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PRIOREL-COMB: A Protocol Framework Supporting Relaying and Packet Combining for Wireless Industrial Networking

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Abstract

The PRIOREL-COMB framework presented here integrates support for relaying and packet combining into wireless industrial networks. The selection of suitable relay nodes is made using distributed algorithms which includes different eligibility tests as well as different priority assignments. The framework improves performance in terms of probability to successfully deliver packets before their deadline and it can be implemented on top of commercial transceivers without modification of the physical layer. This class of protocols will therefore be a valuable addition to future wireless industrial communication systems.

1. Introduction

In wireless industrial networking [1] the problem of jointly guaranteeing timeliness and reliability of packet transmissions is still one of the key challenges. For such critical real-time transmissions the goal is to maximize the probability that a packet can be successfully transmitted before its associated deadline. In industrial networking, however, it is not only the unfriendly error properties of wireless channels that influence the design of appropriate transmission schemes and protocols, it is also a number of other constraints that should be taken into account in such designs. One important constraint is the almost mandatory usage of commercial wireless transceivers designed for office and home environments, like those available for the IEEE 802.11 [2] standard. These transceivers are not optimized for usage in harsh industrial environments with much metallic clutter and obstacles.

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The primary goal of the present work is to design and investigate transmission schemes and protocol mechanisms for wireless industrial networks which on the one hand improve the probability of successful packet transmission before a deadline, and which on the other hand can be implemented on top of commercially available transceivers with their limited functionality on the physical layer. The technical core of this paper centers around two fundamental approaches:

Relaying : In relaying schemes [3, 4, 5] there are a number of *relay nodes* that help in the transmission between a sender and a receiver. These relay nodes possibly receive the sender's packet and can assist in the task of performing retransmissions – a relay is thus incorporated in the operation of an ARQ protocol between sender and receiver. The key advantage is that due to the fact that the sender and relays have different geographical locations, it is possible to exploit *spatial diversity* [6]. Spatial diversity is commonly believed to be the key mechanism to improve transmission reliability over wireless channels. It roughly means that one should try to arrange transmissions such that a receiver receives multiple copies of the same signal from different spatial directions. In the best case the different signals are faded independently and the probability that *all* signals are subject to severe fading decreases with the number of independent signals.

Packet Combining : In packet combining schemes a receiver (which in our case can be the final destination of a packet as well as a potential relay) does not discard erroneous versions of a received packet but keeps the information contained in those copies and tries to use it for decoding the original packet. This is also referred to as type-II or type-III hybrid ARQ [7, 8, 9].

The combination of relaying and packet combining is promising, since a receiver has some chance to restore a packet from multiple erroneous copies received not only from the source, but also from relayers, exploiting the spatial diversity found in wireless networks. The concept of relaying is well-known and lots of research has been carried out by the information theory community to assess the achievable capacity of the relaying channel and to find relaying schemes that are theoretically good [5, 10, 11]. It is, however, another matter to design real and practical protocols on the medium access control (MAC) and link-layer level which incorporate relaying. This has not yet been considered in detail in the literature and is an area of active research. In this paper we present PRIOREL-COMB, a protocol framework which supports both relaying and packet combining, and which takes the specific properties of industrial applications and industrial communication systems into account. In this paper we investigate the PRIOREL-COMB scheme under idealized conditions (no external interference, a certain amount of global network knowledge in the network nodes) in order to focus on the effectiveness of the mechanisms themselves and show that they provide significant gains in terms of joint timeliness and reliability.

The paper is structured as follows: Related work is surveyed in Section 2 and the adopted system model in Section 3. In Section 4 the protocol framework and the packet combining method used in this paper are presented. A set of reference simulation results are presented in Section 5, whereas in Section 6 we investigate a number of relaying strategies over random station placements. Finally, our conclusions are given in Section 7. An extended version of this work can be found in an upcoming technical report [12].

