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Measurement-Based Analysis of Cooperative Relaying in an Industrial Wireless Sensor Network

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***Abstract*—Cooperative relaying is a communication technique that has been shown to improve link reliability between communicating entities. Most results in this area are obtained either analytically or via simulations. Rather few real-world experiments are conducted to backup theoretical results. This paper intends to go a step in this direction of applied research.**

We study the performance of cooperative relaying for industrial applications based on real-world measurements. These link-level measurements are conducted employing low-cost, off-the-shelf IEEE 802.15.4 devices in a factory characterized by a harsh and cluttered environment. Using the measured data, we emulate a simple cooperative relaying protocol to investigate the performance in terms of outage and packet delivery ratio and study parameters suitable for relay selection.

***Index Terms*—Sensor networks, ad hoc networks, cooperative relaying, radio measurements, industrial technology.**

I. Introduction and Motivation

Cooperative relaying is used to improve reliability of wireless communications in fading environments [1]–[3]. It employs a relay node to support point-to-point transmissions between two communicating nodes. The relay overhears source transmissions and can forward the data to the destination. Such a technique profits from space-time diversity. Many aspects of cooperative relaying have been investigated in the past years: capacity bounds, channel coding techniques, medium access protocols, networking aspects, and others. Most contributions are based on mathematical analysis or computer simulations (see, e.g., [4]–[8] and references therein). In contrast to this great body of work, only few real-world experiments and measurements have been conducted to substantiate theoretical findings and gain practical insight into the development of cooperative relaying protocols and their performances (see [9]–[12]). The objective of our work is to further close the gap between theoretical and applied research in this field.

We constrain our analysis to wireless sensor networks (WSNs) consisting of low-cost, low-power embedded devices. Such networks can benefit from cooperative relaying, since the devices have size and cost limitations, and, as a result, advanced signal receiving techniques, multiple antennas for Multiple-Input Multiple-Output (MIMO), or advanced physical layers cannot be used to overcome negative fading effects. In contrast, most changes for cooperative relaying can be implemented by changing the data link layer. This keeps the development and deployment costs low. Further, we focus on industrial applications of WSNs characterized by harsh and heavy-cluttered communication environments leading to significant multipath fading. In addition, such applications require very high reliability of data transmissions, e.g., to monitor and control industrial production processes [13].

We set up a network of IEEE 802.15.4-compatible devices in an industrial storage hall. Measurements are performed at the receiving nodes per frame basis, which is reasonable for the targeted low-complexity hardware. We show that our measurements fit closely with already existing models for industrial environments. Using the obtained real-world measurements of the individual links, we emulate the proposed protocol behavior within the network. The results presented in this paper address the following questions: How reliable is a selected relay over time? How often should relay selection be performed? What is the overall end-to-end performance in terms of outage duration and packet delivery ratio in comparison to a non-cooperative setup? Results give insight into the real-world behavior of cooperative links and can be used to develop more efficient cooperative relaying protocols.

The rest of this paper is organized as follows: Section II gives an overview of related publications concerning indoor path loss models and cooperative relaying experiments. Section III presents the methods used for the experiments. In Section IV we present our link level measurements and compare the results to previous measurements for validation. Then, in Section V, we investigate the behavior of cooperative links and cooperative network performance and compare it to time-diversity. Finally, Section VI concludes the paper.

II. Related Work

Multiple indoor radio propagation models have been developed. Here, only four most common ones are mentioned. Tanghe *et al.* perform measurements in an industrial scenario at various frequencies determining coefficients for the well-known simple path loss model [14]. The general ITU indoor channel propagation model [15] considers floor penetration and includes an empirically determined site-specific factor. The COST 231 project compares three propagation models of different richness of detail [16] of which the multi-wall model led to the best results modeling free space, floor, and wall losses considering different types of walls. With even higher richness of detail in [17] Francisco develops a path loss model for hospitals measuring line-of-sight (LOS) and non-line-of-sight (NLOS) links considering the special equipment found in hospitals. The main trade-off between different types of models is either the need to closely model the premises (and for this to know details such as used materials, dimensions and exact positions of walls, furniture, equipment, etc.) or to use a general model which is less accurate.

