On the Role of Feedback for Industrial Networks Using Relaying and Packet Aggregation

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Abstract— **To be accepted for use in industrial applications, wireless technologies must offer similar performance in terms of reliability and timeliness as provided by current wired solutions. Wireless channels, introducing time-varying packet error rates, impose a significant challenge to fulfill these requirements. One way to improve reliability in industrial wireless networks is to use relaying, whereas packet aggregation is a method that can reduce delay. Hence, in this paper, we propose to use a combination of relaying and packet aggregation. Based on the type of feedback provided by the controller, the relay node can choose the most suitable way to use its allocated time slots such that more packets can reach the controller before their deadlines. The results show that allowing this kind of flexibility at the relay node results in performance improvements. The more flexibility, the greater the gain, and thus further improvements can be made by adjusting the schedule to take different types of feedback into account.**

I. INTRODUCTION

Industrial Wireless Sensor Network (IWSN) standards like WirelessHART [1, 2], WIA-PA [3] or ISA100.11a [4] currently receive significant interest in the research community [5-9]. Wireless access technologies constitute a tractable alternative to cable-based systems in factory or process automation, discrete manufacturing, or environmental monitoring [10, 11]. Often, high requirements in terms of reliability and timeliness need to be fulfilled in these application areas, and thus, transmissions are frequently scheduled in advance to avoid collisions and to establish time guarantees for delay-constrained traffic. Due to this, most IWSNs use time division multiple access (TDMA) to provide predictable channel access delays, where time is divided into time slots, large enough to accommodate transmission of one long packet together with turn-around-time for immediate acknowledgement. A pre-computed TDMA schedule specifies which node is allowed to transmit in which time slot. To overcome packet errors occurring in transmissions over wireless links of varying and sometimes poor quality, some time slots are set aside for retransmissions. An important question is how these retransmission slots should be used. In traditional schemes, without relay nodes, retransmissions are performed by the original sender of the packet. However, since the retransmission is then made through the same wireless channel as the original transmission, the error is likely to remain unless the conditions of the specific wireless channel have changed.

One very interesting approach for performing retransmissions is enabled by the adoption of relaying, exploiting the spatial diversity of wireless channels [12, 13]. In this class of schemes, specific helper nodes, called relay nodes, are allocated retransmission slots in order to aid with retransmissions of packets originating from (other) source nodes. A relay node is set to overhear source packets (as the wireless medium is a broadcast medium) and, when its pre-scheduled time slot comes, it selects one of the packets it has overheard for repeated transmission towards the receiver (often a central controller in IWSN). It has been established in previous works [14-16] that the use of relay nodes can substantially improve the achievable reliability for deadline-constrained data traffic in industrial networks.

In this paper we extend the work of [15, 16], by giving the relayer an additional degree of freedom. Specifically, we allow the relayer to exploit the fact that most data packets in IWSN tend to be small, compared to the size of a typical TDMA time slot. Instead of selecting one (short) data packet for forwarding, the relay node can concatenate more than one overheard data packet into a larger one and instead forward this packet in one of its allocated time slots. This can be done due to the fact that in most TDMA-based IWSNs, the timeslot duration has been chosen so that the largest possible packet (allowed by the standard) can be accommodated. This is termed packet aggregation [17]. *The goal of this paper is to exploit the best use of packet aggregation by the relay node, given different types of feedback received from the central controller.* The best use is defined in terms of two types of performance metrics. The main performance objective is the probability that the central controller receives all source packets before their deadlines in each transmission round – we refer to this objective as the success probability. In many cases, the controller is able to compensate for some lost packets through, e.g., interpolation. However, for any given source node, the controller should not lose too many consecutive packets. Therefore, we also consider the number of packets that are lost consecutively for each source node. This performance indicator is of great importance in industrial systems, as typically some (in most cases two) consecutive erroneous packets can be tolerated, but machines have to be turned into safe mode if more than two sensor reading in a row are missing.

Further, we consider different types of feedback obtained from the control node: (*i*) No feedback – the absence of any feedback from the controller (*ii*) Binary feedback – the controller sends an acknowledgement packet whenever it receives a source packet (or an aggregated packet) correctly or (*iii*) Long-term feedback – the relay node continuously monitors the acknowledgement packets sent to different source nodes such that it can form long-term estimates of the channel quality between each source and the central controller. Based on the type of feedback provided by the controller, the relay node can choose the most suitable way to use its allocated time slots such that more packets can reach the destination before their deadlines.

