An Experimental Study of Selective Cooperative Relaying in Industrial Wireless Sensor Networks

Nikolaj Marchenko, *Student Member, IEEE,* Torsten Andre, *Student Member, IEEE,* Günther Brandner, *Student Member, IEEE,* Wasif Masood, *Student Member, IEEE,* and Christian Bettstetter, *Senior Member, IEEE*

***Abstract*—Strict reliability and delay requirements of factory monitoring and control applications pose challenges for wireless communications in dynamic and cluttered industrial environments. To reduce outage in such fading-rich areas, cooperative relays can be used to overhear source–destination transmissions and forward data packets that a source fails to deliver. This paper presents the results of an experimental study of selective cooperative relaying protocols that are implemented in off-the-shelf IEEE 802.15.4-compatible devices and evaluated in an industrial production plant. Three practical relay update schemes, which define when a new relay selection is triggered, are investigated: 1) periodic; 2) adaptive; and 3) reactive relay selections. The results show that all relaying protocols outperform conventional time diversity retransmissions in delivery ratio and number of retransmissions for packet delivery. Reactive selection provides the best overall delivery ratio of nearly 99% over the tested network. There is a tradeoff, however, between achievable delivery ratio and required selection overhead. This tradeoff depends on protocol and network parameters, and is studied via protocol emulation using empirical channel values.**

***Index Terms*—Cooperative diversity, industrial wireless sensor networks (WSNs), measurements, relay selection, relaying protocols.**

I. Introduction

WIRELESS sensor networks (WSNs) have gained interest for industrial automation as replacement of aging wired industrial communication networks [1]–[3]. Wireless sensors can be placed in locations unreachable with cables and provide maintenance flexibility and cost benefits. Typical applications for industrial WSNs are monitoring and control of production processes. Sensors measure physical or chemical parameters, monitor machine states, and report them wirelessly to the control center. Based on the received measurements, the control center can send commands to machinery actuators.

Applications for industrial automation have very strict requirements on communication reliability and packet delivery time [3]. Mistakes such as irregular pressure reports, delayed actuation of a valve, or a failure to deliver a warning about a potential hazard due to a lossy communication link can damage the equipment or disrupt the production process. Achieving required reliability levels with wireless transmissions is a serious challenge in heavily cluttered and quickly changing environments often found in industrial plants [4]. In such environments, wireless signals can suffer from multipath fading and severe signal shadowing induced by moving machinery or human workers. Comprehensive wireless channel measurements in industrial environments can be found, e.g., in [5]–[7].

Recent communication standards such as WirelessHART (released 2007) and ISA100.11a (released 2009) are used to facilitate the advancement of industrial WSNs [8], [9]. These standards include the following retransmission techniques to improve communication reliability in lossy wireless networks: 1) *time diversity*—retransmission of failed packets later in time to mitigate short outages of the radio channel [10]; 2) *frequency diversity*—retransmission on a different frequency channel to mitigate interference and frequency-selective fading [11]; and 3) *path diversity*—packet retransmission on a different route in the network to mitigate long outages [12]. All retransmissions are scheduled by a central network manager in these networks.

This paper investigates *cooperative diversity*, which is a special form of spatial and temporal diversity that also aims to reduce the outage probability of wireless links in fading-rich environments [13]. It utilizes the broadcast nature of the wireless medium where neighboring nodes can overhear direct transmissions between source and destination nodes. If a direct transmission fails, a selected *relay node* that has already received a copy of the data packet retransmits it to the destination. In this way, signal diversity at the destination is achieved and the transmitted data packet is more likely to be detected and decoded. Such relaying protocols based on cooperative diversity are applied on the data link layer and can be triggered locally at each hop when the direct link is temporarily in outage. The terms cooperative diversity and cooperative relaying are used as synonyms in this paper. The term cooperative link is used to refer to a source–destination link with assisting cooperative relay.

Cooperative relaying has been extensively studied in the last 10 years. For example, theoretical capacity bounds are

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N. Marchenko was with the Mobile Systems Group, Institute of Networked and Embedded Systems, University of Klagenfurt, 9020 Klagenfurt, Austria. URL: http//nes.aau.at

T. Andre, G. Brandner, and W. Masood are with the Mobile Systems Group, Institute of Networked and Embedded Systems, University of Klagenfurt, 9020 Klagenfurt, Austria (e-mail: torsten.andre@aau.at; guenther.brandner@aau.at; wasif.masood@auu.at).

C. Bettstetter is with the Mobile Systems Group, Institute of Networked and Embedded Systems, University of Klagenfurt, 9020 Klagenfurt, Austria; and also with Lakeside Labs GmbH, 9020 Klagenfurt, Austria.

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investigated in [13] and [14], energy efficiency in [15] and [16], and relay selection in [16]–[20]. Relay selection plays an important role in the resulting performance of cooperative relaying protocols. Bletsas *et al.* [17] show that usage of a single relay with the best current channel quality at each transmission results in the same diversity order as retransmission with all potential relays. However, relay selection requires additional coordination overhead and its execution at each transmission can degrade benefits of cooperative relaying.

The timing of new relay selections can be defined by relay update policies, which balance relaying reliability and signaling overhead required for relay selection and coordination. In this paper, the term *selective cooperative relaying* is borrowed from [19] to refer to any cooperative relaying protocol with selection of a relay and its reselection according to a certain update policy. In [19] and [21], the relay is changed whenever the signal-to-noise ratio (SNR) at the destination down-crosses a certain threshold. Marchenko and Bettstetter [20] compare the throughput and energy efficiency of cooperative relaying with update policies based on packet delivery to the destination. Results in all three papers are obtained analytically based on assumptions of identical distribution of channel gains over time, error-free signaling, and ideal channel quality estimation. A protocol specification of relay selection is missing.

Use of cooperative relaying in industrial wireless sensor networks is discussed by Willig [22], [23]. In joint work with Uhlemann, Willig explores the capabilities of cooperative relaying with packet combining [24], relay selection [25], and accurate relay placement [26]. Their results are based on mathematical analysis and simulations without experimental validation.

An experimental investigation of cooperative relaying in an industrial setting is presented in [27]. The authors study the performance of a cooperative protocol for networked control systems in IEEE 802.11 networks. The relay selection is performed at each data packet transmission based on request-to-send (`RTS`) and clear-to-send (`CTS`) message exchange between source and destination, which makes relay selection impossible when the direct channel is in outage. Furthermore, IEEE 802.11 is rarely used in sensor networks, where short messages with sensed data are transmitted.