Besides analytical and simulative work, real world experiments are conducted by a number of researchers. Petrova *et al.* [18] do performance measurements for outdoor and office scenarios for 802.15.4 radio devices to determine their performance and the influence of IEEE 802.11 networks. Tang *et al.* [19] give a good overview of work done in this field, though mostly concentrating on measurements in outdoor or office scenarios. They use sensor nodes comparable to our TelosB motes and do channel assessment in industrial surroundings found in a university work shop.

Cooperative relaying for industrial wireless networks is also studied by Willig in [20]. He proposes a simple relaying protocol and shows significant benefits for packet delivery under a delay constraint. His work closely fits to our own, but it is based on computer simulations only.

III. Experimental Setup and Method

Measurements are conducted using off-the-shelf wireless sensor devices — TelosB motes by Crossbow — in a warehouse of an electronics company. The devices are compatible to IEEE 802.15.4, which is a standard for low-power, wireless personal area networks targeting low-cost, low-complexity and low-rate embedded devices. The standard defines physical and data link layers and is basis for many other standards such as ZigBee, ISA100.11a, and WirelessHART. It defines three physical layers, supporting frequencies at 868 MHz, 902 MHz, and 2.4 GHz. The latter is also shared by other standards such as IEEE 802.11 and Bluetooth. In our case, transmissions are done in the 2.4 GHz band allowing transmission rates of up to 250 kbit/s. The data is appended with a single 16 bit checksum for both header and payload. Medium access control is based on Clear Channel Assessment (CCA), i.e. a mote may access the medium if it does not detect another device transmitting on the same frequency.

The setup of the warehouse is depicted in Figure 1. Items in the warehouse are mainly made of metal and plastic. Motes are deployed at various places with a master mote (node 0) to control the test. It is assured that all motes have single-hop connectivity to the master to be able to receive commands during the test. Note, however, that two nodes at opposite sides of the master may not be able to communicate directly. Between the aisles, about a dozen of people and several forklifters are moving. The motes are attached to shelves made of metal. The shelves are filled, which does not allow for LOS between most of the motes.

The network performance is studied as follows: Out of 13 motes, nine motes act as senders, where one mote after the other broadcasts 8000 frames with a transmission power of 0 dBm and a frame size of 23 bytes. Transmission of a frame occurs every 40 ms leading to a total transmission time of 5 min 20 s per link. All non-sending 12 motes act as receivers

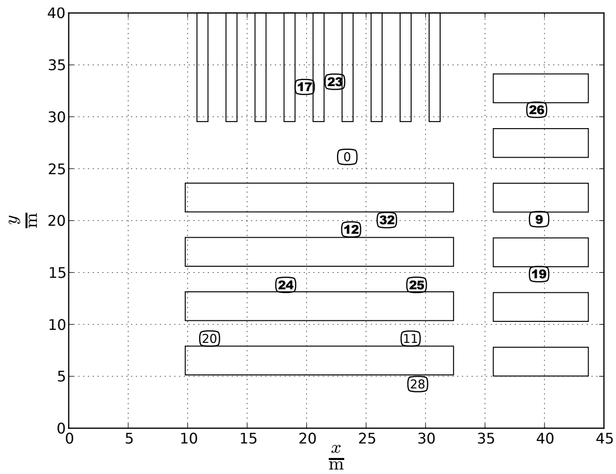

Fig. 1. Warehouse and sensor deployment. The hall has dimensions of 45 m by 40 m. The small racks at the top of the figure store bits and pieces mainly made of metal. The other, big racks are filled from top to bottom with metal and plastic goods; the width of a big rack is 2.9 m. The sensors are attached to either side of the racks in a height of about 1.9 m. Distances between motes are 14.7 m on average with a minimum and maximum distance of 2.9 m and 35.0 m, respectively. Transmitting nodes are illustrated in bold typeface.

and log the successful reception of frames. A frame is received successfully if its checksum is valid. Meta data for the received frames is stored in the motes' 1 MByte flash storage; no frames are dropped due to limited capacity. After test completion, the motes are collected and the flash storage is copied to a computer where sanity checks and analysis of the data are performed. Weak links generally not capable of communicating frames, but transporting single frames from time to time, are neglected. From the setup's 108 possible directed links between nodes, at least single frames are received successfully for 83 links, of which 8 links are neglected.