The remainder of this paper is structured as follows: in Section II we describe our system model, while Section III contains the proposed relay schemes. Following this, in Section IV, simulation results are presented and finally, we conclude the paper in Section V.

II. SYSTEM MODEL

Typical industrial networks consists of a number of *sensors*, measuring temperature, pressure, humidity, etc and sending their readings to a central controller; a *central controller*, generally located in the middle, collecting the sensor data and sending commands to actuators; and finally *actuators*, responsible for e.g., switching a machine into a safe state. Redundant relay nodes are not necessarily present or desired in industrial networks, and thus, existing nodes need to be used for relaying. As sensor nodes often are very simple, battery powered devices; they typically cannot act as relay nodes. Actuators, on the other hand, often have more computing possibilities and permanent power supply, which is important as additional energy is needed at the relay node to overhear source packets. Still, the number of available relay nodes in wireless industrial networks may be sparse compared to the number of sensor nodes in need of help. We therefore consider the case when each relay node is responsible for aiding a set of source nodes.

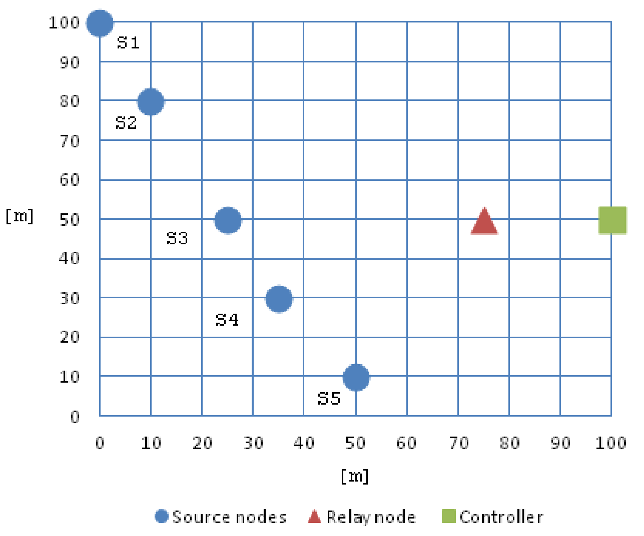

Fig. 1. Investigated node deployment

A. Investigated Node Deployment

For simplicity, we focus only on one segment of the entire network in this paper, isolating a setup with five sensor nodes, one central controller and one actuator. Thus, the actuator is chosen to serve as relay node for five sensor nodes. Following this, we also consider only the subset of time slots allocated to these five sensors for source transmissions and their corresponding retransmissions. The considered setup can be generalized to the full system consisting of several such segments, with corresponding relay nodes and sensor periods. In this work, the nodes are thus placed within a square area as shown in Fig. 1, such that the relay node is located in-between the sources and the central controller. The chosen size of the deployment area, later referred to as "operating area," is 100 m^2, which is the typical communication range for IWSN [18].

B. Wireless Channel

We assume that between each pair of nodes, a separate channel exists which is stochastically independent of all other channels and symmetric in both directions. We adopt a log-distance pathloss channel model [19] with additional frequency-flat block fading such that the block fading gain remains constant during the transmission of one long packet. More precisely, we assume that the received signal can be represented as:

$$r(t) = s(t)\Gamma(d)h(t) + n(t), \tag{1}$$

where $s(t)$ is the transmitted signal, $n(t)$ represents the thermal Gaussian noise process, $\Gamma(d)$ represents the distance-dependent pathloss (the log-distance model prescribes this as

$$\Gamma(d) = PL_0\left(\frac{d_0}{d}\right)^{\gamma}, \tag{2}$$

where γ is the pathloss exponent, d_0 is the so-called reference distance, typically taken to be 1m, and PL_0 is the pathloss at the reference distance), and finally $h(t)$ represents a time-varying fading process. We assume that $h(t)$ is drawn independently from a Rayleigh distribution at the beginning of a time slot and remains constant throughout the slot. Rayleigh fading corresponds to not having any line-of-sight (LOS) path between the communicating nodes, which is the case when e.g. multiple objects are located between nodes. We assume that IEEE 802.15.4-compliant transceivers like, e.g., ChipCon CC2520 [20] are used. Bit rate and transmitted signal power are taken from IEEE 802.15.4 standard. However, for simplicity, binary phase shift keying (BPSK) modulation is used in the simulator as its performance is comparable to OQPSK.

