ENERGY EFFICIENT RELAY SELECTION SCHEMES FOR COOPERATIVE UNIFORMLY DISTRIBUTED WIRELESS SENSOR NETWORKS

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Abstract

Energy Efficient Relay Selection Schemes For Cooperative Uniformly Distributed Wireless Sensor Networks

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Wireless sensor networks (WSNs) are commonly used in many applications. The energy efficiency of the system has become the subject of extensive research lately. In this thesis we will introduce relay selection schemes that attempt to optimize the transmission of data. We use a two phase WSN model where a message is broadcasted from the source then relayed by the overhearing sensors (nodes) to a fusion center (FC). These schemes will reduce the number of bits transmitted from the sensors to the destination as well as minimize the activity of these sensors and lead to a more energy efficient system. The main idea is to have the smallest subset of sensors that contain the entire information relay the message; in an ideal situation the subset will only contain a pair of sensors.

We then investigate the addition of error correcting codes (ECCs) to the node-FC channels. We observe the outage probability of the relay selection schemes using turbo codes on the node-FC channels. We also examine the expected number of bits (including extra parity bits) in the transmissions. We show that under certain channel conditions introducing turbo codes to the node-FC channels leads to longer sensor lifetimes.

Acknowledgments

I would like to start by thanking my supervisor Dr. Walaa Hamouda whose guidance in the past two years was pivotal to my work. Dr. Hamouda's advice was invaluable, he helped me with the selection of my courses and fueled my interest in communications and networks. He was there every step of the way pushing me and encouraging me in my research.

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Nomenclature

AF	amplify-and-forward
BuEC	burst erasure channel
CC	convolutional code
CSI	channel state information
DFT	discrete fourier transform
DTC	distributed turbo code
ECC	error correcting code
FC	fusion center
FSK	frequency shift keying
MAC	medium access control
pdf	probability density function
PPM	pulse position modulation
SNR	signal to noise ratio
WSN	wireless sensor network

1 Introduction

1.1 Wireless sensor networks

A wireless sensor network (WSN) is a collection of sensors (also called nodes) distributed in an area that communicate in short distances. WSNs can monitor physical or environmental conditions such as temperature, sound, pressure etc. and relay the data to a main location [1]. The use of relays in these networks provides the benefit of having short-range communication as opposed to long-range communication which is generally more expensive. More recently these networks have become bi-directional, so as to enable the destination to control sensor activity such as which nodes to relay information. The WSN may consist of thousands of sensors; the main components of these sensors are a radio transceiver with an antenna to be able to receive data and forward it through the channel, a micro controller to control the actions of the sensor and an energy source such as a battery.

Nowadays WSNs are widely used in many applications and industries. They are employed in field trials and performance monitoring of solar panels [2], in target detection through digital cameras [3], in the petrochemical industry field [4] etc.

In a WSN the constraints on the sensors are memory, computational speed, communications bandwidth and most importantly energy. The main challenge for WSNs is the energy constraints on the network. The sensors are powered by batteries and replacing these batteries is extremely difficult if not impossible in most cases (reasons range from location of these sensors to steep cost of replacing the batteries). Much of research is being done on low power dissipation communication protocols that can increase the lifetime of the network while achieving minimum symbol error at the destination. In [5–16] relay selection protocols are introduced that pick a single node to transmit to destination. In [5] the selection is based on geographical information; in [6] the closest relay to destination is selected to transmit. In [7, 8] a "best" relay is chosen based on the source-node and node-destination channels and both source and relay transmit without any power considerations. In [9, 12–14] a best relay is again chosen to transmit along with the source but transmission power is divided between the two in a way that optimizes transmission performance. Having a single node relay the message saves on bandwidth and energy but the tradeoff will come when we look at the symbol error rate at the destination. In large wireless sensor networks the signal experiences fading in the channels and the message is not always received correctly at the destination. One of the methods to combat this is by having multiple nodes cooperate to transmit the message providing spacial diversity [17–19]. It is shown in [16] that multiple relay selection schemes perform much better than their corresponding single relay selection schemes. The question then arises how many nodes should transmit and how to select them considering the energy constraints on the sensors. A variety of schemes have been introduced based on different perspectives [16–28]; some take advantage of the static topology of the network, others attempt to maximize signal to noise ratio (SNR) and some use Amplify-and-Forward (AF) to send the data.

1.2 Motivation

The use of relay cooperation has been shown to provide spacial diversity and reduce the error rate and number of retransmissions of the message. This comes at the price of having multiple nodes active and therefore a higher level of power consumption. A sensor node consumes power for sensing, data processing and communication. The main source of consumption is the data communication. According to [29] one bit transmitted in WSNs consumes about as much power as executing 800 to 1000 instructions. This presents a challenge of selecting the appropriate number of nodes to relay the message in order to minimize the number of bits transmitted. The topic of relay selection has been the center of a lot of research recently, and the range of possibilities are very wide. The reasons behind our focus on these problems are as follows.

1.2.1 Relay selection

Relay selection aims at having less active nodes and as a result less information transmitted in the network while still delivering the message to the destination. Most schemes choose the relays based on the SNR in the channels. On the other hand our selection schemes will focus more on minimizing power consumption without compromising on message delivery. Therefore investigating the outage probability under different channel conditions and examining it's effect on the activity of the nodes is an important issue to tackle. Another related topic of interest is the number of bits being transmitted by the relays to the destination.

1.2.2 Incorporating turbo codes to the transmission

The purpose of turbo codes is to detect, and correct errors in the transmission. Therefore adding error correcting capability to the network will lead to a more reliable communication but at the cost of extra redundant information being sent out. As a result, investigating the affect of turbo codes on the outage probability and consequently the node activity in the channels is a key matter. Also looking at the increase in information being sent through the channels caused by the redundant bits being sent for error detection and correction motivates us to investigate the tradeoff between additional transmitted bits and node activity.

1.3 Summary of contributions

The thesis is split into two main chapters, we first introduce the relay selection schemes where a subset of the nodes in the network will be selected by the fusion center (FC) to transmit. For simplicity we start by assuming that the node-FC channels are perfect. We run simulations for outage probability and expected number of bits transmitted and compare the results for the different schemes and to a widely used scheme where all nodes transmit. We show that using our schemes will prolong the lifetime of the sensors. Finally we show that even without the initial assumption of perfect node-FC channels, we still achieve energy savings in the sensor nodes.

In the second part we introduce error correcting codes to the node-FC channels. We present the new outage probabilities and expected number of bits transmitted while using turbo codes on the node-FC channels. We compare the results to those of the uncoded model and show that under certain channel conditions using turbo codes leads to high energy savings.

The contributions are summarized as follows:

- We introduce three selection schemes that will attempt to minimize the number of bits transmitted and the number of active nodes in the network while insuring the reception of the message error free at the destination.
- We compare these schemes for different channels (Burst erasure channels (BuEC) and Rayleigh fading channels) under various conditions.

- We derive the analytical results for outage probability and expected number of bits transmitted using our first scheme (Fixed pairs, which selects a predefined pair of nodes to relay the message). We compare these results to the ones we obtained from simulation and show their accuracy.
- We show how the reduced number of bits transmitted in our schemes translates to energy savings on the sensor nodes.
- We introduce error correcting codes (turbo codes) to the node-FC channels. We show how under certain conditions they will significantly reduce the expected number of bits transmitted and prolong sensor lifetimes.

- We introduce a technique that allows the destination to pick the constraint length of the code. We show that using only the channel state information (CSI), the FC can pick the appropriate code.

1.4 Thesis overview

The thesis is arranged as follows, in chapter 2 background information on material used in the thesis is provided.

In chapter 3, we introduce the relay selection schemes used in our WSN. We compare results and investigate the performance of these schemes for different channels and under different conditions. An analytical derivation of outage probability and expected number of bits transmitted is then presented. We then illustrate the energy savings in the network resulting from our schemes.

In chapter 4, we investigate the pros and cons of adding error correcting codes (turbo codes) to the node-FC channels. We look at the tradeoff between outage probability and the additional parity (extra) bits. We show under which conditions it will be much more efficient to use turbo codes. We also show how the destination can select the appropriate code based on the information it has on the node-FC channels.

2 Background Information

2.1 Wireless sensor network and energy efficiency

As previously stated energy efficiency in wireless sensor networks is an area of particular interest. Research is being done on relay selection to reduce the energy consumption in these networks. But a great deal of work is being done on every level to try and increase the lifetime of the sensors. In [30] the possibility of recharging sensor nodes is discussed, and its role in energy efficiency in a WSN is highlighted.

At the hardware level, design of microprocessors such as ATmega [31] which are used in WSN sensors provide different power saving modes (idle, power down, power save, ADC noise reduction, standby and extended standby). Other communication subsystems like CC1000 [32] and CC2420 [33] also provide power saving modes such as power down, power save and power off.

On the Data Link layer, in [34] an optimal packet size for data communication is determined. It is based on energy efficiency rather than throughput and is shown to increase the lifetime of the network. On the medium access control (MAC) layer, work has been done on finding a sensor MAC protocol based on an optimal frame size that saves on sensor energy [35].

In [36] a cross layer design for WSNs is introduced based on frequency shift keying (FSK) and pulse position modulation (PPM). It is shown to minimize energy consumption over multiple layers (physical layer, link layer and MAC layer)

The topic of error correcting codes in WSNs has been one of great interest lately. ECCs can reduce the number of retransmissions required. In [37] the authors investigate the role that ECCs play in the route diversity of a WSN. in [38] a new framework for distributed turbo encoding and decoding with parallel concatenation is developed. It is shown to have large coding gains under the assumption of correlated data received from the source.

Another issue addressed in several recent works is whether to encode at the source or at the sensor nodes; whether to decode at the fusion center or have a soft decoding and re-encode at the intermediate nodes. In [39] a new signal processing scheme referred to as decode-compress-and-forward is introduced where turbo coding is applied at both source and relay nodes. The scheme is shown to have better error rate performance than a widely used scheme (amplify-and-forward) for high channel gains. In [40] a turbo code technique based on parallel concatenation is presented. In this technique the message is encoded at the source, sent to the sensor nodes where soft decoding and re-encoding is applied then relayed to the destination. the procedure is shown to provide reliability in the communication while still being energy efficient.

2.2 Network model

One of the benefits of using intermediate nodes to relay information is the shorter transmission distances which lead to a reduced signal transmit power [41–44] and less errors in the channels. Another benefit is the ability for nodes to cooperate in sending data to the destination.

There are several models for WSNs, in [45, 46] a cluster-based model is proposed where the nodes in a cluster transmit to the cluster head (specific node). The cluster head then delivers the data to a base station. In [47] a new clustering approach is proposed where the cluster heads replacement times are reduced, therefore avoiding excessive energy consumption.

In some studies [48], researchers have claimed that multi-hop network implementations for WSNs are more energy efficient than their single-hop counterparts. But in more recent works [49–51], it is shown that the single-hop implementations consume less energy.

In this thesis we will use a two phase, single-hop model of a WSN. In our model the source broadcasts to multiple sensors which in turn relay the information to the destination (FC).

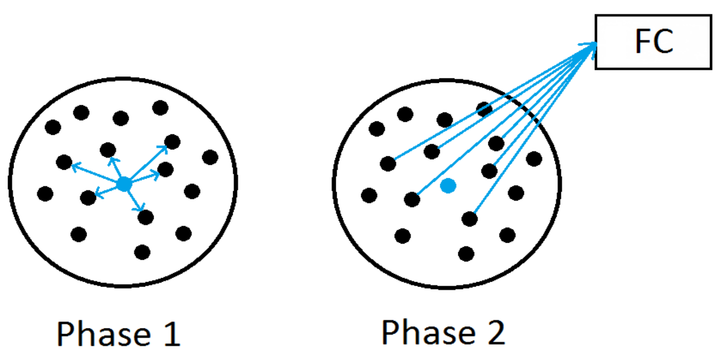

Figure 2.1: Two phase wireless sensor network

We consider a two phase wireless sensor network with no direct source-destination link (Figure 2.1). Communication can only be done through aid of relaying nodes. The source broadcasts its message on the channels and the nodes overhear a noisy version of the message. Upon receiving the message the nodes encode their channel state information (CSI) by a run length code then transmit to the destination. The information needed by the FC to pick the nodes is simply what part of the message each node has received error free. Therefore the run length code sends the position sequences of error free bits to the FC. Using this information the FC will be capable of selecting the appropriate nodes to transmit the entire message.

2.3 Fading channels

There are different models for signal propagation in a wireless network such as Rayleigh fading, Rician fading and others. The most common model for wireless devices with no line of sight is the Rayleigh fading model. This model assumes that the magnitude of the signal passing through the channels varies according to a Rayleigh distribution.

A Rayleigh distribution is a continuous probability distribution, it is the sum of two uncorrelated Gaussian random variables. The Gaussian (normal) distribution probability density function (pdf) is

$$f\left(x\right) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}, \tag{2.1}$$

where μ is the mean and σ^2 is the variance.

The Rayleigh distribution pdf is

$$f\left(x;\sigma\right) = \frac{1}{\sigma^2} e^{-\frac{x^2}{2\sigma^2}}, \tag{2.2}$$

with $x \geq 0$ and where σ^2 is the variance.

2.4 Burst erasure channel (BuEC)

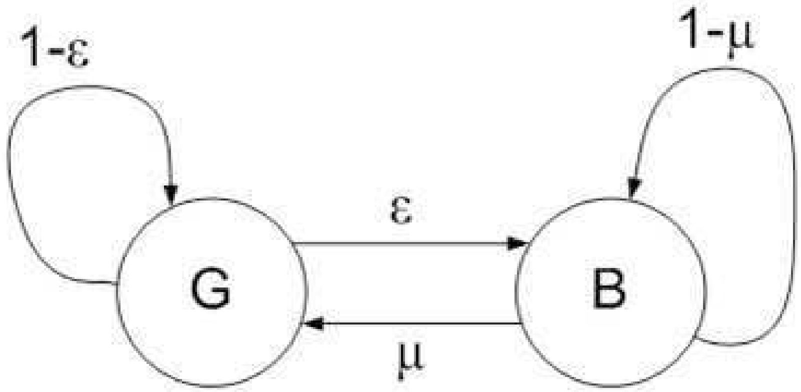

Figure 2.2: Burst erasure channel model

The Gilbert Elliot channel model (Figure 2.2) is a simple model for fading channels. It has a good state when the signal to noise ratio (SNR) in the channel is very high and a bad state when the SNR is very low. The probability of going from good state to bad state is ϵ and the probability of going from bad state to good state is μ. The BuEC is a special case of this model where we assume that the SNR is high in good state and therefore the bit is always received correctly and low in bad state therefore the bit is flagged as erasure. The BuEC can be shown to be a surrogate model to Rayleigh fading channels [52].

Figure 2.3 shows a realization of 6 source-node burst erasure channels with parameters $\epsilon = 5 \times 10^{-4}$and $\mu = 3 \times 10^{-3}$.

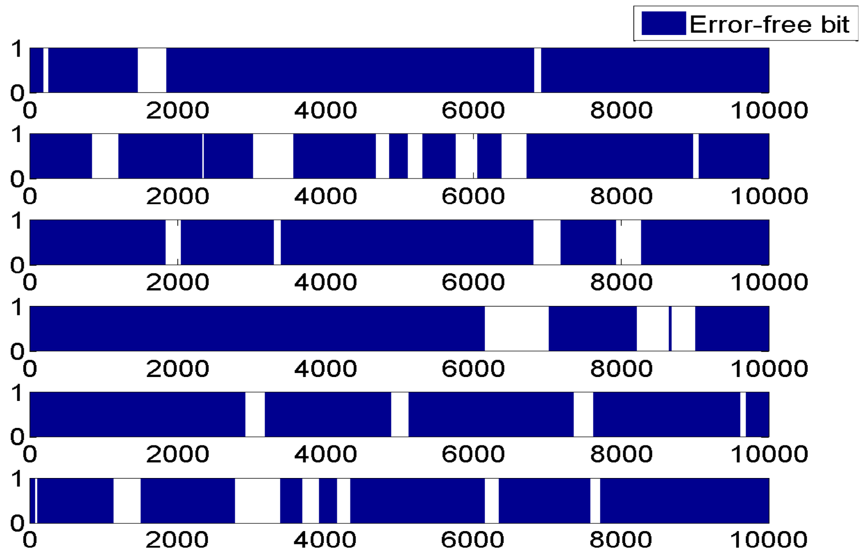

Figure 2.3: One realization of independent burst erasure channels for 6 source-node links

We notice from Figure 2.3 that none of the nodes receive all the bits error free from the source. We also notice that different combinations (subsets) of nodes can provide the FC with the entire message.