To measure performance we use two metrics for each frame: Received Signal Strength Indicator (RSSI) and Link Quality Indicator (LQI). Both are computed by the CC2420 chip used on the TelosB motes. The RSSI value is computed over 128 µs with an accuracy of ± 6 dBm, which is sufficient for our measurements. The LQI is derived from the CORR value, which is computed using a correlation value on the first eight symbols of the frame. The correlation value is specified to be approximately in the interval $[50, 110]$ [21]. While 802.15.4 requires the LQI to be spread among the interval $[0, 255]$, in our measurements we use the values returned by the CC2420, which are in the interval $[44, 108]$.

The measurements are performed in an area with active 802.11b/g/n networks. We assume this is a valid scenario for deployment of industrial WSNs, where coexistence with other technologies using the band at 2.4 GHz cannot be avoided.

IV. Link-Level Measurements

A. Path Loss and Shadowing

Figure 2 shows the RSSI values of all links as a function of distance between motes. Frames are received successfully at distances up to 35 m.

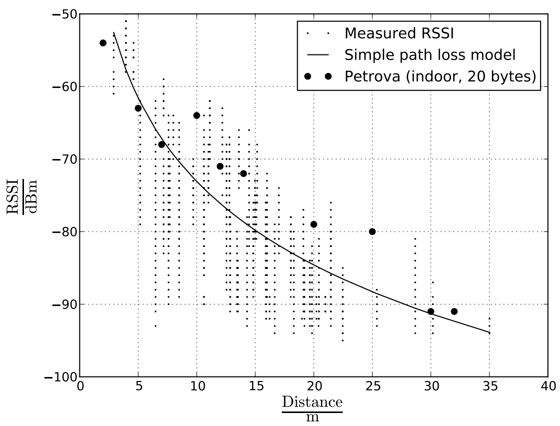

Fig. 2. Received power levels of frames over sender-destination distance.

It is of interest to compare our measurements to commonly used path loss models. From the aforementioned models, the COST-231 and ITU models cannot be employed because necessary parameters for our environment are missing. Thus, we determine parameters of the well-known simple path loss model defined by

$$\mathrm{PL}(d)\,[\mathrm{dB}] = \overline{\mathrm{PL}}(d_0) + 10\,\gamma\,\log_{10}\left(\frac{d}{d_0}\right) + X_\sigma, \quad (1)$$

with path loss exponent γ, reference path loss $\overline{\mathrm{PL}}(d_0)$ in dB at the reference distance d_0, and the normally distributed random variable X_σ modeling shadowing. We differentiate between two options: fixed intercept and non-fixed intercept fitting [14]. In fixed intercept, free-space propagation is assumed up to d_0, hence, its selection strongly influences the resulting parameter γ. In non-fixed intercept, the selection of d_0 is arbitrary. Minimizing the mean squared error between measured values and (1) yields the parameters shown in Table I.

TABLE I
COEFFICIENTS OF THE SIMPLE PATH LOSS MODEL (1)

Experiment	Model	γ	$\overline{\mathrm{PL}}(d_0)$	d_0	σ
Andre *et al.*	fixed	3.8	46.1 dB	2 m	9.6 dB
Andre *et al.*	non-fixed	3.8	79.8 dB	15 m	9.7 dB
Tanghe *et al.*	non-fixed	2.2	71.8 dB	15 m	8.1 dB

We determine the corresponding reference distance d_0 for the fixed intercept model which matches the non-fixed intercept. A reference distance of $d_0 = 2\,\mathrm{m}$ leads to comparable parameters and closely matches the path loss curve. Therefore, only one path loss curve is depicted in Figure 2. For the non-fixed intercept model, our results show an increased exponent γ compared to Tanghe *et al.* [14]. This can be explained by higher shielding of our devices attached directly to metal shelves, whereas in [14] the sender was mounted under the ceiling.

Figure 2 also shows measurement results by Petrova *et al.* [18]. They deployed TelosB motes in an office space. An `RSSI_OFFSET` of $-45\,\mathrm{dBm}$ is added to their measured values according to the CC2420 specification [21]. As expected, the average loss is smaller than in an industrial environment.

B. Frame Error Rate

As another metric for link quality, we evaluate the frame error rate (FER) of each link in the network. It is the ratio of frames not received correctly to the total number of frames sent over this link. The measured FER varies from link to link and is within the interval $[0.14\,\%, 93\,\%]$. The sample distribution of these FERs is shown in Table II: About 75 % of all links experience a FER below 1 %. About 10 % of all links have a FER between 1 % and 10 %; the remaining 15 % suffer from a high FER above 10 %. In the whole network, 21 % of all frames are lost.