2. Related Work

The general idea of *relaying* approaches, sometimes also referred to as *cooperative diversity* [3, 4, 5, 10, 11, 13] has been discussed already in the 70s, and a lot of information-theoretic results concerning the capacity of relay channels and the achievable reliability are available. Relaying is one particular approach to exploit spatial diversity on wireless channels [6]. In contrast to other spatial diversity schemes, most notably MIMO systems, relaying schemes can operate solely with single-antenna stations.

In the last few years, research on the design and evaluation of practical MAC and link layer protocols involving relaying has gained momentum, mostly with the goal of improving throughput performance over existing WLAN technologies like IEEE 802.11 (see for example [14, 15]). In the scope of wireless industrial communication systems, however, relaying has so far not been studied in detail. In [16] a relaying scheme based on polling has been considered for industrial networks, in which stations are frequently polled by a central station to gain the right to

access the medium. When the poll packet is erroneous, it could be relayed by another network member to the target station. Secondly, the central station can also act as a relayer in peer-to-peer communications among stations. Further, in [17, 18] a source-controlled relaying protocol framework designed explicitly for small packet sizes is presented and investigated under different channel models.

3. System Model

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

3.1. Network setup

Many industrial networks have a star topology, i.e. there is a central controller (henceforth called *center*) coordinating a set of other sensor or actuator stations (collectively called *stations*). The center and the stations are the *network members*. We assume that the network consists of the center S_C and a number m of stations, $S_1, \dots, S_m$. A wireless medium is used, and it is assumed that each station S_i is in the communication range of the center S_C , but not necessarily in the communication range of all the other stations. Since the geographical size of factory networks is typically small, we disregard the propagation delay. The center polls the stations frequently, and once being polled, a station has the right to use the medium exclusively for some finite amount of time. We concentrate on the uplink direction, i.e. on the case where stations want to transmit packets to the center. To achieve this, a station can potentially use all other stations as relayers.

Regarding the number and placement of network members we will make the following assumptions. The center is fixed, and a certain member is fixed as the transmitter. One particular assumption for the remaining network members (which can take the role of relayers) is called *random placement with density λ* . In this placement the stations are deployed in a prescribed area according to a two-dimensional Poisson point process of density $\lambda > 0$ [19, Chap. 16]. More specifically, when we have an area A of volume $|A|$, the number N of members is given by $\max\{1, X\}$ where X is drawn according to a Poisson distribution with parameter $\lambda \cdot |A|$. Following the definition of a Poisson point process, the members are placed according to a uniform random distribution over A . This ensures the presence of at least one potential relayer.

It is assumed that basic information about the network (like the number m of stations and their addresses) is known to all network members. It is also assumed that each network member knows the identity of the center and all its immediate neighbours, i.e. all other members that can be reached with a direct transmission. All members use simple half-duplex wireless transceivers. When two or more stations transmit in parallel, a collision at the center results, rendering all packets undecodeable. All network

members work on the same frequency band and always use the same transmission data rate.

We assume that all packets are equipped with a perfect CRC checksum, i.e. we ignore residual errors. The standard behavior of a wireless transceiver is to throw away packets having an incorrect CRC checksum. We assume, however, that this feature can be disabled and that the transceiver can hand over erroneous packets to the higher layer, marked with a flag indicating a checksum error. Such a feature is available for example with the IEEE 802.15.4 compliant ChipCon CC2420 transceiver [20]. Another assumption regarding the transceiver is that it has the ability to detect the presence of energy on the channel, possibly without having acquired carrier- or bit-synchronization. Such a feature is also available with the ChipCon transceiver. We assume further that for acknowledgement packets it is sufficient when the source station senses signal energy on the channel during the acknowledgement time slot and thus it is not required that the source decodes the acknowledgement successfully. This approach is reasonable under our assumption that there are no external interferers. If such interferers (from different systems or from systems of the same type) are present, there is the danger of mistaking this interference for an acknowledgement.

The center is assumed to frequently transmit packets. These can be data packets, poll packets or other control packets. While the precise nature of these packets is not important, it is important to assume that they occur frequently and carry some sequence number, so that the stations can use them as a way to estimate packet error rates towards the center station. This information can be used by relaying schemes.