C. Packet Aggregation Structure

We consider uplink data transmission in a TDMA-based IWSN similar to what is used in WirelessHART and ISA100.11a. The TDMA protocol sub-divides time into consecutive superframes (also referred to as transmission rounds), and each superframe is in turn sub-divided into a fixed number of time slots. One time slot is sufficient to transmit a data packet of maximum size as well as to send and receive an acknowledgement. In WirelessHART, a time slot is 10 ms.

One important limitation of the IEEE 802.15.4 physical layer is that packets can have a maximum length of 127 bytes. The data packets from the sources are in this work assumed to be relatively small and of the same size, so that we can apply data aggregation, i.e., concatenate several source packets into one larger packet, which contains a single header for all data items. More specifically, we use the data aggregation scheme proposed in [17] for WirelessHART. Thus, each un-aggregated packet has a MAC header and trailer of 16 bytes in total (10 bytes header, 4 bytes for a link-level message integrity check field, and 2 bytes for an end-of-frame CRC checksum). In an un-aggregated packet, the MAC header is followed by a network layer header of 16 bytes and the actual payload of x bytes, resulting in an un-aggregated packet length of 16+16+x bytes. In an aggregated packet, the MAC layer header is followed by 8 bytes constituting the common network layer header. Following this, if α different source packets are aggregated, then for each of the aggregated packets, a private network layer header of 9 bytes is needed, followed by the payload of x bytes. So, an aggregated packet has a total length of $16+8+\alpha(9+x)$ bytes, assuming all data packets have the same payload length x. To keep things simple, we assume that the MAC layer CRCs are perfect, i.e. packet errors are always detected. We assume further that the payload size is $x = 24$ bytes. Under this assumption, the relay node can concatenate up to three source payloads into one packet, giving an aggregated packet size of 123 bytes, which is less than the maximum length of 127 bytes. However, since longer packets generally have higher packet loss rates, this functionality needs to be used with care. Comparing the achievable success probability when the relay node sends m original source packets one by one in m different time slots, $\eta_{\text{orig}}(p)$, to the case when the source packets are aggregated into one packet and this packet is sent in m consecutive time slots, $\eta_{\text{aggr}}(p)$, we have:

$$\eta_{orig}(p) = ((1-p)^{h+x})^m = (1-p)^{m(h+x)} \tag{3}$$

$$\eta_{aggr}(p) = 1-(1-(1-p)^{h'+mx})^m, \tag{4}$$

where p is the bit error probability, h and h' are header length for original and aggregated packets respectively, and x is the size of the payload. It can be determined from (3) and (4) that given the header and payload lengths used in this work, the success probability is higher when the relay node sends aggregated packets.

D. Feedback

We furthermore consider three different options of feedback from the controller. Whenever feedback is present, the controller sends it at the end of each time slot, as done e.g. in WirelessHART [1], and for simplicity, we assume that the feedback is reliably received by all nodes. In the first feedback option (referred to as **No feedback**) the controller does not provide any feedback at all, i.e. it never sends any acknowledgement. In the second option (referred to as **Binary feedback**) the controller sends an acknowledgement whenever it has received a packet correctly. In the third option (**Long-term feedback**) the relay node would in practice estimate the long-term packet error probability of each source-controller channel by continuously monitoring the acknowledgement packets sent by the controller to the different source nodes. However, for simplicity, this is modeled in the simulator by using the knowledge of the positions for all source nodes, something that is likely not possible in a real system, but will result in a similar estimate of the long-term channel quality, due to the distance dependent path loss.

III. Proposed Schemes

A. Time Slot Allocation

When TDMA is used in standards for industrial applications, time slots for packet retransmissions are allocated in advance and a sender-receiver pair is predetermined for each time slot. We assume for simplicity that all source packets have the same period and deadline and also that at the beginning of each superframe, a new data packet is ready for transmission at each sensor node (corresponding to the worst scheduling case). Therefore at least N slots in the beginning of each superframe are always allocated to the N sources, so that each source transmits its data packet at least once. Following these source slots, a number of retransmission slots are allocated, where retransmissions can be carried out either by the sources themselves or by relay nodes, depending on the type of scheme. To keep things simple, in this paper we use a setup in which K retransmission slots follow the N source slots. The superframe thus consists of $N + K$ slots.