2.5 Error correcting codes

In the second part of the thesis we will use error correcting codes (ECC) on the node-FC channels. ECCs are distinguished between block codes which work on a block by block basis and convolutional code which work on a bit by bit basis. For the same complexity it is known that convolutional codes perform better than block codes.

2.5.1 Turbo codes

A turbo code is a high performance ECC, it is constituted of multiple convolutional codes (CC). Turbo codes are mainly distinguished between serial concatenation and parallel concatenation. The latter replaced serial concatenation since for the same performance we get a higher rate from the parallel concatenation.

2.5.1.1 Encoding turbo codes

The turbo encoder is made up of two identical CCs (with rate r) and an interleaver (Figure 2.4). The interleaver before the second convolutional code will make the bits appear in a different sequence providing better error correction capability.

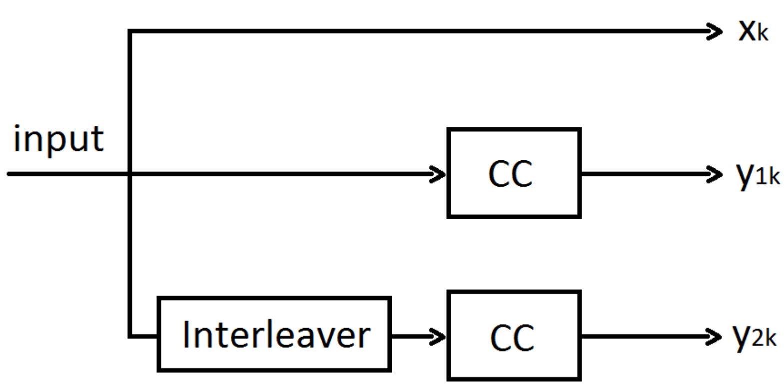

Figure 2.4: Parallel turbo encoder

The output of the encoder is constituted of the input bits x_k and the parity bits from the two CCs y_k. In order to determine the rate of the code we need to find the number of output bits. y_{1k} and y_{2k} are the outputs from each of the two CCs and are made up of only the parity bits that the CC yields

$$y_{1k} = y_{2k} = \frac{x_k}{r} - x_k = x_k \left(\frac{1}{r} - 1 \right), \tag{2.3}$$

$$y_k = y_{1k} + y_{2k} = 2x_k \left(\frac{1}{r} - 1 \right). \tag{2.4}$$

The rate of the code is simply the number of input bits divided by the total number of output bits, using (2.4) we get

$$\begin{aligned} r_t &= \frac{x_k}{x_k + y_k} \\ &= \frac{x_k}{x_k + 2x_k \left(\frac{1}{r} - 1 \right)} \\ &= \frac{1}{1 + \frac{2-2r}{r}} \\ &= \frac{r}{2-r}. \end{aligned} \tag{2.5}$$

As an example if we have rate $r = \frac{1}{2}$ CCs the rate of the turbo code will be

$$r_t = \frac{\frac{1}{2}}{2 - \frac{1}{2}} = \frac{1}{3}.$$

2.5.1.2 Decoding turbo codes

Below is a turbo decoder for the encoder shown in Figure 2.4.

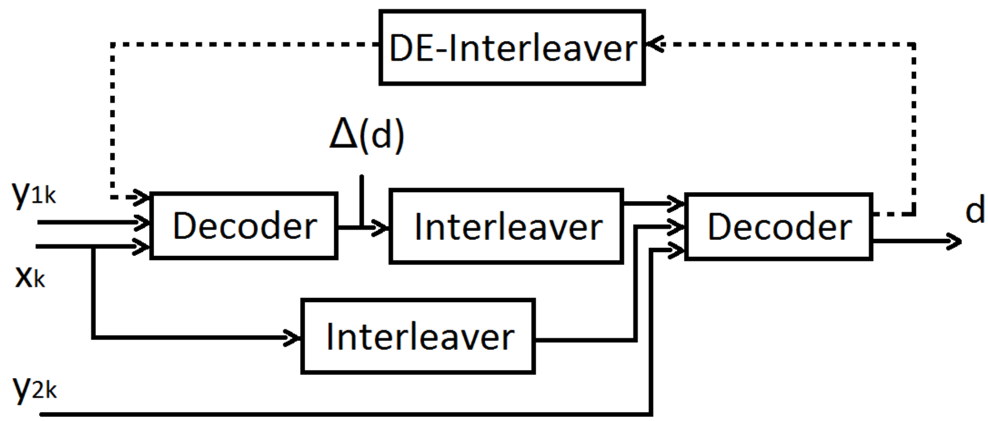

Figure 2.5: Turbo decoder

The turbo decoder shown in Figure 2.5 is comprised of 2 convolutional decoders and the same interleaver as the one in the turbo encoder. The first decoder is intended for the first encoder and therefore takes as input the original bits x_k and the parity bits from the first CC y_{1k}. The output of the first encoder is a soft decision output meaning that it gives the log likelihood of a 0 or 1

$$\Delta\left(d\right) = log\frac{p\left(d=1\right)}{p\left(d=0\right)}. \tag{2.6}$$

This output is then past through the interleaver and input along with the parity bits from the second CC (y_{2k}) and the interleaved information bits x_k into the second decoder. The second decoder corresponds to the second of the constituent encoders from the turbo encoder. Decoding continues for a set number of iterations using the feedback loop with the DE-interleaver. The second decoder gives a hard decision which is the decoded bit.

3 Relay Selection Schemes

3.1 Introduction

We illustrated in chapter 2 how energy efficiency is a key component when designing schemes and protocols for wireless sensor networks. We also saw in chapter 1 how much research is being done on relay selection schemes that conserve energy and increase the lifetime of the network. Our focus in this chapter will be on relay selection and reducing the amount of data being transmitted from the sensor nodes.

In [53] a relay selection scheme that picks two nodes to transmit to the fusion center is proposed. The authors base their selection of the relaying nodes on the SNR in the channels. They show that their scheme performs better than the conventional methods. In [54], a scheme is proposed where a single node is selected to help relay data from the source to the destination with the objective of minimizing the outage probability.

This chapter will start by introducing the proposed relay selection schemes that aim at significantly reducing the number of bits transmitted in the network. We then present the simulation results for outage probability and expected number of bits transmitted. We compare the performance of the schemes to each other and to a widely used scheme where all nodes transmit. We also give simulation results for a more realistic channel model and show that they are comparable to our earlier assumptions for the network model. An analytical derivation of the outage probability and expected number of bits transmitted is then provided validating the simulation results. Furthermore we show the impact of the schemes on the lifetime of the sensor nodes in the network.

3.2 Network model

We consider a WSN with identically distributed nodes, and two phase cooperative protocol. The source transmits and is overheard by multiple nodes which in turn transmit to the destination or fusion center (FC).

We will start by assuming that the channels between the nodes and the FC are ideal. Under this assumption the FC will base it's selection of the nodes to transmit solely on the source-node channels. Figure 3.1 shows a network model with i nodes overhearing the message transmission from the source.

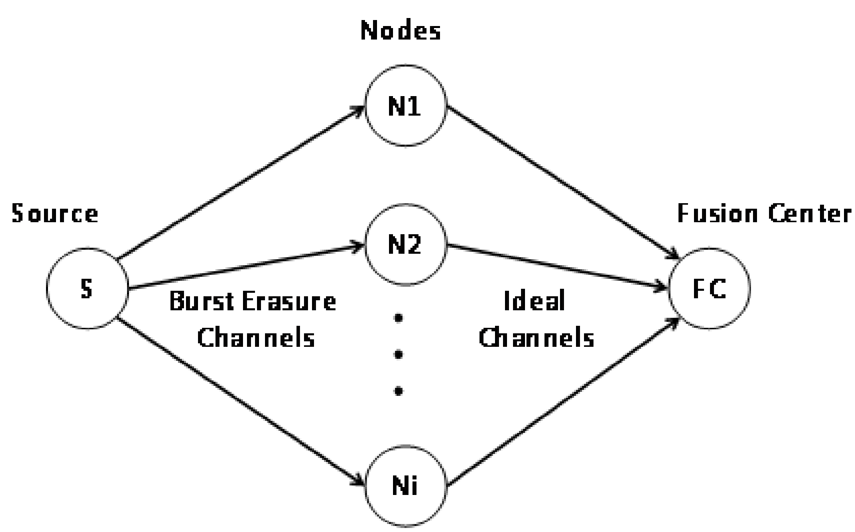

Figure 3.1: Network model

Based on the selection scheme being used, the FC picks the nodes that will transmit and sends feedback bits that will dictate whether each node will transmit or not.

3.3 Relay selection schemes

Upon receiving the CSI from the nodes, the FC will have the task of selecting a subset of these nodes to transmit. We introduce three selection schemes that the FC can use to determine which of these nodes will be active.

We define the outage probability as the probability that none of the subsets of sensors in the network has enough information to reconstruct the message error free at the FC. In this case, the FC checks whether the aggregate information of all sensors is sufficient to decode the message and prompts all nodes to transmit.

We also define the expected number of bits transmitted as the number of bits transmitted by all the active sensors.

3.3.1 Scheme 1: Fixed pairs

The nodes that send their CSI to the FC are divided into clusters of two. For example if we have 6 nodes, we can group nodes 1-2, nodes 3-4 and nodes 5-6. The FC selects the cluster that has enough information to reconstruct the message and has the least amount of bits to transmit. If no cluster is able to provide all the information necessary to reconstruct the message then all nodes transmit. We can expand on this scheme by looking at clusters with three or more nodes. In a network with six nodes, we could group nodes 1-2-3 and 4-5-6.

3.3.2 Scheme 2: All pair combinations

In this scheme, the FC looks at all pair combinations of nodes. For a network with 6 nodes, we would have $\binom{6}{2} = 15$ pairs to choose from. The FC again selects the pair with the least amount of bits to send but enough to reconstruct the message at the destination. As in the previous scheme if no pair has the necessary information to reconstruct the message at the FC, then all nodes transmit.

3.3.3 Scheme 3: Singles, pairs or triplets

The FC in this scheme looks first for nodes that have received the entire message error free. If one is found then it will be selected by the FC to transmit. If none are found then the FC looks for any pair of sensors to transmit (scheme 2). If no pairs are found the FC looks for any cluster of three nodes that has the full information to send. Again if no single node, pair or triplet of nodes has the full message to deliver to the FC then all nodes transmit.

In our schemes, the nodes that are selected will transmit the entire error free information that they have. Therefore the same bit can arrive error free from multiple nodes. A possible improvement on this would be to have the nodes only transmit the necessary bits to reconstruct the message after the selection of the nodes is made. This will require the FC to send more feedback bits to the nodes in order to specify which parts of the message each has to transmit.

3.4 Results and comparison

We consider the case where 6 nodes overhear a message of size $K = 10000$ bits from the source. We fix one of the burst erasure channel parameters ($\epsilon = 5\times10^{-4}$) and vary the other ($\mu$) and run simulations for outage probability (Figure 3.2) and expected number of bits transmitted (Figure 3.3).

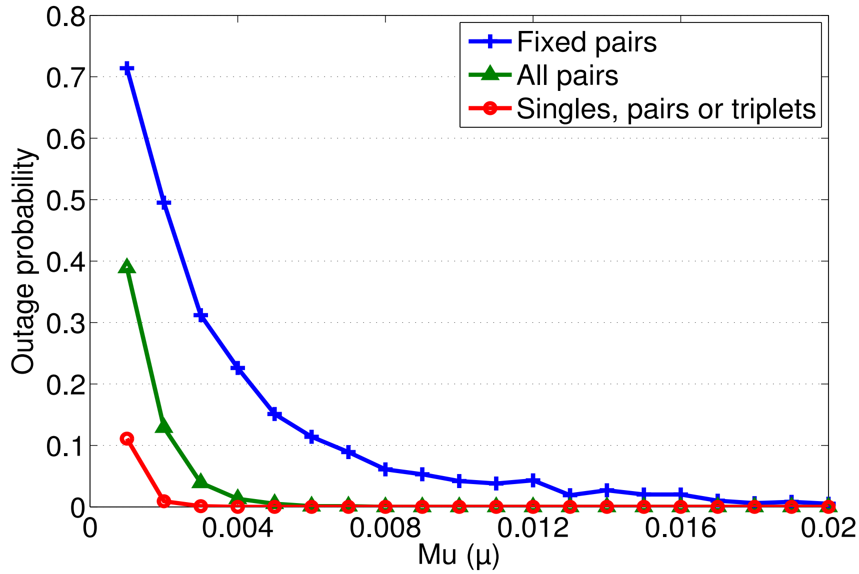

Figure 3.2: Outage probability for varying channel quality

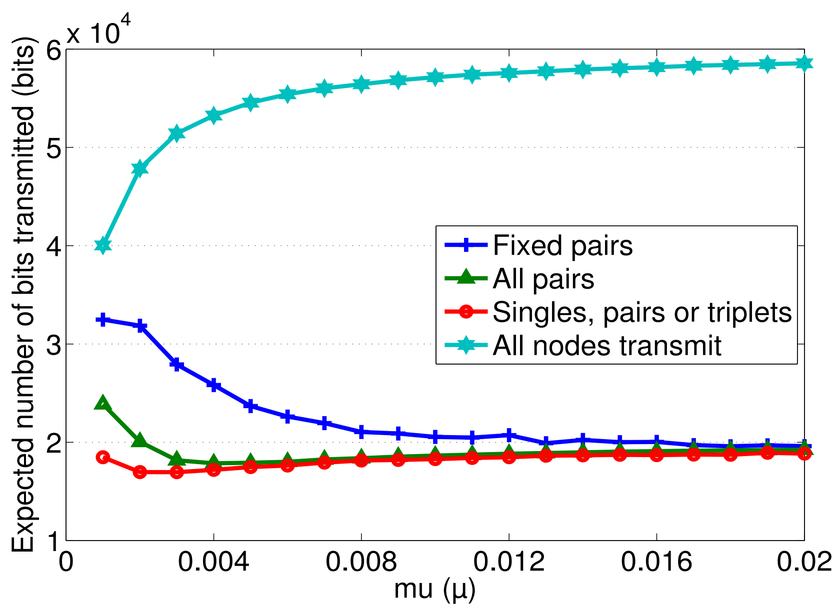

Figure 3.3: Expected number of bits transmitted for varying channel quality

As expected the outage probability and expected number of bits transmitted for all three schemes decrease as the source-node channel quality becomes better (Figure 3.2-3.3). We can also clearly see that for bad channel qualities the outage probability and number of bits transmitted are smallest for scheme 3 (Singles, pairs and triplets), followed by scheme 2 (All pairs) then scheme 1 (Fixed pairs). This is also expected since the FC has more subset combinations of nodes to choose from in schemes 2 and 3. We can say that scheme 3 outperforms scheme 2 which in turn outperforms scheme 1.

As seen in Figure 3.3 the expected number of bits transmitted for the three schemes converges to 20000 bits for all three schemes. This is due to the fact that for good channels we will rarely be in outage and only a pair of nodes will be active ($2 \times 10000 = 20000$ bits). Scheme 3 will have 1 active node and converge to 10000 bits only for perfect channels which are not included in our simulations.

3.5 Analytical derivation of the results

3.5.1 Outage probability

Let us consider that the FC is operating under scheme 1 (Fixed pairs). We start by forming a state diagram of the Markov process that jointly describes channel realizations for two independent source-node channels (Figure 3.4a). We define "G" as an error free bit and "B" as a bit received as erasure.