3.2. Wireless channel model

For each pair of members we assume that there exists a wireless channel with error behavior that is stochastically independent of all other channels. In this paper we restrict to scenarios where channel errors result only from thermal noise and path loss – denoted *static model*. All the channels are symmetric. The static model thus models each channel as an additive white Gaussian noise (AWGN) channel with distance-dependent pathloss. The thermal noise is created in the receiver circuitry and is assumed to be an AWGN process with noise power spectral density $N_0/2$. The value N_0 is a parameter in our system. As a pathloss model we choose a variant of the standard log-distance model [21] which is given by:

$$\text{PL}(d) = \begin{cases} 1 - \text{PL}_0 \cdot \frac{d}{d_0} & : d \leq d_0 \\ (1 - \text{PL}_0) \left(\frac{d_0}{d}\right)^\gamma & : d > d_0 \end{cases}$$

where d is the distance between sender and receiver, d_0 is the so-called far-field reference distance¹, PL_0 is the pathloss at the reference distance, and γ is the pathloss exponent, which typically assumes values between 2 and 6.

¹This far-field distance is antenna-dependent. For the case of wireless LANs and PANs a value of $d_0 = 1$ m is a typical assumption [21].

In our pathloss model we therefore have a linear pathloss for distances smaller than the far-field distance, while beyond this distance the pathloss obeys a power law. In terms of a signal representation, the received signal $r(t)$ can be represented as:

$$r(t) = \text{PL}(d) \cdot s(t) + n(t)$$

where $s(t)$ is the transmitted signal and $n(t)$ is an AWGN process with noise power $N_0/2$. When P_t is the transmitter output power, the signal power at the receiver is given by $P_r = P_t \cdot \text{PL}(d)$. R is the channel bitrate and the bit error rate depends on the modulation scheme and the signal-to-noise ratio $\frac{E_b}{N_0}$ where E_b is the received energy per bit. With our assumptions this ratio is given by:

$$\frac{E_b}{N_0} = \frac{P_r}{R \cdot N_0}.$$

When for example BPSK modulation is used, the resulting bit error rate is given by [22, Sec. 5.2]:

$$\text{BER} = Q\left(\sqrt{2 \cdot \frac{E_b}{N_0}}\right),$$

where

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{(-t^2/2)} dt$$

is the well-known Marcum-Q function.

3.3. Performance Measures

We consider the following performance measures:

- The *success probability* is the probability that a packet can be successfully transmitted before its associated deadline. By successful we mean that the transmitting station must receive an acknowledgement packet for it. The deadline allows transmitting the packet, the corresponding acknowledgement and a fair number of retransmissions, either carried out by the source station or some relay.
- A secondary performance measure is the actual delay experienced by a successful packet. As delay we count the time between the source station starting its service on a packet and the source receiving the corresponding acknowledgement from the center. This delay is closely related to the number of trials that are actually needed to transmit a packet successfully. Less time spent on one packet increases the bandwidth available for other packets.

4. Protocol Framework and Combining Scheme

In this section we describe the PRIOREL-COMB framework. The name is short for “PRIOrity-based RELaying protocol with packet COMBining”. General considerations regarding relaying in industrial communication networks can be found in [18].

The PRIOREL-COMB framework works on the following basic premises:

- A relay only becomes active when it possesses a correct copy of the packet, i.e. when it was able to obtain a correct packet from combination of previous transmissions from the source or from other relayers. In [17] it was shown that this is more advantageous as compared to the case where relayers always forward the packet even if they have an erroneous copy.
- Any station that has successfully decoded the packet from the source station decides independently whether it will become a relay. The source does not exercise any control here. Consequently, there can be several relayers resulting from the broadcast property of the wireless medium and without coordination their retransmitted packets can collide at the destination.
- For the coordination of multiple relayers, no extra control packets shall be used. For wireless industrial networks with stringent timing constraints we want to avoid these because of complexity reasons and because of the extra delays they induce.

