868 MHz: a noiseless environment, but no free lunch for protocol design

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Abstract*—Lossy links are one of the fundamental characteristics of wireless sensor networks (WSNs). A large amount of work has been performed on characterizing link properties of 802.15.4 radios, in particular in the 2.4 GHz band. Unfortunately, the 2.4 GHz band has the apparent disadvantage of a crowded spectrum and considerable external interference, e. g., from WiFi, Bluetooth and even microwave ovens. We therefore investigate the performance of radios operating on the alternative 868 MHz frequency band, which is basically noise-free as determined from extensive experiments on a large-scale indoor testbed featuring more than 100 nodes. Although the lack of external interference eases protocol design, our study reveals that -and characterizes to what extent- wireless links in the 868 MHz band still show large variations in performance that must be accounted for.** ***Please note that this is an updated version of the corresponding INSS 2012 paper.[1]

***Keywords*-Wireless Sensor Networks, Testbeds, 802.15.4**

I. Introduction

Wireless sensor networks are in essence cooperative systems that rely on communication between individual, resource-constrained sensor nodes. While communication is a major primitive of this class of systems, the underlying communication links that low-power radio provide are rather lossy, some may even say lousy. One of the major radio platforms used in sensor networks is based on the 802.15.4 standard. Srinivasan et al. [14] present a comprehensive study of low-power wireless links using 802.15.4 radios focussing on the 2.4 GHz frequency range. However, low-power wireless is more than just 802.15.4 radios. In particular another popular frequency range is around 868 MHz, which has been used in various WSN deployments [2], [3], [11]. In fact these radios seem to even provide an advantage to most 802.15.4 deployments as they avoid the crowded 2.4 GHz band [5], [8], [9], [15], [19]. With the increase of applications on WiFi (802.11b), Bluetooth (802.15.1) and 802.15.4 devices as well as noise from other devices such as microwave ovens, the resulting contention and interference increasingly hampers system operation. As such, WSN deployments using 868 MHz radios might be an attractive alternative. This paper addresses the research question: *What are the characteristic properties of low-power wireless links of 868 MHz radios and how do these affect protocol design?* To this end, we perform numerous testbed experiments on a large-scale indoor testbed. Note that we are not directly interested in the spatial characteristics or physical properties such as placement or orientation of nodes, but rather take them as is. For an investigation of spatial characteristics we refer the reader to earlier work on TR1001 radios [13]. Instead, we are focussing on the link properties from the perspective of protocol design without access to deployment specifics. As such we are focussing on the distribution of links, the temporal characteristics of links, and link asymmetry. To provide a perspective on differences to experiments on 802.15.4, we compare our results to the most comprehensive study by Srinivasan et al. [14] and discuss differences and commonalities.

In a nutshell, we can summarize the contributions of this paper as follows:

- We characterize our large-scale 108 node indoor testbed and perform extensive experiments on the characteristics of low-power lossy links of an 868 MHz radio.
- We analyze the testbed experiments to identify fundamental link properties and compare these to properties of 802.15.4 links.
- We discuss the impact of link properties for protocol design.

Our paper is structured as follows. We discuss our experimental setup in Section II. We follow with detailed experiments investigating noise (Section III) and packet reception rates (Section IV. We proceed with analyzing temporal effects (Section V), link asymmetry (Section VI), and their implications for protocol design (Section VII). Finally, we compare our findings to related work (Section VIII) and summarize our major findings in Section IX.

II. Experimental setup

In this section we detail on the experimental setup. First, we present our 868 MHz testbed on which all experiments are performed. Second, we present the set of measurements that we base our experimental study on. Third, we give a

[1]In this updated paper Fig. 4 is replaced with a new measurements. In the original publication, the figure was based on non-consecutive measurements. To give a clearer picture, this paper introduces results from consecutive measurements. Also, Fig. 8 and Fig. 9 are replaced with updated measurements. Nevertheless, the results stay the same. Additional to changing the figures we corrected some typographical errors.

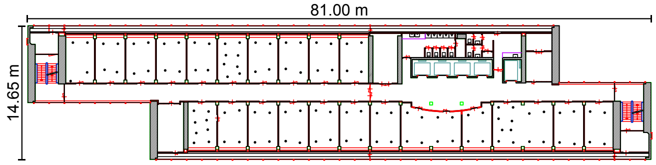

Figure 1. Floor plan of the 9th floor of the EEMCS building. The black dots indicate the locations of the 4 (or 8) nodes per room.

Table I
DEFAULT CONFIGURATION OF THE CC1101 RADIO STACK.

Data rate	19.2 kbps	TX power	–30.2 dBm
Modulation	2-GFSK	Packet length	116 B
Encoding	Manchester	IPI	62.5 ms

Table II
CONNECTIVITY METRICS AT VARIOUS TRANSMISSIONS POWER LEVELS. HIGHLIGHTED IN GRAY ARE THE TRANSMISSION LEVELS THAT ARE USED IN EXPERIMENTS BELOW.

