign conducted at a paper mill in Sweden. From the measurements obtained we observed that the channel characteristics were quite different. While some channels were virtually static others were subject to severe shadow fading, with signal strength variability of as much as 25 dB (Björnemo, Ahlén, & Gidlund, 2010). However, on the

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<sup>1</sup> The Hybrid-ARQ-Adaptive-FEC scheme is explained in Section 3.3.

duration of a packet the channels were constant. In Section 5 we will use both AWGN channels as well as statistics of fading channels, obtained from this measurement campaign, in the investigation of energy expenditure, latency, and packet loss for the Hybrid-ARQ-Adaptive-FEC and ARQ schemes. The analysis will be done via numerical evaluations in MATLAB.

### *Purpose*

The purpose of this thesis is to provide a better understanding of the described trade-off, i.e. between code rate and retransmissions, an understanding that will be transferred to industry and ongoing standardization work on WSNs for process control.

## **1.3 Related Work**

(Howard, Schlegel, & Iniewski, 2006) have studied the energy efficiency of specific error control codes (ECC), for several decoder implementations, in WSNs. They conclude that coding saves energy even at very short distances, but they have not accounted for the increase in packet size, which leads to longer radio on-time. Only the energy consumed by the coding and decoding processes is considered. In (Sankarasubramaniam, Akyildiz, & McLaughlin, 2003) different error control techniques are considered, but the investigation is focused on the question of optimal packet size for WSNs. (Balakrishnan, Yang, Jiang, & Kim, 2007) evaluates the power consumption of three different ECCs, but for specific platforms i.e., FPGA and ASIC.

In (Vuran & Akyildiz, 2009) an analysis of error control schemes in WSNs is presented, which compares ARQ, FEC, and HARQ in terms of energy consumption, latency, and PER. See also (Akyildiz & Vuran, 2010). Here, we use a different network model, and in addition we consider the use of an adaptive FEC scheme.

In (Min, o.a., 2002) and (Shih, Cho, Lee, Calhoun, & Chandrakasan, 2004), only the cost of the decoder is included at the receiver side, and not the total processing cost, which increases with larger packets. Furthermore, their study is based on convolutional codes, where as we focus on block codes.

The use of adaptive FEC has been considered previously in (Cho, 2000), which presents an adaptive error control scheme for multimedia applications in integrated terrestrial-satellite wireless networks. They conclude that under real-time application, the adaptive protocol outperforms the static FEC protocols with respect to packet miss probability. Similar results can be seen in (Shiozaki, Okuno, Suzuki, & Segawa, 1991).

## **2 Theoretical Considerations**

### **2.1 WirelessHART**

WirelessHART is a wireless sensor networking technology based on the Highway Addressable Remote Transducer Protocol (HART). It is essentially the only released standard for wireless communication in the process industry (De Biasi, Snickars, Landernäs, & Isaksson, 2008), and it is the first open standard specifically designed for process control (Song, Han, & Mok, 2008). It was officially released in September 2007. The structure of WirelessHART is depicted in Figure 2.1.

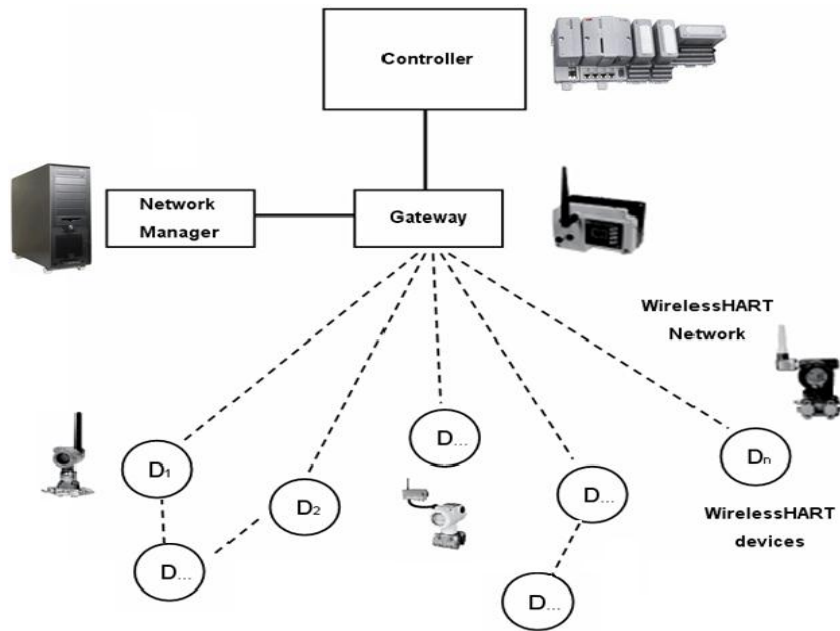


Figure 2.1: The structure of a WirelessHART network

WirelessHART is a TDMA based wireless technology that supports mesh networking. It uses the 2.4GHz ISM radio band, with a bit rate of 250 kbps per channel over totally 15 channels, see (HART Communication Foundation, 2007). For error control it uses ARQ. The physical layer is inherited from the IEEE 802.15.4 standard, and consequently, it uses Offset Quadrature Phase-Shift Keying (OQPSK) modulation. The Physical Layer Protocol Data Unit (PPDU), as specified in (IEEE, 2006), is illustrated in Figure 2.2

		Octets		
		1		variable
Preamble	SFD	Frame length (7 bits)	Reserved (1 bit)	PSDU
SHR		PHR		PHY payload

Figure 2.2: PPDU as specified in IEEE 802.15.4.

The synchronization header (SHR) and the Physical Layer Header (PHR) are required overhead to the PHY payload. The SHR enables the receiving device to find the start of the packet, through correlation with a known sequence, the Preamble. The Start-of-Frame Delimiter (SFD) is a 1-byte value marking the end of the preamble. The PHR contains information about the total size of the packet.

The total length of the overhead, i.e. the SHR and the PHR, for the 2,4 GHz channel, is 6 bytes (IEEE, 2006). The PHY payload, or the Physical Layer Service Data Unit (PSDU), contains the packets inner layers including additional overhead as well as the actual information bits. Hence, the size of the payload depends on the size of the information that is transmitted. In WirelessHART the total packet size is restrained by the timeslot structure, which tolerates packet sizes up to 133 bytes.

## 2.2 Error Control

### 2.2.1 Automatic Repeat Request (ARQ)

In ARQ-based error control the packet is retransmitted if it is found to have errors. Such packets are retransmitted until it is received error free. The error detection is usually implemented through a cyclic redundancy check (CRC). A simple error-detecting code is applied to the packet before transmitting, and at the receiver side a checksum will be calculated to ensure that no error has occurred. If the checksum does not add up to the right value, the packet is retransmitted. The ARQ scheme uses *positive* acknowledgment (ACK) or *negative* acknowledgment (NACK) to send feedback to the transmitter of whether or not the transmission was successful. If ACKs are used, then the transmitter will retransmit if it has not received an ACK packet within a pre-specified timeframe. The additional cost incurred from retransmissions is the major drawback with ARQ.

### 2.2.2 Forward Error Correction (FEC)

FEC or *channel coding* is a method used to increase the performance of error control. This is achieved by the use of error-correcting codes (ECCs) that add redundancy to the packet, which allows a certain amount of bit-errors to be detected and corrected at the receiver side. The main drawback is the cost of the redundancy, *the parity bits*, which increase the packet size. Additionally, FEC introduce encoding and decoding costs. Therefore, FEC is traditionally used in circumstances where retransmissions are relatively costly. There are many types of FEC codes, where the most commonly used are divided into two categories, *block codes* and *convolutional codes*. A block code first divides the message to be transmitted into smaller blocks of a predefined length. These blocks are then encoded individually into *code words*. In the case of convolutional codes each bit is, instead, encoded as a function of a predefined number of preceding bits. Reed-Solomon, Bose Chadhuri Hocquenghem (BCH), and Hamming codes are among the most widely known block codes. The Hamming code is known as one of the pioneering codes, developed by Richard Hamming in 1950, and is still used today in applications as Error-correcting code memory (ECC memory). Over the years more powerful codes have been developed such as Reed-Solomon and BCH.

Block codes are commonly represented by the triple  $(n, k, t)$ , where  $n$  is the length of a code word,  $k$  is the number of information bits in a code word, and  $t$  is the correction capability in terms of the number of bits that can be corrected, see Section 2.4.1. Figure 2.3 illustrates how extra parity bits increase the length of a FEC block. The information bits of length  $k$  together with the parity bits make up a *code word* of length  $(n)$ , from which the, code-specific, *code rate* is defined as  $R_c = k/n$ . Thus, for a given code rate,  $R_c$ , and a message with  $m$  information bits, the encoded packet would consist of  $m/R_c$  bits.

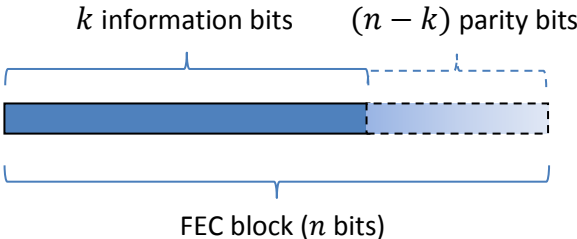


Figure 2.3: Illustration of a FEC block.

In addition to traditional block-, and convolutional codes there exist yet more powerful codes, such as turbo codes and Low-Density Parity-Check (LDPC) codes. Due to their complexity and advanced encoding and decoding processes, they are limited to applications that can handle the computational complexity needed.