4.1. Description of the PRIOREL-COMB protocol framework

The “classical” packet format, consisting of a physical layer (PHY) header, a MAC header, the data and a trailing checksum field (frame check sequence, FCS) is displayed in Figure 1. The MAC header contains at minimum addressing fields (for source and destination address), a sequence number and some further control fields, all summarized into an FC (frame control) field. The FCS concludes the packet.

Figure 1. Classical PHY/MAC-packet format

Our relaying framework requires some modifications to the classical packet format, as displayed in Figure 2. The main change is an extension of the MAC header, inserted between the regular MAC header and the data. This header extension contains two information fields: `RelSlots` denotes the total number of relaying slots, `CurrSlot` denotes the current relaying slot and a separate header checksum (header FCS). The trailing FCS still covers the whole packet, including the new header FCS. The need for a separate header checksum can be explained as follows: since we want to enable the relayers and the destination to perform packet combining, we want to make sure that different copies of the same packet (as identified by source and destination address as well as sequence number) are used for packet combining. To rule out that copies from different packets are used, the validity of address information and sequence numbers must

Figure 2. PHY/MAC-packet format required by our relaying framework

thus be ensured. A second reason is that the extra header fields related to relaying must be reliable as well.

All stations except the source perform the following steps upon reception of a new packet. They first check the trailing FCS. If this is correct, the station is said to *possess the packet*. If the trailing FCS is not correct but the header FCS is (hence, there are errors in the user data or the trailing FCS) and the station does not yet possess the packet, the packet is added to a local *packet cache* whenever its source address, destination address and sequence number match those of the other packets in the cache – otherwise the cache is cleared before the new packet is stored. When the station receives a packet with incorrect header FCS, the packet is silently discarded. When the packet cache contains more than one (erroneous) copy of the same data packet (received either from the source or from some previously active relayer), the station attempts to perform *packet combining*. If this attempt is successful (i.e. the resulting packet has a correct trailing FCS), the station possesses the packet. The actual packet combining scheme is described below.

A packet transaction is subdivided into rounds, Figure 3. The length of individual rounds is controlled by the source station and within the time frame before a packet deadline, the source station might schedule multiple rounds of varying lengths. A round always starts with a packet transmission from the source. There are two types of rounds:

- In a *relaying round* there are a number of *relaying slots* available. The number of relaying slots is controlled by the source and this number is signalled to the relayers with the `RelSlots` field. The `CurrSlot` field is a counter indicating the number of the current relaying slot within a relaying round. It is initialized to zero by the source at the beginning of a round and then incremented by each relayer.
- In a *direct round* there are no relaying slots and consequently no active relayers. A direct round consists only of the data packet transmitted by the source and possibly an acknowledgement packet from the destination. A direct round is signalled by the source by setting the `RelSlots` field to zero.

The source schedules rounds according to its own policy. It can choose any number of relaying slots in a relaying round as long as the round can be fully handled within the remaining time to the packet deadline. The maximum number of relaying slots during a relaying round is a protocol parameter, denoted R_{max} . It might happen at times

Figure 3. Basic outline of the PRIOREL-COMB framework

close to the deadline that a relaying round is not feasible, but a last direct round is.