			Shortest Path	
TX Power (dBm)	Number of Components	Size Largest Component	Mean Length	Max Length
10.7	1	108	1.19	2
5.0	1	108	1.36	3
–0.3	1	108	1.45	3
–5.0	1	108	1.63	4
–15.1	1	108	2.24	5
–20.5	1	108	2.78	7
–30.2	3	106	5.92	16
–34.2	15	32	6.36	21
–59.3	108	1	∞	∞

brief overview of our testbed, its network and link characteristics based on initial experiments.

A. Testbed

Our sensor network testbed, called *the rack*, is part of a large federated European testbed platform called WISEBED[2]. WSN developers can use WISEBED to evaluate and analyze their applications and algorithms on several heterogeneous testbeds, including the rack.

The rack consists of 108 SOWNet G301 sensor nodes, called GNodes in the following. Each GNode comprises a Texas Instruments MSP430F2418 microcontroller (with 116 KB ROM and 8 KB RAM), an Atmel AT45DB081D 8 megabit flash chip and, most importantly for our experimental study, a Texas Instruments CC1101 packet radio operating at 868 MHz. Additionally, GNodes feature a RainSun AN1603 Antenna with a peak gain of 0.5 dBi. Each GNode has a backbone network connection to a PC Engine Alix.1D. A testbed server connects to the Alix to collect serial output and debugging data.

The radios are configured to use Gaussian Frequency Shift Keying (GFSK), in particular 2-GFSK. We typically use channel 0 of the radio at 868.3 MHz. In order to confirm results on a different channel, we select channel 19 at 872.1 MHz for comparison. Table I shows the basic configuration parameters of our communication stack, including packet size and inter-packet interval (IPI), i. e., the time between consecutive packets.

Nodes are placed in the ceiling of the 9th floor of a university office building. Figure 1 depicts the floor plan of the building and details on the placement of nodes within the individual rooms. The activity in the building is regulated by strict access policies, which result in no human activity outside of office hours (7:00-22:30) and in particular on the weekends. This allows us to compare busy, dynamic office hours with very static weekend periods.

[2]http://wisebed.eu/

B. Measurements

Our experiments rely on two metrics: We measure what fraction of packets that are sent is actually received by means of (missing) sequence numbers. To avoid self interference, the nodes are in turn commanded to send out a burst of packets, after which the neighboring nodes can record the *packet reception rate*, or PRR for short. We are additionally interested in the *noise floor* of each node. Hence, we sample the RSSI register of the radio that provides and estimation of signal power level before and after each transmission in order to capture ambient noise.
We classify links into three classes [14]. *Good* links have a PRR ≥ 0.9. *Bad* links have a PRR ≤ 0.1. *Intermediate* links in the "gray zone" [13], [18] are in between.

C. Transmission power and connectivity

The transmission power setting has an important effect on the resulting topology of the testbed, which varies from a set of disconnected nodes to an almost completely connected (single cell) graph entailing all 108 nodes. Table II displays some of the network topologies of the testbed at different transmission levels. In the table, we count only good links for the network connectivity. We indicate for each transmission level whether the network is strongly connected (if the number of strongly connected components is 1), how large the biggest component is and finally some statistics on shortest path lengths. The testbed setup allows us to emulate very dense deployments at large transmission powers. At a transmission power of 10.7 dBm the testbed builds a near single-cell network with a mean shortest path length of 1.19. At the lowest transmission power nodes are completely disconnected. Our experiments explore opposite ends of the spectrum using two different transmission powers: At –30.2 dBm we have an interesting multi-hop setup that includes (almost) all of the nodes, and at –0.3 dBm we have a very dense network with a few multi-hop links. Most of

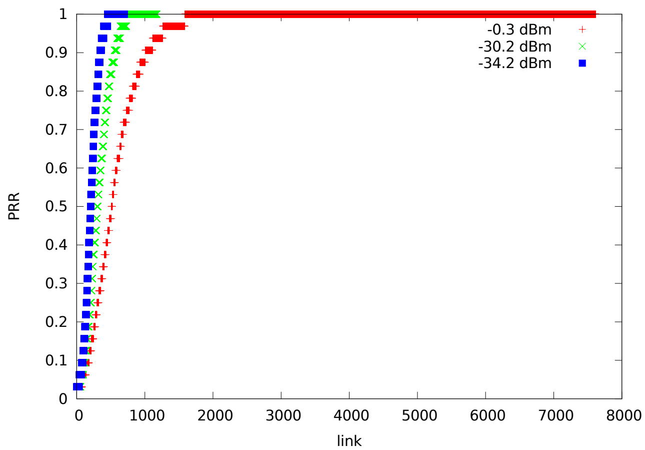

Figure 2. Distribution of the PRR at –0.3 dBm, –30.2 dBm and –34.2 dBm.

