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Scheduling relay nodes for reliable wireless real-time communications

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Scheduling Relay Nodes for Reliable Wireless Real-Time Communications

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Abstract

We consider wireless relay networks for use in industrial applications with strict requirements on both timely and reliable communications. Frequently, more than one suitable relay node is available for retransmitting an erroneous packet. However, if commercially available transceivers are to be used; concurrent transmissions will result in collisions. Further, in a typical industrial network, there may be several data packets that need to travel from source to destination during the same time period. Consequently, relay nodes need to be scheduled to data packets and time instances such that as many packets as possible can be received at their destinations with as high reliability as possible before their respective deadlines. Our goal is thus to increase the data reliability in industrial wireless networks, while respecting real-time deadlines.

1. Introduction

The problem of jointly guaranteeing timeliness and data reliability of packet transmissions in industrial wireless networks remains a key challenge [1]. Retransmitting erroneous packets is a commonly used method to increase the data reliability in the network. However, due to the timing constraints, the number of retransmissions must be limited and we therefore need to make the best use possible of each retransmission such that sufficient reliability can be achieved within a reasonable time limit. Various information theoretical results have demonstrated the advantages of one or several relay nodes assisting with retransmissions in a wireless network, e.g., [2]. However, if commercially available transceivers intended for wireless local area networks should be used; only hard decision detector outputs are typically available. In addition, concurrent transmissions on the same frequency channel will result in collisions. Therefore information theoretical results

are not directly applicable. This implies that it may not always be beneficial to use relay nodes. However, it was concluded in [3] that a relay node in a network of commercially available transceivers can increase the reliability of a packet at the destination node, by taking over a retransmission if a number of criteria are satisfied:

1. The relay node possesses a correct copy of the packet to be retransmitted.
2. The relay node is located closer to the destination node than the source node is.
3. The relay node has a reasonable channel to access the destination node, i.e., it is not in outage, currently experiencing deep fading or interference.

For a network with fixed nodes, criterion 2 is known *a priori*, whereas criteria 1 and 3 always are random and time variant. Typically, criterion 1 is only known internally within each relay node, whereas criterion 3 could be known by the destination and potentially by the respective relay nodes if packet success rates are continuously monitored. However, for rapidly changing channel conditions, criterion 3 becomes more difficult to assess.

In many practical scenarios, more than one node is a suitable relay node. This set available relay nodes is thus of random size and varies over time. To avoid collisions one relay node must be selected from the set. Three approaches for relay selection can be imagined [3]: source-controlled relay selection, relay-controlled relay selection and destination-controlled relay selection. When a source-controlled method is used in a static wireless network [3], the source have to decide upfront, without knowledge of criteria 1 and 3, which relay nodes to select. With relay-controlled relay selection [4] the selection procedure becomes decentralized and therefore more vulnerable to collisions, but each relay node knows criteria 1 and 2, and potentially also criterion 3. Finally, with destination-controlled relay selection, we again have a centralized procedure with knowledge of criterion 2, limited knowledge of criteria 3, but no prior knowledge of criterion 1.

Not all nodes in the network are necessarily involved in every transmission. Further, some nodes may be needed by more than one transmission simultaneously. This is when scheduling becomes important. *Given a set*

of data packets, each with a dedicated source and destination, a deadline and its current data reliability at the destination, how do we assign retransmissions to different relay nodes such that the deadline miss ratio is minimized? We define missing a deadline as not having achieved sufficient data reliability at the destination at the time of the deadline. Note that for each data packet there exists a set of potential relay nodes that can be classified according to the three criteria listed above.

In distributed scenarios, each node may potentially be able to help n other nodes, but must individually decide whom to help, without knowing if other relay nodes may be able to assist. In [5] this idea is generalized into a protocol called fixed priority selection, which allows each node to assist n other nodes and provides diversity $n+1$ over the network. For example, if each node agrees to cooperate with (at least) two other nodes, network-wide diversity of 3 can be achieved despite unavailability of information about network geometry and lack of centralized control. Our work differs from [5] in one important aspect; rather than trying to achieve full diversity or minimize the average outage probability over all users, we attempt to minimize the deadline miss ratio.

Section 2 contains our system model, basic assumptions and performance measures whereas Section 3 describes the work in progress and Section 4 contains a short summary.

2. System Model

We consider an example scenario with seven stationary network stations or nodes, Figure 1. For each pair of nodes there exists a wireless channel with error behavior that is stochastically independent of all other channels. We assume initially that all channels are symmetric and all nodes are stationary. Further, in the first phase of the work we do not take additional interference from other, co-located systems into account and thus channel errors are the result of thermal noise, pathloss and multipath fading. The thermal noise, $n(t)$, created in the receiver circuitry is assumed to be additive white Gaussian noise (AWGN) with power spectral density $N_0/2$. The chosen path loss model, $l(d)$, is the
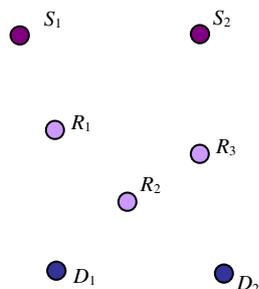

Figure 1. Network scenario

standard log-distance model [6], where d is the distance between the transmitter and the receiver. Hence, we assume that the received signal energy is inversely proportional to d^γ, where the pathloss component, γ, is chosen as $\gamma = 2$. We further model the fading as a two-state Markov chain. During either of the two states the fading attenuation is constant, but one state can be considered "good" and the other "bad". We will try different attenuations and different state holding times to determine how the protocol reacts to these parameters. For example, the breakpoint where the fading state is more influential than the pathloss is of particular interest. The received signal is then $r(t) = l(d)h(t)s(t) + n(t)$, 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.