Two well-known and widely used network topologies, using TDMA based time slot allocation, are star and mesh. In star networks, source retransmissions are typically adopted to increase the reliability of the system. In case of lost or corrupted packets at the destination, the corresponding sources repeat their transmissions. The time diversity, introduced by packet retransmissions might result in correct reception of the retransmitted packet even though it is sent from the same source and through the same physical channel. Several retransmissions are often allowed for each packet before its deadline, Fig. 2. These retransmission time slots can be located consecutively for each source or interlaced, such that all retransmission slots occur after the original source transmissions, depending on the chosen scheduling strategy. In a star topology, if a packet retransmission is not needed, the time slot allocated for it stays empty. Mesh schemes, on the other hand, use both time and space diversity. In case both the initial transmission and its retransmission have failed, an alternative route through one or more intermediate nodes is chosen and the second retransmission is made through this route, Fig. 2, much like relaying. In the case of a retransmission using an alternative route, the source first transmits its data to the relaying node (orange colored slots in Fig. 2) and then, in the next time slot, the relay forwards the data to the controller, if it received the packet correctly. However, if the packet is corrupted at the relay node, the corresponding time slot stays empty.

In our work, termed “our approach” in Fig. 2, we consider several different scenarios which all are based on a sender-receiver pair being pre-allocated to each time slot. In the time slots where specific sensor nodes are assigned as senders, a relay node may listen, to try to overhear packets that it can later relay to the gateway in its designated slots. If the time slots for source transmissions are located consecutively in the first N slots, all remaining K retransmission slots can be used by the relay node, by assigning the relay node and the central controller as the sender-receiver pair for these slots. Alternatively, N additional slots can be assigned for retransmissions directly from the source nodes (purple colored slots in Fig. 2) if additional fault tolerance is required by the system. This would simply give the relay node an increased possibility to overhear all source packets. By starting each superframe with N slots allocated to the source nodes (or alternatively N + N slots if required) and allowing the relay node to overhear source packets in these slots, the probability of time slots remaining empty is minimized. The relay node can decide how to best use its allocated time slots in each situation, possibly with the help of feedback from the controller, such that performance in terms of delay and reliability can be improved.

Fig. 2. Time slots allocation for the evaluated schemes

Our approach can be implemented in a star topology, given that some nodes are allowed to act as relay nodes. The reliability of our approach is likely greater than the star topology using source retransmissions, partly because our scheme exploits both time and space diversity, and partly because slots are less likely to remain empty due to assignment of a sender that does not need to retransmit.

Our approach can also be implemented in a mesh topology. There are two main differences between our proposed approach and the traditional mesh protocol. Firstly, we allow the relay node to overhear packets from source nodes even if it is not stated as the final destination. Doing this we can save the time slots, which are usually allocated to source nodes to send their data to the relay node (orange colored time slots in the Fig. 2). Secondly, in our scheme the relay is given a chance to overhear all source packets before it is allocated time to transmit. Thus, the relay node does not have to keep quiet in case it did not receive a particular source packet, but can instead retransmit another packet.

B. *Evaluated Relaying Schemes*

Firstly, note that the time slots allocated for retransmissions directly from the sources (purple colored in Fig. 2) are disregarded in the performance comparison, as they are present in all considered schemes. Although these extra retransmission slots from the source nodes would be beneficial for our proposed schemes, as they give the relay node an increased possibility to overhear all source packets, we choose to exclude them to reduce the simulation time, knowing that this feature can be introduced later to further improve performance. As one of our performance indicators is the probability of lost or erroneous packets from a specific source node in several consecutive superframes, we need to run simulations such that enough statistics is obtained for evaluating such error events. Allowing excessive retransmissions would make the probability of having three consecutive packet errors too small to evaluate in a computer (most random number generators are only accurate enough to evaluate probabilities down to 10^{-5}). Thus, we consider a scenario where only K = 3 time slots in total are available for retransmissions before the end of the superframe and consequently, before the source packet deadlines. These slots can either be allocated to the sources, as would be the case, e.g., in a star topology using a traditional ARQ approach, or given to the relay node as in our approach. We compare four different schemes; "no ARQ," "only ARQ," "only Relying" and finally "Relaying and Aggregation". Considering that K retransmission slots are allocated to a relay node, it has to make a decision on how to best use these slots, given that a random subset of the source packets has been overheard during the first N slots of a superframe – we denote the (random) number of source packets the relay has overheard as n. The relay node therefore makes a decision about what to transmit at the beginning of each relay slot, taking into account the particular subset of source packets and the available feedback regarding previous relay and source slots. Three types of feedback are considered.