As mentioned in (Goldsmith, 2005), BCH codes constitute a class of cyclic, linear block codes. They are powerful codes that, for moderate to high SNR, generally outperform all other block codes at high rates<sup>2</sup>. As explained in (Vuran & Akyildiz, 2009) BCH codes do, in some cases, outperform convolutional codes in terms of energy efficiency. The results of (Sankarasubramaniam, Akyildiz, & McLaughlin, 2003) show that BCH codes outperform the most energy efficient convolutional codes by nearly 15%. Similar results are presented in (Balakrishnan, Yang, Jiang, & Kim, 2007). In Table 2.1 the  $(n, k, t)$  characteristics of 70 BCH codes are presented.

Table 2.1: BCH Codes (IEEE, 1964)

$n$	$k$	$t$	$n$	$k$	$t$	$n$	$k$	$t$
7	4	1	127	92	5	255	163	12
15	11	1	127	85	6	255	155	13
15	7	2	127	78	7	255	147	14
15	5	3	127	71	9	255	139	15
31	26	1	127	64	10	255	131	18
31	21	2	127	57	11	255	123	19
31	16	3	127	50	13	255	115	21
31	11	5	127	43	14	255	107	22
31	6	7	127	36	15	255	99	23
63	57	1	127	29	21	255	91	25
63	51	2	127	22	23	255	87	26
63	45	3	127	15	27	255	79	27
63	39	4	127	8	31	255	71	29
63	36	5	255	247	1	255	63	30
63	30	6	255	239	2	255	55	31
63	24	7	255	231	3	255	47	42
63	18	10	255	223	4	255	45	43
63	16	11	255	215	5	255	37	45
63	10	13	255	207	6	255	29	47
63	7	15	255	199	7	255	21	55
127	120	1	255	191	8	255	13	59
127	113	2	255	187	9	255	9	63
127	106	3	255	179	10			
127	99	4	255	171	11			

### 2.2.2.1 Adaptive Coding (ska stycket finnas kvar?)

In (Gungor & Hancke, 2009), the authors aim to provide a contemporary look at the current state of the art in industrial WSNs. They present a list with eight “Design Goals” to serve as a guide line for future research. One goal on the list is “Adaptive network operation”, where the need for adaptive protocols is stressed in order to cope with varying channel conditions. *Adaptive coding* allows for varying the code strength and complexity (Goldsmith, 2005). For example, a simple code could be

<sup>2</sup> Compared to other block codes with the same  $n$  and  $k$ .



used for a good channel, while more powerful codes could be applied when the channel is poor. Multiplexing and puncturing are two ways to implement adaptive coding. Multiplexing combine codes with different error correction capabilities, while puncturing varies the code strength by including more or less of the coded bits in the transmission, depending on if the coded packet was correctly received or not.

### 2.2.3 Hybrid Automatic Repeat Request (HARQ)

ARQ provides reliable communication through retransmissions, which will be costly in poor channels where retransmissions occur frequently. FEC performs better in poor channels, while the redundant bits become an undesired cost when channel conditions are good. HARQ schemes exploit the advantages of both, by methods of combining ARQ and FEC. Generally there exist two types of HARQ, HARQ-I and HARQ-II. In essence the HARQ-I scheme transmits a coded packet, which is retransmitted if the receiver was not able to correct all errors. HARQ-II is more complex, and during the first transmission attempt only a limited amount of FEC parity bits are included. If the packet is uncorrectable, the retransmitted packet only includes extra parity. At the receiver side, the extra parity bits are combined with the previous transmission, which allows the decoder to again attempt to correct the induced errors, but now with more redundancy information. While HARQ-II decreases bandwidth usage, HARQ-I does not require the previously sent packages to be stored (Vuran & Akyildiz, 2009).

### 2.2.4 Error Control in WSNs

When designing an error control scheme for WSNs, energy efficiency is critical. Therefore the extra energy costs inferred by FEC coding must be compared with what might be saved in terms of less retransmission. The main cost to consider is the extended packet lengths, which results in longer radio on-time. There is also the additional cost of the coding and decoding processes. These costs, and in particular the decoding costs, are mentioned in (Vuran & Akyildiz, 2009), in connection with measurements from the SA-1100 processor. Considering instead a low-power processor, such as the MSP430, (Björnemo E. , 2009) makes the assumption that “the processing energy consumption for coding and decoding is negligible in relation to other processing costs”. This is supported by the results of (Howard, Schlegel, & Iniewski, 2006).

An error control design based on FEC or HARQ will have the advantage of being able to correct a certain amount of errors in a packet. In essence the benefit is a lower packet error rate (PER) in comparison with ARQ, at the cost of larger packets. Considering a multi-hop network, the lower PER can be exploited in three ways, described next.

#### *Avoid retransmissions*

The lower PER induced by FEC or HARQ could simply be used to avoid retransmissions. When the packet is transmitted over a poor channel the PER would increase with a simple ARQ scheme, and retransmissions would occur. The retransmission cost in terms of energy consumption and latency, could be avoided to some extent if a FEC or HARQ scheme would be implemented.

#### *Hop Length Extension*

In (Akyildiz & Vuran, 2010) a technique called *hop length extension* is suggested, whereby the lower PER could be exploited by making longer hops in a multi-hop network. This would result in that a

fewer amount hops would be needed for a transmitted packet to reach its destination. In turn fewer hops would lead to increased energy efficiency and lower latency<sup>3</sup>. The hop length extension technique is illustrated in Figure 2.4.

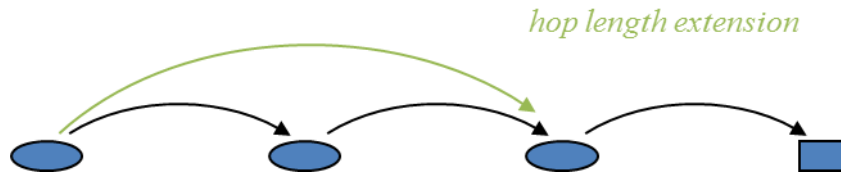


Figure 2.4: Illustration of the hop length extension technique. By using FEC or HARQ the green arrow illustrate the one extra hop can be avoided.

### Transmit Power Control

Consider a system designed with a target bit error rate (BER). With FEC or HARQ the transmit power could be reduced compared to ARQ, but still achieve the target BER. In that way energy consumption could be constrained. In coding theory, this is described as *coding gain*, which is the difference between the signal-to-noise ratios (SNR) levels required to reach the same target PER, with and without FEC.

## 2.3 Path Loss

Path loss (or path attenuation) is the reduction in power density of an electromagnetic wave as it propagates through the wireless radio channel. Path loss may be due to many effects, such as terrain contours, different environments (indoors or outdoors, urban or rural), and the distance between transmitter and receiver. There exist several models used to approximate signal propagation, e.g. *free-space path loss*, *ray-tracing propagation*, and *log-distance path loss model*.

As mentioned in (Goldsmith, 2005), the log-distance path loss model is a simplified model, commonly used for general trade-off analysis of various system designs. It is difficult to obtain a model that accurately describes the complexity of a specific signal propagation, but without resorting to complicated path loss models, the log-distance path loss model captures the essence of signal propagation

$$P_r = P_t K \left( \frac{d_0}{d} \right)^\gamma \quad (2.1)$$

Here  $K$  is a constant that depends on antenna characteristics and channel attenuation, and  $d_0$  is a reference distance. The path loss exponent,  $\gamma$ , is determined based on the propagation environment. Typical values for  $\gamma$  in a factory environment ranges from 1.6 - 3.3 (Goldsmith, 2005).

## 2.4 Error Probability

### 2.4.1 Bit Error Probability

When propagating through the wireless channel the signal is subject to disturbance, such as noise and interference, which may cause the received bits to be altered. Inaccuracies and limitations in the transmitter, or the receiver, such as e.g. bad synchronization, could have the same effect. The *bit*

<sup>3</sup>For implementation a channel-aware routing protocol is needed.

*error rate* (BER) states how many percent of the received bits that have been altered during the transmission.

The *bit error probability* can be estimated for different combinations of channels and digital modulation schemes. In the case of an *Additive White Gaussian Noise* (AWGN) channel, where the modulation scheme *Binary Phase-Shift Keying* (BPSK) is implemented and perfect synchronization<sup>4</sup> is assumed, an exact expression of the bit error probability is given by

$$p_b = Q\left(\sqrt{\frac{2E_b}{N_0}}\right) \quad (2.2)$$

where  $Q$  is a scaled form of the *complementary Gaussian error function* (Goldsmith, 2005).

The bit error probability for *Quadrature Phase-Shift Keying* (QPSK) is the same as for BPSK, since QPSK modulated signal can be viewed as signal with BPSK modulation on both the in-phase and quadrature components of the signal. Offset QPSK (OQPSK) have the same theoretical bit error performance as BPSK and QPSK (Sklar, 2003).

#### 2.4.2 Packet Error Probability

For an uncoded transmission of a data packet of length  $m$  bits, the packet error probability can be calculated as

$$p_p = 1 - (1 - p_b)^m \quad (2.3)$$

where  $p_b$  is the bit error probability, for BPSK and QPSK given by (2.2).