We assume that all packets carry a CRC checksum at the end of the packet. The checksum covers the whole packet and is assumed to have a negligible rate of undetected errors. Thus, this CRC check can be used to determine two things: if a retransmission is necessary and if the quality of a received packet is good enough to relay. The former check is made by the destination and the latter by each potential relay node individually. The feedback channel is assumed to be error free and thus no acknowledgement messages are ever lost or corrupted. Further, the additional energy used to transmit acknowledgement packets is ignored.

Two major performance measures for industrial communications are *success probability* and *confirmation delay* [3]. The success probability is the probability of delivering a packet successfully such that the source receives an acknowledgement within a prescribed deadline. This measure is directly related to the deadline miss ratio. The confirmation delay measures the duration between when the source starts and stops working on a packet – note that stopping can happen either due to reception of an acknowledgement or deadline violation. This measure indicates how fast sufficient reliability is achieved.

3. Work in Progress

We consider two possible scenarios. In the first one each node is either polled periodically by a central controller, or has a dedicated time slot in which to transmit. We term this the distributed scenario. In the second scenario a central controller decides which node to poll or assign a time slot to at any given moment. This scenario is termed the centralized scenario. In both scenarios all transceivers that have not yet achieved a correct copy of the intended message are listening.

Assume that at a particular time instant in the distributed scenario, node R_2 is allowed to transmit. It must then decide which packet to retransmit based on a number of criteria:

i. Which of the packets that needs to be retransmitted does R_2 possess a correct copy of? The answer to this question is influenced by how many packets that currently needs to be retransmitted, i.e., the channels between individual source-destination pairs, $S_1 \Rightarrow D_1$ and $S_2 \Rightarrow D_2$, as well as if R_2 managed to correctly receive them, i.e., the individual channels between the respective sources of the packets and R_2, i.e., $S_1 \Rightarrow R_2$ and $S_2 \Rightarrow R_2$.

ii. How much is the reliability of a particular packet increased at the destination if R_2 were to retransmit it? The answer to this question is influenced by the individual channels between R_2 and the respective destinations of the packets, i.e., $R_2 \Rightarrow D_1$ and $R_2 \Rightarrow D_2$.

iii. Which message is most urgent to transmit? The answer to this question is influenced by the deadline of each message – but also potentially by knowledge of the static network, the time slots (or polling scheme) and thereby if another node with an upcoming transmission opportunity has a better chance of retransmitting the message than R_2.

In the centralized scenario, a central controller decides which relay node to poll based on the following criteria:

i. Which message is most urgent to transmit?
ii. Which relay node has the best chance of retransmitting it?

Note that if the relay node selected by the central controller does not possess a correct copy of the most urgent message it may be unable to assist.

In the centralized scenario the bandwidth can be distributed unevenly between relay nodes with the aim to reduce the deadline miss ratio of all messages in the network. In the distributed scenario, the relay nodes share the bandwidth equally, but instead different messages are prioritized within each relay node. It is not obvious that it is always best to transmit the message with the earliest deadline. The performance of the two scenarios is greatly influenced by the knowledge of different parameters at different places in the system. For example the central controller and the individual relay nodes may or may not know instantaneous channel conditions and which nodes that currently possess correct copies of which packets. Hence, if no relay node currently has a good channel to the destination, it may be better to postpone the most urgent message for a less urgent until a better opportunity presents itself. With the objective of taking advantage of spatial diversity [7] it may also be relevant to enforce that each retransmission takes a different way through the network than previous transmissions have.

The problem of scheduling retransmissions to relay nodes for increased reliability while minimizing the deadline miss ratio extends the work in [3] and [4] since not only relay selection is considered but also multiple messages with priority based on deadlines and data reliability. It differs from [5] since we consider minimizing the deadline miss ratio rather than trying to achieve full diversity or minimize the average outage probability over all users. Finally, it differs from traditional real-time scheduling since not only the deadline is considered but also the reliability.

4. Summary

In this paper we have presented our ongoing work on message scheduling in wireless relay networks. We believe that the proposed approach of scheduling retransmissions to relay nodes based on both timing and reliability is a step towards deploying wireless relay networks for applications with strict requirements on predictable message transmissions in harsh industrial environments.

Once the work presented in this paper is completed, a future extension is to adapt the approach such that it can cope with message transmissions on multiple channels, i.e., parallel transmission of messages.

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