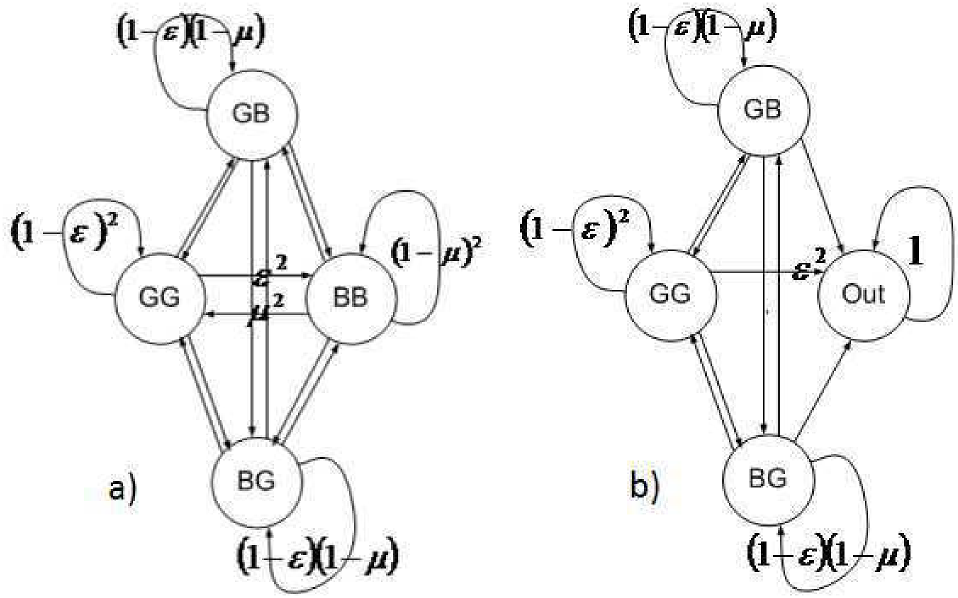

Figure 3.4: State diagrams for joint CSI of two relays that belong to the same set

The marginal probability of being in good and bad states are

$$
\begin{aligned}
P_G &= P_{(G\to G)|G} \times P_G + P_{(B\to G)|B} \times P_B \\
&= P_{(G\to G)|G} \times P_G + P_{(B\to G)|B} \times (1 - P_G) \\
&= \frac{P_{(B\to G)|B}}{1 + P_{(B\to G)|B} - P_{(G\to G)|G}} \\
&= \frac{\mu}{1 + \mu - (1 - \epsilon)} \\
&= \frac{\mu}{\epsilon + \mu},
\end{aligned} \tag{3.1}
$$

$$
\begin{aligned}
P_B &= 1 - P_G \\
&= 1 - \frac{\mu}{\epsilon + \mu} \\
&= \frac{\epsilon}{\epsilon + \mu}.
\end{aligned} \tag{3.2}
$$

Since the channels are independent, we can easily find the probability of the states that describe two source-node channels using (3.1) and (3.2),

$$P_{GG} = P_G \times P_G = \frac{\mu^2}{(\epsilon + \mu)^2}, \tag{3.3}$$

$$P_{GB} = P_G \times P_B = \frac{\mu\epsilon}{(\epsilon + \mu)^2}, \tag{3.4}$$

$$P_{BG} = P_B \times P_G = \frac{\epsilon\mu}{(\epsilon + \mu)^2}, \tag{3.5}$$

$$P_{BB} = P_B \times P_B = \frac{\epsilon^2}{(\epsilon + \mu)^2}. \tag{3.6}$$

Since we are using uncoded communication between source and nodes, if state BB is visited at least once then the cluster will not have enough aggregate information to reconstruct the whole message. We define a new state “Out” which is an absorbing state that when entered cannot be left. We go to state “Out” once state “BB” is visited for the first time. The new state diagram is shown in Figure 3.4b.

To calculate the outage probability we first express the transition matrix of the state diagram shown in Figure 3.4b. Element Q_{ij} represents the transition probability from state i to state j where the states are labeled as shown in table 3.1.

Table 3.1: State labeling for transition matrix

Label	State
1	GG
2	GB
3	BG
4	Out

Below is the the transition matrix for the state diagram shown in Figure 3.4b

$$Q = \begin{bmatrix} (1-\epsilon)^2 & \epsilon(1-\epsilon) & \epsilon(1-\epsilon) & \epsilon^2 \\ \mu(1-\epsilon) & (1-\mu)(1-\epsilon) & \mu\epsilon & \epsilon(1-\mu) \\ \mu(1-\epsilon) & \mu\epsilon & (1-\mu)(1-\epsilon) & \epsilon(1-\mu) \\ 0 & 0 & 0 & 1 \end{bmatrix}.$$

The outage probability for a given message size K, is the probability that we end up in state "Out" after K transitions

$$P_{out}(K,2) = \left(AQ^k\right)_4, \tag{3.7}$$

where A is the vector of marginal state probabilities taken from (3.3) (3.4) (3.5) and (3.6)

$$A = \begin{bmatrix} \frac{\mu^2}{(\mu+\epsilon)^2} & \frac{\epsilon\mu}{(\mu+\epsilon)^2} & \frac{\epsilon\mu}{(\mu+\epsilon)^2} & \frac{\epsilon^2}{(\mu+\epsilon)^2} \end{bmatrix},$$

and Q^k is the matrix of transition probabilities after k transitions (It is proven that element ij of Q^k is the probability that we end up in state j after k transitions). Multiplying Q^k by the initial probabilities for each state A gives the probability that we reach any of the states after k transitions. The 4^{th} element of AQ^k gives the probability that we reach state "Out" after k transitions which is why we added the subscript 4 to $\left(AQ^k\right)_4$.

The 2 in $P_{Out}(K,2)$ indicates that this is the outage probability for a cluster of 2 nodes. We will show later on how to find the outage probability for clusters with more than 2 nodes.

The outage probability for a network with n clusters will be $(P_{Out}(K,2))^n$.

Using (3.7) we calculate the outage probability for the case where 6 nodes $n=3$ clusters overhear a message of size $K=10000$ bits. We consider burst erasure channel parameters $\epsilon = 5\times10^{-4}$ and vary μ. We compare the results with the ones we obtained from simulations (Figure 3.5); we can see that they match almost perfectly.

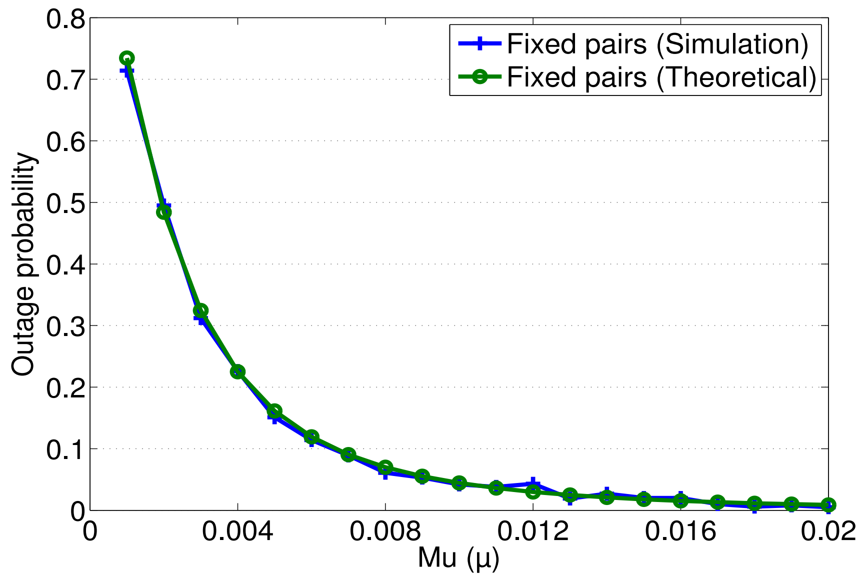

Figure 3.5: Simulation vs theoretical outage probability

3.5.2 Expected number of bits transmitted

We continue on the previous considerations that the FC is using scheme 1.

The theoretical total outage probability for a network with n clusters ($2\times n$ nodes) is $(P_{out}(K,2))^n$.

The marginal probability of being in the good state (receiving an error free bit) is $\frac{\mu}{\mu+\epsilon}$ (3.1). Therefore the expected number of bits received correctly through each burst erasure channel is $\frac{\mu}{\mu+\epsilon} \times K$. We can then write that for a cluster of 2 nodes, the expected number of bits transmitted is

$$E\left(B_c\right) = \frac{2\mu}{\mu+\epsilon} K, \tag{3.8}$$

where $E\left(B_c\right)$ is the expected number of bits received correctly by a single cluster.

The total expected number of bits transmitted by the nodes is given by

$$E\left(B\right) = \left(1 - P_{out}^{n}\left(K,2\right)\right) E\left(B_c\right) + P_{out}^{n}\left(K,2\right) \times nE\left(B_c\right), \tag{3.9}$$

where the first term is the probability that at least one of the clusters is not in outage multiplied by the expected number of bits transmitted by a cluster. The second term in (3.9) is the probability that all clusters are in outage multiplied by the expected number of bits when all nodes transmit (all n clusters).

We consider the same configuration as before, 6 nodes ($n = 3$ clusters) that overhear a message of size $K = 10000$ bits. We consider burst erasure channel parameters $\epsilon = 5 \times 10^{-4}$ and vary μ. We have shown in the previous subsection how to calculate $P_{out}\left(K,2\right)$ using (3.7). Now using (3.8) and (3.9), we can calculate the expected number of bits transmitted in the network. We compare the results with the ones we obtained from simulations (Figure 3.6), and again the results match validating our earlier work.

3.6 Impact on node activity and power dissipation

We know that in all three proposed schemes if there is no subset that is able to reconstruct the message then all nodes transmit to the FC. Therefore the outage probability plays an important role in how many nodes will be active during a transmission.

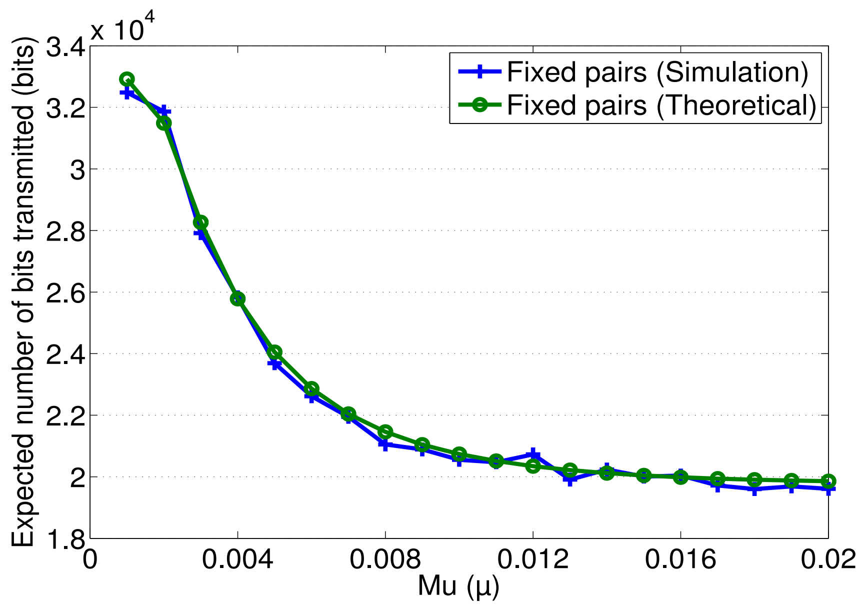

Figure 3.6: Simulation vs theoretical expected number of bits transmitted

Figure 3.7 shows the percentage of times that a specific node will be inactive during the transmission of messages that 6 nodes overhear.

We can see from Figure 3.7 that as the quality of source-node channels improves the nodes will be less active while still delivering complete messages. Similar to the outage probability, scheme 3 yields the best results followed by scheme 2 and then scheme 1. For good channel qualities all three schemes converge and the percentage of transmissions that nodes are inactive goes to 66% (only 2 are active for good channels and 6 nodes overhear the message; $\frac{6-2}{6} \times 100\% = 66\%$).

In [55, 56] it is proposed that the energy (E) consumed by a sensor for transmitting a message is a linear function of the size of the message

$$E = m \times size + b, \tag{3.10}$$

where b is a constant dependent on device state and channel acquisition overhead,

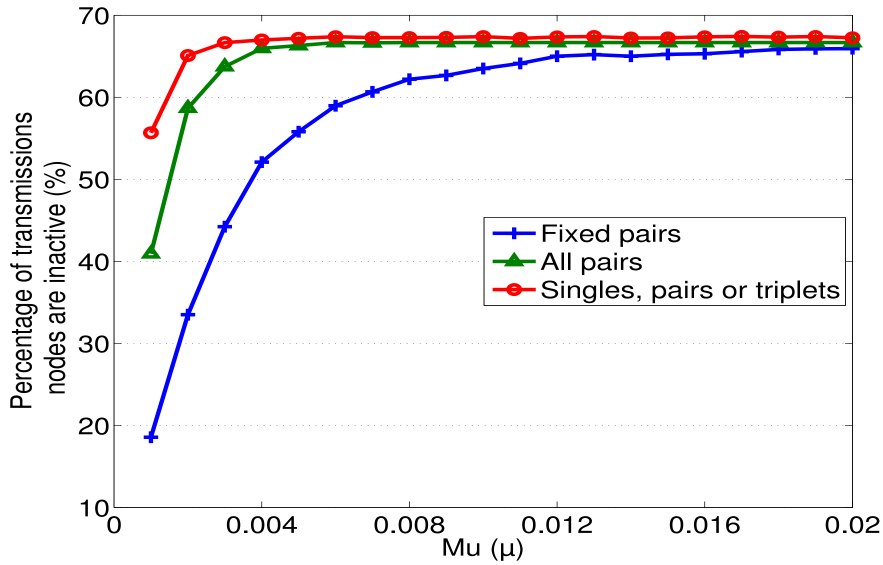

Figure 3.7: Node inactivity for varying channel quality

and $m \times size$ is an incremental component proportional to the size of the message. For large messages, b is negligible and we can assume that the energy consumed by a sensor to relay a message is directly proportional to the size of the message.

Let us consider that each time a relay is active and transmitting to destination it consumes $E = 1$ unit of power for each bit transmitted. We assume that each relay has a battery containing 5×10^6 units of power. We consider a network where the source transmits a message of size $K = 10000$ bits to destination once every hour. Figure 3.8 shows the lifetime in hours of the relay that first consumes all its power for realizations of 6, 8 and 10 overhearing relays and burst erasure channels with parameters $\epsilon = 5 \times 10^{-4}$and $\mu = 5 \times 10^{-3}$.

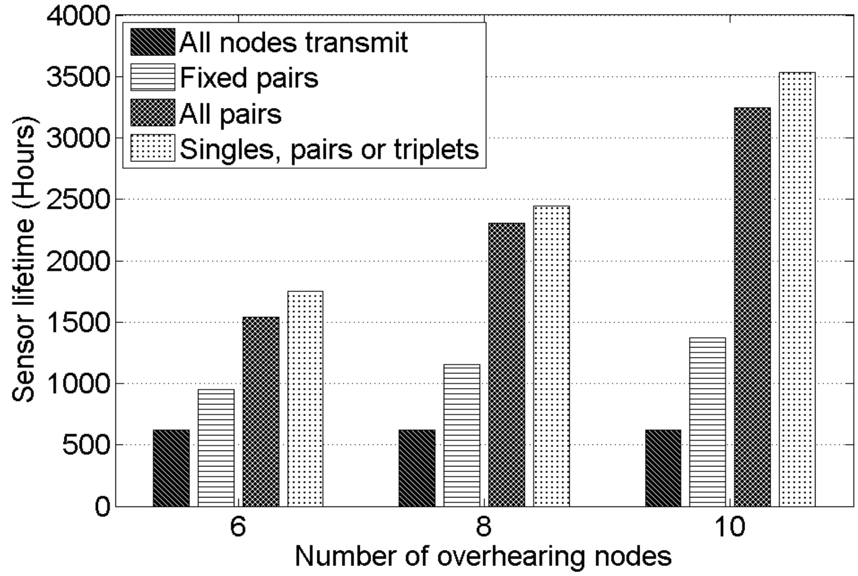

Figure 3.8: Sensor lifetime

We would like to point out that in all simulations we noticed that the number of transmissions is spread evenly among the relays regardless of the channel quality. Therefore when the first relay consumes all of its energy all the remaining relays are also very close to consuming their energy.

We notice from Figure 3.8 that the expected lifetime of the relays is significantly longer under the 3 proposed schemes than when all the relays transmit. Scheme 3 yields the best results followed by scheme 2 then scheme 1. We also notice that for larger networks the performance of the schemes improves. This is due to the higher number of subsets of relays and consequently smaller outage probabilities.

3.7 Results for Rayleigh fading channels

A more realistic channel model for wireless networks would be the Rayleigh fading model. The signal passing through the channel is subjected to random fading according to a Rayleigh distribution (sum of two uncorrelated Gaussian random variables). We will show that the results using this model will resemble very closely those of the BuEC model.

We will generate Rayleigh fading channels using the inverse discrete Fourier transform (DFT) method as was proposed in [57]. We consider the parameters $fftsize = 1000$, $blocksize = 10000$, $samplingfrequency = 10KHz$ and $dopplershift = 10Hz$. We add 0 dB variance white Gaussian noise to the channels.

We consider the case where 6 nodes overhear a message of size $K = 10000$ bits from the source. We run simulations for outage probability (Figure 3.9) and expected number of bits transmitted (Figure 3.10) for different values of signal to noise ratio (SNR) per node for the source-node channels.