#### 2.4.3 Code Word Error Probability

In the case of a transmission with an implemented error control scheme that uses FEC codes, equation (2.3) can be expressed in terms of *code word error probability*<sup>5</sup>

$$p_p = 1 - (1 - p_w)^w \quad (2.4)$$

where  $w$  is the number of code words in a packet. Code word error probability can, in turn, be expressed as a function of bit error probability. As mentioned in (Proakis, 2001), for the specific case of a linear binary block code, with characteristic  $(n, k, t)$ , a decoder using *hard-decision* will be able to correct any number of errors up to

$$t = \left\lfloor \frac{1}{2}(d_{min} - 1) \right\rfloor \quad (2.5)$$

This is a lower bound on the *correction capability* ( $t$ ) since it is a function of the *minimum Hamming distance* ( $d_{min}$ ) between any two different code words. Hence, a code word might be correctable even with more than  $t$  errors. Moreover, according to the *binomial theorem*, the probability of having  $\varepsilon$  errors in a code word of  $n$  bits is

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<sup>4</sup> By *perfect synchronization*, we here mean coherent detection and perfect recovery of the carrier frequency and phase.

<sup>5</sup> This is true for the specific case of *block codes*. With other types of FEC codes, such as convolutional codes, the definition of a *code word* does not exist in the same sense, since they do not use blocks.

$$p(\varepsilon, n) = \binom{n}{\varepsilon} p_b^\varepsilon (1 - p_b)^{n-\varepsilon}. \quad (2.6)$$

Finally, an upper bound on the probability of code word error is given by

$$p_w \leq \sum_{\varepsilon=t+1}^n \binom{n}{\varepsilon} p_b^\varepsilon (1 - p_b)^{n-\varepsilon} \quad (2.7)$$

which is the sum of probabilities for all uncorrectable number of errors  $\varepsilon > t$ .

### 3 System model

In this section we present the network and path loss model that will be used in the sequel. Furthermore we introduce the Hybrid-ARQ-Adaptive-FEC scheme, which will be compared to ARQ in Section 5.

#### 3.1 Network Model

In process control applications latency requirements frequently limit the number of hops that can be performed between sensor nodes and a shared Gateway ( $GW$ ). This motivates us to introduce a simple network model consisting of three equidistant nodes ( $n_1, n_2, n_3$ ) connected to a  $GW$ , see Figure 3.1. Each node, which can relay packets and thereby enable multi-hopping, is assumed to possess re-coding capabilities. Packets are sent to the  $GW$  from the node furthest away ( $n_3$ ), either through single-hop or multi-hop. There exist three different routes to the  $GW$ ; via  $h_1$ , via  $h_2$  and  $h_3$ , or via three hops of type  $h_3$ .

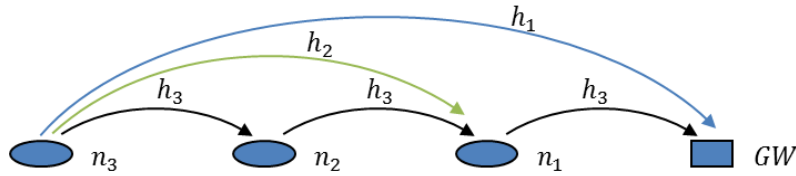


Figure 3.1: Network Model. Data from the  $n_3$  node can reach the gateway via a single or multiple hops.

In addition to alternative routes there will be, in the case of the Hybrid-ARQ-Adaptive-FEC scheme, an option of using different codes. To simplify we make the assumption that routing information as well as information about what codes to use exist in all nodes. In practice this could be achieved by the use of a centralized scheme where the  $GW$  is responsible for error control, including routing. The  $GW$  would have the necessary CSI in terms of signal-to-noise ratios (SNR), here defined as  $E_b/N_0$ <sup>6</sup>, from previous network activity, make decisions of what route and codes to be used, as well as keeping the network updated with this information through periodic broadcasting of sync packets. In other words; based on CSI, the  $GW$  will decide on the route and codes for the transmission, and it will also communicate this information to the respective nodes. Note that this is a simplified model that would need further investigation, but that it still is highly relevant and provides important insights of how to use different FEC schemes. As an alternative to letting the  $GW$  govern all error control decisions, is the use of a decentralized scheme where the choice of code rate is handled locally in the nodes by feeding back channel state information (CSI), such as SNRs, in the ACK packets.

<sup>6</sup> Here  $E_b$  is the energy per bit whereas  $N_0$  is the spectral density of the thermal noise.

### 3.2 Path Loss Model

Considering an industrial environment where the channel quality may vary due to the positioning of nodes, as well as the distance from other nodes and the GW, the numerical evaluation will be performed as a function of SNR. In order to estimate how the SNR varies between the hops, a path loss model, which approximates the effects of the signal propagating through the wireless channel, is used. Here, we consider the path loss model described in Section 2.3. Given the received signal power ( $P_{r_3}$ ) after transmitting over a short hop ( $h_3$ ), the received signal power over the longer hops  $h_1$  or  $h_2$  can, by using equation (2.1), be expressed as

$$P_{r_j} = P_{r_3}(\delta_j)^\gamma \quad (3.1)$$

where  $\delta_j$  is the relative hop distance over  $h_j$  with respect to  $h_3$ , that is,  $\delta_j = \frac{d_3}{d_j}; j = 1, 2$ , and  $d_j$  is the distance over hop  $h_j$ . For simplicity, the constants  $K$ ,  $d_0$ , and the path loss exponent,  $\gamma$ , are assumed to be the same for all hops. Equation (3.1) can furthermore be expressed in terms of signal-to-noise ratios as

$$SNR_j = SNR_3(\delta_j)^\gamma \quad (3.2)$$

where  $SNR_j, j = 1, 2$ , is the SNR at node  $n_j$ .

### 3.3 Hybrid-ARQ-Adaptive-FEC scheme

We will investigate the pros and cons of ARQ and Hybrid-ARQ-Adaptive-FEC in terms of energy efficiency and latency. The Hybrid-ARQ-Adaptive-FEC scheme used here is a HARQ-I scheme, as explained in Section 2.2.3. By Adaptive-FEC we here mean transmission where the code rate is based on (CSI). In other words, based on CSI a more powerful code will be applied in case of a poor channel, while codes with less complexity will be used for a good channel. Hence, unnecessary redundancy in the packet will be avoided under good channel conditions, while the correcting capabilities of more advanced codes will be exploited under bad conditions.

Furthermore, the set of 70 BCH codes presented in Table 2.1 are used for forward error correction. BCH codes are linear block codes represented by  $(n, k, t)$ . The BCH codes that will be used vary in complexity, and their correction capability ( $t$ ) range from  $t = 1$  to  $t = 63$ . We have chosen BCH codes for the evaluation of FEC in line with the arguments in Section 2.2.2, where BCH codes are presented as powerful block codes that outperform convolutional codes in terms of energy efficiency. At the same time they are not as complex as turbo codes or LDPC codes, and are therefore appropriate for the processors frequently used in the sensor nodes, and they fit well into the protocols used for wireless process control.

## 4 Numerical Analysis

In this section, we describe the analysis model that will be used to compare ARQ and Hybrid-ARQ-Adaptive-FEC in terms of energy consumption and latency. Both energy consumption and latency depend on the packet error probability, which can be approximated for a specific channel and modulation. Consider transmission of data over an AWGN channel using OQPSK modulation. As described in Section 2.1, OQPSK is used in the IEEE 802.15.4 and the WirelessHART standards (HART Communication Foundation, 2007) (IEEE, 2006). Real measurements from industrial plants, see

Section 1.2, show that we can expect the channel to be block fading, see e.g., (Björnemo, Ahlén, & Gidlund, 2010). However, over the duration of a packet the channel is approximately constant. Hence, our AWGN model is appropriate, and with perfect CSI we can use AWGN in our analysis.

We will use the derivation of the packet error probability as explained in Section 2.4. Let all channels associated with each hop  $h_j$  be independent and identically Gaussian distributed. Further, let the corresponding bit error probability be denoted  $p_{b_j}$ . From (2.3), we can then express the packet error probability over hop  $h_j$ , for the ARQ scheme as

$$p_{p_j}^{ARQ} = 1 - (1 - p_{b_j})^m \quad (4.1)$$

where  $m$  is the number of bits in the packet. Consequently, for the Hybrid-ARQ-Adaptive-FEC scheme, assuming hard-decoding, the packet error probability is given by, see (2.7), as

$$p_{p_j}^{HAF} = 1 - \left( 1 - \sum_{\varepsilon=t+1}^n \binom{n}{\varepsilon} p_{b_j}^\varepsilon (1 - p_{b_j})^{n-\varepsilon} \right)^w \quad (4.2)$$

where  $n$  is the length of the coded word,  $w$  is the number of code words in a packet,  $t$  is the correcting capability, and where  $p_{b_j}$  for an AWGN channel using OQPSK modulation is given by, see (2.2),

$$p_{b_j} = Q\left(\sqrt{2SNR_j}\right). \quad (4.3)$$

The number of code words,  $w$ , in a packet is determined by the number of information bits,  $m$ , and the code word length,  $k$ , i.e.,

$$w = \left\lceil \frac{m}{k} \right\rceil. \quad (4.4)$$

The *ceiling function*  $\lceil \cdot \rceil$  is used due to that  $N_w$  must be an integer in a practical implementation.

## 4.1 Latency Analysis

An all-encompassing model of the latency would have many components, such as the nodes processing capability, the number of hops in the link, the network size and topology, and the communication protocols. In multi-hop networks such as WSNs, a major latency component is the number of retransmissions. The effect in terms of end-to-end packet delay depends very much on how the network is designed to handle retransmissions. We will here model latency ( $L$ ) as *the number of transmissions to receive a successfully decoded packet*. This is, of course, a simplification, but it still provides an indication of how the different error control schemes perform in terms of latency. Apart from increasing latency, retransmissions may also have other negative effects such as contribution to congestion, which is a particular problem in networks, e.g., WSNs.