There are only few studies that provide experimental evaluation of cooperative relaying in WSNs. Dubois-Ferrière *et al.* [28] and O'Rourke and Brennan [29] investigate simple packet combining in low-cost wireless sensors for cooperative relaying on the link level in IEEE 802.15.4 networks. Ilyas *et al.* [30] studied a setup with several IEEE 802.15.4 nodes receiving data from a single source; if a data packet cannot be decoded at one of the receivers, a copy from other receivers is requested. Neither of these studies considers relay selection aspects.

The potential benefits of selective cooperative relaying in industrial wireless sensor networks and lack of its experimental evaluation and practical insight serve as motivation for this paper. Three relay update schemes, adapted from [19] and [20], are studied in a real-world industrial setting: 1) *periodic selection* triggered at constant time intervals; 2) *adaptive selection* triggered when the delivery ratio on the cooperative link is below a threshold; and 3) *reactive selection* triggered by each failed direct source–destination transmission.

Our contributions are as follows.

1) Implementation proposal of three selective cooperative relaying protocols with aforementioned relay update schemes for the IEEE 802.15.4 software protocol stack.
2) Empirical comparison of these protocols in terms of delivery ratio and selection overhead in a network of IEEE 802.15.4 devices deployed in a production plant.
3) Tradeoff analysis between communication reliability and selection overhead over a range of system settings using protocol emulation on collected channel measurements.

The paper explores the potential benefits and drawbacks of selective cooperative relaying in an industrial environment without detailed discussion of the protocol integration within various existing communication standards (which would require additional examination and is left for future work). WirelessHART and ISA100.11a make use of centralized path diversity on the network layer and require coordinated route discovery and maintenance by a central network manager [12], but they do not specify routing and update algorithms. Our evaluation provides insight on how relays can be efficiently selected locally on the data link layer to overcome outages of a direct channel in a small sensor network. The obtained results can be also helpful in the development of networking protocols in industrial wireless sensor networks.

The paper at hand significantly extends the authors' preliminary work in [31] and [32]. Andre *et al.* [31] evaluated radio channel characteristics and performed simplified analysis of cooperative relaying. Andre *et al.* [32] studied periodic and adaptive relay selections in a single network scenario. Relay selection is initialized by message exchange between source and destination. Similar to [27], such an approach makes relay selection impossible whenever the direct channel is in outage. The protocols presented in the paper at hand show significantly better delivery ratios than the ones in [32]. Furthermore, the impact of protocol parameters on communication performance and the resulting tradeoff between reliability and overhead are studied in a broader variety of network topologies.

The rest of the paper is structured as follows. Section II introduces selective cooperative relaying protocols with three different relay update schemes. Section III describes the network setup and performance metrics. Section IV presents the trace-based analysis of selective cooperative relaying protocols to cover a large range of protocol parameters. Section V explains the conducted experiments and presents the protocol performance in direct comparison. Section VI concludes the paper.

II. Selective Cooperative Relaying Protocols

The following three aspects of relay selection influence the performance of a selective cooperative relaying protocol.

1) *Local selection metrics* such as channel state information and remaining battery life can be used to identify a relay that maximizes the performance on the cooperative link and over the network.
2) *Coordination overhead* among neighboring nodes is required to avoid collisions, notify nodes about a relay selection, and trigger retransmissions.

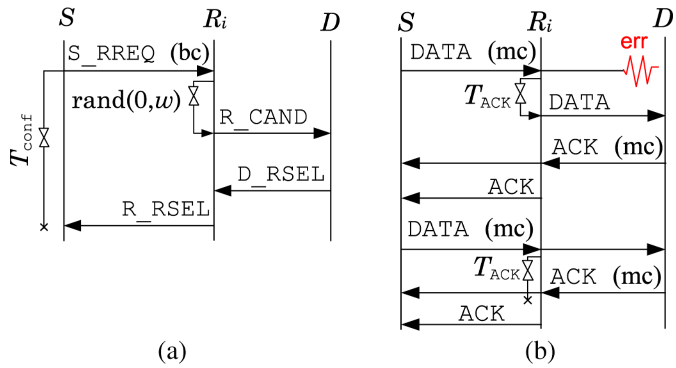

Fig. 1. Message flow for periodic and adaptive relay selection and relay operation after its selection. (a) Relay selection. (b) Relay retransmission.

3) *Relay updates* are necessary in a changing environment to ensure that an optimal relay is used. Update rules also aim to reduce the total number of new relay selections and, as a result, the overall signaling overhead.

The protocols discussed in this paper consider the instantaneous channel information available at each received packet in IEEE 802.15.4 radios as link quality indicator (LQI). In particular, the LQI of channels from a source to potential relays and from these relays to the destination are taken into account.

We now explain the implementation of cooperative relaying with periodic, adaptive, and reactive relay update schemes.

A. Periodic Relay Selection

As the name suggests, the periodic selection scheme triggers a relay selection on a given link strictly periodically at intervals T_{sel} independent of the current relay performance.

Fig. 1(a) shows the implementation of this selection scheme. A source S broadcasts a relay request message S_RREQ, which also includes the ID of the destination node D for the following DATA packets. Here, (bc) and (mc) stand for broadcast and multicast, respectively. All nodes that receive this request message (except D) start a random timer $T_c = \text{rand}(0, w)$ for a transmission in the following contention window of duration w. When the timer of a node expires, the node sends a candidate message R_CAND to D. This message includes the LQI value measured on the S_RREQ received from S and the value of $w - T_c$ so that D can identify the end of the contention window even if it does not receive S_RREQ. Nodes whose candidate message R_CAND is received at D form a relay candidate set R. When the contention ends, D evaluates the end-to-end link for each candidate node $R_i \in R$ by taking the minimum of two LQI values

$$Q_i = \min(Q_{SR_i}, Q_{R_iD}) \tag{1}$$

where Q_{SR_i} and Q_{R_iD} are the LQI values from S to R_i and from R_i to D, respectively [17]. A node R_i is selected as relay if it has the maximum Q_i among all candidate relays in R. The destination sends a D_RSEL message to notify R_i that it has been selected. After receiving this message, R_i sends the message R_RSEL to S confirming successful selection.

Fig. 1(b) illustrates a retransmission by the selected relay when a direct DATA delivery fails. Whenever the selected relay R_i receives a DATA packet from S, it starts the timer T_{ACK}. If it does not receive an ACK from D within this time, it relays its copy of DATA to D. If D receives DATA correctly, it multicasts an ACK to R_i and S. Regardless of whether R_i relayed DATA or not, whenever it receives an ACK from D, it always forwards it to S.