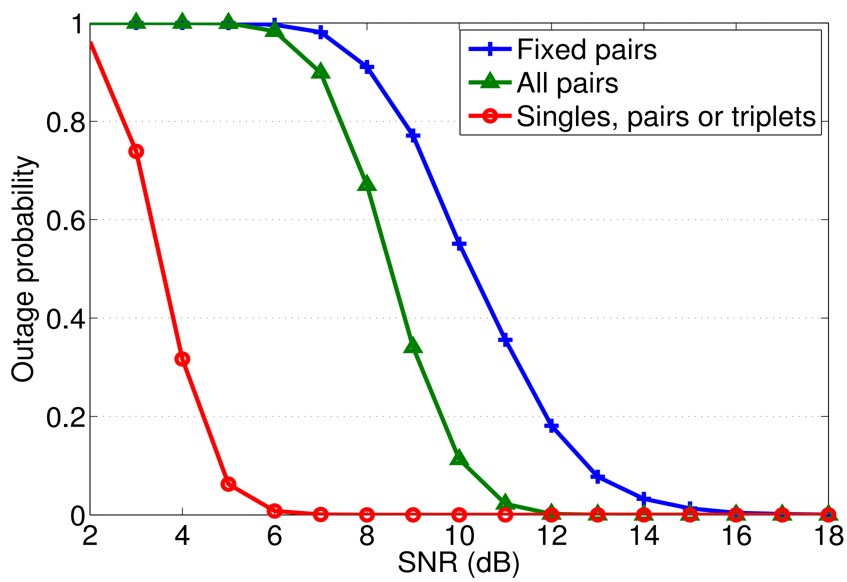

Figure 3.9: Outage probability for Rayleigh channel model

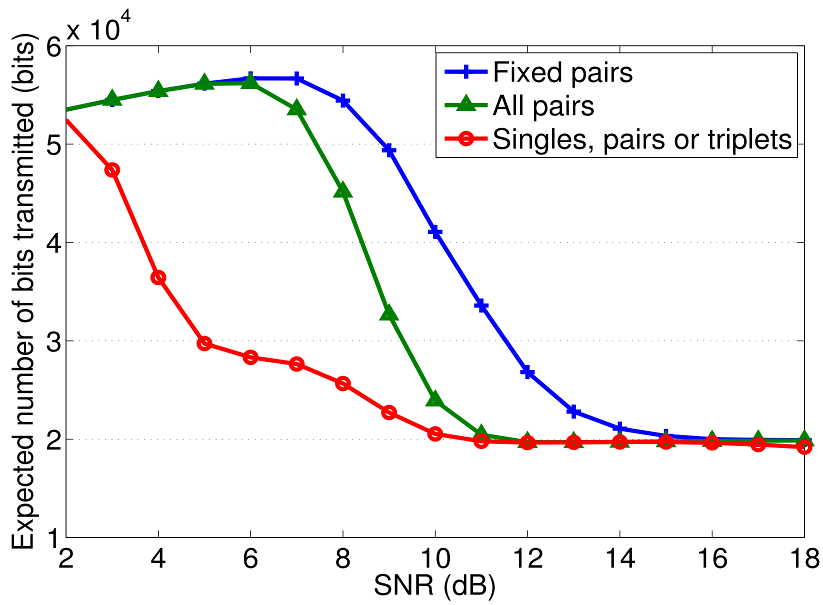

Figure 3.10: Expected number of bits transmitted for Rayleigh channel model

We examine the performance of the proposed relay selection schemes in terms of outage probability and expected number of bits transmitted in Figure 3.9-3.10. We can see that both outage probability and number of bits transmitted for all three schemes decreases as the source-node channel quality improves (increasing the SNR). We can also clearly see that for poor channel qualities scheme 2 (All pairs) outperforms scheme 1 (Fixed pairs), and Scheme 3 (Singles, pairs or triplets) outperform both.

We have shown that the results for the BuEC channel model and the Rayleigh fading channel model are very similar. This validates that our model is a suitable surrogate to a more realistic Rayleigh fading model.

3.8 Clusters with 3 or more nodes

In this section we present some guidelines on how to evaluate the outage probability and expected number of transmitted bits for the proposed relay selection scheme in cases with three or more nodes. We illustrate it by presenting the results for clusters of $x = 3$ nodes.

We start by forming a state diagram of the Markov process that jointly describes channel realizations for x independent source-node channels. The state diagram will have 2^x states (we will have 8 states for $x = 3$). As defined earlier "G" is an error free bit and "B" is a bit received as erasure.

If the state with all the bits as erasure is visited at least once then the cluster will not have enough aggregate information to reconstruct the whole message. We enter the absorbing state "Out" when all x bits are received as erasure at once for the first time (for $x = 3$ it is once state "BBB" is visited).

The transition matrix Q for clusters with x nodes will have $2^x \times 2^x$ dimensions (for $x = 3$, Q will be an 8×8 matrix). Element Q_{ij} represents the transition probability from state i to state j. Below is the the transition matrix for $x = 3$

$$Q = \begin{bmatrix} (1-\epsilon)^3 & \epsilon(1-\epsilon)^2 & \epsilon(1-\epsilon)^2 & \epsilon(1-\epsilon)^2 & \epsilon^2(1-\epsilon) & \epsilon^2(1-\epsilon) & \epsilon^2(1-\epsilon) & \epsilon^3 \\ \mu(1-\epsilon)^2 & (1-\mu)(1-\epsilon)^2 & \epsilon\mu(1-\epsilon) & \epsilon\mu(1-\epsilon) & \epsilon(1-\epsilon)(1-\mu) & \epsilon(1-\epsilon)(1-\mu) & \mu\epsilon^2 & (1-\mu)\epsilon^2 \\ \mu(1-\epsilon)^2 & \epsilon\mu(1-\epsilon) & (1-\mu)(1-\epsilon)^2 & \epsilon\mu(1-\epsilon) & \epsilon(1-\epsilon)(1-\mu) & \mu\epsilon^2 & \epsilon(1-\epsilon)(1-\mu) & (1-\mu)\epsilon^2 \\ \mu(1-\epsilon)^2 & \epsilon\mu(1-\epsilon) & \epsilon\mu(1-\epsilon) & (1-\mu)(1-\epsilon)^2 & \mu\epsilon^2 & \epsilon(1-\epsilon)(1-\mu) & \epsilon(1-\epsilon)(1-\mu) & (1-\mu)\epsilon^2 \\ (1-\epsilon)\mu^2 & \mu(1-\epsilon)(1-\mu) & \mu(1-\epsilon)(1-\mu) & \epsilon\mu^2 & (1-\epsilon)(1-\mu)^2 & \epsilon\mu(1-\mu) & \epsilon\mu(1-\mu) & \epsilon(1-\mu)^2 \\ (1-\epsilon)\mu^2 & \mu(1-\epsilon)(1-\mu) & \epsilon\mu^2 & \mu(1-\epsilon)(1-\mu) & \epsilon\mu(1-\mu) & (1-\epsilon)(1-\mu)^2 & \epsilon\mu(1-\mu) & \epsilon(1-\mu)^2 \\ (1-\epsilon)\mu^2 & \epsilon\mu^2 & \mu(1-\epsilon)(1-\mu) & \mu(1-\epsilon)(1-\mu) & \epsilon\mu(1-\mu) & \epsilon\mu(1-\mu) & (1-\epsilon)(1-\mu)^2 & \epsilon(1-\mu)^2 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}.$$

The outage probability for a given message size K, is the probability that we end up in state "Out" after K transitions

$$P_{out}(K, x) = \left(AQ^k\right)_{2^x}, \tag{3.11}$$

where A in (3.11) is the vector of marginal state probabilities with dimensions 1×2^x. And Q^k is the matrix of transition probabilities after k transitions (It is proven that element ij of Q^k is the probability that we end up in state j after k transitions). Multiplying Q^k by the initial probabilities for each state A gives the probability that we reach any of the states after k transitions. The $(2^x)^{th}$ element of AQ^k gives the probability that we reach state "Out" after k transitions which is why we added the subscript 2^x to $\left(AQ^k\right)_{2^x}$.

For the case of $x = 3$ nodes per cluster we have

$$P_{out}\left(K, 3\right) = \left(AQ^k\right)_8, \tag{3.12}$$

where A is the vector of marginal state probabilities, derived the same way we did for pairs from (3.1) and (3.2)

$$A = \begin{bmatrix} \frac{\mu^3}{(\epsilon+\mu)^3} & \frac{\epsilon\mu^2}{(\epsilon+\mu)^3} & \frac{\epsilon\mu^2}{(\epsilon+\mu)^3} & \frac{\epsilon\mu^2}{(\epsilon+\mu)^3} & \frac{\mu\epsilon^2}{(\epsilon+\mu)^3} & \frac{\mu\epsilon^2}{(\epsilon+\mu)^3} & \frac{\mu\epsilon^2}{(\epsilon+\mu)^3} & \frac{\epsilon^3}{(\epsilon+\mu)^3} \end{bmatrix}.$$

The 3 in $P_{Out}\left(K, 2\right)$ indicates that this is the outage probability for a cluster of 3 nodes.

The outage probability for a network with n clusters will be $\left(P_{Out}\left(K, x\right)\right)^n$.

Using (3.12) we calculate the outage probability for $x = 3$ nodes per cluster. We run simulations where 6 nodes overhear a message of size $K = 10000$ bits and for burst erasure channel parameters $\epsilon = 5 \times 10^{-4}$ and vary μ. We compare the results to those from the clusters with 2 nodes (Figure 3.11).

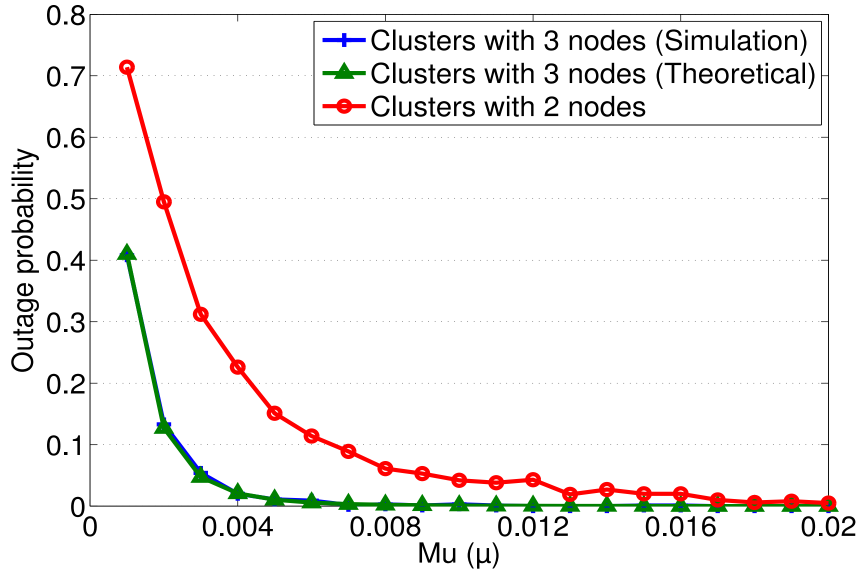

Figure 3.11: Simulation vs theoretical outage probability

We can see from Figure 3.11 that the simulation and theoretical results match. We also notice that the outage probability for clusters with 3 nodes is lower than that of clusters with 2 nodes.

The total outage probability for a network with n clusters and x nodes per cluster ($x \times n$ total nodes) is $(P_{out}(K, x))^n$.

The marginal probability of being in the good state (receiving an error free bit) is $\frac{\mu}{\mu+\epsilon}$ (3.1). Hence the expected number of bits received correctly through each burst erasure channel is $\frac{\mu}{\mu+\epsilon} \times K$. Therefore we can write that for a cluster of x nodes

$$E(B_c) = \frac{x\mu}{\mu + \epsilon} K, \tag{3.13}$$

where $E(B_c)$ is the expected number of bits received correctly by a single cluster.

The total expected number of bits transmitted by the nodes is given by

$$E(B) = (1 - P_{out}^{n}(K,x))\, E(B_c) + P_{out}^{n}(K,x) \times nE(B_c)\,. \tag{3.14}$$

For the case of $x = 3$ nodes and $n = 2$ clusters, we have

$$E(B_c) = \frac{3\mu}{\mu + \epsilon} K, \tag{3.15}$$

and

$$E(B) = \left(1 - P_{out}^{2}(K,3)\right) E(B_c) + P_{out}^{2}(K,3) \times 2E(B_c)\,, \tag{3.16}$$

where the first term is the probability that at least one of the clusters is not in outage multiplied by the expected number of bits transmitted by a cluster. And the second term in (3.16) is the probability that all clusters are in outage multiplied by the expected number of bits when all nodes transmit (all n clusters).

We consider the same configuration as before, 6 nodes and $x = 3$ nodes per cluster ($n = 2$ clusters) that overhear a message of size $K = 10000$ bits. We consider burst erasure channel parameters $\epsilon = 5 \times 10^{-4}$ and vary μ. We have shown in the previous subsection how to calculate $P_{out}(K,3)$ from (3.12). Using (3.15) and (3.16), we can now calculate the expected number of bits transmitted by all nodes. We compare the results to those we obtained from the simulations and to the results from the clusters with 2 nodes (Figure 3.12) . We also show the average number of active nodes per transmission for clusters with 2 and 3 nodes (Figure 3.13).

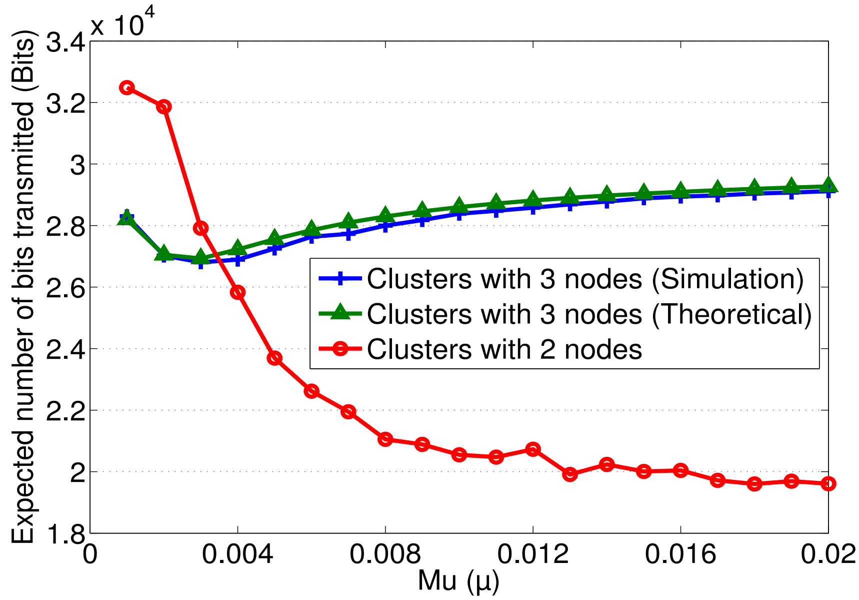

Figure 3.12: Simulation vs theoretical expected number of bits transmitted

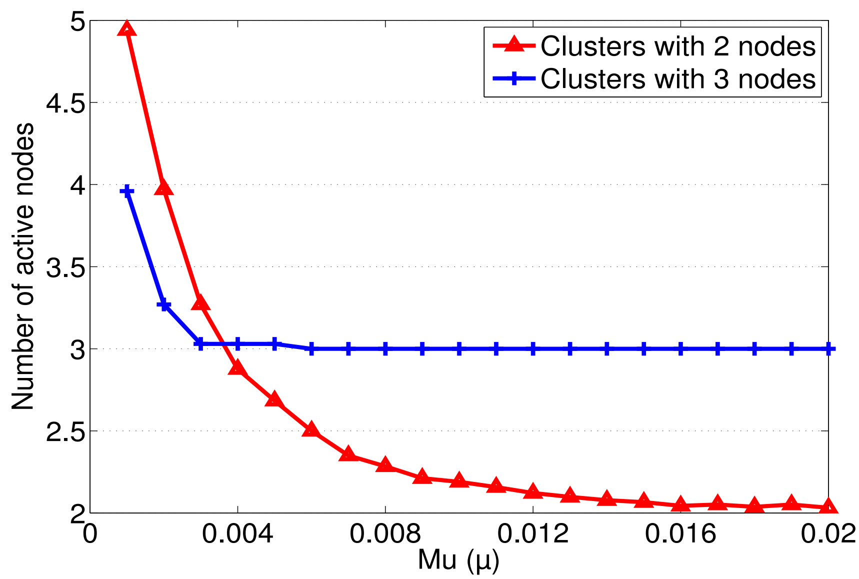

Figure 3.13: Node activity for clusters with 2 and 3 nodes

Again we can see that the theoretical and simulation results in Figure 3.12 coincide. We also notice from Figures 3.12 and 3.13 that for bad channels (smaller values of μ) the number of bits transmitted and the number of active nodes is higher in the clusters with 2 nodes than in the clusters of 3. For better channels (larger values of μ) the clusters with 3 nodes transmit more bits and more nodes are active.

We can extrapolate by saying that for good channels smaller clusters of nodes will have enough information to send the full message. Therefore we will have less active nodes and less bits transmitted compared to larger clusters of nodes. On the other hand, for poor channels the smaller clusters will have a higher outage probability and more often than not all the nodes will have to be active. Larger clusters will have a larger likelihood of having the entire message to relay hence the smaller outage probability and expected number of bits transmitted for poor channels.