1) *No feedback*

In this scheme, the relayer has no information at all about which packets the controller has received. Also no feedback is sent from the controller to the relay node during the relay slots. In the absence of any such information, the best relay strategy is fairly straightforward:

- If the relay has n = 0 source packets it remains quiet.
- If the relay has n = 1 source packet, the best thing it can do is to send this packet in all K of its allocated slots. The relay node thus uses the same strategy for both the "only Relaying" and the "Relaying and Aggregation" schemes.
- If the relay has n = 2 different source packets, it relays both of these, and then repeats one packet (randomly chosen) twice, in case of "only Relaying". With the "Relaying and Aggregation" strategy, the relay node aggregates both source packets into one and sends this aggregated packet three times.
- If the relay has n = 3 source packets, it sends one packet in each slot, in case of "only Relaying" whereas one aggregated packet consisting of all three packets is repeated three times in the case of "Relaying and Aggregation".
- If the relay has $4 \le n \le N = 5$ different source packets (i.e. more packets than the number of relay time slots or source payloads in one aggregated packet), it relays three randomly selected packets with the "only Relaying" scheme or alternatively sends three different aggregated

packets (with three payloads in each) in the case of "Relaying and Aggregation". While constructing the different aggregated packets, the relay node tries to include all the source packets at least once. When this is not possible and some packets appear more than once, these are chosen randomly.

2) Binary feedback

In the case of binary feedback, the relay node has information about which packets are missing at the destination. Based on this information and the set of the packets the relay has overheard correctly from the sources, it selects which packets to relay. After each transmission, when the relay node gets binary feedback from the controller; all correctly received source packets are removed from the queue.

- If the relay has $n = 0$ source packets, it remains quiet.
- If the relay has $n = 1$ source packets, the only thing it can do is to send this packet until a positive acknowledgment is received or until all relaying slots are used.
- If the relay has $n = 2$ different source packets, and acts according to the "only Relaying" scheme, it first relays both packets in two slots. The third time slot is used for a second attempt for one of the packets if needed. If both packets need to be retransmitted, one of them (randomly chosen) is repeated. A relay node, acting according to the "Relaying and Aggregation" protocol, aggregates both packets into one. This packet is repeated until the controller receives it correctly or until all relaying slots are used.
- If the relay has $n = 3$ different source packets, the "only Relaying" scheme sends all three packets once in three consecutive slots. In the "Relaying and Aggregation" scheme, all three source packets will be concatenated into one and sent to the destination. If such a concatenated transmission fails, the same aggregated packet will be retransmitted.
- If the relay has $4 \leq n \leq N = 5$ different source packets, it relays three randomly chosen packets according to the "only Relaying" scheme or it sends different aggregated packets. While populating the payloads in the aggregation packets, the relay node tries to include all its packets an equal amount of times. When this is not possible and some, randomly chosen, packets will get more resources.

3) Long-term feedback

Having both binary and long-term feedback information available, the relay node can first decide, based on the binary feedback, which packets that are candidates for relaying or aggregation in the first place, i.e., which packet that are missing at the destination. The queue of candidates is ordered while prioritizing the packets originating from sources with the highest estimated long-term PER. Higher priority packets, for which also the relay retransmission has failed, are relayed again immediately, delaying the rest of the queue. This scheme can reduce the number of consecutive errors, compared to the "Binary feedback" case, as packets from sources with the highest chance for consecutive errors are prioritized.

- The "only Relaying" and "Relaying and Aggregation" schemes with Long-term feedback all work similarly to the case with Binary feedback, except that for excess time slots or excess payloads in aggregated packets, source packets are not selected randomly, but prioritized according to the Long-term feedback.

Note that the "Only ARQ" scheme works similarly for all of the considered feedback cases. In case of $K = 3$ time slots available for retransmissions, only three out of five sources are allowed to retransmit. With no feedback or binary feedback, the retransmission slots are pre-assigned to three randomly selected source nodes. However, as the TDMA transmission schedule is set in advance, feedback cannot change this pre-allocation of source/receiver pairs. Thus, receiving positive acknowledgment only results in the source node staying quiet, to save energy. No other source can transmit in the temporarily empty time slot. When long-term feedback is available, on the other hand, we let this information be known at startup, such that the three sources with the highest estimated packet error rates will be assigned retransmission slots.