If S does not receive any confirmation R_RSEL within a certain time interval T_{conf} [Fig. 1(a)], it assumes that the relay selection failed and transmits the DATA without any assigned relay. The next relay selection is performed again directly before the following DATA transmission. If a relay is not selected after L such selection attempts, S operates in a time diversity mode without an assisting relay for the interval T_{sel}. This means it retransmits the DATA once when no ACK is received from D within T_{ACK}. When T_{sel} expires, a new relay selection process starts.

In this paper, only basic retransmission schemes without bit-level combining of failed packets at D are considered. The presented cooperative relaying protocols can also be referred to as cooperative Automatic Repeat-reQuest (ARQ) protocols. Information combining can slightly increase the performance of the relaying (see [24], [33]), but in turn requires additional computational resources and is out of scope of this paper.

The introduced periodic relay selection can be considered as a more general and practical adaptation of proactive relay selection described in [34], where a new relay is selected before each DATA transmission. As explained in Section IV, a tradeoff between delivery ratio and selection overhead can be achieved by varying T_{sel}. When $T_{\text{sel}} \to \infty$, a relay is selected only once and does not change over the network operation time. Such a case is considered in [20].

B. Adaptive Relay Selection

In the adaptive relay selection scheme, a new relay selection is triggered depending on the recent delivery ratio performance over the cooperative link. S keeps track of acknowledgments for transmitted DATA packets. If the ACK for a DATA is missing, it assumes that neither S nor the currently assigned relay R_i could deliver the DATA.

Only the W_a most recent packets are taken into account. If the ratio of missing ACKs from these W_a DATA packets is equal or higher than ε_a, a new relay selection is triggered, and a new count of missing ACKs begins. Parameters W_a and ε_a define how sensitive the protocol is to losses on communication links. If $\varepsilon_a = 1/W_a$, a new selection is triggered after each missing ACK. Another extreme is $\varepsilon_a = 1$, where a relay selection is triggered when all W_a are not acknowledged. The adaptive relay selection tries to adapt to changing channels and minimize the number of resulting relay selections. Besides the difference in the timing of updates, cooperative relaying with adaptive relay selection operates in the same way as shown in Fig. 1.

This adaptive selection can be considered as a generalization of switch-and-stay selection [19]. In that scheme, a new relay is selected when the overall SNR over the cooperative link with a given relay drops below a certain threshold. Another adaptive scheme is analyzed in [20], where relay selection is triggered whenever neither S nor the current relay R are able to deliver the DATA to D. In the adaptive selection presented in this paper, this can be the case when $W_a = 1$ and $\varepsilon_a = 1$. The impact of the

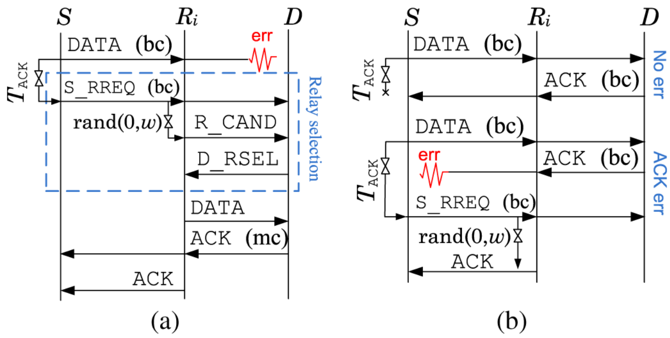

Fig. 2. Message flow for cooperative relaying with reactive relay selection. (a) D fails to receive DATA from S. (b) D receives DATA from S.

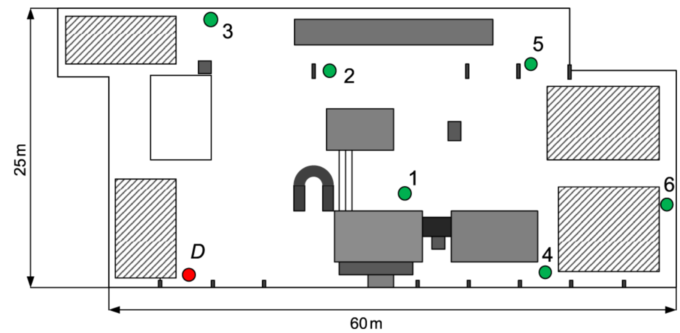

Fig. 3. Factory layout and deployed sensor network.

parameters W_a and ε_a on the delivery ratio and number of triggered selections is studied in Section IV.

C. Reactive Relay Selection

Reactive relay selection is triggered after each failed direct transmission of a DATA packet from S to D [17]. Its benefit is the full use of selection diversity among all potential relay candidates on all failed direct packets. In this paper, we propose to trigger a reactive relay selection by S if no ACK from D is received within time T_{ACK}, as it is shown in Fig. 2. In this way, reactive relaying can be used in nonperiodic transmissions, and the delivery of ACKs is ensured, which can be critical in some control applications.

Source S broadcasts an S_RREQ message each time it does not receive an ACK for its direct DATA transmission to D. This message includes the ID of D and the sequence ID of the corresponding DATA packet. Only nodes receiving both the requested DATA and following S_RREQ contend for selection.

There are two cases for missing ACKs. First, as shown in Fig. 2(a), the DATA is not delivered to D. In such a case, similar to the contention procedure of periodic and adaptive relay selection in Fig. 1(a), each of the relay candidates starts a random timer $T_w = \text{rand}(0, w)$. Upon its expiration, the node sends an R_CAND message to D. Node D selects a relay based on (1). After the selected relay receives the confirmation message D_RSEL, it starts transmitting its copy of DATA back to D. If D does not receive any R_CAND but receives S_RREQ from the source, it sends a D_RSEL message to S and S retransmits its DATA. After the retransmission, the selected relay R_i waits for an ACK from D. Upon receiving it, R_i forwards the ACK to S.

The second case, as shown in Fig. 2(b), occurs when a DATA from S has been delivered to D, but the corresponding ACK has not been received by S. As a result, after time T_{ACK}, S sends S_RREQ for relay selection. However, since ACK has been broadcasted, some surrounding nodes might have received it. The nodes that received both S_RREQ from S and the corresponding ACK from D start a random timer $T_w = \text{rand}(0, w)$. They forward ACK to S upon timer expiration. Some nodes that receive S_RREQ and the requested DATA but do not receive the corresponding ACK from D still send R_CAND to D, but D ignores such messages based on the requested packet ID. In this way, ACK can be delivered to S and an unnecessary retransmission of DATA is avoided.

