The Effects of Channel Characteristics on Relay Behavior and Position in Wireless Industrial Networks

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Abstract - In wireless industrial networks consisting of distributed sensors and actuators, the problem of providing reliable and timely communication is still one of the key challenges. Previous research has proved that relaying or so-called cooperative communications can be fruitfully deployed in wireless industrial networks. The goal of the present work is to investigate how different types of channels encountered in industrial environments affect the benefits, the behavior and the position of a relay node. We consider two types of behavior: either the relay node only retransmits a packet if it has obtained a correct copy of it, or it always retransmits the packet even if the CRC check has failed. We conduct simulations for different positions of the relay node and for two types of channels: a channel with a strong line-of-sight (LOS) represented by AWGN and one with no LOS, represented by Rayleigh fading. The results clearly show that the benefit of using relay nodes depends on the wireless channel. The best behavior of a relay node depends on if bit errors appear randomly or in bursts, whereas the best position of a relay node depends on the fading characteristics but also on the overall distance between the source and the final destination.

I. INTRODUCTION

The technical core of the work centers around relaying or cooperative communication as it is considered the most suitable technique for applying in wireless industrial sensor networks.

There are several techniques from research on coding and information theory which can be used to increase networks reliability: multiple-input multiple-output (MIMO) schemes, relaying or cooperative communication, network coding, distributed space-time coding or cooperative coding or fountain codes. In industrial networks, devices are limited by size and hardware complexity to one antenna, [1], so MIMO systems cannot be used. Also it is usually needed to transmit data from one sensor to one central node, so we cannot benefit from using network coding, which gives best results in many-to-many broadcast networks, or fountain codes which usually used in one-to-many communications. In addition, the use of low complexity, off-the-shelf components in industry generally prevents the use of sophisticated space-time codes. However, the idea of cooperative diversity using relaying looks promising.

In relaying schemes (e.g., [2]) there are a number of relay nodes that help in the transmission between a source node and a destination. These relay nodes may receive the packet correctly, even if the destination does not and then they can retransmit it to the final destination. The key advantage is that due to the fact that the source and the relay nodes have different geographical locations, it is possible to exploit spatial diversity [3]. Spatial diversity is commonly believed to be the key mechanism to improve transmission reliability over wireless channels.

One of the first examples of practical cooperative diversity protocols was proposed by Laneman, Tse and Wornell in [4]. The authors showed that relaying has the potential to improve outage performance. Cooperative communication was studied in two scenarios: amplify-and-
forward relaying and decode-and-forward relaying.

In paper [5] authors presented an algorithm for amplify-and-forward and decode-and-forward relay node placement and sensor assignment in wireless sensor networks, which attempts to reduce the probability of error. The results are presented in form of pictures with estimated geometrical shapes of regions where sensors should be optimally assigned to the same relay (for a given set of relay positions). These results cannot be fully applicable for wireless industrial networks as is this case the goal is to find an optimal relaying strategy for a given sensor, not relay node position.

The alternative approach was proposed in paper [6]. Authors presented a strategy for relay nodes placement in wireless sensor network monitoring underground tunnel infrastructure. The goal was to find the best relay node positions for a given set of locations of the sensor nodes. The simulation results showed that the choice of path loss model and fading distribution model effect the optimal amount and the positions of relay nodes. This conclusion is similar to ours. The difference is that in paper [6] authors considered only one specific kind of environment – underground tunnels.

One more simple and practically implementable protocol in which relaying and packet combining work together to improve the probability that packets are delivered within a prescribed deadline over fading channels was designed in [7]. The results indicate that such a combination can be fruitfully employed in wireless industrial networks. This paper differs from [7] as we were more interested in the effects of channel characteristics on relay behavior and position. We did not consider packet combining, but instead we carried out simulations for two different models of wireless channels.

The reminder of this paper is structured as follows: in Section II the system model is described. Following this, in Section III we describe two relaying schemes used in this paper and in Section IV we provide simulation results comparing these schemes for different placements of the source, the relay node and the destination. We conclude the paper in Section V.

II. SYSTEM MODEL

In this section we describe the network setup, the channel model and the performance measure considered in this paper.

A. Network setup

We consider the network with three stations or nodes: a source, a relayer and a destination node. All the nodes are half-duplex transceivers, working on the same frequency and with the same data transmission rate. The distance between the source and the destination is \( d \). In scenarios with a relay node, it is placed in between the source and the destination. For different simulations we used different positions: \( 0.25d \), \( 0.5d \) and \( 0.75d \), where \( d \) is the distance between the source and the destination. Fig. 1.

