Probabilistic Scheduling and Adaptive Relaying for WirelessHART Networks

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***Abstract* — This paper deals with a way to probabilistically guarantee reliable packet delivery in WirelessHART based networks suitable for industrial control systems. We propose a new scheduling scheme, called Iterative Probabilistic Scheduling with Adaptive Relaying (IPS-AR), which consists of a static part (IPS) and a dynamic part (AR). IPS takes into account the channel characteristics and exploits relaying to achieve a minimum reliability threshold as requested by the supported industrial application. In the AR part, each relay node decides the packet to be sent based on online assessment of both the number of consecutive errors experienced by previous packets belonging to the same flow, as well as the number of copies of the packet currently available at the other relay nodes. This enables IPS-AR to achieve the desired reliability level while using the available resources in terms of time and bandwidth more efficiently.**

1. INTRODUCTION

In order to be fully accepted in industrial environments, wireless systems must fulfill strict requirements on timeliness and reliability, since delays or packet errors in industrial networks can lead to significant economic losses, due to, e.g., production stops, or even danger to humans. Consequently, approaches to deal with packet errors introduced by the wireless channel are required to support industrial applications.

An interesting approach to increase communication reliability in delay-constrained networks is exploiting spatial diversity, where relaying is one of the possible options. With relaying, intermediate nodes are allowed to overhear the transmissions of their neighboring nodes and to forward these overheard packets to their final destinations. The transmission schedule is crucial for the proper functionality of industrial control systems and the performance improvement achieved by relaying can be significantly increased if a suitable schedule is used. Due to the mainly periodic nature of industrial data traffic, Time Division Multiple Access (TDMA) or topology management techniques [1] are often used to provide predictable channel access delays. In TDMA schemes like the one used by WirelessHART, which is the main focus of this paper, every timeslot is preassigned to a specific sender-receiver pair. The time interval available before the packet deadline is typically split into timeslots used for direct transmissions, for retransmissions and for forwarding along alternative paths. This allocation has to be known to all the nodes before the network operation starts.

In this paper, we specifically look at the case when relaying is introduced in a WirelessHART network. We propose a new approach, called Iterative Probabilistic Scheduling with Adaptive Relaying (IPS-AR) that aims to increase the reliability of Industrial Wireless Sensor Networks (IWSNs). The proposed approach supports multiple channels and consists of a static part, IPS, and a dynamic part, AR. IPS is run offline, taking into account the channel characteristics and exploiting relaying to achieve the minimum reliability threshold required by the supported industrial application. AR is instead run online, and the relay nodes decide the packets to be sent in a distributed fashion, based on assessment of both the number of consecutive errors experienced by the flow the packet belongs to and the number of copies of the packet currently available at the other relay nodes. The proposed scheme thus combines TDMA-based offline scheduling, which allows to run a schedulability test to assess if the desired level of reliability is probabilistically achieved, with the flexibility given to the relay nodes to dynamically select which packet to transmit, based on awareness of the instantaneous behavior of the wireless network obtained from the overheard acknowledgments. Thus, compared to static offline schedules built based on WirelessHART recommendations, IPS-AR achieves the required reliability level using a lower number of timeslots or provides higher reliability while using the same number of timeslots.

The paper is organized as follows. Section II describes WirelessHART scheduling and formulates the problem. Sections III and IV present the proposed protocol and preliminary results, while Section V concludes the paper.

2. SCHEDULING FOR WIRELESSHART

A typical WirelessHART network consists of several nodes with different roles. *Sensor nodes* measuring e.g., temperature, pressure, humidity, sending their readings through an *access point* to a *gateway* (*GW*). The latter collects sensor data and transfers the sensor readings to one or more *control nodes* (*PLC*) are connected. The control node runs a control application and sets the output values for *actuators*, which are responsible for some actions, such as turning a machine into safe mode in case of an emergency. In addition, the *network manager* (*NM*) configures the network, schedules the communications between devices, manages message routes and monitors the network health. Finally, a *security manager* (*SM*) manages and distributes security encryption keys and holds the list of devices that are authorized to join the network.