Since a retransmission occurs each time a packet is unrecoverable by the FEC, we can calculate the number of transmissions from the packet error probability,  $p_p$ . The probability of successfully transmitting a packet,  $p_s$ , on the  $i^{th}$  attempt is described by the *geometric probability distribution*

$$p_s = (1 - p_{p_j})p_{p_j}^{(i-1)} \quad (4.5)$$

from which the expected latency, i.e., number of transmissions, over hop  $h_j$  is given by, see (Spiegel, 1992),

$$E[L_j] = \frac{1}{1 - p_{p_j}}. \quad (4.6)$$

To calculate the expected number of transmissions end-to-end, say  $E[L_{tot}]$ , we add the expected values according to (4.6) for the different hop patterns. For example, for the case when we have three hops end-to-end we obtain a  $E[L_{tot}] = 3 * E[L_3]$ . For two hops  $E[L_{tot}] = E[L_2] + E[L_3]$  and so forth.

## 4.2 Energy Consumption Analysis

In this section we derive the energy consumption model that will be used. According to Section 2.2.4, the costs of the coding and decoding processes are assumed to be negligible in relation to other processing costs.

There is a risk of having an unsuccessful transmission, which would lead to a retransmission. Hence, the energy consumption ( $\mathcal{E}$ ) depends on the total number of transmissions, here referred to as the latency,  $L$ , needed to successfully transmit a packet. Additionally the energy consumption depends on the amount of time ( $t$ ) that the transmitter and the receiver need to be turned on for a single transmission. Accordingly, we can express the expected energy consumption over hop  $h_j$ , for a fixed transmit power, as

$$E[\mathcal{E}_j] = E[L_j](E[P_{TX}]t_{TX} + E[P_{RX}]t_{RX}) \quad (4.7)$$

where  $P_{TX}$  and  $P_{RX}$  are the total power consumed by the transmitting and receiving node respectively. Here  $t_{TX}$  and  $t_{RX}$  are the transmitting and receiving times respectively. To simplify the equation we assume  $t_{TX} = t_{RX} = t$ . Thus we can rewrite (4.7) as

$$E[\mathcal{E}_j] = E[L_j]E[P_{TX} + P_{RX}]t. \quad (4.8)$$

The approximation  $t_{TX} = t_{RX} = t$  is, of course, somewhat coarse since  $t_{TX} < t_{RX}$  in most scenarios. The reason is that the receiver must start to listen some time before the packet has actually reached the receiver. The amount of time spent listening before the packet arrives is, however, not dependent on the type of FEC code used. Therefore the approximation will only introduce a scaling factor i.e., a constant increase in energy expenditure, per transmission attempt.

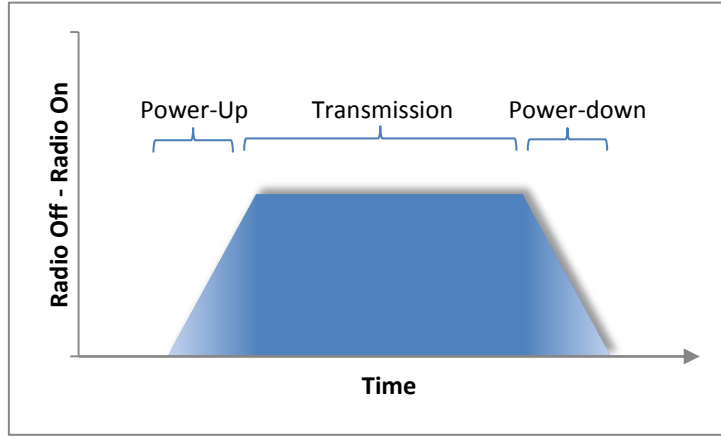


Figure 4.1: Illustration of a radio's on-time components.

Moreover, if we neglect the time needed for power-up and power-down of the radios, illustrated in Figure 4.1, we can express  $t$  in terms of the number of bits in a transmitted packet multiplied by the time needed to transmit a single bit ( $t_b$ ). As mentioned in Section 2.1, the packet is required to contain some overhead needed for synchronization, which is never coded. The number of bits in a packet is thus the sum of the coded message and the overhead. Let  $m$  be the message length, and  $m_{oh}$  the length of the overhead. Then, for a FEC code with modified code rate  $R_c^*$ <sup>7</sup>, we can express  $t$  as

$$t = (R_c^*m + m_{oh})t_b \quad (4.9)$$

where the modified code rate,  $R_c^*$ , is given by

$$R_c^* = \frac{m}{n * w} \quad (4.10)$$

where  $n$  is the length of a code word for a specific FEC code and  $w$  is the number of code words, see Section 4. Note that, for uncoded transmission  $R_c^* = 1$ .

We do not aim to make an energy consumption analysis for a specific radio, but rather a general comparison of the performance of the two error control schemes, ARQ and Hybrid-ARQ-Adaptive-FEC. Therefore, we can normalize equation (4.8) with the energy consumption for a single-hop, single-transmission of an uncoded packet ( $E[P_{TX} + P_{RX}](m + m_{oh})t_b$ ), which in combination with Equation (4.9) yields

$$E[E_j] = E[L_j] \frac{m/R_c^* + m_{oh}}{m + m_{oh}} \quad (4.11)$$

<sup>7</sup> The code rate is modified to reflect the increase in packet size when the length of the message is not evenly divisible with the length of a specific FEC code's uncoded word, and thus needs padding.



where  $E[E_j]$  now is the expected value of the *normalized* energy consumption,  $E_j$ , over hop  $h_j$ . Finally, the expected energy consumption end-to-end for each route is obtained as the summation of the expected values for each hop in the route, similarly to the expected total latency in Section 4.1.

## 5 Numerical Evaluation

In this section we will present the results of the numerical evaluation performed in MATLAB. It is based on the system model described in Section 3. The results will illustrate differences between ARQ and Hybrid-ARQ-Adaptive-FEC in terms of energy consumption, latency, and packet loss. For all results the code and routes are optimized with respect to energy efficiency. The parameters displayed in Table 5.1 are used for all numerical evaluations. The uncoded packet size,  $m$ , and overhead size,  $m_{oh}$ , are selected according to the packet structure of WirelessHART, see Section 2.1. The overhead is a 5-byte synchronization header (SHR), as seen in Figure 2.2. Since perfect sync is assumed this sequence will not affect the calculated PER, but it contributes to the required radio transmitter/receiver energy.

Table 5.1

Parameters			
$m$	512 bits	FEC	BCH $(n, k, t)$
$m_{oh}$	40 bits	Decoding	Hard
Path Loss	Log-distance	Channel	AWGN
$\gamma$	3	Modulation	O-QPSK
$\delta_1$	1/3	Assumptions	Perfect Sync
$\delta_2$	1/2		

The set of 70 BCH codes presented in Table 2.1 is used. The performance evaluation computes the normalized expected energy consumption,  $E[E_j]$ , as a function of the signal-to-noise ratio ( $SNR_3$ ), see (3.2), over the short hop  $h_3$ . In the sequel  $SNR_3$  is referred to as  $SNR$  for simplicity. In addition, Hybrid-ARQ-Adaptive-FEC is abbreviated as HAF in plot legends. The different modules used in the performance evaluation are depicted in Figure 5.1, and described next.

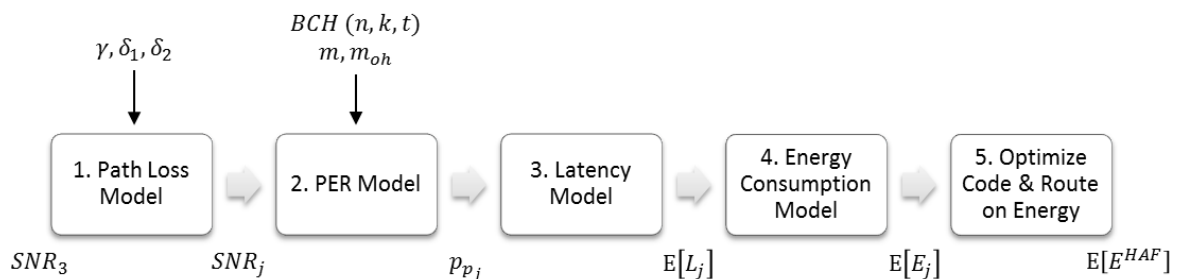


Figure 5.1: Block diagram illustrating the numerical evaluation, where  $E[E^{HAF}]$  represent the energy expenditure with optimized route and BCH code

- 1) The input  $SNR_3$  values, which correspond to the short hop  $h_3$ , is translated into  $SNR$  values for the two longer hops ( $SNR_2, SNR_1$ ), see Figure 3.1.
- 2) The packet error probability  $p_{p_j}$  is computed for all combinations of hops and BCH code rates, for example, see Figure 5.2 (a).

- 3) The expected latency  $E[L]$  in (4.6), is calculated for all combinations of hops and BCH code rates.
- 4) Based on the expected latency  $E[L]$ , the expected energy consumption (4.11) is calculated for all combinations of hops and BCH code rates, for example, see Figure 5.2 (b).
- 5) Considering the Hybrid-ARQ-Adaptive-FEC scheme, the optimal code rate and route combination with regard to energy efficiency is chosen for each  $SNR$  value. The same computation is performed for the ARQ scheme, but without codes, and the optimal route is chosen.