We now explain the structure of a relaying slot. A relaying slot has a size sufficient to accommodate one retransmission trial by a relayer, the acknowledgement packet from the destination (if any) and also time required to resolve contention between multiple relayers. The contention among several relayers is solved by the use of so called *minislots*. Each relaying slot starts with a number of M minislots, numbered from 0 to $M - 1$. The minislots start the moment when the source and the relayers have determined that the destination has not sent an acknowledgement for the data packet transmitted by the source (or by a relayer in a previous relaying slot). The size of a minislot is chosen such that one transceiver-turnaround operation and an energy-detect or carrier-sensing operation can be performed within a minislot.² The contention process works as follows: a relayer picks a *priority value*, say i , which is a number between 0 and $M - 1$. An active relayer R_1 that has drawn priority $i = 0$ starts transmitting in the first minislot. When the active relayer R_1 has drawn minislot $i > 0$ it remains in receive mode during the first $i - 1$ minislots. If another active relayer, e.g., R_2 starts transmitting in a previous minislot, relayer R_1 notices this from finding energy on the medium, waits for the end of R_2 's data packet and senses the medium for the presence of an acknowledgement. When there is an acknowledgement, relayer R_1 stops further actions, otherwise the next relaying slot starts. On the other hand, when no other relayer has started in the previous $i - 1$ minislots, the relayer R_1 switches its transceiver into transmit mode at the beginning of minislot i (without doing an additional carrier sense operation) and starts to transmit the packet. At the end of the packet, the source and all the relayers (including R_1) listen for the presence of an acknowledgement packet (or at least of energy). If there is nothing on the medium, the next relaying slot starts if there is still

²Stated differently, a minislot should be just large enough so that at the beginning of a slot $i + 1$ it is known whether someone else started in slot i or not.

one available in the current relaying round. The source and each relayer are individually responsible for properly tracking the current relaying slot. They achieve this by tracking ongoing transmissions and by properly updating the *CurrSlot* field in the relaying MAC header.

As a special case it might happen that the packet sent by the source is not correctly received by any other node. In this case there are no relayer candidates and especially no active relayers and all the minislots following the failed trial of the source remain empty. The source tracks the minislots and starts the next round with its own transmission of the data packet (provided there is still sufficient time for a relaying round).

A crucial point in the overall scheme is the activation of relayers. For a node to become a relayer it is of course a necessary condition that it possesses the packet. When this condition is fulfilled, the node performs an *eligibility test* to decide whether it really wants to become an *active relayer*, i.e. a relayer that participates in the minislot-based contention process. This eligibility test can be based on different criteria, for example on an estimate of the bit / packet error rate between the relayer candidate and the destination – a node who itself has a bad channel to the destination is not a good relayer. After the eligibility test has decided that a node should indeed become an active relayer, another important decision has to be made: the active relayer has to pick a priority value. The eligibility test and the choice of priority value together form the relaying policy which a node follows and this relaying policy is a major design aspect of the whole protocol framework. The eligibility test and the priority assignment are repeated at the beginning of each new relaying slot.

Summarizing the above description, the (possibly random set of) active relayers access the channel within a relaying slot according to a CSMA scheme with priority-dependent initial backoff. In this framework a number of issues arises:

- When the priorities of different active relayers are the same, collisions arise. It might also happen that two active relayers with different priorities are hidden terminals to each other, i.e. the relayer having chosen a later minislot does not hear that the transmission has already started.
- The usage of a CSMA-based scheme for priority resolution among active relayers makes the framework susceptible to interference from co-located systems.

The fundamental control knobs available in this protocol framework (and known *a priori* to all members) are (i) the number M of minislots, (ii) the number R_{max} of relaying slots (iii) the assignment of priorities to stations, (iv) the eligibility test, and (v) the precise packet combining strategy. The choice of the number M of minislots as well as the choice of R_{max} will be influenced by the deadline and the expected number of active relayers, which in turn is influenced by the member density, the packet combin-

ing process, and policies like the priority assignment and eligibility test.

4.2. Description of the Packet Combining Scheme

Packet combining schemes, termed type-III hybrid ARQ schemes [9], have the property that the receiver does not throw away erroneous copies of a packet but instead uses the information contained therein by combining all copies pertaining to the same source packet. In the present case, packet combining has to be performed on the sequence of bits that the transceiver delivers after demodulating a packet. Packet combining can be applied the same way both in the relay nodes and in the destination node.