The value \( 0.25d \) refers to a situation where the distance between source and relay is 25% of \( d \) and thus the distance between relay and destination is 75% of \( d \).

![Fig. 1. Investigated node deployment](image)

B. Channel model

For each pair of nodes there is a wireless channel with behavior which is stochastically independent from all other channels. We assume that all channels are symmetric and all nodes are stationary. The additional interference from other systems is not taken in to account. We considered two channel models:

1. transmission errors are only result of thermal noise and path loss;
2. transmission errors are result of thermal noise, path loss and multipath fading.
The thermal noise, \( n(t) \), is a parameter in our model. It is created in the receiver circuitry and assumed to be additive white Gaussian noise (AWGN) with power spectral density \( N_0 / 2 \). We choose the standard log-distance path loss model \([10]\), \( l(d) \), where \( d \) is the distance between the transmitter and the receiver. Hence, we assume that the received signal energy is inversely proportional to \( d^\gamma \) where the path loss component, \( \gamma \), is chosen as \( \gamma = 2 \). For the second channel model we also assume frequency-flat block Rayleigh fading, \( h(t) \), on each path loss AWGN channel. It is considered that the fading remains constant during the whole period of one packet transmission. The block-fading assumption is justified by the dominance of small packets in industrial applications. For our simulations we choose a packet size of 160 bits. We draw the value of \( h(t) \) periodically from Rayleigh distribution and keep it constant for the duration of the packet. The received signal can be expressed as \( r(t) = l(d)h(t)s(t) + n(t) \), where \( s(t) \) is the transmitted signal. We assume binary phase shift keying (BPSK) modulation such that a binary 0 is mapped to \(-\sqrt{E_c}\) and a binary 1 to \(\sqrt{E_c}\) where \(E_c\) is the energy of a transmitted bit.

C. Protocol assumptions

An important thing in our retransmission scenarios is how the feedback information is delivered to the source and relay nodes. In our simulations we assumed that the source and relay node know if the retransmission is needed; the source knows if the relay node is going to retransmit or not. Thus our results can be considered as the lower bound for the possible BER. We adopted this assumption as it can help us to evaluate in general how relaying affects the resulting BER. If relaying turns out to be beneficial, our future work will be to find a scheme to provide efficient feedback information from the destination to the source.

D. Performance measure

The performance measure considered in this paper is the bit error rate (BER) as a function of the signal-to-noise ratio, \( E_b/ N_0 \) in dB, where \( E_b \) is the information bit energy and \( N_0 \) is the noise power spectral density. It should be noted that whenever we use an uncoded system without retransmissions from source or relay nodes, the energy spent for an information bit, \( E_b \), is the same as the energy of each bit transmitted over the channel, \( E_c \). However, if we have a coded system either using an error control code or using the repetition code implicit for retransmissions, \( E_b \) is no longer equal to \( E_c \). In the case of a rate 1/2 code, e.g., one retransmission of an entire uncoded packet, either from the source node or from a relay node, we have \( E_b = 2E_c \). A system allowing retransmissions only when needed will have different code rates for different attempts and thus the overall code rate is the average of all these attempts. The simulation is thus carried out for a specific \( E_b/N_0 \) and the BER obtained is then plotted at the resulting \( E_b/N_0 \) after compensating for the increased energy due to the retransmissions.

III. PROTOCOL DESIGN

In this section we explain how the relaying schemes are organized, how the relay node determines if it should retransmit the packet or if it is better to let the source retransmit. We evaluated two different scenarios: “always” and “only correct”. We call these strategies “always” and “only correct”, since they cannot be directly translated to the commonly used nomenclature “decode-and-forward” and “amplify-and-forward” (as we do not have access to the received observables, due to the use of commercial transceivers).

A. “Always”

While working according to the first algorithm, “always”, the relaying node is supposed to forward the message without checking if it is correct or not. The nodes work as follows: the source transmits the packet, the relay and the destination listen to receive it. The destination node checks the correctness of the packet. If the data is not correct, the relay node sends the packet, if it has got it. The relay node does not check if its packet is correct or not. After that the resulting BER is calculated.
B. “Only correct”

The second scheme, “only correct”, assumes that the relayer checks the packet first and sends it only if it has a correct copy. The source first transmits the packet, the destination node listen to try to receive it and checks the correctness. If the received data contain errors, the relayer can retransmit the packet but only if it has a correct copy. If the packet the relayer has is erroneous, it does not transmit anything. Instead, the source retransmits the packet.