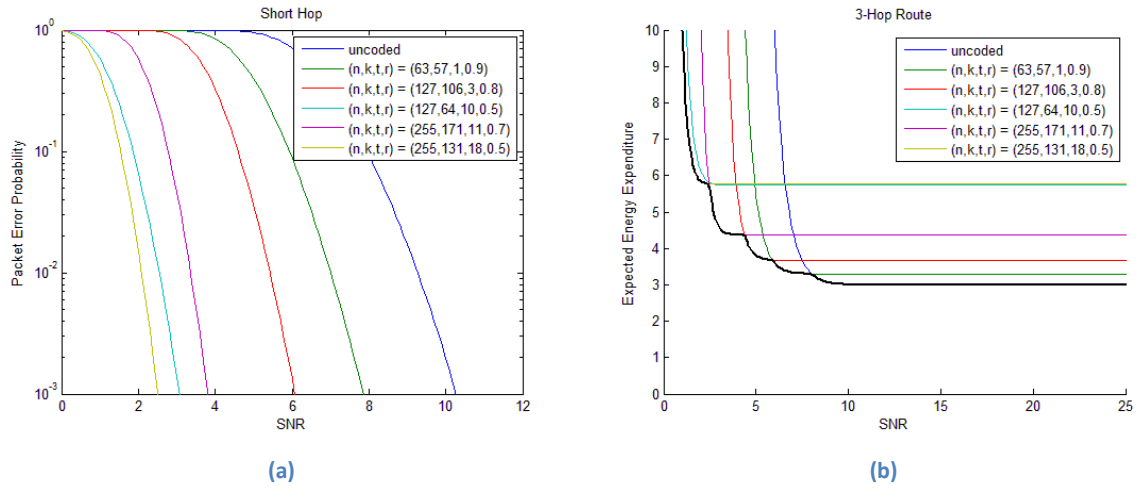


Figure 5.2: Illustrates how the (a) packet error probability, and the (b) expected energy consumption,  $E(E^{HAF})$ , varies between different codes and without coding. In (b), the black curve illustrates how the optimization selects the code that minimizes the energy consumption.

## 5.1 Energy Consumption

In Figure 5.3, the expected energy consumption of the ARQ and the Hybrid-ARQ-Adaptive-FEC schemes are depicted as a function of  $SNR$ . The bars above the figure represent the routes selected by the optimization for each scheme, and indicate at what  $SNR$  it is advantageous to hop. If we compare the bars for Hybrid-ARQ-Adaptive-FEC and ARQ we observe that, by adapting the code rate, Hybrid-ARQ-Adaptive-FEC only needs one hop down to a  $SNR \approx 16$  dB. For this  $SNR$  ARQ requires two hops. Yet Hybrid-ARQ-Adaptive-FEC is superior with respect to both energy expenditure and latency. While ARQ needs three hops from  $SNR \approx 16$  dB and downwards, Hybrid-ARQ-Adaptive-FEC will hop three times first at  $SNR \approx 11$  dB. In other words, we gain  $\sim 5$  dB by using Hybrid-ARQ-Adaptive-FEC instead of ARQ. The same holds for two hops.

The performance gain for Hybrid-ARQ-Adaptive-FEC ranges from 0 % to 100 % in the  $SNR$  intervals 21 dB – 16 dB and 16 dB – 11 dB, respectively. For the latency, the gain is one transmission in the same intervals, see Figure 5.5. Furthermore, the code rate curve illustrates which codes are used for the Hybrid-ARQ-Adaptive-FEC scheme. Note that in the center-region, where the two-hop route is used, the code rate curve represents the code rate applied at the longer of the two hops, i.e.  $h_2$ . In this region it is optimal not to use coding for the shorter hop  $h_3$ . From Figure 5.3 we also note that, the energy consumption of Hybrid-ARQ-Adaptive-FEC is never greater than that of ARQ. However, for bad channels, with  $SNR < 7.5$  dB, we note that Hybrid-ARQ-Adaptive-FEC dramatically outperforms ARQ, and for  $SNR < 6$  dB the energy consumption of ARQ reaches extreme values due to too many retransmissions.

In Figure 5.4 the variability in energy expenditure is illustrated by the 95<sup>th</sup> percentile. Clearly the variability in expected energy consumption is significantly larger for ARQ than for Hybrid-ARQ-Adaptive-FEC. Additionally, through the numerical evaluations we, have seen that the 75<sup>th</sup> percentile does not exceed the expectation values for any of the plotted *SNRs*.

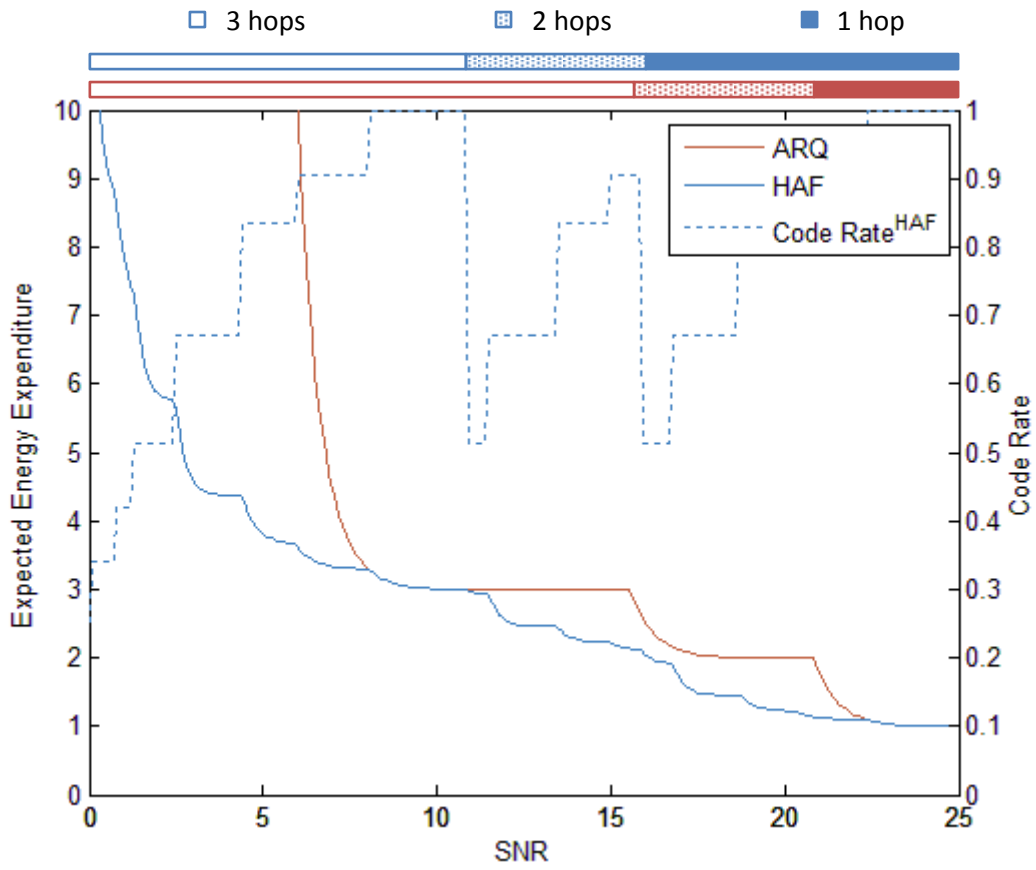


Figure 5.3: Expected energy consumption versus  $SNR$ . Energy Consumption is normalized to that of a single-hop, single-transmission for an uncoded packet.

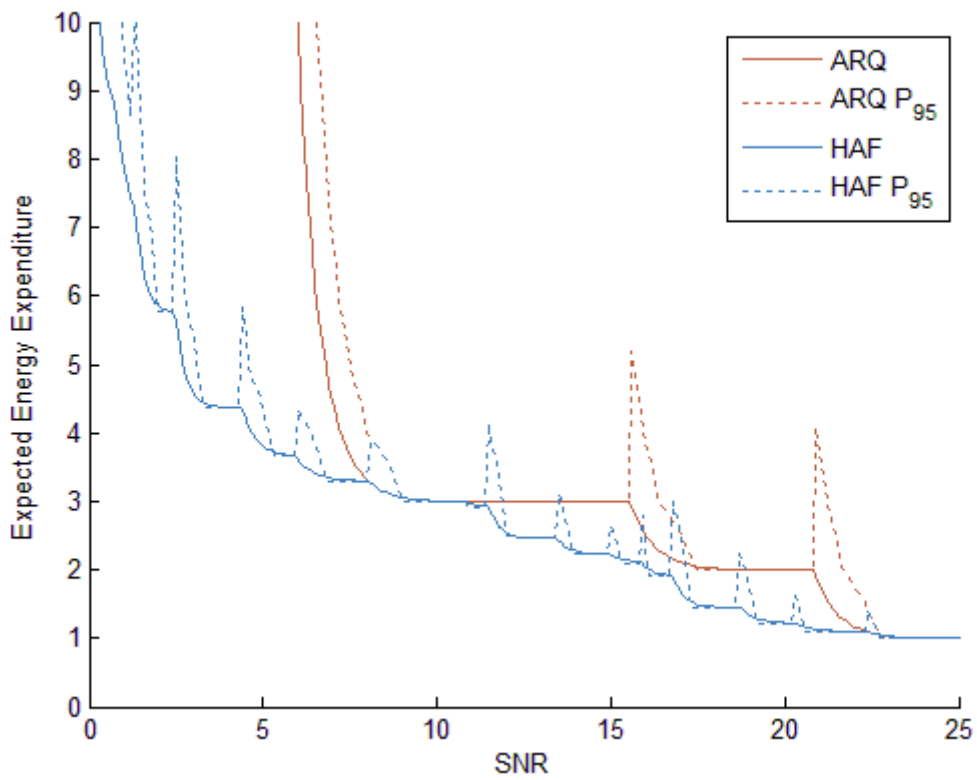


Figure 5.4: Illustrates the spread of the energy consumption via the 95<sup>th</sup> percentile.