A simple example of a combining scheme operating on demodulated bits is bitwise majority voting (MV), which can be uniquely applied for any odd numbers of packets in the packet cache. For any even number of packets MV cannot be directly applied. In this paper we therefore use an algorithm, which combines MV with *combinatorial testing*, and which runs each time a new packet is added to the cache. It works as follows: whenever the number of packets stored in the cache is odd, the receiver performs bitwise MV on all stored packets. If the resulting packet checksum is correct, the packet is accepted. Whenever the number of stored packets is even, the receiver performs bit-wise MV over all packets, but memorizes those bit positions that have the same number of zero and one votes (termed *undecided bits*). Let their number be n . For the undecided bits a combinatorial testing procedure is adopted in which different allocations of zeroes and ones to the undecided bits are tested (the total number of distinct zero-one allocations to the undecided bits is 2^n). For each tested allocation a checksum test is performed and if this test is successful the packet is accepted, otherwise the next allocation is tried. The receiver is assumed to have the ability to test 2^m allocations within the time needed to send an acknowledgement. It is anticipated that this requires hardware support. The receiver stops when the checksum is correct or when 2^m allocations have been tested without success. In the remainder of the paper we assume that $m = 8$ holds, i.e. up to 256 allocations can be tested.

5. Reference Simulation Results

In this section we present reference simulation results for a specific scenario without any relayers but with packet combining in place.

5.1. Methodology

For evaluating the protocols we have adopted a simulation-based approach. Specifically, simulations were made using a proprietary discrete-event simulator written in Common Lisp [23, 24]. The simulation handles one packet at a time: one packet arrives to the source node, this packet is then handled by the protocol and only when the outcome for this packet is known (either success

PHY parameters	Values
Transmit power P_t	1 mW (-30 dB)
Noise power N_0	-173.0 dBW/Hz
Reference distance d_0	1 m
Reference path loss PL_0	-50 dB (see [26, 27])
Path loss exponent γ	3
Modulation and data rate	BPSK@250 kbps
Transceiver turnover times	40 bit times
MAC- and PRIOREL Parameters	Values
MAC header size	60 bits
Relaying extension header size	16 bits
MAC packet trailer (FCS)	16 bits
Acknowledgement size	56 bits
Minislot size	80 bits
Simulation precision parameters	Values
Confidence level	1%
Required absolute prec.	1%
Minimum # simulated packets	10000

Table 1. Fixed simulation parameters

or failure) the next packet arrives. This, together with the “memoryless” channel model, implies that the simulation is of regenerative type. Therefore, to achieve a prescribed statistical significance for one set of parameters, it suffices to run the simulator for a sufficient number of independent packets, termed a *simulation run*.

The stopping rule for an individual simulation run (a replication) is based on the observed probability for successful delivery of a packet before its deadline. As soon as the confidence interval of this probability at a confidence level of 1% has reached a half-width of 1%, the simulation is stopped. However, a minimum number of 10,000 transactions is always simulated, and in some scenarios more. Since these confidence intervals are so tight, we prefer not to indicate them in the graphs (as error bars), because they would be indistinguishable from individual points.

5.2. Reference results

In the next section we will investigate various scenarios and relaying schemes. To make those results comparable to the reference results in this section, we fix a number of parameters used for all the simulations. The reference results provided here allow on the one hand to assess the effectiveness of packet combining in a scenario without any relayers, and on the other hand the reference results can be compared against the results with relayers in place to show the improvements.

The major fixed parameters for all the following scenarios are summarized in Table 1. The source is placed at position (0, 0) and the destination at position (12, 12), no further stations are present. All geographical units are in meters. The physical layer parameters are oriented towards the PHY parameters of the 2.4 GHz PHY described in the IEEE 802.15.4 standard [25].