3.9 Non-perfect direct link channel model

Previously we considered the node-FC channels to be perfect. Here we consider both channels as burst erasure channels; we can now look at the source-FC as a concatenation of two BuECs. The direct link from source to destination can be modeled by a BuEC with new Good and Bad states and new values for ϵ and μ (Figure 3.14).

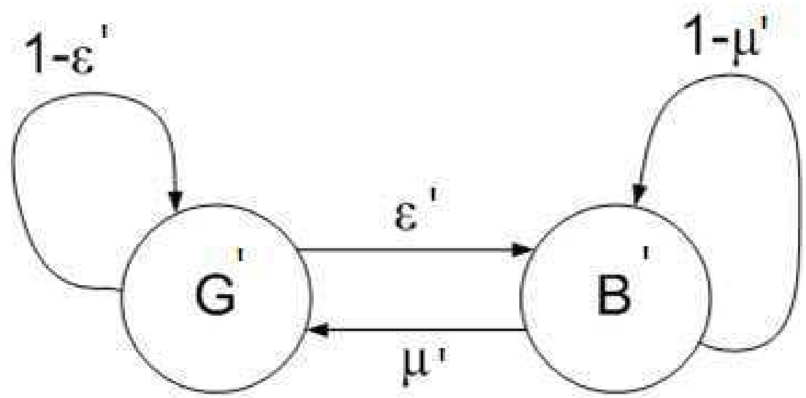

Figure 3.14: Direct link channel model

Figure 3.14 shows the Gilbert Elliot channel model where ϵ' and μ' are the new parameters of the concatenated channel. ϵ' and μ' are function of the individual parameters of both source-node and node-FC BuEC channels.

3.10 Derivation of the new states and transition probabilities

We will now show how to calculate ϵ' and μ' with the knowledge of the parameters of both source-node and node-FC channels. If the intermediate node is centered between the source and the fusion center we can assume that the channels are the same. But we will start by examining the case where the nodes might be closer to either the source or the destination and the channels can have different parameters.

3.10.1 Source-node and node-FC channels are different

In order for a bit to arrive error free from source to the FC it has to be received correctly in both source-node and node-FC channels. Therefore we are in G' (Direct link Good state) when both channels are in good state ($G' = GG$). On the other hand we will be in B' (Direct link Bad state) if at least one of the two channels is in bad state ($B' = GB + BG + BB$).

Let the source-node channel parameters be ϵ_1 and μ_1 and the node-FC channel parameters be ϵ_2 and μ_2.

We begin by finding the marginal probabilities of being in the direct link good (G') and bad (B') states

$$\begin{aligned} p\left(G'\right) &= p\left(GG\right) \\ &= \frac{\mu_1 \mu_2}{\left(\epsilon_1 + \mu_1\right)\left(\epsilon_2 + \mu_2\right)}, \end{aligned} \tag{3.17}$$

$$\begin{aligned} p\left(B'\right) &= p\left(GB\right) + p\left(BG\right) + p\left(BB\right) \\ &= \frac{\mu_1 \epsilon_2}{\left(\epsilon_1 + \mu_1\right)\left(\epsilon_2 + \mu_2\right)} + \frac{\mu_2 \epsilon_1}{\left(\epsilon_1 + \mu_1\right)\left(\epsilon_2 + \mu_2\right)} + \frac{\epsilon_1 \epsilon_2}{\left(\epsilon_1 + \mu_1\right)\left(\epsilon_2 + \mu_2\right)} \\ &= \frac{\mu_1 \epsilon_2 + \mu_2 \epsilon_1 + \epsilon_1 \epsilon_2}{\left(\epsilon_1 + \mu_1\right)\left(\epsilon_2 + \mu_2\right)}, \end{aligned} \tag{3.18}$$

$$p\left(G'\right) + p\left(B'\right) = 1. \tag{3.19}$$

Now we calculate the transition probabilities from G'

$$\epsilon' = p\left(G' \to B'\right) = \epsilon_1 \epsilon_2 + \epsilon_1\left(1 - \epsilon_2\right) + \epsilon_2\left(1 - \epsilon_1\right), \tag{3.20}$$

$$1 - \epsilon' = p\left(G' \to G'\right) = \left(1 - \epsilon_1\right)\left(1 - \epsilon_2\right), \tag{3.21}$$

$$p\left(G' \to G'\right) + p\left(G' \to B'\right) = 1. \tag{3.22}$$

Finally we calculate the transition probabilities from B'. We must first find the conditional probabilities of being in GB knowing we are in B', BG knowing we are in B' and BB knowing we are in B'

$$
\begin{aligned}
p\left(BB|B'\right) &= \frac{1}{\frac{p(GB)+p(BG)}{p(BB)}+1} \\
&= \frac{1}{\frac{\left[\frac{\epsilon_2\mu_1+\epsilon_1\mu_2}{(\epsilon_1+\mu_1)(\epsilon_2+\mu_2)}\right]}{\left[\frac{\epsilon_1\epsilon_2}{(\epsilon_1+\mu_1)(\epsilon_2+\mu_2)}\right]}+1} \\
&= \frac{1}{\frac{\epsilon_2\mu_1+\epsilon_1\mu_2}{\epsilon_1\epsilon_2}+1} \\
&= \frac{\epsilon_1\epsilon_2}{\mu_1\epsilon_2+\mu_2\epsilon_1+\epsilon_1\epsilon_2},
\end{aligned} \tag{3.23}
$$

$$
\begin{aligned}
p(GB|B') &= \frac{1}{\frac{p(BG)+p(BB)}{p(GB)}+1} \\
&= \frac{1}{\frac{\left[\frac{\epsilon_2\epsilon_1+\epsilon_1\mu_2}{(\epsilon_1+\mu_1)(\epsilon_2+\mu_2)}\right]}{\left[\frac{\epsilon_2\mu_1}{(\epsilon_1+\mu_1)(\epsilon_2+\mu_2)}\right]}+1} \\
&= \frac{1}{\frac{\epsilon_2\epsilon_1+\epsilon_1\mu_2}{\epsilon_2\mu_1}+1} \\
&= \frac{\epsilon_2\mu_1}{\mu_1\epsilon_2+\mu_2\epsilon_1+\epsilon_1\epsilon_2},
\end{aligned} \tag{3.24}
$$

$$
\begin{aligned}
p(BG|B') &= \frac{1}{\frac{p(GB)+p(BB)}{p(BG)}+1} \\
&= \frac{1}{\frac{\left[\frac{\epsilon_2\mu_1+\epsilon_1\epsilon_2}{(\epsilon_1+\mu_1)(\epsilon_2+\mu_2)}\right]}{\left[\frac{\epsilon_1\mu_2}{(\epsilon_1+\mu_1)(\epsilon_2+\mu_2)}\right]}+1} \\
&= \frac{1}{\frac{\epsilon_2\mu_1+\epsilon_1\mu_2}{\epsilon_1\mu_2}+1} \\
&= \frac{\epsilon_1\mu_2}{\mu_1\epsilon_2+\mu_2\epsilon_1+\epsilon_1\epsilon_2},
\end{aligned} \tag{3.25}
$$

$$
\begin{aligned}
\mu' &= p\left(B' \to G'\right) \\
&= p\left(BB|B'\right) \times p\left(BB \to GG\right) + p\left(GB|B'\right) \times p\left(GB \to GG\right) \\
&\qquad\qquad + p\left(BG|B'\right) \times p\left(BG \to GG\right) \\
&= \left[\frac{\epsilon_1\epsilon_2}{\mu_1\epsilon_2 + \mu_2\epsilon_1 + \epsilon_1\epsilon_2} \times \mu_1\mu_2\right] + \left[\frac{\epsilon_2\mu_1}{\mu_1\epsilon_2 + \mu_2\epsilon_1 + \epsilon_1\epsilon_2} \times \left(1-\epsilon_1\right)\mu_2\right] \\
&\qquad\qquad + \left[\frac{\epsilon_1\mu_2}{\mu_1\epsilon_2 + \mu_2\epsilon_1 + \epsilon_1\epsilon_2} \times \left(1-\epsilon_2\right)\mu_1\right].
\end{aligned}
\tag{3.26}
$$

Now that we have derived the parameters (ϵ' and μ') for the new burst erasure channel we can use (3.11) to calculate the new outage probabilities. We can also use (3.13) and (3.14) to obtain the new expected number of bits transmitted for the resulting BuEC.

To confirm our results we run simulations for outage probability (Figure 3.15) and expected number of bits transmitted (Figure 3.16). We consider BuEC channels with parameters $\epsilon_1 = 2 \times 10^{-4}$, $\mu_1 = 6 \times 10^{-3}$, $\epsilon_2 = 4 \times 10^{-4}$ and vary μ_2. We compare the simulation results to the theoretical results derived from the previous model and show that they are almost identical, therefore validating our calculations.

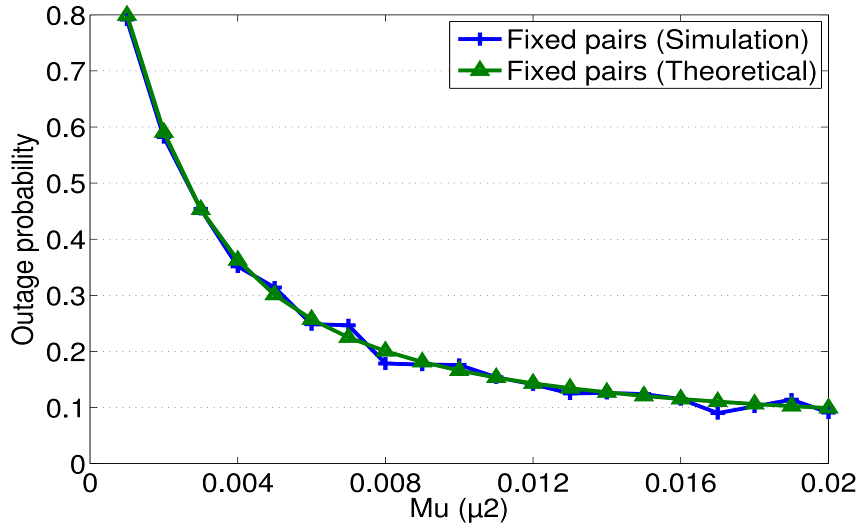

Figure 3.15: Simulation vs theory direct link outage probability

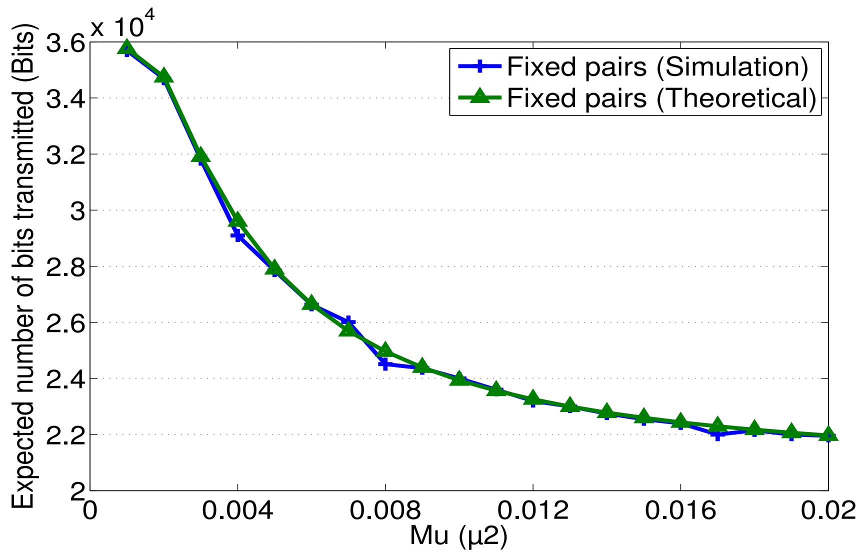

Figure 3.16: Simulation vs theory expected number of bits transmitted

3.10.2 Source-node and node-FC channels are the same

If the sensors in the network are equidistant from the source and FC we can assume that the source-node and node-FC channels are the same. This is a simplification of the previous calculations where we have $\epsilon = \epsilon_1 = \epsilon_2$ and $\mu = \mu_1 = \mu_2$. The marginal probabilities of being in good state (G') and bad state (B') reduce to

$$\begin{aligned} p(G') &= p(GG) \\ &= \frac{\mu^2}{(\epsilon+\mu)^2}, \end{aligned} \tag{3.27}$$

$$\begin{aligned} p(B') &= p(GB) + p(BG) + p(BB) \\ &= \frac{\epsilon\mu}{(\epsilon+\mu)^2} + \frac{\epsilon\mu}{(\epsilon+\mu)^2} + \frac{\epsilon^2}{(\epsilon+\mu)^2} \\ &= \frac{\epsilon^2 + 2\epsilon\mu}{(\epsilon+\mu)^2}, \end{aligned} \tag{3.28}$$

$$p(G') + p(B') = 1. \tag{3.29}$$

The transition probabilities from G' are

$$\epsilon' = p(G' \to B') = \epsilon^2 + 2\epsilon(1-\epsilon) = 2\epsilon - \epsilon^2, \tag{3.30}$$

$$1 - \epsilon' = p(G' \to G') = (1-\epsilon)^2, \tag{3.31}$$

$$p(G' \to G') + p(G' \to B') = 1. \tag{3.32}$$

The transition probabilities from B' are

$$
\begin{aligned}
p\left(BB|B'\right) &= \frac{1}{\frac{p(GB)+p(BG)}{p(BB)}+1} \\
&= \frac{1}{\frac{\frac{\epsilon\mu+\epsilon\mu}{(\epsilon+\mu)^2}}{\frac{\epsilon^2}{(\epsilon+\mu)^2}}+1} \\
&= \frac{1}{\frac{2\epsilon\mu}{\epsilon^2}+1} \\
&= \frac{\epsilon}{2\mu+\epsilon},
\end{aligned} \tag{3.33}
$$

$$
\begin{aligned}
p\left(GB|B'\right) &= \frac{1}{\frac{p(BG)+p(BB)}{p(GB)}+1} \\
&= \frac{1}{\frac{\frac{\epsilon^2+\epsilon\mu}{(\epsilon+\mu)^2}}{\frac{\epsilon\mu}{(\epsilon+\mu)^2}}+1} \\
&= \frac{1}{\frac{\epsilon\mu+\epsilon^2}{\epsilon\mu}+1} \\
&= \frac{\mu}{2\mu+\epsilon},
\end{aligned} \tag{3.34}
$$

$$
\begin{aligned}
p\left(BG|B'\right) &= \frac{1}{\frac{p(GB)+p(BB)}{p(BG)}+1} \\
&= \frac{1}{\frac{\frac{\epsilon^2+\epsilon\mu}{(\epsilon+\mu)^2}}{\frac{\epsilon\mu}{(\epsilon+\mu)^2}}+1} \\
&= \frac{1}{\frac{\epsilon\mu+\epsilon^2}{\epsilon\mu}+1} \\
&= \frac{\mu}{2\mu+\epsilon},
\end{aligned} \tag{3.35}
$$

$$\mu' = p(B' \to G')$$
$$= p(BB|B') \times p(BB \to GG) + p(GB|B') \times p(GB \to GG)$$
$$+ p(BG|B') \times p(BG \to GG)$$
$$= \left[\frac{\epsilon}{2\mu+\epsilon} \times \mu^2\right] + \left[\frac{\mu}{2\mu+\epsilon} \times (1-\epsilon)\mu\right] + \left[\frac{\mu}{2\mu+\epsilon} \times (1-\epsilon)\mu\right]$$
$$= \frac{\mu^2(2-\epsilon)}{2\mu+\epsilon}. \tag{3.36}$$

We would like to note that the answers we arrived to coincide with the formulas we get from taking $\epsilon_1 = \epsilon_2$ and $\mu_1 = \mu_2$ in the previous calculations therefore validating them. We again run simulations for outage probability (Figure 3.17) and expected number of bits transmitted (Figure 3.18) and compare them to the analytical results. We consider BuEC channel parameters $\epsilon_1 = \epsilon_2 = 2.5 \times 10^{-4}$ and vary $\mu_1 = \mu_2$.