## 5.2 Latency

In Figure 5.5 the expected latency is seen as a function of received  $SNR$ , where latency is defined as the total number of end-to-end transmissions, including retransmissions. Note that codes and routes are optimized on energy efficiency. Latency, depicted here, is a consequence of this optimization. The expected latency in Figure 5.5 shows a similar behavior as the expected energy in Figure 5.3. We note that Hybrid-ARQ-Adaptive-FEC outperforms ARQ in terms of latency for a wide range of  $SNRs$ . As also seen in Figure 5.3 the ARQ scheme cannot handle  $SNR < 6 \text{ dB}$ , while Hybrid-ARQ-Adaptive-FEC can cope with a latency of less than four transmissions end-to-end for  $SNR > 0.4 \text{ dB}$ . The two drastic changes in code rate, that appear at around  $11 \text{ dB}$  and  $16 \text{ dB}$ , corresponds to a switch in route. Moreover, the peaks in the Hybrid-ARQ-Adaptive-FEC curve are due to a higher expectancy of retransmissions. The results confirm what is intuitive, that more powerful codes are used for channels with lower  $SNRs$ .

Moreover, if we follow the Hybrid-ARQ-Adaptive-FEC curve from right to left, meaning a decreasing channel quality, and we bear in mind that the results are optimized on energy efficiency, we observe how the Hybrid-ARQ-Adaptive-FEC scheme suppresses the number of retransmissions by utilizing increasingly more powerful codes, until it reaches a breakpoint where it is more energy efficient to use a route with more hops. Observe that the peaks in the latency curve correspond to a change in code rate. This suggests that the cost, in terms of energy, that are added by the use of FEC codes, are less than the cost of retransmissions.

In Figure 5.6 the variability is illustrated by the 95<sup>th</sup> percentile. The behavior is similar to that in Figure 5.4. Note, however, that the largest variability in the number of transmissions for Hybrid-ARQ-Adaptive-FEC coincides with the peaks in the expected latency curve for Hybrid-ARQ-Adaptive-FEC. Additionally, through the numerical evaluations we have seen that if the 75<sup>th</sup> percentile is used, then no significant variability can be observed.

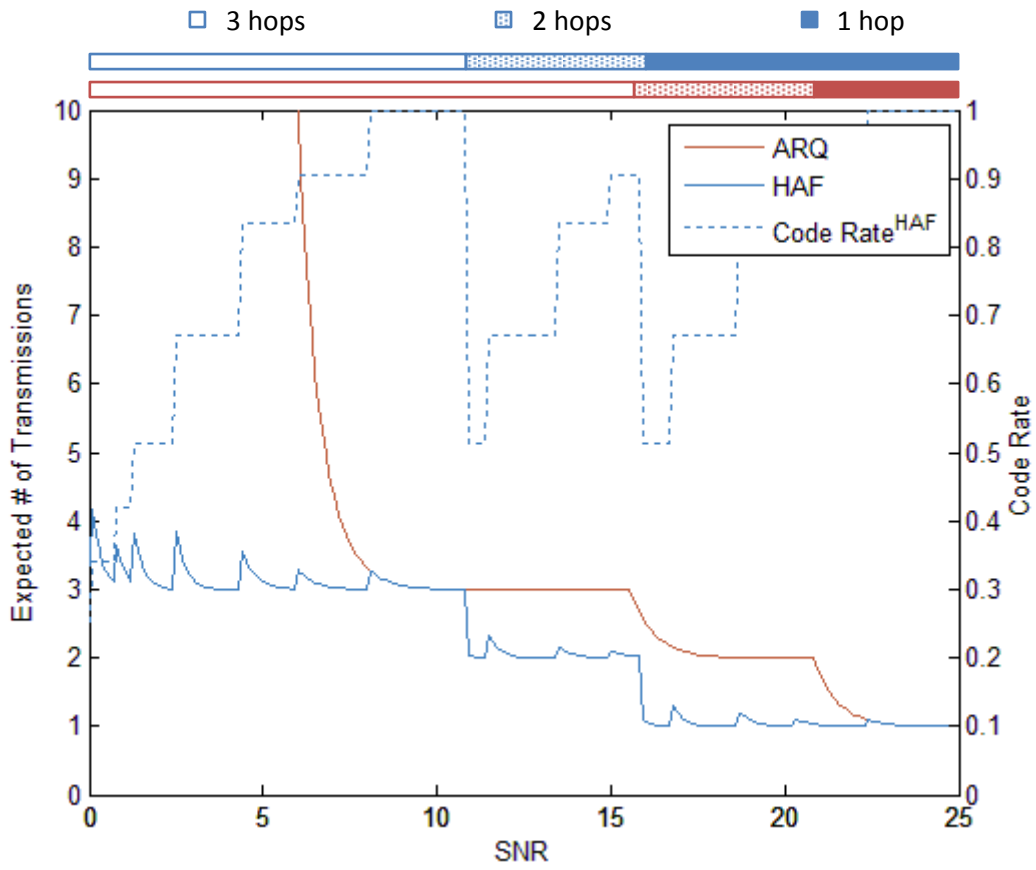


Figure 5.5: Expected latency versus  $SNR$ . Latency is defined as the number of transmissions end-to-end, including retransmissions.

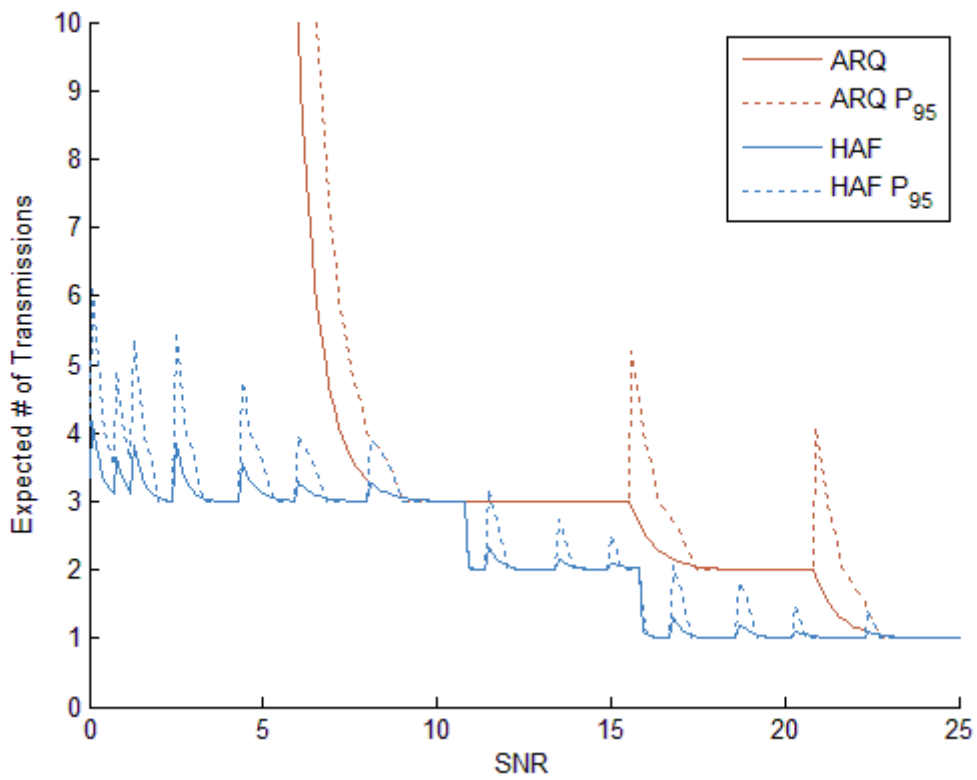


Figure 5.6: Illustrates the spread of the latency via the 95th percentile.

### 5.3 Constraint on Latency

In the results, presented so far, both schemes are set to optimize with respect to energy efficiency. For ARQ this means selecting the optimal route, whereas for Hybrid-ARQ-Adaptive-FEC it means choosing the optimal combination of code and route. In Figure 5.7 and Figure 5.8 we illustrate the performance of the two schemes, when constraints are laid on the latency. Here, we still optimize on energy efficiency, but now with the condition that the 99<sup>th</sup> percentile for the latency never should exceed one retransmission. Looking from right to left in Figure 5.7 we observe that ARQ is forced to switch to the routes with more hops sooner than was the case in Figure 5.5, and finally it collapses at around 8 *dB*. Interestingly, the Hybrid-ARQ-Adaptive-FEC applies more powerful codes to adapt to the constraint, and, at the cost of a minor increase in energy consumption, the hop switch points are hardly affected. This is a very attractive feature of Hybrid-ARQ-Adaptive-FEC.