III. Network Setup and Performance Metrics

All cooperative relaying protocols are implemented on TelosB nodes [35]. These devices are compatible with IEEE 802.15.4—a standard designed for communication of low-power devices. The devices operate on unlicensed frequency bands at 2.4 GHz and provide a transmission rate of 250 kbit/s. The physical layer of IEEE 802.15.4 is also used in WirelessHART and ISA100.11a standards for industrial WSNs.

Seven nodes are deployed inside a production plant of a packaging company. The layout of the plant is shown schematically in Fig. 3. The production environment consists of multiple shielded and unshielded machines (gray areas) that cut and transport cardboard packages. Up to a dozen of human operators and three forklifts move inside the plant during the measurements. Dashed areas are the storage spaces.

Two main performance metrics for comparison of the protocols are: 1) *delivery ratio* of DATA packets to D; and 2) *number of relay selection attempts* showing the overall selection overhead.

IV. Trace-Based Analysis of System Parameters

The protocol performance depends on protocol parameters and the number and location of potential relays. Experimental comparison over such a wide range of settings is hardly possible. A broadcast-based experiment was conducted that enables us to *emulate* the operation of cooperative relaying with different parameters based on the logged data.

A. Experiment Description

The most distant node 6 is set as source S and sends a DATA packet to D every 160 ms. All other nodes $i \in \{1, 2, 3, 4, 5\}$ listen to the DATA from S and, upon receiving it, log its LQI and relay the packet to D after $15 \cdot i$ ms to avoid collisions with other nodes. The packets received at D are stored with their LQI values and the transmitter IDs. In total, 50 000 DATA packets are transmitted by S.

Based on the stored data for each packet transmitted by S one can identify whether a packet is delivered to D via relay node i or not and determine the node with the maximum Q_i according to (1). As a result, one can emulate the operation of the protocols with the obtained traces and vary the protocol parameters arbitrarily [36]. The drawback of this method is that it does not involve real relay selection through contention but follows rather idealistic assumptions based on channel information. The main

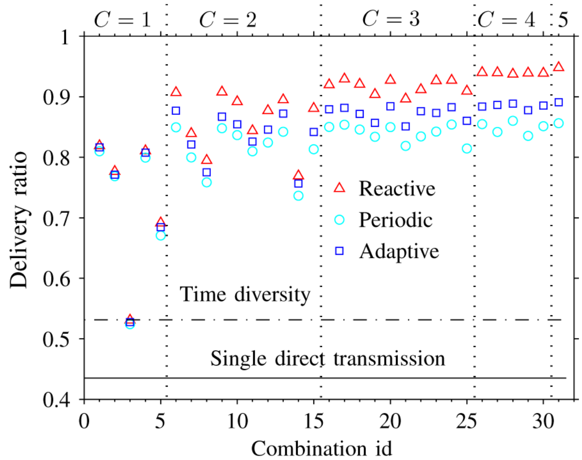

Fig. 4. Delivery ratio of various retransmission protocols for different combinations of surrounding nodes.

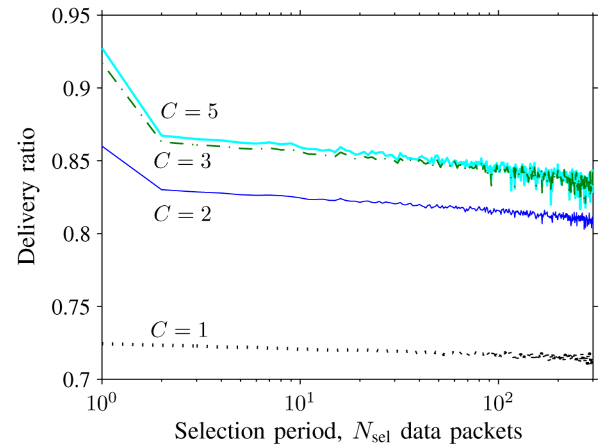

Fig. 5. Delivery ratio with periodic relay selection as a function of relay update interval.

advantage compared to a computer simulation is that it uses real channel measurements.

The three cooperative protocols are also compared with two noncooperative schemes: 1) *single direct transmission* by S; and 2) *time diversity*—a single retransmission by S done when the first transmission does not succeed (i.e., an ACK from D is not received within time $T_{\texttt{ACK}}$). In this section, we consider time diversity with one retransmission, i.e., DATA is dropped if it is not delivered with the one retransmission. Multiple retransmissions are studied in Section V.

B. Results

Fig. 4 shows the mean delivery ratio of cooperative relaying for 31 unique possible combinations of nodes that can be relays. For a given $1 \leq C \leq 5$, $\binom{5}{C}$ unique combinations of available relay nodes can be formed. Each node ID $i \in \{1, 2, \ldots, 5\}$ used in a given combination serves as a digit to form the smallest number. For example, the number 235 corresponds to the combination of nodes with IDs 2, 3, and 5. It means that for this case, only these three nodes are considered during the selection of a relaying node while all other nodes in the network are ignored. All such unique numbers are then sorted in ascending order and assigned combination IDs from 1 to 31 for simpler representation in the figure.

With the periodic scheme, a new selection is triggered every $T_{\text{sel}} = 32$ s (here, it corresponds to $N_{\text{sel}} = 200$ packets). With the adaptive scheme, a relay update is performed when a threshold of five lost DATA packets ($\varepsilon_a = 0.1$) in the window of $W_a = 50$ most recently sent packets is reached.

Fig. 4 shows that all cooperative schemes perform better than noncooperative ones with one exception when only node 3 can serve as relay. This node appears to have a very weak link to S, and, therefore, cannot relay the DATA to D in a reliable manner. As a result, cooperative schemes provide nearly the same delivery ratio as time diversity. Another observation in Fig. 4 is that, for a given cooperative scheme and a given C, the fluctuation in delivery ratio within the group of different node combinations is the highest for $C = 1$ relay node. It decreases with growing number of available nodes C and almost flattens out for $C = 4$.

Fig. 5 shows the impact of the update interval N_{sel} on the delivery ratio with periodic relay selection. The curves for different number of nodes C represent the mean values over all possible combinations of nodes with the same C. If only one relay is available, the delivery ratio almost does not change for increasing selection period, since there are no better relays to switch to. The slight degrade can be explained by intervals when a relay is not selected after the limit of $L = 5$ attempts, and the protocol operates without an assisting relay for the next N_{sel} packets.