S. Girs and E. Uhlemann are partly funded by the Knowledge Foundation through the WIRE project. E. Uhlemann and M. Björkman are partly funded by the Knowledge Foundation through the READY project.

To guarantee deterministic and real-time data delivery, WirelessHART uses a TDMA structure with 10 ms long timeslots, which are large enough to host the transmission of one maximum-sized packet and an immediate acknowledgment [2]. Timeslots are joined into superframes (SF). The WirelessHART standard does not specify any scheduling scheme, but it defines a number of requirements which must be fulfilled [2]:

- Timeslots for three transmission attempts must be assigned to each packet before its corresponding deadline. The first two attempts, i.e., the original transmission and one retransmission, are done on the same path, while the third one exploits a different route.
- In multi-hop paths, longer paths must be scheduled first.
- Slot allocation starts with the packets with the earliest deadlines.
- Parallel transmissions on different channel are allowed, but no device can be scheduled to listen twice during one slot.

A. *Related Work*

Since WirelessHART does not define a scheduling scheme, different scheduling algorithms aiming to improve the efficiency of the resource use or to increase the network reliability have been proposed [3-9]. Routing and real-time scheduling schemes for typical WirelessHART networks were presented in [3, 4]. A thorough analysis of the energy consumption of WirelessHART based TDMA together with a new scheme minimizing its energy consumption were presented in [5] and a protocol providing more efficient use of the available resources was proposed in [6]. Scheduling for WirelessHART control systems using two access points was considered in [7], while in [8] a schedule minimizing the number of required timeslots and channels for data collection from sensor nodes in WirelessHART networks was proposed. Scheduling for wireless networks with relaying was addressed in [9], where the authors constructed several TDMA-based deadline-aware schedules, which were shown to reduce the average number of packets not meeting their deadlines.

B. *Problem Formulation*

In a WirelessHART network, an *error* occurs when a packet is not delivered before its deadline. As mentioned before, according to the WirelessHART standard, three transmission attempts are given to each packet to avoid errors and increase the reliability. In case of a successful source transmission, the timeslots allocated for retransmissions or forwarding through alternative routes stay empty. However, unutilized slots implies a longer superframe and bandwidth wastage. For this reason, a protocol combining TDMA and slotted Aloha was proposed in [6], in which the unused slots are shared between nodes operating according to the slotted Aloha protocol.

In this work, we propose to keep the plain WirelessHART offline assignment of timeslots to specific senders enabling three attempts, i.e., no shared slots, but instead assigning them according to the wireless channel conditions. Thus, instead of using the same number of slots for all the links independently of their link characteristics, the proposed schedule assigns additional slots to the links characterized by lower Packet Delivery Ratio (PDR) and reduces the number of slots given to the links with high PDR. Further, we provide the intermediate nodes with the flexibility/capability to decide at runtime what to do during the slots assigned to them, i.e., each relay node decides by itself which packet to send using prioritization.

3. IPS-AR Design

In this work, we consider the wireless part of a typical WirelessHART network. Communication between the nodes can take place either through one-hop links or multi-hop paths, if the source and the destination nodes cannot hear each other. The nodes that forward the packets from the source to the destination are here called *relay nodes* and it is envisaged that actuators play the roles as relay nodes since they usually have more power to stay awake and listen to the network. We consider uplink transmission of packets created periodically by the sensor nodes. All packets originating from a particular node are referred as a *flow* and we set the superframe size equal to the smallest period among the periods of all the flows. For simplicity, we assume that each pair of nodes is connected by a wireless channel that is independent of all the other channels and symmetric in both directions. The channels are assumed to be stable and the matrix with the channel PDR values for all the links in the network is assumed to be known to the network manager before the schedule is built. The channel PDR can be obtained by e.g., allowing all nodes to do channel estimations based on the number of overheard packets and acknowledgments and sending these estimates to the controller.