IV. RESULTS

In this section we present the results for the BER versus the ratio between the bit energy, $E_b$, and the noise, $N_0$, for ARQ schemes with different parameters. The BER is number of bits still erroneous after all possible retransmissions. For reference, two schemes without relaying are also plotted on all of the pictures: the first one does not allow retransmissions at all, the second one allows only one retransmission but from the source only, i.e., no relaying.

A. AWGN channel

First two simulations were carried out for the channel model with only with thermal noise and path loss. The results are shown on Fig. 2 and Fig. 3. It can be seen from the figures that the introduction of one retransmission from the source not only does not improve the performance, but even increases the BER. The retransmission is made by the same source, from the same position, through the same channel, thus the second transmission gives the same probability of error that we had after the first transmission. In total that leads to an increase of BER when using retransmission from the source. The reason for that is that when bringing in retransmissions we achieve data redundancy. Introduction of redundancy from a retransmission is equivalent to two times increase of the energy spent for one received information bit without necessarily correcting the corresponding number of erroneous bits. Fig. 2 shows the comparison while retransmitting from three different relay nodes. All the relay nodes work according to the “only correct” algorithm. The relayers are placed at $d/4$, $d/2$, and $3d/4$, where $d$ is the distance between the source and the destination node. In the legend “relay at 25% (50% or 75%)” means that the relay node is situated at the distance $0.25d$ ($0.5d$ or $0.25d$) from the source and $0.75d$ ($0.5d$ or $0.25d$) from the destination node. It can be seen from the figure that BER decreases while the value of $E_b/N_0$ is growing.

![Fig. 2. BER for schemes with relay nodes at different locations (AWGN channel)](image-url)

Relay node at 25% is the closest to the sender, so it first starts receiving correct packets and, thus, taking part in the cooperative communication scheme also for low $E_b/N_0$. However, it is still 75% of the way left to the destination, and therefore this relay node may not be successful with its retransmission. Relayer at 75% is closer to the destination than to the source. Because of that it begins receiving correct packets only when the $E_b/N_0$ value is more than 4 dB. The best results can be achieved while using a relay node at 50%.

In Fig. 3 two different relay schemes are compared: “always” and “only correct”. The relay node is placed exactly in the middle between source and destination in the both cases, as this was the best option according to the findings in Fig. 2.
It can be seen from the figure that the scheme where the relay node acts according to the “always” scenario gives the lowest values of bit error rate. The reason for that is gain achieved by the reduced distance, i.e. the transmission of a packet from the source to the destination leads to a higher amount of errors than a transmission from the source to a relay node followed by a transmission from the relay node to the destination. Therefore it is more beneficial to relay a packet with small amount of errors, which was received by relay node, than to retransmit a completely correct packet from the source. Had the channel been of a burst nature such that the packet received at the relay node contained several errors, the result would likely be affected.

B. Rayleigh fading channel

The next two figures, Fig. 4 and Fig. 5, correspond to the case of fading channel, i.e., errors appear in bursts. Fig. 4 shows the comparison between the retransmission effectiveness while relay nodes are placed in three different positions. All the nodes work according to the “only correct” algorithm.

From Fig. 4 it can be seen that for a fading channel even one retransmission from the source improves BER. In channels with fading, errors come in bursts, thus one retransmission leads to correcting of several erroneous bits. During the next time slot needed to retransmit the packet, channel characteristics will be different, so the data can be successfully delivered even from the same source as it was previously transmitted. In the case of fading channel the best position of a relay node depends on the overall distance between the source and the final destination.

Fig. 5 shows the results of using one relay node in two different scenarios: “always” and “only correct”. In both cases the relay node is located exactly in the middle between source and destination.
schemes in the used channels. In a channel with fading, errors appear in bursts, i.e. the major part of a short industrial packet can be corrupted. That means that if relay node gets an erroneous copy of the packet, it is better to let the source retransmit rather than relaying the corrupted packet.

V. CONCLUSIONS

The main goal of this paper was to evaluate how different types of communication channel affect the choice of the relaying scheme. We built several simulation models and tried different relaying scenarios for two channels. From the simulation results it can be clearly seen that the benefit of using relaying is very different depending on the channel model. Thus, as the next step we plan to carry out a set of measurements on the territory of real industrial settings. From the measured data we plan to build a channel model which can be used for industrial environment characterization as well as for evaluating our relaying schemes.

REFERENCES