A significant improvement in mean delivery ratio is observed when the number of relays increases from $C = 1$ to 2 and 3. The difference between the curves for $C = 4$ and 5 is hardly noticeable, and, therefore, only the curve for $C = 5$ is plotted. This confirms the trend shown theoretically in [20]. If $N_{\text{sel}} = 1$, a relay selection is performed at each DATA packet. However, for cases with $C > 1$, already a change of the update period to two packets significantly reduces the delivery ratio. With further increase of the selection period, the delivery ratio degrades only slowly (consider the logarithmic scale of the x-axis). The selection of a wrong relay or no selection of a relay at all can have significant impact on the delivery ratio at high N_{sel} in our data set of 50 000 packets. As a result, fluctuations in the delivery ratio can be seen.

The number of relay selections per DATA packet with periodic relay selection is found to be proportional to $1/N_{\text{sel}}$ and is nearly the same for all C. It is only slightly higher when only a single node is available ($C = 1$), since more attempts are required when the only node is not available for selection. The corresponding figure is omitted here. It can be concluded that the selection overhead can be decreased significantly by increasing the selection period with only moderate loss in delivery ratio.

Fig. 6 shows the impact of the threshold error rate ε_a within the window of $W_a = 50$ most recently sent packets in adaptive relay selection. The allowed error rate ε_a varies from $1/W_a$ (when a relay is updated immediately after the first delivery failure on the cooperative link) to 1 (when a relay is selected only when all W_a packets fail). Clearly, the delivery ratio is the highest when the triggering error rate is $\varepsilon_a = 1/W_a$, but it is still lower than the one of the reactive selection scheme. The delivery ratio decreases slowly for $C > 1$ since the window of 50 packets ensures that

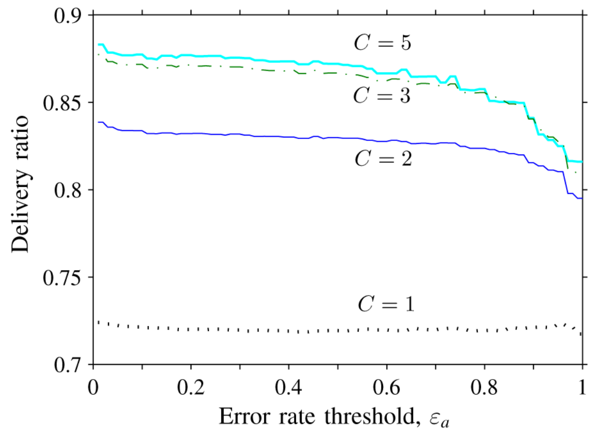

Fig. 6. Delivery ratio with adaptive relay selection as a function of error rate threshold over 50 transmitted DATA packets.

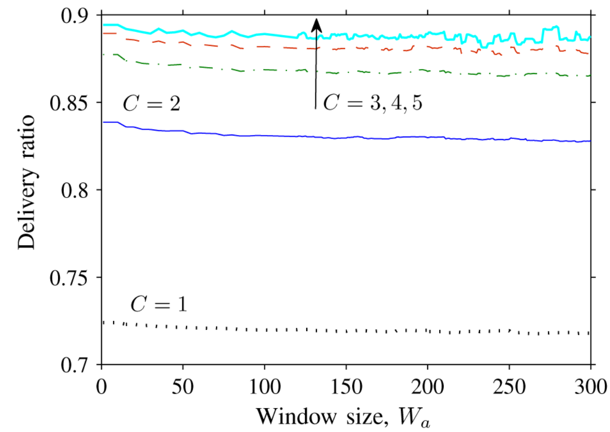

Fig. 8. Delivery ratio with adaptive relay selection as a function of adaptive window W_a at $\varepsilon_a = 0.1$.

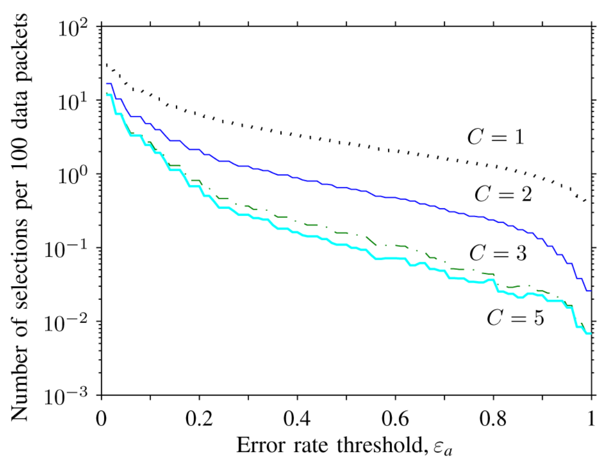

Fig. 7. Number of triggered relay selection attempts with adaptive relay selection per 100 transmitted DATA packets.

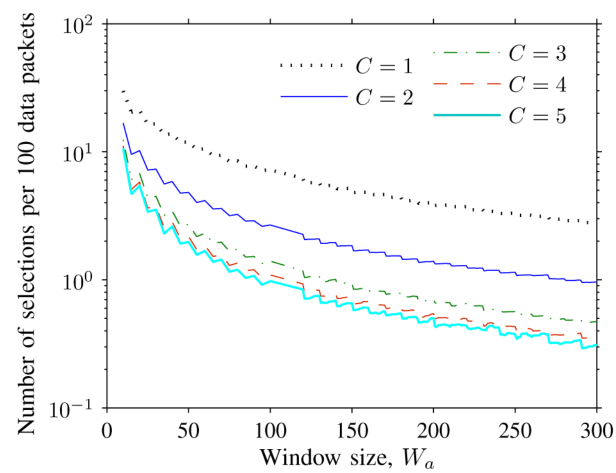

Fig. 9. Number of triggered relay selections as a function of adaptive window W_a with $\varepsilon_a = 0.1$.

long outage intervals are not tolerated. When ε_a becomes larger than 80%, however, the delivery ratio starts dropping significantly as relay selections become rare.

The number of selection attempts versus the tolerated error rate is plotted in Fig. 7. The results show that significantly fewer selections are triggered with higher ε_a and C. The impact of the window size W_a on delivery ratio, for given C and ε_a, is shown in Fig. 8. It can be seen that an increasing W_a reduces the delivery ratio only slightly. This is due to the fact that errors occur in bursts. A larger window tolerates more packet errors, but this has only small effect on the delivery ratio as long as a new relay selection is triggered. If ε_a is larger, there will be a larger effect of W_a on the delivery ratio (figure omitted).

Finally, Fig. 9 shows the number of adaptively triggered relay selections as a function of W_a. Here, the threshold error rate ε_a is fixed to 0.1. With growing W_a, the number of selections reduces since more errors on the cooperative link have to take place to trigger a new relay selection. It can be concluded that an increase in W_a and ε_a reduces significantly the selection overhead and only slightly degrades the delivery ratio. The presented results imply that network and protocol settings can be adjusted to fit the requirements on reliability and overhead of WSN applications, and support trends analytically studied in [19] and [20].