We propose a new scheduling scheme, IPS-AR, for WirelessHART networks, which aims to create an efficient and reliable schedule, i.e., a schedule that allows obtaining a reliability equal to or higher than a minimum threshold required by the application, for all flows in the system. The schedule is computed offline by assigning a sender-receiver pair to each timeslot, where the sender can be either the source or a relay node and where the receiver can be either a relay node or the destination, respectively. Note that although we allow all relay nodes, located within the range of the transmitting node and tuned to the corresponding channel, to listen to the transmission, only the assigned receiver can send an acknowledgment. All relay nodes that have successfully received a particular packet, store it in their buffers and can decide to forward it later during their assigned timeslots.

During the first iteration of the IPS, a schedule is created. Then, the schedule is tested through the *schedulability test* as described below. If the schedule does not probabilistically achieve the desired reliability threshold, iterations are made. During the iterations, the schedule is modified according to the procedure described below and tested again until the schedulability test succeeds. The schedulability test evaluates

$$P_{i,y,A} \ge T_r , \tag{1}$$

where T_r is the minimum PDR threshold required by the application and $P_{i,y,A}$ is the probability that the i-th node got a packet from flow A in the y-th timeslot. Note that if i is the source of the packet (i.e., not a relay node), $P_{i,1,A} = 1$, otherwise $P_{i,1,A} = 0$. Moreover, as it is pointless to consider packets that have missed their deadlines, it is assumed that $y \in [0, t_s]$, where t_s is the number of timeslots available between the creation of a packet at the sender and its deadline. $P_{i,1,A}$ can be found as

$$P_{i,y,A} = \max_{\alpha \in N} \{ P_{i,\alpha} \times P_{\alpha,y-1,A} \} , \tag{2}$$

where $P_{i,\alpha}$ is the PDR for the link between nodes i and α, and N is the set of all the nodes in the network. The schedulability test is run for all the flows in the network, one by one. If the test fails for even one of the flows, the schedule is considered not to be sufficiently reliable. The iterative offline algorithm consists of the following steps:

1. The first schedule is computed by assigning each sender a timeslot in the superframe. The very first timeslots of the superframe are assigned to those senders that are more distant from the final destination. When several nodes are equally distant from the destination and have packets with the same deadlines, one is chosen randomly. Next, all the relay nodes are assigned a timeslot for each flow they are entitled to forward. Relay nodes are assigned to assist sources based on their geographical positions. When only one relay node is used, the node located as close as possible to midway between the source and the final destination is chosen, based on [10]. In case of multiple relay nodes, the relays are chosen according to the exhaustive search algorithm in [11]. In this offline part of the schedule, it is assumed that the timeslots assigned to the relay nodes are ordered in FIFO manner, i.e., a packet arriving to a relay node in an earlier timeslot gets an earlier timeslot to be forwarded. Note that the FIFO strategy only implies that timeslots are assigned to relay nodes based on FIFO, but that this in turn does not mean that the flows will be prioritized according to FIFO during the online phase. For scheduling purposes, however, we assume that the allocated timeslots cannot be changed or shared between flows.
2. Once the first schedule is computed, i.e., all relevant nodes have been assigned timeslots according to Step 1, the *schedulability test* is performed. If the test is positive, i.e., the schedule is considered reliable, the network operation is initiated, using this schedule.
3. If the test fails, the schedule is adjusted by adding additional timeslots to the weakest links. One of the previously unused timeslots is assigned to each of the links with a PDR lower than a certain threshold, in order to cater for an extra transmission attempt. After that, the schedule is tested again. This step is repeated until the schedulability test is positive or all unused timeslots have been exhausted.
4. If all unused timeslots have been exhausted and no reliable schedule is found, we return the unused timeslots as it was before step 3, and instead assign an additional flow to each relay node to support. After this, the schedule is tested again. If it still fails, we go back to step 2 and add unused timeslots to the weakest links.
5. Steps 2 and 3 are iteratively repeated until the test concludes that the schedule is reliable according to (1). If it does not and there are no more free timeslots or relay nodes to assign, the network is concluded not to be schedulable as some re-design is needed. For instance the number of flows in the network has to be decreased.