TABLE II
DISTRIBUTION OF LINK FERS

Links with FER $\leq y$	75 %	85 %	90 %	95 %
y in %	0.9	10.5	67.5	81.2

Using Pearson's correlation coefficient, we compute the correlation between mean RSSI and FER as well as correlation between mean LQI and FER over all links. We obtain $\rho_{\mathrm{RSSI}} = -0.53$ and $\rho_{\mathrm{LQI}} = -0.89$. Tang *et al.* [19] obtain similar results, $|\rho_{\mathrm{RSSI}}| = 0.43$ and $|\rho_{\mathrm{LQI}}| = 0.73$, concluding that LQI is a better indicator than RSSI, since the absolute value of the correlation to FER is higher.

C. Outage Duration

Finally, we study the link reliability in terms of outage duration Γ. A link is considered to be in outage whenever the destination node of this link does not receive frames successfully. Table III shows the distribution of Γ in number of frames. A link fails for the duration of only one frame in $45\,\%$ of all cases; in such cases, simple frame retransmission is a good countermeasure. The outage duration is two frames in $16\,\%$ of all cases. Outages are three frames or longer in $30\,\%$ of all cases; here other forms of diversity are needed.

TABLE III
DISTRIBUTION OF OUTAGE DURATIONS IN FRAMES

$\mathrm{P}(\Gamma \leq x)$	0.45	0.61	0.70	0.80	0.90	0.95	0.99
x in frames	1	2	3	5	12	23	100

Assuming the current frame is in outage, the probability that the next frame delivery will be successful is

$$\sum_{x=1}^{\infty} \frac{\mathrm{P}(\Gamma = x)}{x} = 0.45 + \frac{0.16}{2} + \frac{0.09}{3} + \ldots \approx 59\,\%\,. \quad (2)$$

V. PERFORMANCE OF COOPERATIVE LINKS

This section evaluates the performance of a simple cooperative relaying protocol. Questions addressed are: How good is a selected relay over time? What is the distribution of the end-to-end outage duration? What is the impact on overall end-to-end performance in terms of outage and packet delivery ratio? To answer these questions, we perform a hybrid approach: We log each transmitted frame on each communication link in the experiment described above. The protocol behavior is then emulated over these real-world data.[1] This hybrid approach has been chosen for pragmatic reasons to gain first insights for protocol development. In future work, results can be used to implement more efficient cooperative relaying protocols on real hardware and do performance measurements of a cooperative network in the same scenario.

A. Protocol Description

For a given source node, the cooperative relaying protocol determines in a first step a set of *relay candidates*, from which in a second step the actual *relay* is selected.

A node i is recognized as relay candidate C_i to source node S, if C_i receives a request from S in a given frame and S receives a confirmation from C_i in the next frame.

To select one relay R out of the candidate set $\{C_i\}$, a measure of quality is assigned to each candidate. The measure is computed by an utility function, which maps a set of quality indicators to a single quality value. The utility function can control a backoff timer for each candidate, such that well-suited candidates are likely to be selected [6]. Quality indicators can be as follows: instantaneous channel state measurements [6], long-term channel relay reliability in terms of the expected FER on the S-R and R-D links, and the node's residual battery level [22]. In our approach, we use instantaneous LQI values as a single quality value. As it was shown before, LQI is measured at each received frame and is better correlated with FER than RSSI. From the set of candidates $\{C_i\}$, the node with the highest S-R LQI is selected:

$$R = \arg\max_i \mathrm{LQI}_{SC_i} \,. \tag{3}$$

Once relay selection is completed, the source S starts transmitting data to the destination D. One packet is transmitted per time frame. If D receives the data successfully, the frame transmission is complete and a new frame can be sent. If D does not receive the data successfully, the relay R has to help. If R receives the data successfully, it will forward the data to D in the following frame. If D is still not able to receive the data, the packet is dropped.

B. Parameters of Relay Selection

Figure 3 shows how often different nodes become relay candidates and how often they are selected as relay. The percentage of frames for which no relay candidate can be found is negligibly small (node ID$= -1$ in the figure). As expected, some nodes are selected much more frequently than others. This fact can reduce the overall network lifetime and should be considered as a metric for relay selection.

[1]Our hybrid approach neglects some of the spatial correlation in shadowing. In a real protocol, the source-destination and source-relay transmissions occur at the same time instance, while we have measured links at different time instances and use these measurement values for performance evaluation.