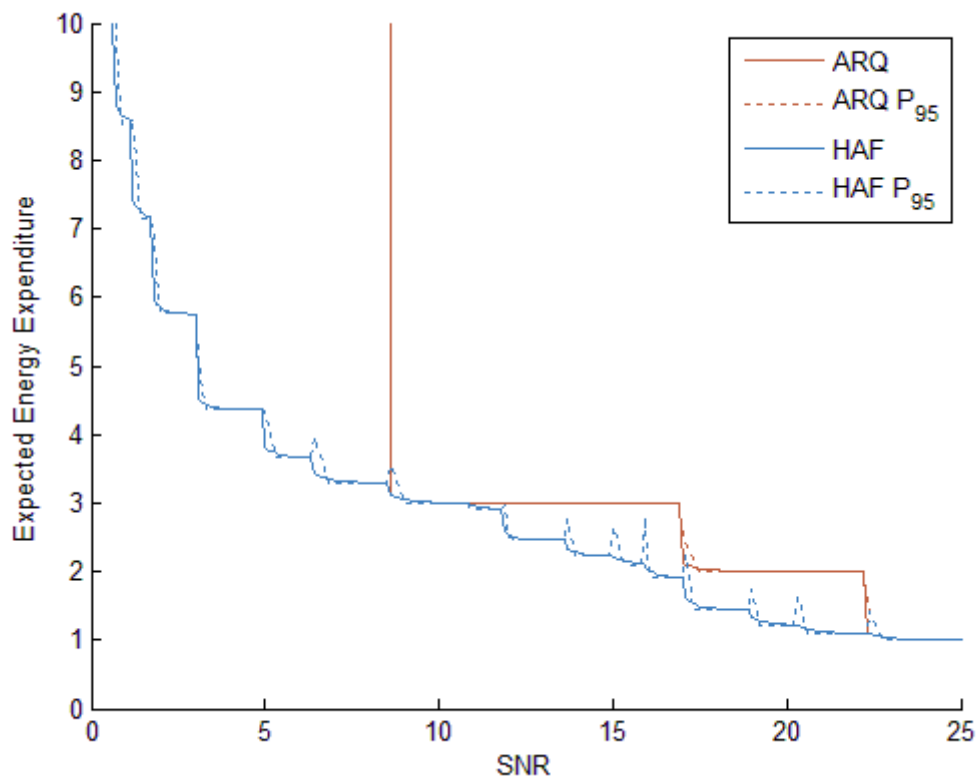


Figure 5.7: Expected energy consumption with a constraint that the 99<sup>th</sup> percentile for the latency cannot exceed one retransmission.

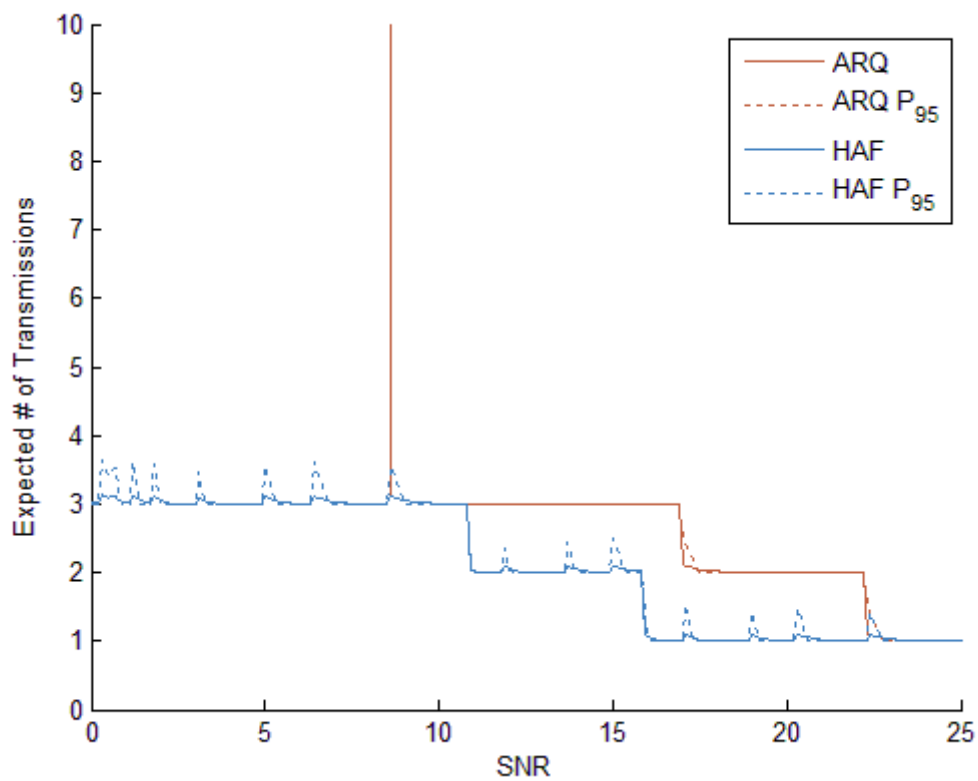


Figure 5.8: Expected latency with a constraint that the 99<sup>th</sup> percentile for the latency cannot exceed one retransmission.



## 5.4 Fading Channels

The fading channel used here is from a paper mill environment, see Section 1.2, where a measurement campaign was conducted. The channel is depicted in Figure 5.9, normalized at 0 dB. It resembles a Rayleigh fading channel.

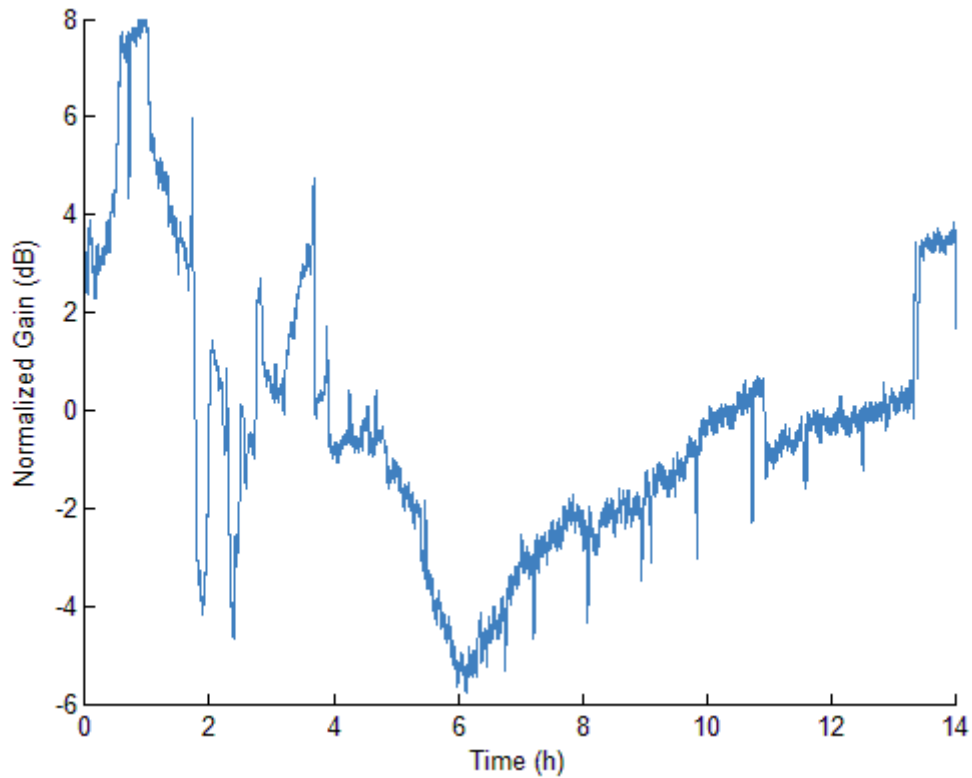


Figure 5.9: Fading channel from a radio channel measurement campaign conducted at a paper mill in Sweden.

Packets were transmitted to a number of sensor nodes, distributed in the paper mill. Each node logged the received signal strength over a time span of 14 hours. Here, the gain is defined as signal strength over transmitted power. Some nodes indicated worse channels than others, and the channel used in this evaluation represents a typical medium condition channel. From Figure 5.9 the gain distribution was computed, see Figure 5.10

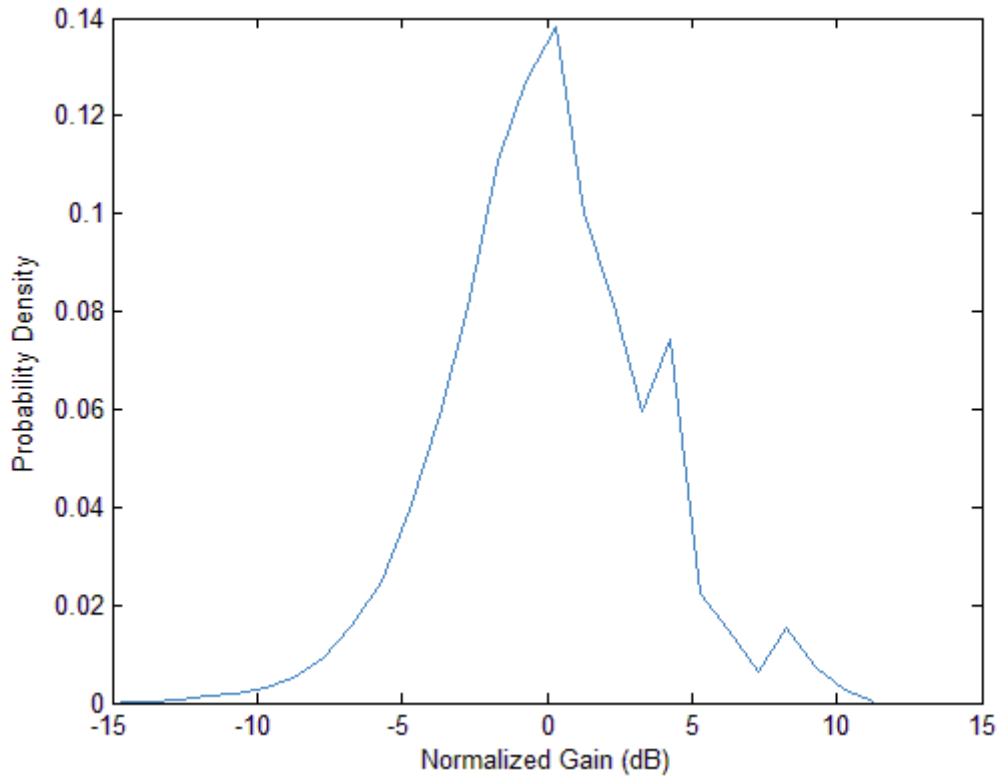


Figure 5.10: The probability density function of the normalized channel gain.