In the schedule constructed by the IPS, each timeslot is assigned to a specific sender-receiver pair and the schedulability test is computed assuming that the nodes will transmit a specific packet in a specific timeslot. However, even if this is the only option for the source nodes, this is not the case for the relay nodes. Since the schedule is computed based on static PDRs between the nodes, it can happen that some timeslots are assigned to transmit packets which have already been successfully received by the destination, or alternatively, that a relay node does not have a correct copy of the packet it should transmit. To avoid leaving timeslots empty, the dynamic part of the schedule gives the relay nodes the flexibility to decide which packet to send in the timeslots assigned to them, if the originally planned transmission is not needed or not possible. This flexibility allows to improve the overall reliability of the system. However, since these decisions are made online, the schedulability test does not consider them and thus it is slightly pessimistic. The following criteria are considered in online phase when a relay node decides which packet to send if the originally planned transmission is not possible or not needed:

– The number of consecutive errors experienced by every flow, i.e., the relay node prioritizes a packet from the flow which had two consecutive errors in two prior slots. This approach is of interest in IWSNs, since industrial systems can often tolerate two, but not three consecutive errors in the same flow, as then machines have to be switched off.
– The number of other relay nodes that have transmission slots after the current node and which have better chances to overhear and forward the considered packet. The relay node prioritizes the packet having the lowest chance to be successfully received and forwarded by the upcoming relay nodes later in the schedule. Note that for this to be possible, the relay nodes must either know or be able to estimate the channel PDRs between all other nodes. However, it is likely that the static PDR used to calculate the offline schedule can be disseminated to all nodes.

When several packets have the same priority based on both criteria above, the packet to transmit is chosen randomly.

4. PRELIMINARY RESULTS

In this section we present the preliminary results of the comparison between WirelessHART and our proposed scheduling scheme. We consider the network in Fig. 1 with nodes placed to represent two extreme cases. In both cases, the relay nodes (nodes D - E) are placed on the second dashed line from the left but the source nodes (nodes A- C), sending their data to the access point (node F), are either placed on the third dashed line from left, the “best case”, or on the fourth dashed line from the left, the “worst case”.

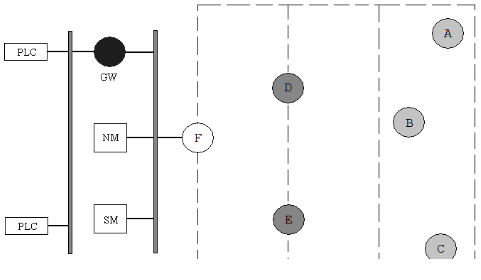
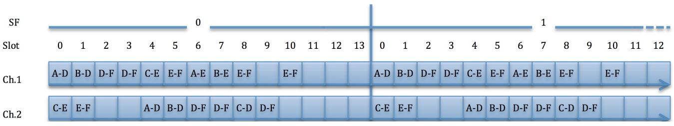


Fig. 1. WirelessHART network architecture

In the considered example, transmissions are allowed on two channels. The channels are assumed to follow the Additive White Gaussian Noise (AWGN) model and the PDR matrixes are characterized by a signal to noise ratio, $E_b/N_0 = 4$ dB for channel 1 and $E_b/N_0 = 3$ dB for channel 2, i.e., channel 1 is characterized by a higher E_b/N_0. The packet size is 48 bytes. The periods of the flows generated by nodes A, B and C are equal to 140 ms, 280 ms and 140 ms, respectively. It is assumed that the application under study requires a PDR level equal to 0.85. This PDR level may be too low for some industrial applications, but it simplifies the calculations here, due to reduced complexity since less retransmission attempts are needed to achieve the required reliability level.

First, we look at the schedule built following the recommendations of the WirelessHART standard, assigning three delivery attempts in each SF for each of the three source nodes, Fig. 2. Note that no management or keep-alive timeslots are shown, since their consideration is out of the scope of this paper. The presented schedule assigns timeslots for one transmission and two retransmissions to all three source nodes, as it is specified by the standard. The resulting PDR calculated after each of the delivery attempts in the "worst case" scenario from Fig. 1, are presented in Table 1.