For providing a set of reference values, we have obtained the success probability for the case of using a leanly

Experiment	Succ. Prob.
PRIOREL (3 ms deadline, no combining)	0.006
PRIOREL (3 ms deadline, with combining)	0.055
PRIOREL (10 ms deadline, no combining)	0.0133
PRIOREL (10 ms deadline, with combining)	0.149
Pure ARQ (deadline = 3 ms, no combining)	0.00775
Pure ARQ (deadline = 3 ms, with combining)	0.057
Pure ARQ (deadline = 10 ms, no combining)	0.0298
Pure ARQ (deadline = 10 ms, with combining)	0.211

Table 2. Reference results for success probability without relayers (PRIOREL-COMB is configured with one minislot)

configured PRIOREL-COMB protocol without relayers (the number of minislots equals one) and for a pure ARQ protocol in which the source retransmits the packet without interruption until success or deadline expiration. The user data size has been set to 80 bits, and as packet deadlines we have used values of 3 ms and 10 ms, respectively. The packet combining methods used are the null method (i.e. no packet combining) and the MV plus combinatorial testing scheme, where the main parameter is the maximum number of testable assignments, set to eight.

The results of these reference simulations are displayed in Table 2. The results are consistent with intuition, in that the usage of combining improves the success probability by roughly one order of magnitude, and that the pure ARQ protocol is more efficient since there is no (useless) overhead for assigning relayers.

6. Relayer-controlled schemes for random numbers of relayers

In this section we investigate the behaviour of different relayer-controlled schemes for scenarios with randomly placed relayers. The goal is to identify good schemes allowing a relayer to decide about eligibility and its priority.

6.1. Methodology

We again placed the source and destination nodes at positions (0,0) and (12,12) respectively, but added a number of relayers according to a random placement with density $\lambda > 0$ (see Section 3.1) in a squared area with edge positions $(-20, -20)$ and $(20, 20)$, corresponding to 1600 square meters. For each chosen density $\lambda \in \{0.00625, 0.01, 0.0125, 0.015, 0.0175, 0.02, 0.025, 0.03\}$ we generate a number of independent replications by generating independent instances of the relayer placements. For any single replication i for a fixed parameter value λ we simulate until the relative precision for the success probability $p_{\lambda,i}$ at a confidence level of 1% is below 1% of the achieved success probability, however, a minimum of 30,000 transactions is always simulated. The

values $p_{\lambda,i}$ belonging to the same λ are averaged, giving $p_{\lambda} = \frac{1}{R} \sum_{i=1}^R p_{\lambda,i}$, and the number R of replications is chosen such that the absolute precision for p_{λ} is below 2% at a confidence level of 5%.

6.2. Strategies for priority choice and eligibility tests

We consider the following strategies for the choice of priorities:

- *Uniform random assignment*: an active relayer chooses each minislot with the same probability.
- *Binomial-CSI assignment* (Binomial assignment according to long-term channel-state information): since the center/destination station frequently broadcasts control packets equipped with sequence numbers, each relayer r can estimate a long-term success rate P_r towards the destination, defined as the fraction of successful received control packets over the duration of the simulation. The success rate is initialized with zero and updated upon every arrival of a correct control packet. When there are M minislots, a relayer with success rate P_r picks its minislot according to a binomial distribution with parameters M and $1 - P_r$. By this choice, relayers with high success rates choose small minislot numbers, whereas relayers with small success rates pick high minislot numbers.

For the eligibility test we evaluate the following alternatives:

- *Always-true*: in this test a relayer candidate always chooses to become an active relayer.
- *Longterm-relay-success-test*: this is a probabilistic test based on the long-term success rate of this relayer. Specifically, whenever the relayer r transmits a relayed packet, it checks the following acknowledgement slot. When an acknowledgement is sensed, a counter $C_{r,succ}$ for the successful relay trials is increased, otherwise a counter $C_{r,fail}$ for failed relaying trials is increased. For any given slot, the relayer candidate r then becomes an active relayer with probability

$$\frac{C_0 + C_{r,succ}}{C_0 + C_{r,succ} + C_{r,fail}}$$

The parameter $C_0 > 0$ has been fixed to 10. A relayer candidate applies this test independently for each new relaying slot.

We have simulated all four combinations of priority and eligibility schemes. The settings for the other important parameters in this experiments are summarized in Table 3. All parameters not mentioned here have been chosen according to Table 1.