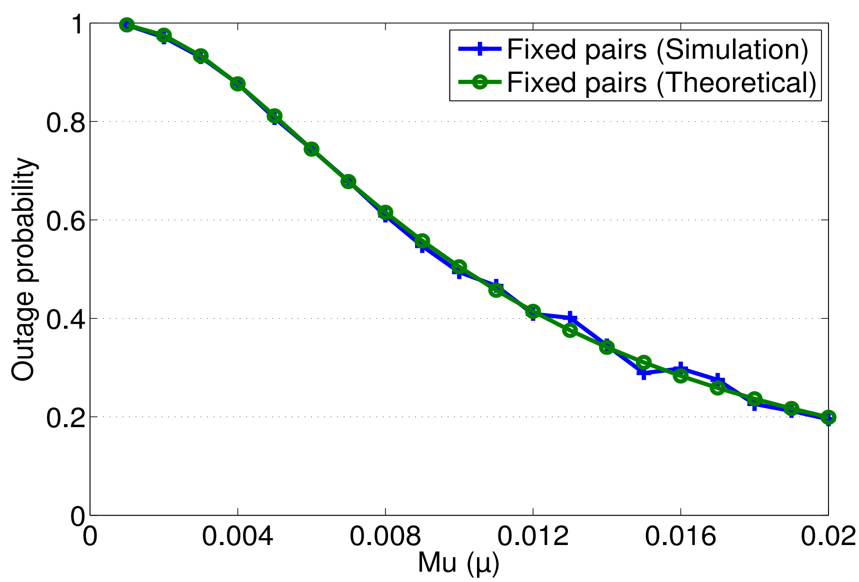

Figure 3.17: Simulation vs Theory direct link outage probability

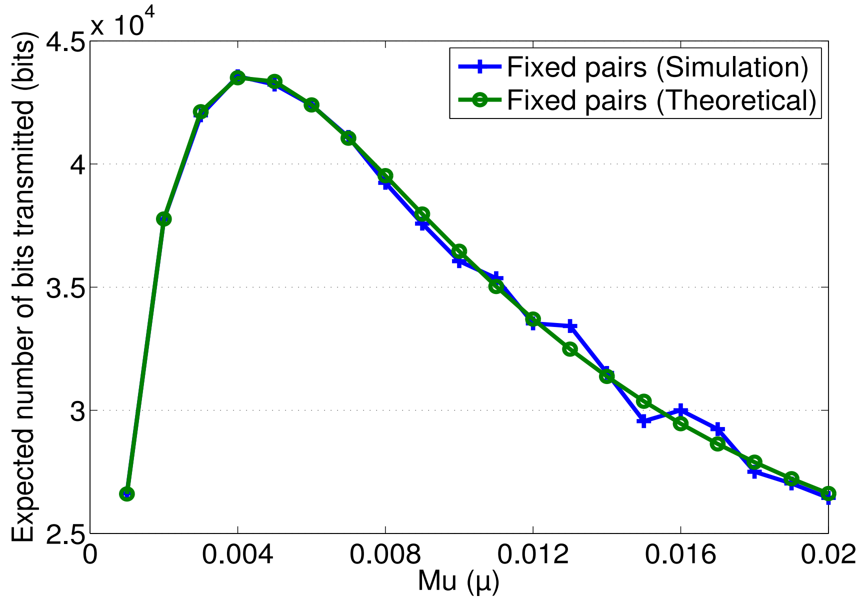

Figure 3.18: Simulation vs Theory direct link expected number of bits transmitted

From Figures 3.17-3.18 we clearly see that the results are almost identical validating our calculations.

We notice that in the direct link model where the node-FC channels are not perfect, the expected number of bits transmitted increases until it reaches a peak value then decreases when μ increases. This is different from the case we considered earlier where the node-FC channels were perfect and the expected number of bits transmitted was always decreasing. This can be explained by examining the expected number of bits transmitted in (3.14).

We start by simplifying the equation which reduces to:

$$\begin{aligned} B &= (1 - P) \times (C) + P \times (nC) \\ &= C - CP + nCP \\ &= C + (n - 1)\, CP, \end{aligned} \tag{3.37}$$

where B is the total expected number of bits transmitted, P is the outage probability, and C is the number of transmitted bits by a single cluster if it is active.

C in (3.13) is given by $E(B_c) = \frac{x\mu}{\mu+\epsilon}K$, where x, K and ϵ are constants, therefore when the channel quality improves (μ increases) C will be an increasing function. This is logical since for better channels more bits will arrive error free to the nodes. We have also shown that the outage probability (P) decreases when the channel quality improves. Multiplying an increasing and decreasing function results in a decreasing function therefore $(n-1)CP$ is decreasing. Adding an increasing and decreasing function $(C+(n-1)CP)$ results in a function that will behave according to the faster rate of change of the two functions (larger absolute value of the derivative)

For very poor channels, $(n-1)CP$ decreases at a slower rate than the increase in C. This leads to an overall increase in the number of bits (B) being transmitted in the first part of Figure 3.18. This is a very extreme case where the channels are extremely poor. After a certain peak point the overall expected number of bits starts decreasing again (under normal conditions). We can see this in the direct link model where the node-FC channels are not perfect since the concatenation of two poor channels results in a very poor channel (extreme case mentioned).

By examining (3.30) $\epsilon' = 2\epsilon - \epsilon^2$, where $0 \leq \epsilon \leq 1$ and $0 \leq \epsilon' \leq 1$, we can find a relationship between the perfect node-FC channel and the non perfect one:

We notice that when $\epsilon \to 0$, $\epsilon^2 \to 0$ and $\epsilon' \to 2\epsilon$. We can also see that when $\epsilon \to 1$, $\epsilon^2 \to \epsilon$ and $\epsilon' \to \epsilon$. Therefore we can say that ϵ and 2ϵ are bounds for ϵ'; for very large ϵ, the model will perform nearly twice as bad as when we had the assumption of a perfect node-FC channels. For very small ϵ, the performance of the direct link model will approach that of the perfect Node-FC model.

3.11 Simulation results for non-perfect links

We now compare the proposed schemes to each other and to the case where all nodes transmit for the model where the node-FC channels are not considered perfect anymore.

3.11.1 Source-node and node-FC channels are the same

We consider the case where 6 nodes overhear a message of size $K = 10000$ bits from the source. We fix $\epsilon_1 = \epsilon_2 = 5 \times 10^{-4}$ and vary $\mu = \mu_1 = \mu_2$ and observe the outage probability (Figure 3.19) and the expected number of bits transmitted (Figure 3.20).

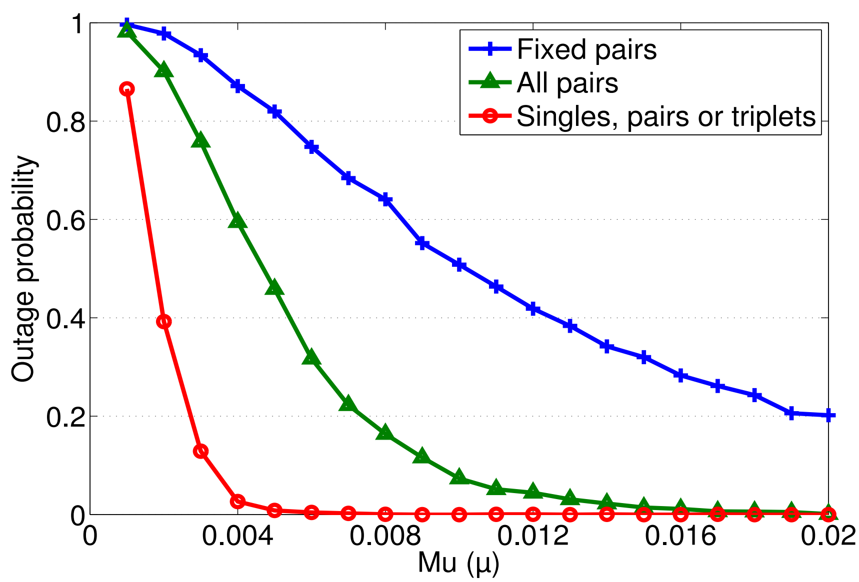

Figure 3.19: Direct link outage probability for identical channels

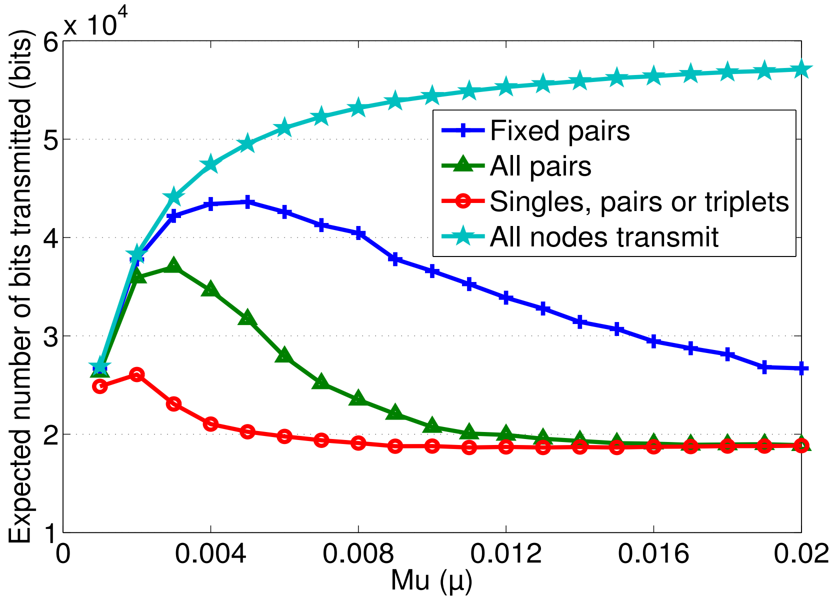

Figure 3.20: Direct link expected number of bits transmitted for identical channels

We can see from Figures 3.19-3.20 that as in the case of the perfect node-FC channels, the outage probability and the expected number of bits transmitted both decrease as the channel quality improves. Also we see that less bits are being sent through the channels while using our schemes compared to the case when all overhearing nodes transmit.

The performance of the schemes is not as good as under the assumption of perfect node-FC channels. This is expected since now we have concatenated fading channels and we showed that the result is a BuEC with parameters worse than those of the individual BuEC channels. This results in higher outage probabilities and number of bits transmitted (Table 3.2 shows a comparison of the results).

Table 3.2: Difference between non-perfect (direct link) and perfect node-FC channels

Mu (μ)	Outage probability		Expected number of bits transmitted	
	direct link	Perfect Node-FC	direct link	Perfect Node-FC
0.004	0.877	0.226	43560	25829
0.012	0.4090	0.043	33529	20727
0.02	0.1950	0.005	26442	19607

3.11.2 Source-node and node-FC channels are different

We consider the case where 6 nodes overhear a message of size $K = 10000$ bits from the source. We fix $\epsilon_1 = \epsilon_2 = 2.5 \times 10^{-4}$, $\mu_1 = 2 \times 10^{-2}$ and vary μ_2 and inspect the outage probability (Figure 3.21) and the expected number of bits transmitted (Figure 3.22).

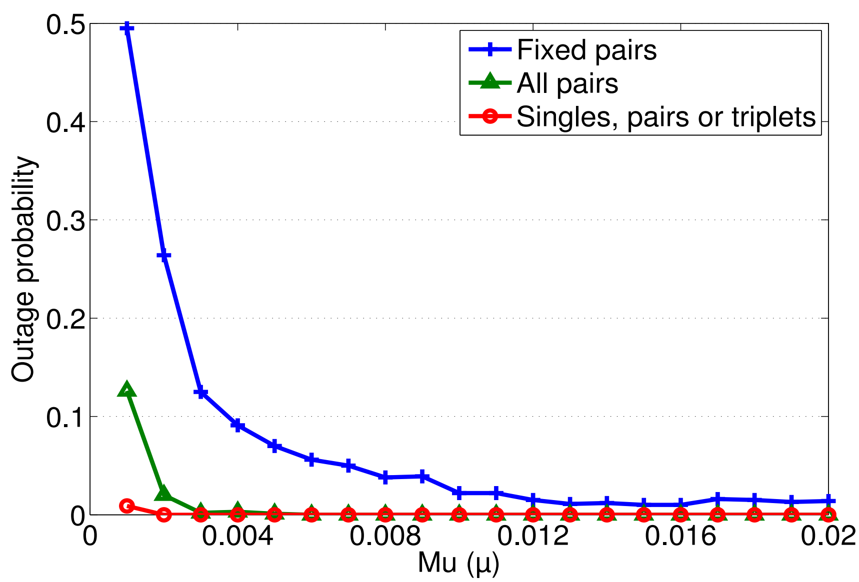

Figure 3.21: Outage probability for varying node-FC channels

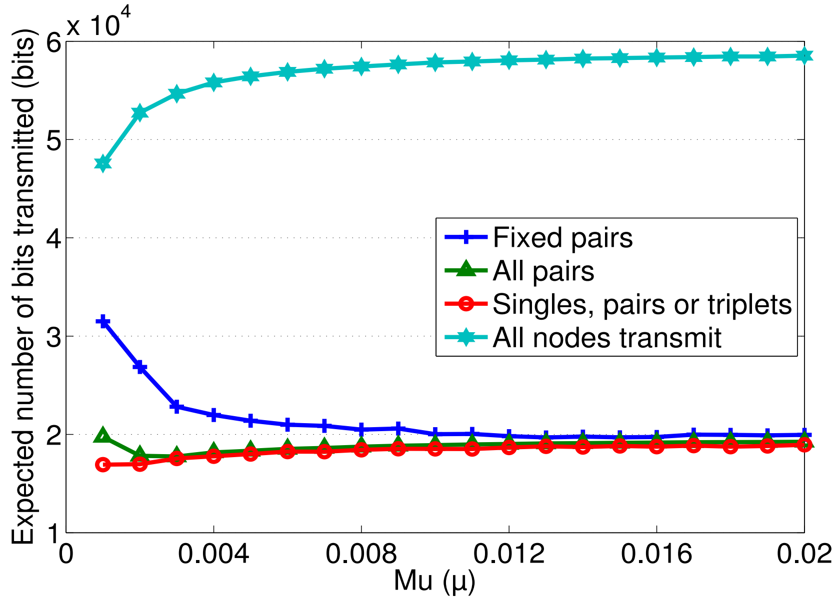

Figure 3.22: Expected number of bits transmitted for varying node-FC channels

As expected both outage probability and number of bits transmitted (Figures 3.21-3.22) decrease when the channel quality improves similar to the case where we assumed that the node-FC channels were perfect. However the overall performance is slightly worse than the ideal case of perfect node-FC channels as expected since we are cascading two BuEC channels.

3.11.3 Direct link model results for Rayleigh fading channels

We will now show that our results are consistent with the more realistic Rayleigh fading channel model. We consider the case where 6 nodes overhear a message of size $K = 10000$ bits from the source. We run simulations for outage probability (Figure 3.23) and expected number of bits transmitted (Figure 3.24) for different values of SNR.

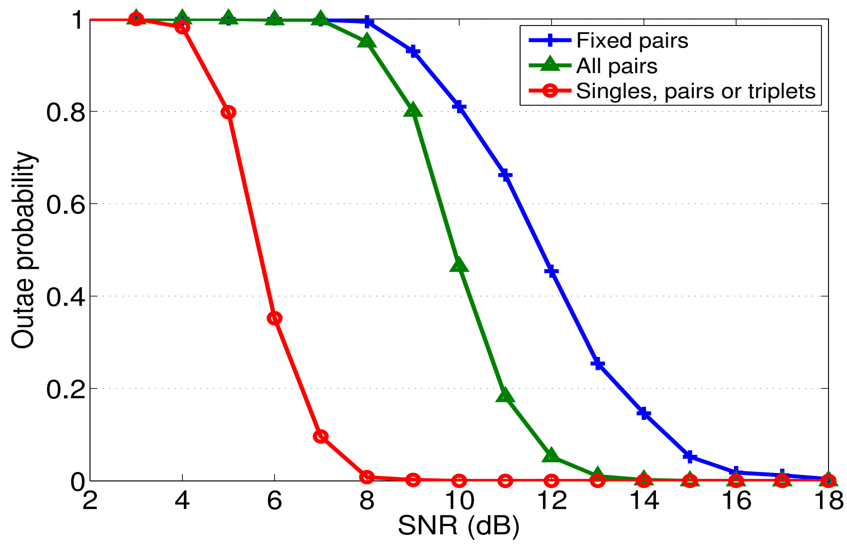

Figure 3.23: Direct link outage probability for Rayleigh model

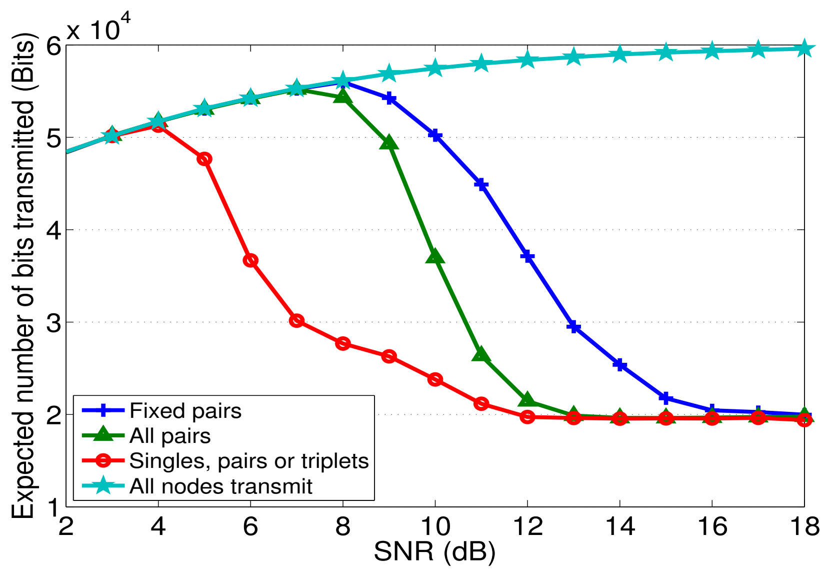

Figure 3.24: Direct link expected number of bits transmitted for Rayleigh model

We can see from Figures 3.23-3.24 that the outage probability and expected number of bits transmitted behave the same way with Rayleigh channels as with BuEC channels. Both decrease as the channel quality improves and scheme 3 outperforms scheme 2 which in turn performs better than scheme 1.