IV. RESULTS

In this section, the results from the performance comparison are presented. We implement the system model presented in Section II and the protocol design from Section III in Matlab. For each chosen scheme we simulate at least 600 000 superframes, or more, until we get at least 160 packet errors.

The first performance indicator: success probability is shown in Fig. 3. There are six sub-plots: the upper five plots display the PER for each of the five sources separately, while the sixth plot shows the joint success probability (i.e. the probability that all five source packets are correctly received at the destination). Source 1 in Fig. 3 is the one located furthest away in Fig. 1, and thus has the highest estimated long-term packet error rate, while Source 5 in Fig. 3 has the best long-term channel conditions among all sources, i.e., corresponding to Source 5 in Fig. 1. The three groups of bars in each graph represent the evaluated feedback cases: no feedback, binary feedback and long-term feedback respectively. The relay schemes with and without packet aggregation are presented in different colors. For reference, the "no ARQ" case, with PER resulting from initial source transmissions only, and the "only ARQ" case, allowing retransmissions only from the original source nodes, are also shown in different colors in the figure. Note, that since the figure shows PER in log scale, a bar reaching far down is better than a shallow bar.

Looking at the results for the "only ARQ" scheme for different cases, it can be noticed that the PER improvements that can be made due to binary feedback are quite small as the scheme is not flexible enough to take full advantage of feedback. Performance is improved only when long-term feedback is available, and then only for the first three sources. In the "only ARQ" scheme, source nodes are responsible for all packet retransmissions, and thus, packets are retransmitted from the same geographical positions though the same physical channels and consequently, have a high probability of still being in error. When a relay node is present, on the other hand, packets are retransmitted through alternative routes (i.e., the spatial diversity plays out its advantages). However, similarly to the case with "only ARQ", the "only Relaying" scheme can help a maximum of three sources in one superframe, given that it is only assigned three time slots. Nevertheless, when the relay node has feedback knowledge, it can change its strategy. In the case of No feedback, the relay node simply tries to be fair to all sources, while in the case of Binary feedback, it aims to help all sources with packets missing at the destination. Therefore, relay node only stays quiet in the No feedback case when it has no correct source packets at all. In cases with feedback, the relay node stays quiet when all the packets it has, have already been correctly received by the central controller. In presence of long-term feedback, the "only Relaying" scheme prioritizes the three source nodes located furthest away, given that it has received these packets correctly and the destination has not. Although this strategy is likely to minimize the number of consecutive errors from any particular source node in the set, it is not necessarily the best strategy in terms of average PER when considering a specific individual source node. Consider that in case of Long-term feedback, packets from sources located close by, i.e., Sources 4 and 5, get retransmitted only when the relay node does not have packets from the prioritized first three sources (or if all three prioritized packets already arrived at the controller without errors). It can be concluded that the "only Relaying" scheme performs better with feedback, as the relay node can change its strategy based on the feedback, rather than wasting time slots on transmissions of packets already present at the destination. The best performance of all investigated cases is achieved with the "Relaying and Aggregation" scheme, regardless of the type of feedback available. In this scheme the relay has a possibility to retransmit $\alpha K = 9$ packet payloads given three available time slots. Thus, in most of the cases, all the packets which the relay has overheard can be transmitted at least once, whereas packets, from the sources with bad channel quality, are transmitted several times when long-term feedback is available.