In this comparison we have put the latency constraint to be  $\leq 3$  on the total number of retransmissions. The energy curves for the fading scenario are averaged over the fading distribution in Figure 5.10. In Figure 5.11 and Figure 5.12 we compare the expected energy and packet loss probability for an AWGN and a fading scenario. If we compare ARQ for AWGN and fading channels we note that the packet loss probability starts increasing from almost zero at  $\sim 8$  dB in the AWGN case whereas this happens at  $\sim 17$  dB in the fading case. The corresponding SNRs for the Hybrid-ARQ-Adaptive-FEC case are  $\sim 1$  dB and  $\sim 10$  dB, respectively. In other words, we lose some 9 dB due to the fading environment. Further, if we compare the performance for the expected energy in the interval [1 – 7] (packet loss probabilities in the interval [0.1 – 0.7]) we have a gain in SNR of  $\sim 6$  dB for Hybrid-ARQ-Adaptive-FEC in comparison to ARQ for the AWGN case. The gain is 5 dB in the fading case. It is also worth noting that the expected energy expenditure for Hybrid-ARQ-Adaptive-FEC in the SNR interval [0 – 9] dB of the fading case is higher than the corresponding figures for the ARQ case. This is however due to the fact that Hybrid-ARQ-Adaptive-FEC uses increasingly lower code rates to keep the packet loss low. Compare, for example, the fading case at SNR = 7 dB. Then Hybrid-ARQ-Adaptive-FEC has an expected energy expenditure which is  $\sim 15$  % higher than ARQ but the packet loss probability for ARQ is 0.6 whereas it is 0.05 for Hybrid-ARQ-Adaptive-FEC. Another point of interest in the fading case is at SNR = 9 dB when ARQ and Hybrid-ARQ-Adaptive-FEC have the same energy expenditure. Then the packet loss probability is 0.3 for ARQ whereas it is almost zero in the Hybrid-ARQ-Adaptive-FEC case. This comparison shows the power of Hybrid-ARQ-Adaptive-FEC in comparison to ARQ also in the fading case.

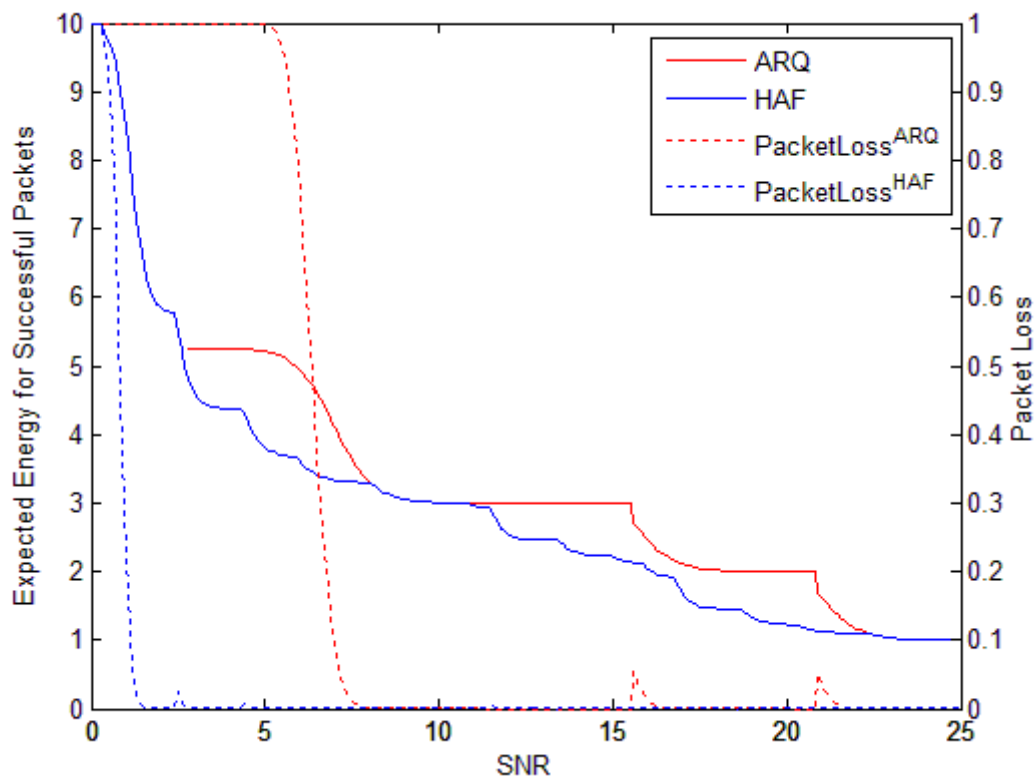


Figure 5.11: Expected energy consumption for successful packets and packet loss probability are depicted, for an AWGN channel.

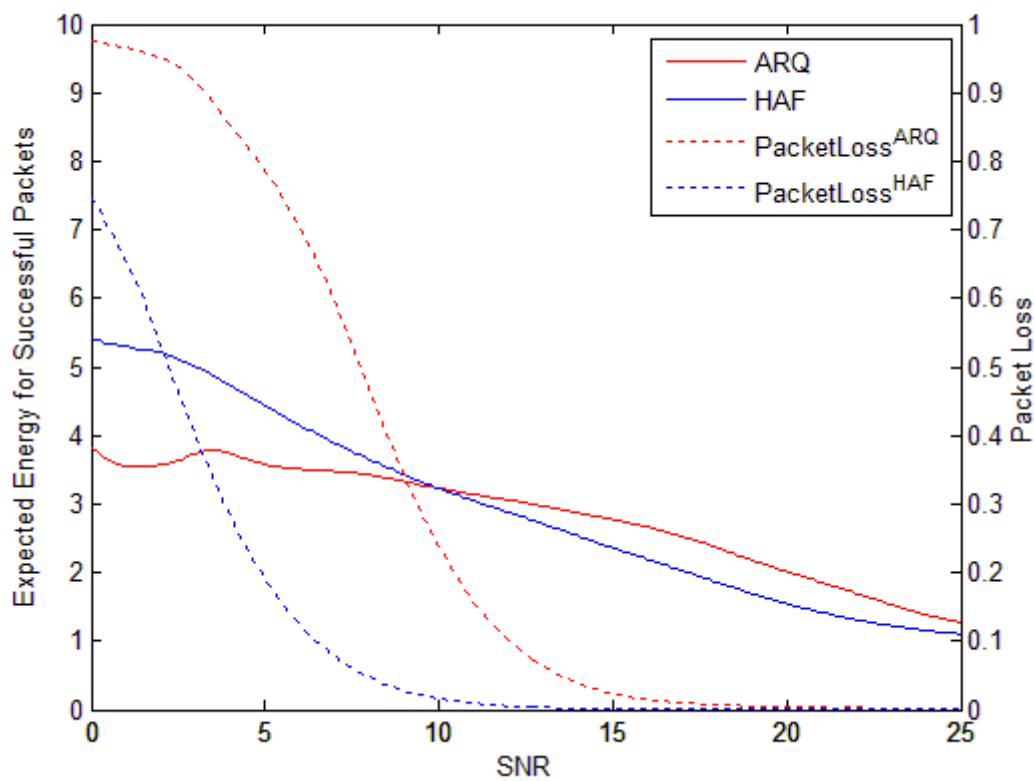


Figure 5.12: Expected energy consumption for successful packets and packet loss probability are depicted for a fading channel from an industrial site.

## 6 Discussion and Conclusions

We have shown that Hybrid-ARQ-Adaptive-FEC shows significant advantages in comparison to ARQ in terms of expected energy expenditure, latency, and packet loss.

Overall, the Hybrid-ARQ-Adaptive-FEC has less energy expenditure compared to ARQ. In certain regions of SNR the improvement is as much as  $\sim 4$  dB, with equivalent energy consumption for both schemes. There is a trade-off between the energy expenditure and minimizing the number of hops. This trade-off limit is reduced by 5 – 6 dB with Hybrid-ARQ-Adaptive-FEC compared to ARQ. In other words, with equal constraints on energy consumption, Hybrid-ARQ-Adaptive-FEC is able to use less hops. The Hybrid-ARQ-Adaptive-FEC scheme is also able to sustain acceptable packet error rates when channel conditions are worsened by 6dB compared to the ARQ case.

This suggests that if CSI can be fed back from receiving nodes, then it would be very attractive to use Hybrid-ARQ-Adaptive-FEC, or any similar adaptive coding scheme. A possible way to benefit from the use of Hybrid-ARQ-Adaptive-FEC in a process control scenario would be to e.g., include CSI in the ACK-packets of WirelessHART. This is under current investigation.

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