At optimal performance the FC under our schemes will only require a pair of nodes to transmit (with the exception of scheme 3 which for perfect channels will only have 1 active node). The size of the message is $K = 10000$ bits, therefore the expected number of bits transmitted settles at $2 \times 10000 = 20000$ bits.

3.12 Conclusion

We introduced three selection schemes that aim at decreasing the number of active nodes in a wireless sensor network and send less information through the network while maintaining a certain level of performance. We saw how the reduced number of bits transmitted leads to energy saving for the sensor nodes in the network. We also showed that even without the initial assumption of perfect node-FC channels we are still able to gain a significant improvement on the the lifetime of the sensors when using our proposed schemes.

4 Turbo Codes

4.1 Introduction

When we examined the performance for a model with non perfect node-FC channels in chapter 3, we noted a significant degradation in the outage probability and bits transmitted. This is due to the cascading of two BuEC channels. To counteract this we employ error correcting codes (ECCs) on the node-FC channels. Error correcting codes give rise to extra bits being sent (parity bits). On the other hand errors in the node-FC channels are reduced and consequently we will have a lower outage probability.

There are different types of ECCs, in our model, we will be using turbo codes which have a very high performance.

In the literature, a distributed turbo code (DTC) is introduced in [22, 58, 59] where the source encodes the message and sends it to both relay and destination. The relay decodes, interleaves and re-encodes the message before forwarding to the destination. For instance, in [60] a variation of the DTC is introduced (DTC-SIR) where the relay forwards a soft decision output to the destination. This is shown to overcome errors in decoding at the relays.

The application of turbo codes to wireless sensor networks has been addressed in many studies. In [61] a relay process is introduced that encodes the message at the source and decodes at the receiver thus omitting the decoding and re-encoding at the intermediate nodes. This is shown to reduce processing at the intermediate nodes.

In this chapter we start by proposing a model for transmission using turbo codes. We follow up by examining the outage probability and it's affect on node activity in the WSN. After that we observe the expected number of bits transmitted for our turbo code model and compare it to the uncoded model discussed in chapter 3. We then show for what range of channel quality the turbo code model will yield better results and save on sensor energy.

4.2 Incorporating turbo codes in our system

In Chapter 3 we showed that for perfect node-FC channels we were able to achieve a small outage probability and a low number of bits transmitted using the relay selection schemes that we introduced. When examining the case of non perfect node-FC channels (resulting in two concatenated error channels) the results dropped, specially when both source-node and node-FC channels were poor. For this reason we will employ turbo codes on the node-FC channels. This will introduce extra bits being sent through the node-FC channels but will allow us to choose the nodes that will transmit based solely on the source-node channels.

In Chapter 3 we considered a system with 6 nodes for simplicity and calculations. Our selection schemes will normally have 2 nodes transmitting when functioning. Since we are using rate $r_t = \frac{1}{3}$ turbo codes the number of bits transmitted will be tripled and we will be sending the same number of bits as if all 6 nodes are transmitting. For this reason, we will be considering larger WSNs for where more than 6 nodes overhear the message broadcast from the source.

4.3 Outage probability

We start by using a rate $r_t = \frac{1}{3}$ turbo code (rate $r = \frac{1}{2}$ constituent CCs) which outputs 3 bits for every 1 input bit. We run simulations for 12 BuECs with parameters $\epsilon = 5 \times 10^{-4}$ and vary μ while using the turbo codes on the node-FC channels. We examine the outage probability for our relay selection schemes in Figure 4.1 and compare the results for the fixed pairs scheme to the outage probability of the uncoded model (Figure 4.2).

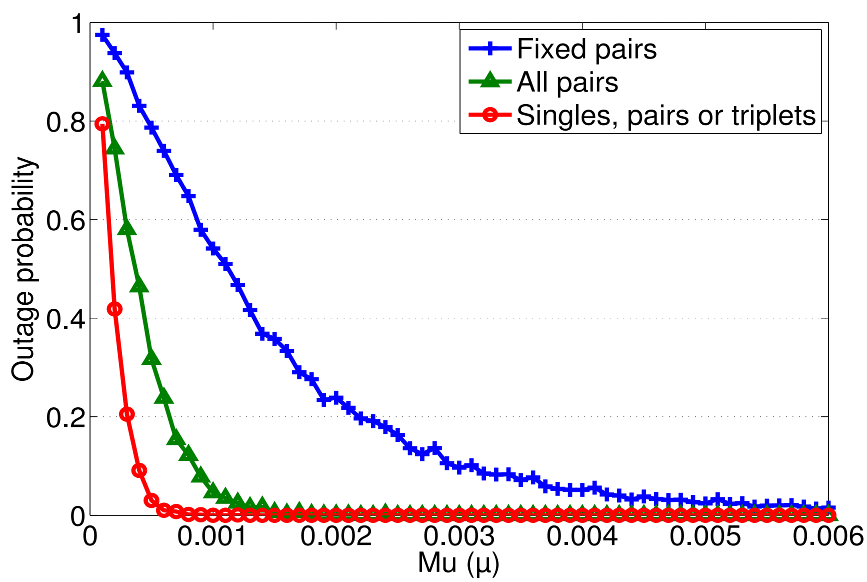

Figure 4.1: Outage probability with turbo coding

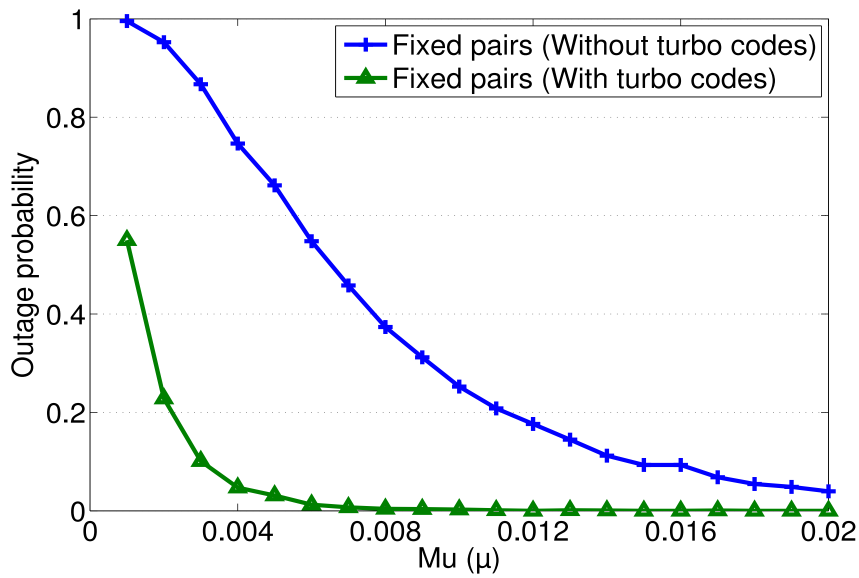

Figure 4.2: Turbo code model vs uncoded model outage probability

We notice that the outage probability for all three schemes decreases when the channel quality improves (Figures 4.1). The outage probabilities for the turbo code model are significantly lower than those from the direct link model (Figure 4.2). This is a result of the turbo codes correcting most if not all of the errors in the node-FC channels. One of the major advantages of using turbo codes is that this smaller outage probability will impact the node activity. The number of active nodes in the network is considerably reduced.

Next we examine the node activity for the fixed pairs scheme (Figure 4.3).

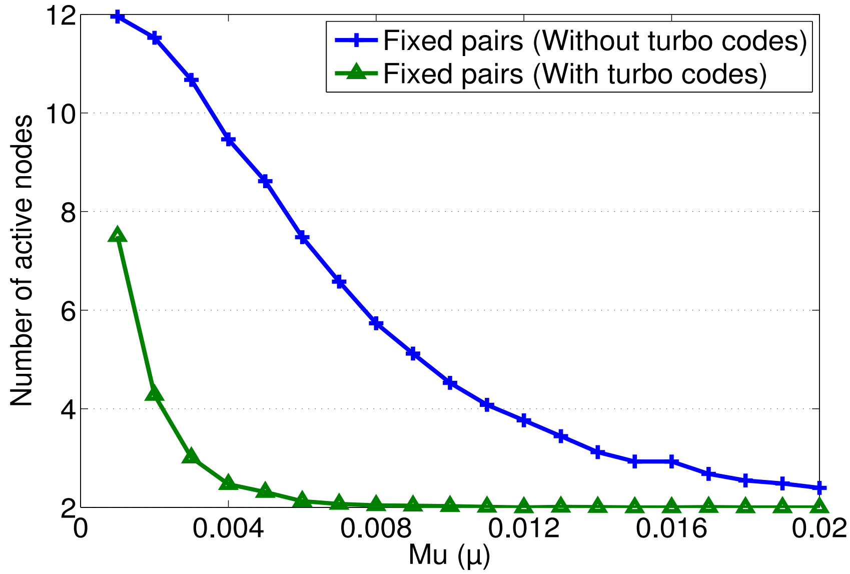

Figure 4.3: Turbo code model vs uncoded model node activity

As expected, using turbo codes results in less number of active nodes in the network (Figure 4.3).

4.4 Expected number of bits transmitted bits

We run the same simulations for 12 BuECs with parameters $\epsilon = 5 \times 10^{-4}$ and vary μ while using the turbo codes on the node-FC channels. We observe the expected number of bits transmitted for our relay selection schemes.

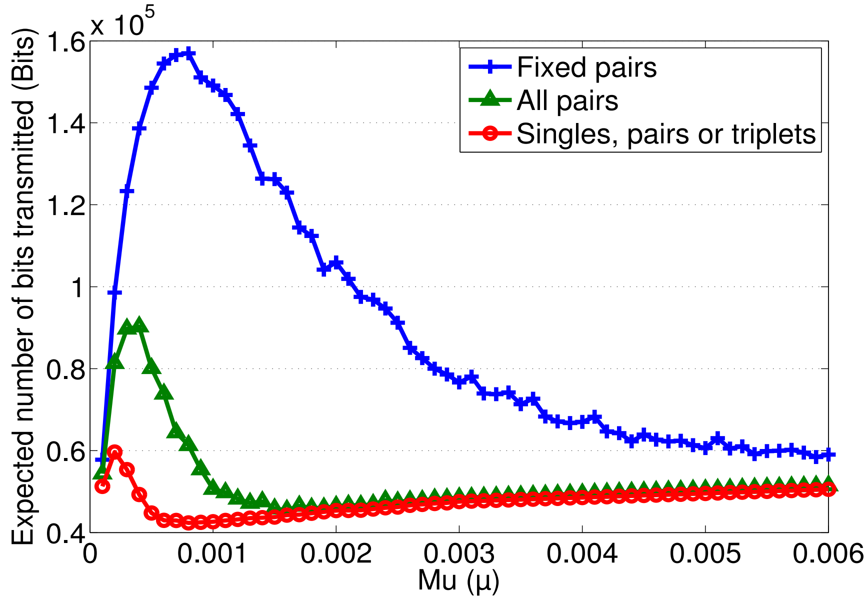

Figure 4.4: Expected number of bits transmitted with turbo coding

Figure 4.4 shows that as before the expected number of bits transmitted while using turbo codes decreases as we improve the quality of the channels. Schemes 2 and 3 perform better than scheme 1 for poor channels. As the channel quality improves, the number of bits transmitted settles at around 6×10^4. This is because at optimal performance of all three schemes, the FC will only pick 2 nodes to transmit (with the exception of scheme 3 which for perfect channels will only have 1 active node). Each node is encoding a message of size $K = 10000$ bits using a rate $r_t = \frac{1}{3}$ turbo code therefore tripling the number of bits $2 \times 3 \times 10000 = 60000$ bits.

We now compare the results for the Fixed pairs scheme using the turbo code model to those of the uncoded model (Figure 4.5).

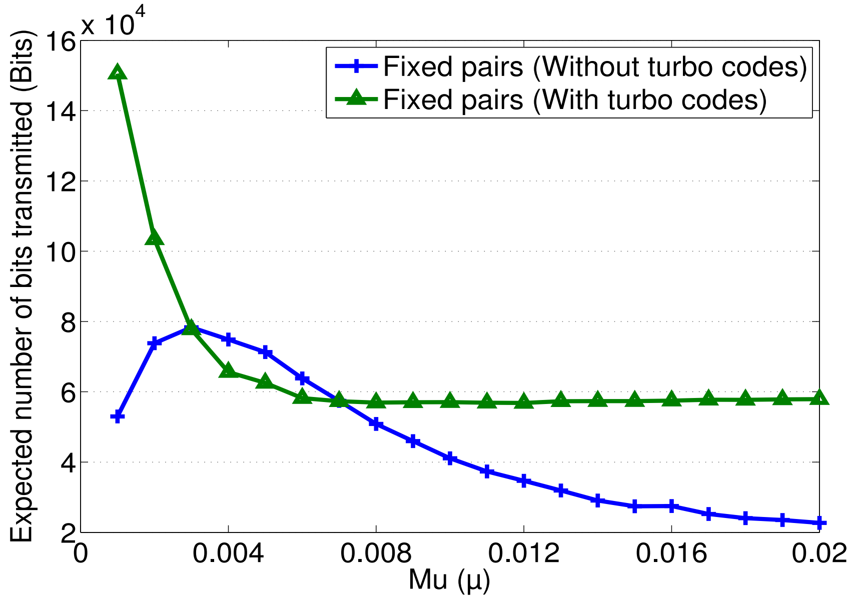

Figure 4.5: Turbo code model vs uncoded model expected number of bits transmitted

By inspecting Figure 4.5 we notice that the number of bits transmitted for the turbo code model is higher for poor channels and for good to near perfect channels. For average to good channel quality (μ roughly between 0.003 and 0.007) the turbo code model outperforms the uncoded model by sending less bits to the FC.

4.5 Rayleigh fading channel model

Here we consider a more realistic Rayleigh fading channel model. We consider the case where 12 nodes overhear a message of size $K = 10000$ bits from the source. We run simulations for outage probability (Figure 4.6), node activity (Figure 4.7) and expected number of bits transmitted (Figure 4.8) for different values of SNR.