V. Experimental Assessment of Protocol Performance

A. Experiment Description

The purpose of this experiment is to empirically evaluate and compare the performance of the proposed cooperative relaying schemes in a real-world setting. The network setup is the same as in Fig. 3. All six nodes (with IDs $i \in \{1, \ldots, 6\}$) are used as source nodes to send DATA to the destination D. This reflects a typical setup of a wireless sensor network where remote sensors monitor the environment and report data to a sink.

In the experiment, each source node generates and transmits $K = 45\,000$ DATA packets. For better analysis of individual links, the operation of each source node is separated in time: i.e., node 2 starts transmitting its DATA packets only after node 1

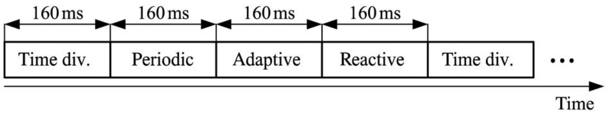

Fig. 10. Sequential execution of cooperative relaying protocols with different relay selection schemes.

finished sending all its K packets, and so on. In this way, the performance of individual links is tested avoiding medium access and interference aspects, which are out of scope of this paper but covered, e.g., in [37] and [38].

To compare the three cooperative relaying protocols explained earlier, they are executed sequentially as shown in Fig. 10.

A new DATA packet is generated at the source every 160 ms. Depending on the packet sequence number $k \in \{1, 2, 3, \ldots\}$, packets are handled by a certain retransmission protocol:

1) Time diversity: Packets $1, 5, \ldots, 1 + 4(k-1), \ldots, K-3$;
2) Periodic: Packets $2, 6, \ldots, 2 + 4(k-1), \ldots, K-2$;
3) Adaptive: Packets $3, 7, \ldots, 3 + 4(k-1), \ldots, K-1$;
4) Reactive: Packets $4, 8, \ldots, 4 + 4(k-1), \ldots, K$.

Thus, the protocols are executed completely independently from each other within allocated time frames of 160 ms.

For a given protocol, packets are generated periodically every 640 ms, which may correspond to a typical application for a monitoring process. The execution of different protocols is just shifted in time with respect to each other by 160, 320, and 480 ms. Such sequential independent testing of protocols provides a fair comparison of their performance.

The time diversity protocol is implemented in its own time slot. Here, a DATA packet is retransmitted by the currently active source node if it does not receive the corresponding ACK within $T_{\text{ACK}} = 20$ ms time. Up to four retransmissions by the source are allowed within its 160 ms time slot.

Periodic relay selection is performed $T_{\text{sel}} = 64$ s after the previous successful periodic selection. For convenience, it is also expressed as the expected number of DATA packets transmitted with a periodically selected relay, $N_{\text{sel}} = 100$. The maximum number of selection attempts L is set to five. Adaptive relay selection is triggered if more than five ACKs are not received by the source for the $W_a = 100$ most recent transmissions ($\varepsilon_a = 0.05$). The contention window w is 30 ms.

The size of DATA and ACK packets is 127 and 19 bytes, respectively, including Medium access control (MAC) and physical (PHY) layer overhead. All other coordination messages are 24 bytes long. The transmission power is -4 dBm for all packets.

The experiment was performed on 3 days for 12 h on each day. In total, 810 000 DATA packets were transmitted by source nodes over the network within 36 h. This results in 33 750 packets for each retransmission scheme on each link to D over 6 h of measurement time.

B. Overall Protocol Performance

The mean measured values for delivery ratio and number of selections per 100 transmitted packets over all links are collected in Table I. Note that these results are different from the respective values in Fig. 4 since only one source node was considered in Section V-B. Confidence intervals of 5% and 95% are obtained using the moving block bootstrap method suited to correlated time series [39].

TABLE I
DELIVERY RATIO AND PROTOCOL OVERHEAD

	Delivery ratio			Selections per 100 pkts		
	5%	Mean	95%	5%	Mean	95%
Single direct tx.	0.806	0.812	0.817	—	—	—
Time div., 1 retx.	0.847	0.853	0.858	—	—	—
Time div., 2 retx.	0.854	0.860	0.865	—	—	—
Time div., 3 retx.	0.860	0.865	0.870	—	—	—
Time div., 4 retx.	0.863	0.868	0.873	—	—	—
Periodic	0.967	0.969	0.971	1.00	1.03	1.04
Adaptive	0.978	0.979	0.980	1.00	1.07	1.12
Reactive	0.988	0.989	0.989	21.85	22.59	23.22

TABLE II
ADDITIONAL PERFORMANCE METRICS

	Periodic	Adaptive	Reactive
Number of candidates	3.69	3.86	3.43
Selection success	0.94	0.91	0.92
Successful relaying (when selected)	0.78	0.82	0.95

For time diversity, the impact of the maximum number of allowed retransmissions is shown. Additional retransmissions by the source provide a clear gain in the delivery ratio compared to a single direct transmission. However, the largest gain is achieved with the first retransmission, while further retransmissions do not bring a significant benefit. This shows that although an occasional packet failure might be recovered by an immediate source retransmission, most outage events on direct source–destination channels are of longer duration where time diversity retransmissions are ineffective.

Table I also shows that all cooperative schemes outperform noncooperative ones in terms of delivery ratio. Cooperative relaying with reactive selection provides the mean delivery ratio of nearly 99%. The number of relay selection attempts reflects how much coordination overhead is necessary during the protocol operation. Here, periodic and adaptive selections perform very similar. For periodic relay selection, the number of selections in a sample is slightly different than the expected constant 1/100 since up to five relay selection attempts can be performed until a relay is successfully selected. Cooperative relaying with reactive selection requires significantly more relay updates than the two other schemes since relay selection is triggered at each failed ACK message.

Table II shows additional data on relay selection. On average, 3.43 nodes participate in the relay selection process for reactive relay update, which is slightly less than by periodic and adaptive relay selections. This is due to the fact that with the reactive scheme, only nodes that receive both DATA and S_RREQ from S

participate in the contention. This is different for periodic and adaptive selections, where, as shown in Fig. 1, all nodes that receive an S_RREQ message from S participate in contention for serving as relay.

The success of relay selection is above 90%. For periodic and adaptive schemes, a relay selection is counted as successful when the selected node receives the D_RSEL from D. For the reactive scheme, only selections triggered by failed DATA packets are considered.

Finally, the last row shows how successful the relays are in retransmitting the DATA to the destination. Adaptive and periodic relay updates provide similar performance. Reactive relay selection results in significantly improved relaying delivery ratio, since the best relay is selected at each failed direct transmission.