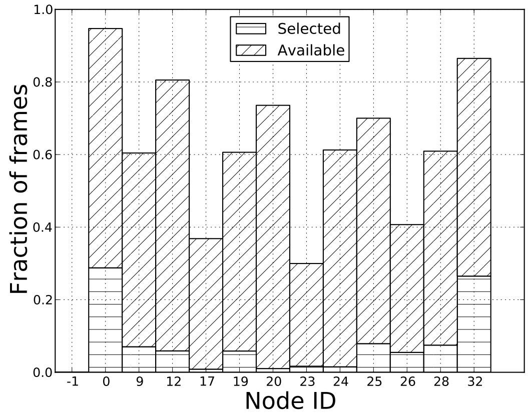

Fig. 3. Percentage of frames each node is a valid relay candidate and percentage of frames it is selected as relay.

Relay selection can lead to significant overhead if performed too often. A *relay update interval* needs to be chosen, trading off relay quality and message overhead. The choice of this interval should consider the temporal stability of the S-R and R-D links. For example, if these links are very stable (unstable), updates need to be done seldom (often). To gain more insight, we study the number of consecutive frames that a selected relay receives successfully from the source before the next outage between these nodes occurs. This length of such a successful burst is denoted by the random variable L in the following; the set of all L-values collected in the experiment is called $\{L\}$. Figure 4 (solid line) depicts the empirical cumulative distribution function (CDF) of L in the S-R link. The behavior of the R-D link is similar. The S-R link is without errors for a period longer than $L = 100$ consecutive frames in about $82\,\%$ of all L-values.

Recall that Table III shows that $70\,\%$ of all outages are three frames or shorter. This means that even if an outage occurs, there is a high chance that the selected relay becomes again available after few erroneous frames, making a new relay selection unnecessary. By tolerating such short outage on the S-R link, the update interval can be increased significantly. We distinguish two types of error tolerance: a) absolute number of frame errors e and b) S-R link FERs $\bar{e}$. After each frame, the error statistics is computed anew and it is decided whether a new relay will be selected or not. Relay selection will be made once both more than e errors occur and the FER over L frames exceeds $\bar{e}$.

As shown in Figure 4 (dashed line), we can increase the update interval from $L = 10$ to 120 frames if we tolerate three frame errors with a probability of $90\,\%$. In other words, choosing a relay update interval (update rate) of up to 300 frames ($0.1\,\mathrm{s}^{-1}$) ensures us with high probability ($p \geq 90\,\%$) that L is at least as long as the update interval. If we allow a FER $\bar{e}$ (dashed-dotted line), the update interval can

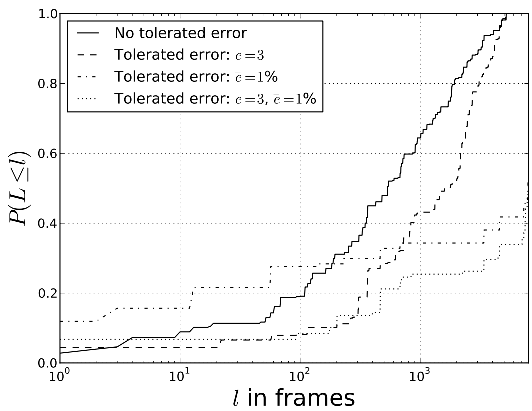

Fig. 4. Stability of selected relays. Allowing small relative errors increases the time of association between relay and sender.

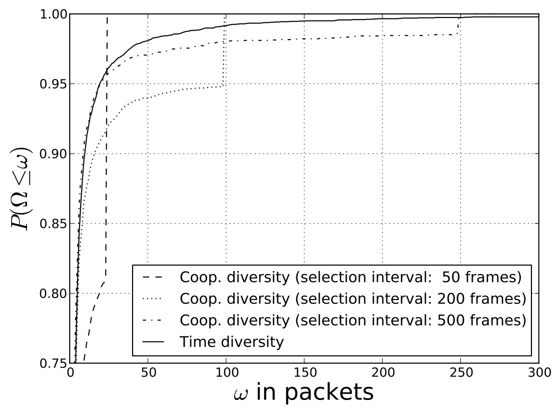

Fig. 5. Outage duration CDF for time and cooperative diversity. The corresponding relay update interval is indicated in brackets.

be increased for high values of L.[2] Finally, allowing both error types (dotted line) yields the longest update intervals. In summary, tolerating some few frame errors and a nonzero FER between source and relay enables us to increase the update interval significantly.