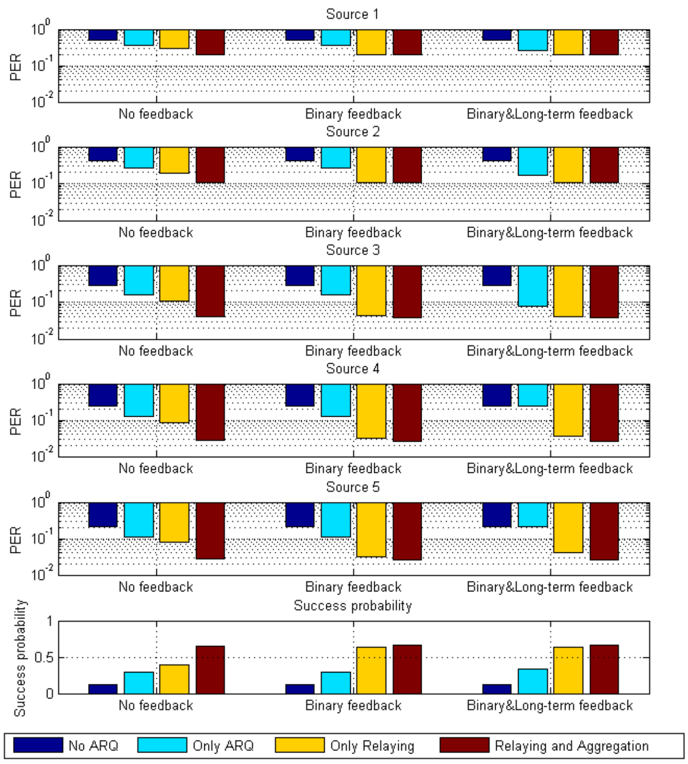

Fig. 3. Different feedback schemes: PER for individual sources and success probability for all evaluated schemes

The second performance measure considered in this paper is the number of erroneous packets at the controller consecutively received from a particular source. The fraction of consecutive packet errors for bursts of length 2 and 3 are shown in Table 1 for "only ARQ", "only Relaying" and "Relaying and Aggregation" schemes, both for individual source nodes as well as averaged over all sources.

Table 1. Percentage of 2 and 3 consecutive packet errors for three of the evaluated schemes and different types of feedback

		only ARQ		only Relaying		Relaying and Aggregation	
		2	3	2	3	2	3
Src. 1	No fdb.	23,08173	8,38768	20,73423	6,16243	15,52769	3,04271
	Binary fdb.	23,08670	8,40742	15,89930	3,21309	15,53942	3,04319
	Binary&Long-term fdb.	19,45834	5,10530	15,57518	3,00213	15,57405	3,00122
Src. 2	No fdb.	19,35289	5,09400	15,81827	3,06839	9,43898	0,96390
	Binary fdb.	19,32747	5,05577	9,70103	1,09638	9,21517	0,98184
	Binary&Long-term fdb.	13,83101	2,36927	9,49498	1,05942	9,47373	1,05477
Src. 3	No fdb.	13,28627	2,10722	9,50628	0,99876	3,76052	0,16572
	Binary fdb.	13,32170	2,15965	4,12849	0,19008	3,66779	0,15794
	Binary&Long-term fdb.	7,24818	0,62060	3,98300	0,16596	3,75601	0,16029
Src. 4	No fdb.	11,06421	1,49246	7,78474	0,68409	2,66634	0,03686
	Binary fdb.	11,12195	1,44797	3,11896	0,08359	2,59067	0,07491
	Binary&Long-term fdb.	18,14085	4,25336	3,44490	0,09803	2,70406	0,06901
Src. 5	No fdb.	9,84744	1,05471	7,02299	0,56081	2,63787	0,11042
	Binary fdb.	10,02922	1,14370	3,15442	0,14609	2,63480	0,11596
	Binary&Long-term fdb.	16,70178	3,52379	3,94387	0,13873	2,32158	0,06378
Average	No fdb.	15,32651	3,62721	12,17330	2,29490	6,80628	0,86392
	Binary fdb.	15,37741	3,64290	7,20044	0,94584	6,72957	0,87477
	Binary&Long-term fdb.	15,07603	3,17446	7,28839	0,89285	6,76589	0,86981

Bursts of two and three consecutive errors are of particular interest in industrial systems as many applications can tolerate two, but not three consecutively sensor readings missing. Considering this second performance measure reported in Table 1, it is clear that "Relaying and Aggregation" outperforms all schemes for all the evaluated feedback scenarios.

V. CONCLUSIONS

The main goal of this paper was to evaluate the performance of relaying schemes with and without packet aggregation, for systems with different types of feedback information available. The results show that allowing a relay node the flexibility to adapt its retransmission strategy based on available feedback, results in noteworthy performance improvements. The more flexibility, the greater the gain, i.e., a relaying scheme performs better than a traditional ARQ scheme, whereas a relay node able to use packet aggregation is better than only relaying. In addition, if the slot allocation in the TDMA schedule can be recalculated occasionally, additional performance improvements can be gained from collecting long-term feedback to estimate the channel quality and adjusting the schedule based on this. Finally, it can be concluded that a scheme using both relaying and aggregation performs equally well over all considered types of feedback, and even the lack thereof.

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