C. Short-Term Protocol Behavior

Besides taking into account the time average of performance metrics over the whole duration of the experiment, we consider short-term behavior as well. Such analysis is important to reveal short communication outages, which can be critical for monitoring and control applications.

For a given selection scheme, DATA packets are indexed by $j \in \{1, \ldots, K_p\}$, where $K_p = K/4 = 11\,250$ is the number of packets transmitted for each scheme on one day. The binary sequence $X_i = \{X_i(j)\}_{j=1}^{K_p} = \{X_i(1), \ldots, X_i(K_p)\}$ describes the packet delivery from source $i \in \{1, 2, \ldots, 6\}$ to D by the given protocol

$$X_i(j) = \begin{cases} 1, & \text{packet } j \text{ is delivered} \\ 0, & \text{packet } j \text{ is not delivered.} \end{cases} \tag{2}$$

A subsequence $X_i(j_0, m) \subseteq X_i$ of length $m \in \{1, \ldots, K_p\}$ is defined as $X_i(j_0, m) = \{X_i(j)\}_{j=j_0}^{j_0+m-1}$, where j_0 is the starting index of the subsequence in X_i. In this paper, the subsequence $X_i(j_0, m)$ is also referred to as a sample.

The mean over the values in a sample is

$$\overline{X_i}(j_0, m) = \frac{1}{m} \sum_{j=j_0}^{j_0+m-1} X_i(j) \tag{3}$$

which corresponds to the packet delivery ratio in the sample for a given protocol. It also applies to single direct transmission and time diversity. By incrementing j_0 from 0 to $K_p - m + 1$, i.e., by sliding the sample window of a given size m over the sequence X_i, the delivery ratio over short-term intervals on the communication link i can be calculated. A sample size of $m = 100$ is used, which corresponds to a sample period of $T_m = 64$ s. The samples collected over 3 days of experiments are considered jointly, which corresponds to more than 800 000 samples overall.

Fig. 11 shows the cumulative distribution function (cdf) for the delivery ratio of each protocol within a sample of $m = 100$ transmitted DATA packets according to (3). More than 10% of all samples have a delivery ratio of less than 50% for direct transmissions. Time diversity retransmission improves the delivery ratio significantly only if the direct delivery ratio is higher than 90%. When the direct delivery ratio is lower than 50%, the direct channel remains bad most of the time, and time diversity retransmissions provide hardly any benefit. In contrast, all cooperative protocols achieve a significant gain in delivery ratio. Reactive relay selection provides the highest delivery ratio in a sample window, and the adaptive update scheme performs just marginally better than the periodic one.

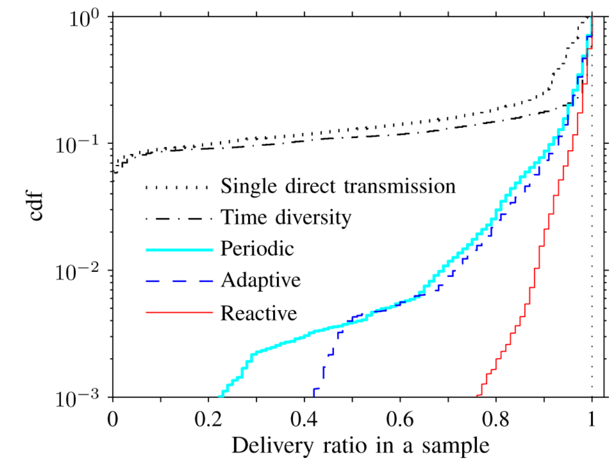

Fig. 11. Delivery ratio in a sample of 100 packets.

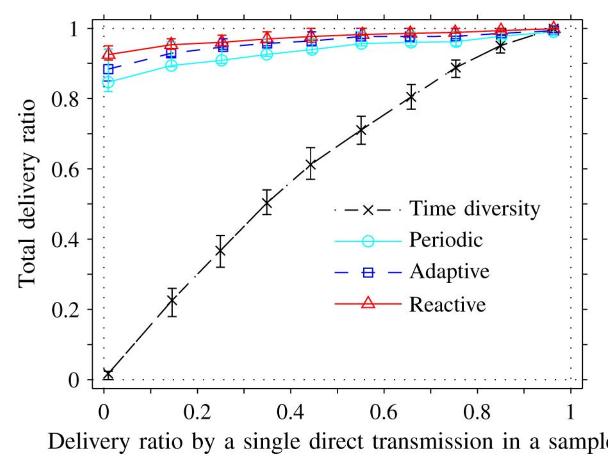

Fig. 12. Total delivery ratio for cooperative and time diversity retransmission protocols as a function of delivery ratio by single direct transmission.

Fig. 12 gives another comparison of the delivery ratio on the sample level. The delivery ratio of a given protocol in each sample is plotted versus the delivery ratio of a single direct transmission in the same sample. To avoid plotting more than 800 000 scattered points on the graph, the points are collected according to the x-axis value into 10 groups with boundaries $0.1(v-1) \leq x < 0.1v$, for $v = 1, \ldots, 9$, and $0.1(v-1) \leq x \leq 0.1v$ for $v = 10$. Within each such group, the arithmetic means over x and y values are calculated and plotted along with 25% and 75% quantiles of the data distribution.

As can be expected, the performance of time diversity is clearly correlated to the direct delivery ratio on the x-axis. In contrast, the performance of all cooperative schemes changes

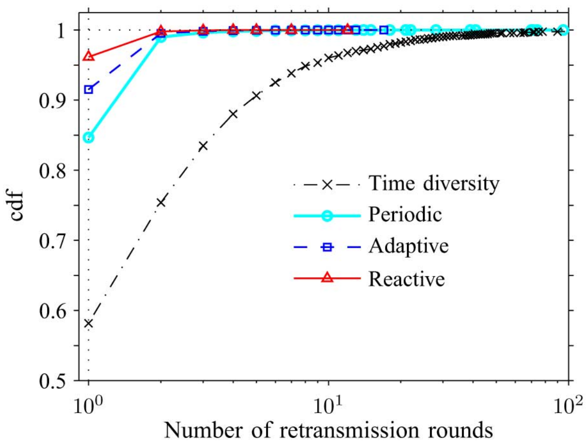

Fig. 13. Number of retransmissions until packet delivery.

only slightly. Therefore, cooperative relaying proves to be also beneficial at short time intervals when an S–D channel suffers from deep outage. Reactive selection provides slightly better delivery ratio than other relay update schemes. Its mean delivery ratio never falls below 90%.