C. End-to-End Outage Duration

We now study the dynamics of the end-to-end connection between S and D using cooperative relaying. A cooperative link is considered to be in outage if D can neither receive direct S-D transmissions nor S-R-D transmissions. A relay is selected anew after a fixed update interval. We compare performance to a simple time diversity scheme, in which S transmits the data once again if D does not receive the first transmission successfully. The packet is dropped if the second transmission is unsuccessful. In case of successful delivery, a new packet is transmitted immediately, else after one retransmission. Note that some packets require one frame (no retransmission needed) and others require two frames (retransmission needed). The number of consecutively dropped packets is called outage duration and is denoted by Ω.

Figure 5 shows the empirical CDF of Ω for time diversity and cooperative relaying with different relay update intervals. Using time diversity, most outage durations are short, namely shorter than 25 packets in about 96 % of all cases; nevertheless, also very long outage durations beyond 250 packets occur. Using cooperative relaying, the outage duration statistics depends on the update interval. As depicted, outage durations are limited by the relay selection interval with high probability. Here, limitation is to half the update interval as each outage takes two frames (transmission and retransmission), where, in the worst case, the maximum outage duration in packets corresponds to half the update interval in frames. In environments where long outage durations are likely, the relay selection interval should be decreased to increase reliability at the cost of more overhead.

[2]For durations shorter than 250 frames, the probability of short L is significantly higher than for no tolerated errors (solid line). Note, however, that the absolute numbers do not increase and are equal in both cases because one erroneous frame below $L = 100$ immediately exceeds the tolerated error margin: $\frac{1}{L} > 1\,\% \;\forall L = 1, .., 99$.

D. End-to-End Delivery Ratio

We finally evaluate the delivery ratio of cooperative relaying with different relay update intervals and compare it to that of time diversity (see Table IV). The network is studied for all links with a duration of 8000 frames each. The number of transmitted packets varies due to the number of diversity transmissions (two frames each) and overhead caused by relay selection; relay selection is assumed to take two frames according to [6]. For a fair comparison, signaling packets are not considered to compute the delivery ratio.

TABLE IV
PERFORMANCE OF TIME DIVERSITY AND COOPERATIVE RELAYING WITH DIFFERENT RELAY UPDATE INTERVALS.

Attribute	Cooperative relaying			Time div.
Update interval in frames	50	200	500	n/a
Packets transmitted by S or R				
Total	541 238	539 525	539 206	538 967
Signaling in %	4.4	1.1	0.4	0.0
Delivery ratio (packets received successfully at D)				
Total in %	94.5	94.6	94.6	89.7
First transmission in %	88.7	88.7	88.7	88.7
Retransmission in %	5.8	5.9	5.9	1.0
Delivery ratio of retransmissions (packets received successfully at D)				
Successful in %	51.5	52.0	52.4	9.2

As shown in Table IV, relay selection leads to a signaling overhead of 4.4 % for an interval of 50 frames and 0.4 % for 500 frames. It is shown that, in this environment, the update interval has only little influence on the delivery ratio. The delivery ratio of retransmissions — i.e., the number of successful retransmissions over all retransmission attempts — is similar for all relaying intervals. The cooperative networks investigated here perform better than a comparable network with time diversity. Packet delivery ratio is increased from about 90 % to almost 95 %, mainly due to the fact that the delivery ratio of retransmissions from relays is much higher than that from the source. This gain can be explained by Table III and (2): time diversity is only successful for frames in outage if the next frame allows successful delivery.

VI. Conclusions

We used measurements to analyze performance of cooperative relaying in WSN. An experiment was conducted in an industrial setting with cluttered environment. Based on channel measurements, we derived a path loss model and showed that it closely matches results from existing models for industrial environments.

We used the measured data to emulate a simple cooperative relaying protocol in the network. We found that the outage duration usually is rather short (in 70 % shorter than three frames). As a result, a correctly selected relay can operate successfully for a significantly longer time if a number of relay outages can be tolerated. We demonstrated that the relay update interval has strong impact on the outage duration CDF. Finally, we showed that the whole network can benefit from cooperative transmissions at reasonable overhead costs, since the overall packet delivery ratio improves.

Acknowledgment

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