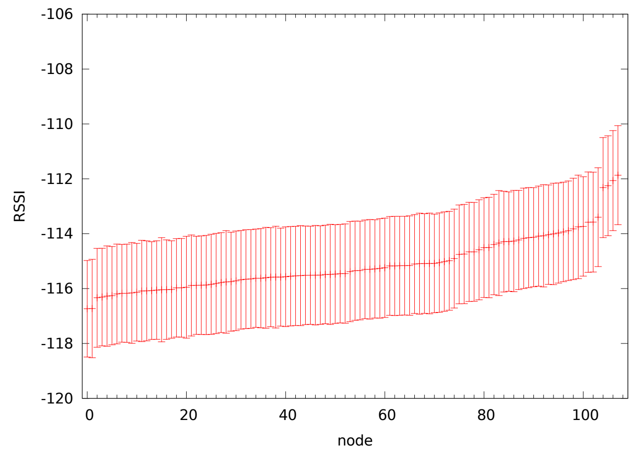

Figure 3. Ambient noise measurements on our testbed measured for 24 hours at 2 Hz during the week.

our experiments are performed on a multi-hop setup at a transmission power of –30.2 dBm. As we can see from the table, this transmission power results in a complex network, with an average span of 6 and a maximum span of 16. Note that the network in this case is not strongly connected since two nodes only have a good link in one direction. To compare with a denser network setup, we additionally use –0.3 dBm. In this case, we have a dense network with a mean shortest path length of 1.45 and a maximum shortest path length of 3.

Figure 2 displays the corresponding link distribution for both power levels, where links that never received a packet are omitted. There are several things worth noticing: Firstly, with a higher transmission power the total number of links increases. Secondly, the number of good links increases as well. Due to the increased number of good links the corresponding network is better connected. Lastly, the fraction of intermediate links in the gray region is smaller for the higher transmission level (11 % for 0 dBm versus 37 % for –30 dBm). This is mostly due to the fact that in our dense deployment the number of good links increases, i. e., for 0 dBm about 86 % of the links are good links. Nevertheless the absolute number of intermediate links increases for the higher power level from 433 for –30 dBm to 823 for 0 dBm. We can see a similar effect when further decreasing the transmission power to –34.2 dBm in the figure. Our experiments on a different channel (19) are very similar and confirm these results. We further detail on link distribution in Section IV.

III. Noise

As a first step in characterizing the 868 MHz channel, we perform experiments to determine ambient noise. We sample the received signal strength with 2 Hz for a 24 hour period during a weekday. Since our testbed is located within an office building, we previously have experienced considerable noise in the 2.4 GHz band [8]. However if we look at the ambient noise measurements in Figure 3, we can see that there is little noise in the environment; the average noise observed by a node is a mere –115 dBm. A comparison to the specified receiver sensitivity of the radio, which we measure at –126 dBm, shows that the effect of noise on communication can be neglected. There is little variance in noise as displayed by the standard deviation, which is on average only 1.8 dBm. Moreover, the noise is balanced among the set of nodes with a maximal difference of 4.9 dBm between the individual mean ambient noise. Additionally, we investigated whether the noise measurements feature some periodicity and determined the autocorrelation of the noise signal per node that showed that there is no (short-term) periodicity in the noise signal. We repeated the experiments at different weekdays; in particular, we measured the ambient noise on the weekend with very similar results. Measurements on channel 19 further confirm the noise-free environment. In summary, we can conclude that the noise floor for our 868 MHz radio is very low, stable and homogeneous and thus very different to experiences with 802.15.4 in the 2.4 GHz band.

As a comparison we performed measurements using a Tmote Sky node with a 802.15.4 radio in the 2.4 GHz band. In particular, we selected the least noisiest channel (26) and collected over 320,000 samples (samples were taken with the smallest possible interval of $\approx$ 1 ms throughout a workday). The average measured noise level was –96 dBm (compared to a minimum of –110 dBm). These result indicate that even the “noise-free” channel 26 of 802.15.4 nodes experiences considerably more external interference than sensor nodes using a 868 MHz radio.

Observations and comparison: Different to 802.15.4, radios on 868 MHz are less exposed to a noisy medium. Additionally, there is no difference when choosing different channels. Obviously the use of multiple channels is still relevant when we use frequency-diversity to provide more

Table III
COMPARING THE FRACTION OF INTERMEDIATE LINKS FOR OUR EXPERIMENTS TO PREVIOUS WORK [14].