Next we assume that each DATA packet, that is not delivered to D in its 160 ms slot, is transmitted again in the next time slot of a given protocol. This enables us to determine the number of required retransmission rounds until the DATA is delivered to D for each protocol. It can also be defined as the outage duration (when $X_i(j) = 0$) between two consecutive successful packet deliveries ($X_i(j) = 1$) for a given protocol.

Fig. 13 shows the empirical cdf for the number of necessary retransmission rounds until DATA packet delivery to D. Nearly 60% of all failed packets can be successfully delivered by the following time diversity retransmission from S. However, there are also longer outages where time diversity is not helpful. Such outages are particularly critical for industrial control processes. All cooperative schemes outperform time diversity schemes in delivery ratio, and reactive relay selection performs best of all. It can be seen that less than 10 packets (out of 200 000) would require more than two retransmission rounds with adaptive or reactive schemes. With the periodic selection scheme, the number of packets would be around several hundreds, which is still low. However, when strict delay guarantees on mission-critical messages are required, a closer integration with MAC, routing, and scheduling is required.

In summary, the results show that reactive relay selection provides the highest delivery ratio by fully utilizing the selection diversity among surrounding nodes. This robust communication comes at significant signaling costs in terms of selection overhead—about 20 times more selections are required than by adaptive relay selection. Additionally, with cooperative relaying, nearly all packets are delivered within the allocated time slot, and only few packets require additional retransmissions. With respect to energy consumption, it should be mentioned that reactive relay selection requires other nodes to listen to all S–D transmissions, which can be energy inefficient [20]. Adaptive relay selection requires similar overall selection overhead as periodic selection but provides better delivery ratio.

VI. Conclusion

This paper analyzed selective cooperative relaying protocols with different relay selection schemes: 1) periodic; 2) adaptive; and 3) reactive. These protocols have been implemented in IEEE 802.15.4 devices and deployed in an industrial production plant. Performance tests were conducted in a way to allow direct comparison of cooperative and noncooperative protocols for periodic monitoring processes.

Results show that selective cooperative relaying outperforms conventional retransmissions and can provide mean delivery ratio close to 99% over the whole network. The most significant performance increase takes place over short-term intervals when the direct delivery ratio is low. Here, the delivery ratio of cooperative relaying does not fall below 80% even when the direct delivery ratio is very low over the same intervals. The number of retransmissions is also dramatically reduced by cooperative relaying—nearly, all failed source packets are delivered with three or less retransmissions.

Relay selection parameters were investigated in different network topologies via protocol emulation based on the empirical channel measurements. Typically, three available relays are sufficient for reliable performance; only marginal gains in delivery ratio are achieved with more relay candidates. The delivery ratio can also be increased by shorter selection intervals $T_{\rm sel}$ for periodic selection and a lower error rate threshold ε_a for adaptive selection. However, even small gains require significant additional relay selection overhead. The tradeoff between delivery ratio and selection overhead must be adjusted based on the application requirements.

These results illustrate that selective cooperative relaying is a viable technique for improving communication reliability in industrial wireless sensor networks. In particular, adaptive selection provides good tradeoff between high delivery ratio and required selection overhead. The following issues are subject for future research: 1) integration with MAC and routing protocols and into existing industrial standards; 2) performance evaluation in presence of interference; and 3) integration with energy-efficient sleep scheduling and evaluation of energy consumption.

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Nikolaj Marchenko (S'07) received the Diploma degree in computer engineering from RWTH Aachen University, Aachen, Germany, in 2007, and the Ph.D. degree in information technology from the University of Klagenfurt, Klagenfurt, Austria, in 2013.

In 2011, he was a Visiting Research Scholar with Smart Antenna Research Laboratory, Georgia Institute of Technology, Atlanta, GA, USA. He also worked with Siemens Corporate Research, Princeton, NJ, USA, and Ericsson Eurolab, Aachen. His research interests include cooperative communication protocols.

Torsten Andre (S'11) received the Diploma degree from RWTH Aachen University, Aachen, Germany, in 2010, and he is pursuing the Ph.D. degree in information technology at the Institute of Networked and Embedded Systems, Alpen-Adria-Universität Klagenfurt, Klagenfurt, Austria.

He is a Researcher with the Institute of Networked and Embedded Systems, Alpen-Adria-Universität Klagenfurt. His research interests include the coordination of multirobot systems in indoor environments allowing collaborative tasks.

Günther Brandner (S'08) received the Dipl.-Ing. degrees in applied computing and mathematics in 2007 and 2008, respectively, and the Ph.D. degree in mathematics, specializing in the field of cryptography, in 2011, and is currently pursuing the second Ph.D. degree in information technology from the University of Klagenfurt, Klagenfurt, Austria.

Since 2007, he has been a Research and Teaching Staff Member and Doctoral Student with the Institute of Networked and Embedded Systems, University of Klagenfurt. His research interests include relay selection methods for cooperative relaying, time synchronization, and the implementation and evaluation of protocols on hardware platforms.

Wasif Masood (S'12) received the Master's degree in software systems engineering from RWTH Aachen University, Aachen, Germany, in 2011, and he is pursuing the Ph.D. degree in information technology at the University of Klagenfurt, Klagenfurt, Austria.

He has worked with Ericsson Eurolab, Aachen. In May 2011, he joined as a Research Associate with the Institute of Networked Systems (iNets), RWTH Aachen University. Before joining the Mobile Systems Group, the Institute of Networked and Embedded Systems (NES), Klagenfurt, he worked with the Multimedia Communications Lab (KOM), Technische Universität (TU) Darmstadt, Germany. Since April 2012, he has been a Researcher with the University of Klagenfurt.

Christian Bettstetter (S'98–M'04–SM'09) received the Dipl.-Ing. degree in electrical engineering and information technology from the Technische Universität München (TUM), Munich, Germany, in 1998, and the Dr.-Ing. degree (summa cum laude) in electrical engineering and information technology in 2004.

He was a Staff Member with the Communications Networks Institute, TUM, until 2003. From 2003 to 2005, he was a Senior Researcher with the DOCOMO Euro-Labs, Munich. Since 2005, he has been a Professor and Head of the Institute of Networked and Embedded Systems, University of Klagenfurt, Klagenfurt, Austria. He is also Scientific Director and Founder of Lakeside Lab, Klagenfurt, a research cluster on self-organizing networked systems. He also coauthored the textbook *GSM—Architecture, Protocols and Services* (Wiley).

Mr. Bettstetter received Best Paper Awards from the IEEE Vehicular Technology Society and the German Information Technology Society (ITG).