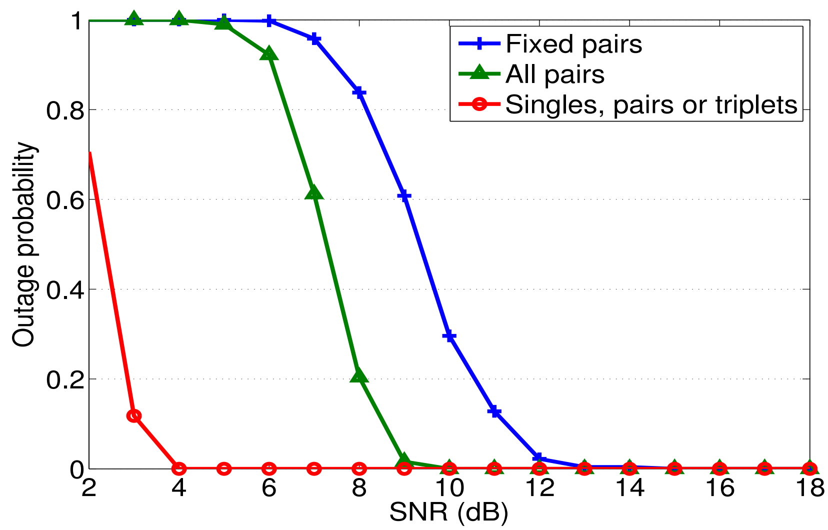

Figure 4.6: Turbo code model outage probability for Rayleigh channels

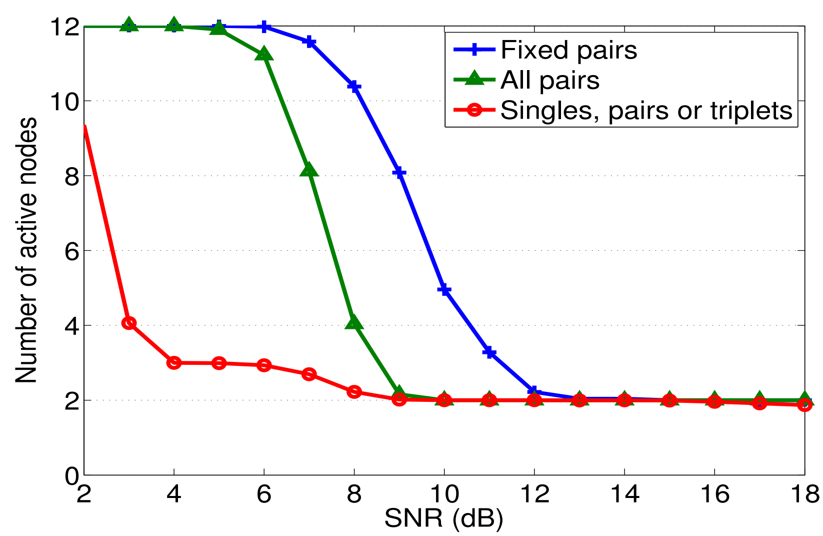

Figure 4.7: Turbo code model node activity for Rayleigh channels

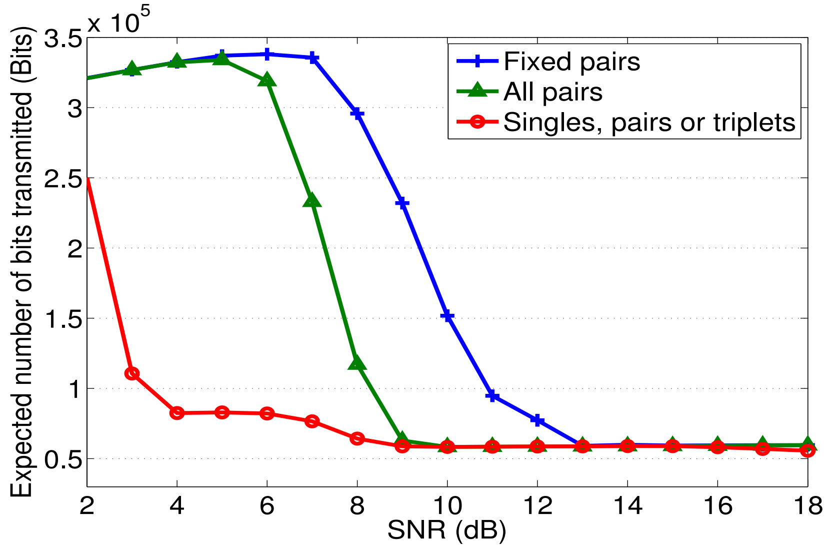

Figure 4.8: Turbo code model expected number of bits transmitted for Rayleigh channels

We can see from Figures 4.6-4.7 that the outage probability and node activity behave the same way with Rayleigh channels as with BuEC channels. Both decrease as the channel quality improves and so does the expected number of bits transmitted (Figure 4.8). Scheme 3 outperforms scheme 2 which in turn performs better than scheme 1. We also notice that the outage probability goes to 0 for better channels and the number of active nodes goes to 2 (at optimal performance our schemes only require a pair of nodes to transmit with the exception of scheme 3 for perfect channels). For this reason the expected number of bits transmitted for a message of size $K = 10000$ bits and using rate $r_t = \frac{1}{3}$ goes to $2 \times 3 \times 10000 = 60000$ bits.

We now compare the results for the fixed pairs scheme from the turbo code model to those of the uncoded model. We consider a network with 30 nodes, a message size of $K = 10000$ bits and Rayleigh fading channels. We examine the outage probability (Figure 4.9) and expected number of bits transmitted (Figure 4.10).

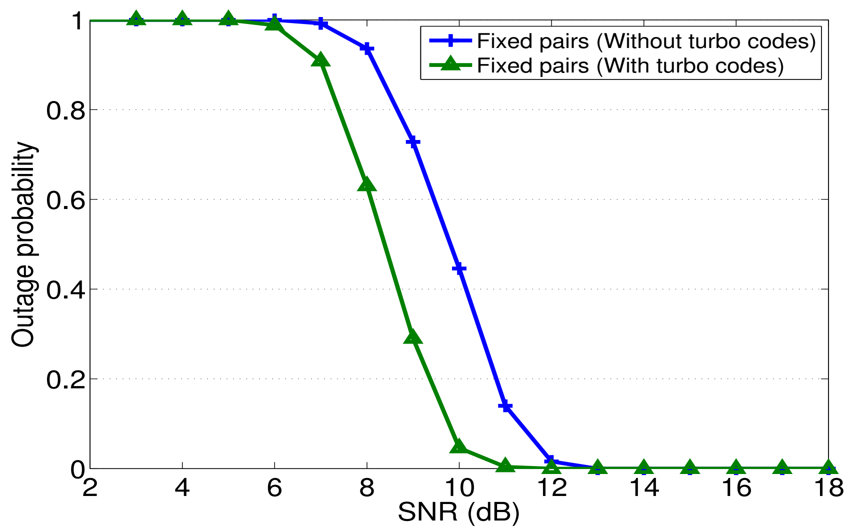

Figure 4.9: Turbo code vs uncoded model outage probability for Rayleigh channels

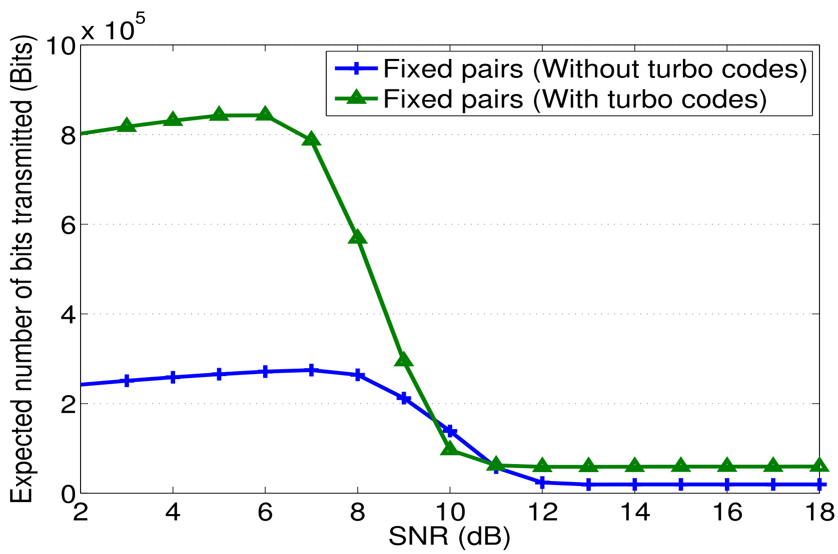

Figure 4.10: Turbo code vs uncoded model number of bits for Rayleigh channels

Inspecting Figures 4.9-4.10 we can see that the outage probability while using turbo codes is lower than those of the uncoded model (Figure 4.9). We also notice that as in the case with BuEC channels (Figure 4.5), the expected number of bits transmitted with turbo codes is lower for only a small range of channel quality (Figure 4.10). The more nodes we have in the network the larger that range will be. Only within that range does the model with turbo codes outperform the uncoded model. In that range, the number of bits transmitted is reduced and we save on sensor node energy.

4.6 Energy savings

We have shown that when using turbo codes in the node-FC channels we are less likely to be in outage. This means it will be more likely to find a pair of nodes that complement each other, and therefore have less active nodes compared to the uncoded model. On the other hand, when using turbo codes we introduce extra parity bits. In our simulations, we used a rate $r_t = \frac{1}{3}$ turbo code which leads to overhead parity bits added to the transmission. There is always a tradeoff, and in this case it is between the number of bits transmitted and the number of active nodes.

We continue on the assumption from chapter 3 that the energy consumed by a sensor to relay a message is directly proportional to the size of the message.

For the extreme cases where the channel quality is either really poor or near perfect, we notice the number of bits transmitted was much higher for the turbo code model (Figure 4.5). We can therefore say that for these cases it would be better not to use turbo codes since they will not conserve much energy. As for the case of average channel quality (μ roughly between 0.003 and 0.007) we noticed that the number of bits transmitted was smaller (Figure 4.5) resulting in large power savings. We will illustrate these power savings by simulations for power consumption for the turbo code model and compare them to the uncoded model.

Let us consider that each time a relay is active and transmitting to destination it consumes $E = 1$ unit of power for each uncoded information bit transmitted and $E = 1$ unit of power for every codeword. We consider a network where the source transmits a message of size $K = 10000$ bits to destination and is overheard by 12 nodes. We take BuEC channel parameters $\epsilon = 5 \times 10^{-4}$and vary μ. Figure 4.11 shows the average power consumed for transmitting a message to the destination.

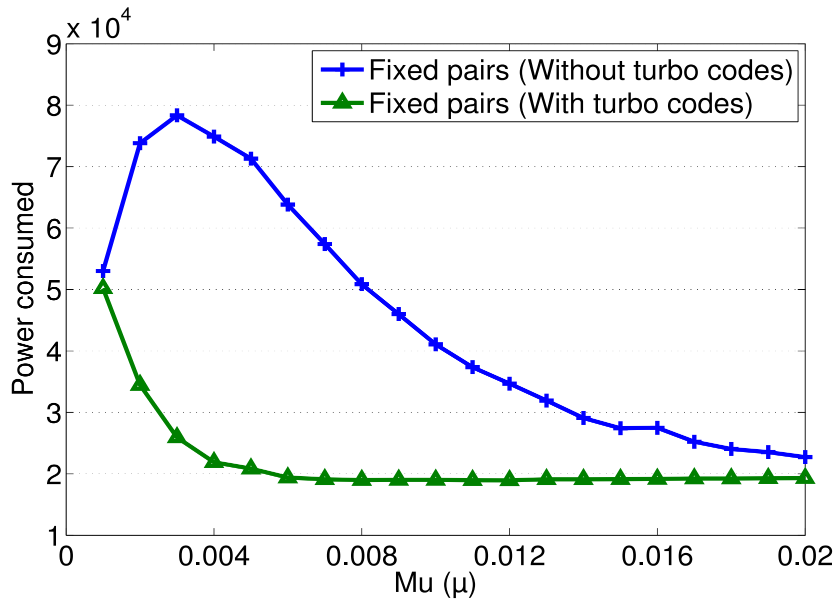

Figure 4.11: Power consumption with turbo codes

We can clearly see from Figure 4.11 that the turbo code model yields better results, decreasing the power consumed for transmitting a message. But we also notice that we only see significant improvement for average channel qualities where we showed earlier that the expected number of bits transmitted was lower for the coded model. We conclude that under certain channel conditions which we have determined earlier in Figure 4.5, using turbo codes on the node-FC channels will considerably reduce energy consumption.

4.7 Turbo code selection

We established in the previous chapter that the FC picks the subset of nodes to transmit by sending feedback bits to the nodes. It can also add some bits in order to pick the constraint length of the code being used.

The number of feedback bits (b) will depend on the possible constraint lengths of the codes being used

$$b = \lceil log_2 n \rceil , \tag{4.1}$$

where n is the number of different constraint lengths to choose from.

In our simulations the code can have one of three constraint lengths (1, 2 or 3). Therefore the FC will need $b = 2$ feedback bits to be able to pick the appropriate code length (Table 4.1).

Table 4.1: Constituent convolutional code constraint length selection

Feedback bits	Constraint length chosen
00	1
01	2
10	3
11	N/A

The selection of the constraint length is based on the SNR of the node-FC channels (whose CSI is sent to the FC prior to the relay selection). It is chosen in such a way that the FC can decode the information and recover the message error free.

We can see from Table 4.2 that for larger constraint lengths we get a larger number of states, larger Hamming distance d^H_{min} and more error correcting capability. This comes at the cost of complexity, the larger the code the more complex it is.

Table 4.2: Rate $r = \frac{1}{2}$ optimum convolutional codes

Constraint length	Number of states	Octal representation	Free Hamming distance d^H_{min}	Error correcting capability t
1	2	$(3, 1)$	3	1
2	4	$(5, 7)$	5	2
3	8	$(13, 17)$	6	2

We now show the error rate for a turbo code with rate $r_t = \frac{1}{3}$ and constituent convolutional codes with rate $r = \frac{1}{2}$ (Figure 4.12).

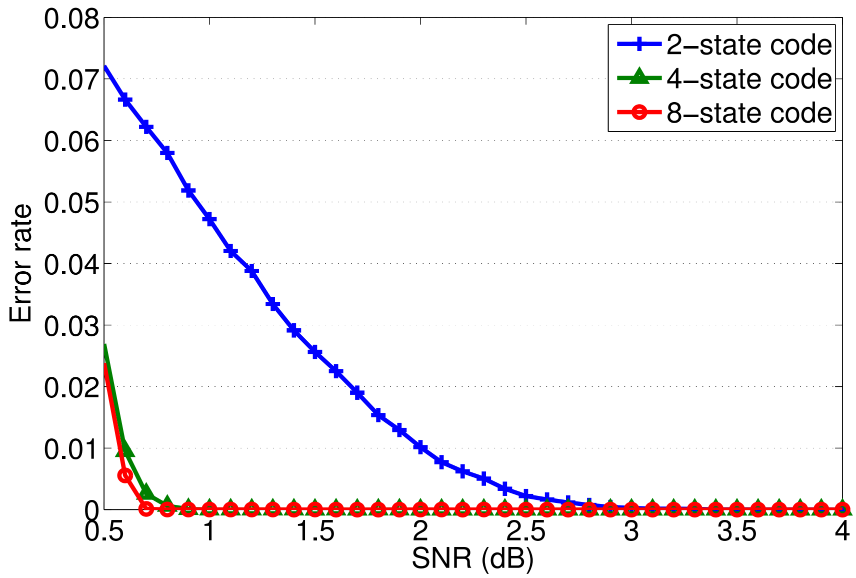

Figure 4.12: Error rate vs SNR

We can see in Figure 4.12 the error rates while using different size turbo codes. We notice that each code is capable of correcting all errors after a certain SNR. Below we show the values for which these codes can receive an error free message.

Table 4.3: Rate $r_t = \frac{1}{3}$ turbo code cut-off points

Number of states	Error cut-off point (SNR)
2	3.2 dB
4	1 dB
8	0.8 dB

These cutoff points will determine which code will be used. The FC, having the channel state information (CSI) of the node-FC channels, will pick the smallest code that will still be capable of correcting all the errors based on the SNR of the channels. From Table 4.2 we can see that for channels with SNR larger than 3.2 we can use the turbo code with the 2-state constituent CCs. For Channels with SNR between 1 dB and 3.2 dB, we use the 4-state constituent CCs, and for channels with SNR between 0.8 dB and 1 dB we use the 8-state constituent CCs.

4.8 Conclusion

We showed that using turbo codes on the node-FC channels leads to a tradeoff. It increases the number of bits transmitted per node through the channels, but decreases the number of active nodes in the network. We then determined a range of channel quality for which using turbo codes will decrease the total number of bits transmitted and significantly prolong the lifetime of the nodes. We also described how the FC can dictate the size of the code in order to minimize complexity while still having the capability of correcting all the errors in the channel.

5 Conclusions and Future Work

In this chapter we will summarize the main contributions of the thesis and present possible ideas for future work that can be done to extend on the research.

5.1 Conclusions

- Chapters 1 and 2 give a detailed description of wireless sensor networks, fading channels and turbo codes. Previous work on energy efficiency in wireless sensor networks is reviewed and the research topic of relay selection is then introduced and a thorough literature review of prior work done is presented.
- In chapter 3 we introduced the new relay selection schemes. We showed how the outage probability, number of active nodes and the expected number of bits transmitted for our schemes are minimized compared to a widely used scheme (all nodes transmit). We illustrated how the reduced number of bits transmitted translates to energy savings in the sensor nodes.
- In chapter 4, we showed how adding turbo codes to the node-FC channels can further reduce the number of bits transmitted under certain conditions in the network. We demonstrated how this will prolong the lifetime of the sensor nodes. We also introduced a scheme for the FC to be able to pick the constraint length of the codes and showed that we can achieve an error free transmission

while choosing the smallest size code.

5.2 Future work

- In our work we assumed that the CSI is always delivered error free to the FC. We also assumed that there are no errors when the FC sends feedback bits to the sensors in order to select the nodes to transmit. Addressing these issues, by looking at the possibility of having errors in those transmissions could be a topic of interest.
- An analytical derivation of the results for the “all pairs” and the “singles, pairs or triplets” schemes could be an extension to the work done in this thesis.
- Looking into making the FC capable of choosing the rate of the turbo code could also be a related topic of interest.

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