Parameter	Value range
Packet deadline	10 ms
user data size	80 bits
Number of minislots	4
R_{max}	2
Eligibility test	Always-true, Longterm-relay-success
Priority assignment	Uniform, Binomial-CSI

Table 3. Simulation parameters for evaluating the relay-controlled schemes for random placements

6.3 Results for success probability and delay

We show the success probabilities for the case of four minislots in Figure 4. The following points are noteworthy:

- The setting for the eligibility test has much more impact than the setting for the priority assignment. Specifically, the policies where the “longterm-success” test is used perform significantly better on average than when “always-true” is used. This is even true when “always true” is combined with the channel-aware binomial-CSI priority selection scheme. A possible explanation for this is that the longterm-success eligibility test jointly reflects the channel quality between the source and a relay, the relay and the destination (which must be good) as well as the contention situation (to which a node adapts) simultaneously, whereas the always-true scheme with binomial-CSI reflects only the channel between relay and destination.
- The schemes using the longterm-success eligibility test show improved average success probability when increasing the node density. This shows that the longterm-success scheme has the ability to exploit the presence of relayers at good positions, and at the same time it has the capability to regulate channel access among those. On the other hand, the schemes using the always-true eligibility test suffer from too many contending relayers as the node density increases, leading to collisions.
- When the “longterm-success” eligibility test is used, the usage of channel-state information in selecting the relayers priority (binomial-CSI scheme) has even adverse effects. A possible explanation is the following: as a result of the longterm-success eligibility test, only relayers that have a good channel towards the destination survive as possible relayers. The choice of the binomial-CSI priority selection, however, lets these few survivors concentrate on the first slots, and hence they experience there a slightly increased collision rate, which in turn impacts their eligibility negatively.

Figure 4. Average success probability of different relaying schemes for varying node density λ , the number of minislots is 4 (the graphs have an absolute precision of 2% at a confidence-level of 5%)

- When the “always-true” eligibility test is used, the pressure on the channel is reduced when the binomial-CSI priority scheme is used, but the general trend that the average success probability decreases with increasing node density remains.

These results imply that in our PRIOREL-COMB framework it is not sufficient to use only channel-state information towards the destination. It is instead much more effective for a relay to evaluate the feedback from its previous relaying trials. The longterm-success scheme lets a relay learn about its environment and adapt to it, and at the same time it is very simple. It has the additional advantage that it does not heavily rely on the presence of explicit channel state information obtained from frequent transmissions from the destination. It is therefore a good candidate for usage in scenarios where frequent transmissions from the destination are not available.

In Figure 5 we show the indication delay. The curves confirm that, especially for higher node densities, the eligibility test has much more impact on achieving a good performance than the priority assignment. However, in this case the binomial-CSI priority selection scheme, when combined with the longterm-eligibility test, shows the best performance (i.e. the lowest indication delay). This can be explained by the preference of the binomial-CSI scheme to select early relaying slots when the channel to the destination is good.

7. Conclusions

In this paper we have presented the PRIOREL-COMB framework, which integrates relaying and packet combining. The simulation results show that this combination is very promising for improving the probability to successfully deliver packets before their deadline. It should also

Figure 5. Average indication delay of different relaying schemes for varying node density λ , the number of minislots is 4

be noted that the assumptions and constraints made in this paper enable implementation of the framework on top of commercial transceivers without any modifications of the physical layer. We are therefore convinced that this class of protocols can be a useful addition to future wireless industrial communication systems.

There is a significant potential for future work. One limitation of this paper is the channel model, which does not consider multipath fading processes nor any external interference. Since the PRIOREL-COMB framework rests on energy-sensing, external interference can lead to performance degradations which need to be properly understood. Secondly, the role of hidden-terminal situations among relayers needs to be assessed more thoroughly. There are also a number of design aspects which clearly can be improved: the design of further packet combining schemes or the design of alternative schemes by which relayers can learn about good eligibility probabilities and priority values. Finally, it can be expected that a lot of further insights can be gained from implementation and practical experiments.

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