SF	0														1												
Slot	0	1	2	3	4	5	6	7	8	9	10	11	12	13	0	1	2	3	4	5	6	7	8	9	10	11	12
Ch.1	A-D	B-D	D-F	D-F	C-E	E-F	A-E	B-E	E-F		E-F				A-D	B-D	D-F	D-F	C-E	E-F	A-E	B-E	E-F		E-F		
Ch.2	C-E	E-F			A-D	B-D	D-F	D-F	C-D	D-F					C-E	E-F			A-D	B-D	D-F	D-F	C-D	D-F			

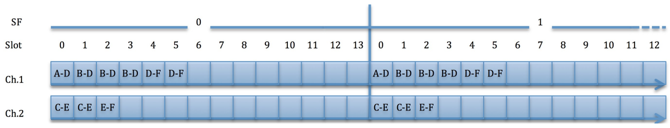
Fig. 2. Schedule built according to WirelessHART requirements

Table 1. Final PDR for WirelessHART scheduling, the "worst case" scenario.

	Attempt 1	**Attempt 2**	**Attempt 3**
Node A	**0.86**	0.94	0.95
Node B	0.56	0.65	**0.90**
Node C	0.46	**0.89**	0.90

It can be seen from Table 1 that in the "worst case" node placement, node A achieves the required PDR of 0.85 at the first attempt, while nodes B and C need three and two attempts respectively. Thus, in total six timeslots in SF0 are highly likely to stay empty. When the "best case" scenario according to Fig. 1 is considered, the required reliability level is achieved at the first attempt for all the source nodes and thus all twelve timeslots allocated for retransmissions in SF0 are likely to stay empty. Additionally, timeslots allocated for the packet from node B in SF1 are not used due to its higher period.

Next, we build the schedule for the "worst case" scenario according to Fig. 1, when using IPS, Fig. 3. The retransmission timeslots are assigned until all the flows reach the required reliability level according to (1). The resulting PDR values are shown in Table 2.



SF	0														1												
Slot	0	1	2	3	4	5	6	7	8	9	10	11	12	13	0	1	2	3	4	5	6	7	8	9	10	11	12
Ch.1	A-D	B-D	B-D	B-D	D-F	D-F									A-D	B-D	B-D	B-D	D-F	D-F							
Ch.2	C-E	C-E	E-F												C-E	C-E	E-F										

Fig. 3. Schedule built with the IPS approach in the "worst case" scenario

Table 2. Resulting PDR for the IPS approach in the "worst case" scenario.

	Attempt 1	**Attempt 2**	**Attempt 3**
Node A	**0.86**	-	-
Node B	0.56	0.79	**0.90**
Node C	0.46	**0.95**	-

Looking at the Fig. 2-3 and Tables 1-2 it can be seen that a system working with an IPS-based schedule achieves the required reliability level of 0.85 using much fewer timeslots, compared to a network using a static schedule built according to WirelessHART requirements. Since in IPS the timeslots are scheduled based on packet delivery probabilities, no extra slots for not needed retransmissions are assigned. Thus, almost 50 % of the timeslots can be saved with IPS compared to the schedule built following the recommendation of the WirelessHART standard in the "worst case" scenario, while in the "best case" 60 % of the timeslots are saved. These slots can either be used to increase the number of schedulable flows, or alternatively, to increase the reliability of the existing flows. For instance, if the network operates with an IPS-based schedule and more attempts are added while still only using the same number of timeslots as the WirelessHART schedule does, the achievable PDR levels for nodes A, B and C are 0.99, 0.98 and 0.99, respectively. Note that so far only IPS, i.e., the static part of IPS-AR was considered. Evaluation of the full protocol is within the planned future work and the use of AR can be expected to increase the gain even further.

5. CONCLUSIONS AND FUTURE WORK

Our preliminary results show that our proposed scheme is able to achieve the reliability level as required by the application while using a lower number of timeslots compared to the schedule built following the WirlessHART recommendations. Thanks to its property, shorter superframes are used, thus allowing to increase the number of flows to be served in the same network and supporting applications with faster dynamics. When using the same number of timeslots, our scheme provides a significantly higher reliability than the WirelessHART one.

Future work will address dynamically varying channels and additional types of strategies applied at the relay nodes when choosing which packet to relay. Moreover, the impact of the introduction of AR will be evaluated.

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