Frequency	2.4 GHz (802.15.4)			916 MHz	868 MHz	
Testbed	Mirage	Uni	Lake	TR1000	–30 dBm	0 dBm
Gray zone	19 %	5 %	14 %	50 %	6 %	19 %

bandwidth rather than robustness. Nevertheless, the lack of noise in the 868 MHz band simplifies protocol design and does not require sophisticated mechanisms to cope with external interference [8], [9], [15].

IV. LINK DISTRIBUTION

Let us revisit the question of how links are distributed w. r. t. PRR. We focus in this section on the gray zone, i. e., the set of intermediate links. In particular, we compare the distribution of links in our testbed to previous work by Srinivasan et al. [14]. Table III presents an overview of the gray region of several[3] experiments including ours. Please note that in order to compare to previous work (and different to Section II-C) we consider all theoretically possible links (108*107 = 11,556) in the network, i. e., including the ones over which not a single packet was transmitted. Adding these non-existent links considerably increases the fraction of bad links compared to the numbers in Section II, in particular for the –30 dBm experiments.

Please note that the experiments by Srinivasan et al. were performed with an IPI of 10 ms and over only 200 packets. In contrast our experiments used an IPI of 62.5 ms and we repeated the experiment over more than 100 hours for more than 3,200 packets per link. In that respect we can additionally compare to longer-term experiments that Srinivasan et al. performed at a larger IPI (with 200 samples) that faired worse: Intermediate links at the University testbed increased to 19 % at 1 s IPI and at Mirage to 23 % at 15 s IPI. While these results indicate similar behavior of 868 MHz and 2.4 GHz radios, experiments on gray zones are generally difficult to interpret because of their inherent dependence on testbed and network setup. Thus, previous studies have been somewhat contradicting [1].

Furthermore, we can analyze our hourly collected data w. r. t. the stability of the gray zone and the fraction of good links. Figure 4 shows the fraction of good links and intermediate links based on link PRR over time for –30 dBm. There are two variants plotted: one shows the *instant* mean PRR for each link in a given hour (i. e., based on 32 measurements), the other is *long-term average* and integrates all previous measurements for a given link to determine a mean. The instant mean fraction of links stays fairly constant over time. Nevertheless, we can see that the long-term average fraction of intermediate links increases

[3]We abbreviated the University testbed as Uni in the table. The TR1000 experiments are originally from Zhao et al. [18]

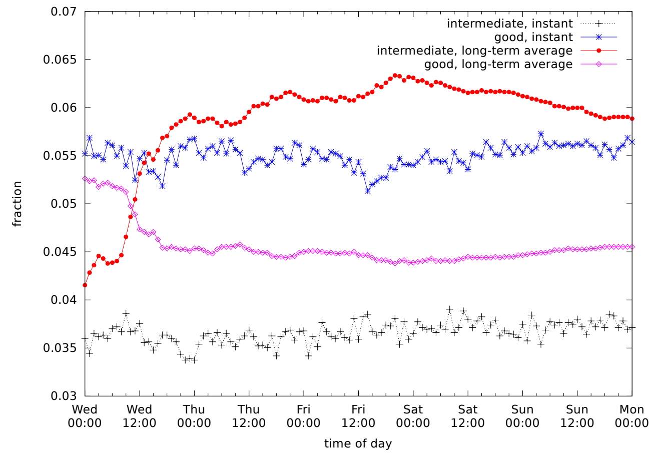

Figure 4. Gray zone over time for –30 dBm

and similarly the fraction of good links drops. These results indicate that the fraction of good and intermediate links stay fairly constant over time. However, the specific links within these fractions may change, i. e., a link may be good in one hour but intermediate in the following. These changes result in a decrease in the long-term average fraction of good links. This decrease leads to a stable state of the fractions after a day. We can additionally see that the fraction of instant good links drops around during working hours on weekdays (especially around noon), as there is the most activity in the building. In contrast, on the weekend the good link fraction is much more stable.

We performed the same experiments for 0 dBm; the results are very similar, however the changes are less pronounced. This is also due to the fact that at 0 dBm a very large fraction of good nodes is very well connected and not affected by any environmental fluctuations. We repeated the experiments on channel 19 with very similar results.

Observations and comparison: We can conclude that the 868 MHz testbed performs very similar to 802.15.4 studies. The gray zone is quite small, i. e., there are few intermediate links. In the case of 868 MHz, channel selection does not make a difference on the link distribution. Similar to 802.15.4, we can see that the fraction of good and intermediate links fluctuates over time. We investigate this observation further in the following section.

V. TEMPORAL CHARACTERISTICS

Given that there is little and constant noise in the environment, a developer might hope that links are stable and thus easy to predict. Hence, we evaluate the temporal characteristics of links; we focus on experiments for –30 dBm. The results for 0 dBm are largely the same. We start by looking at the distribution of PRR for all (existing) links in the network. Figure 5 shows the mean PRR over 96 1-hour experiments. As we can see, the PRR is highly dependent on the time of day. On the weekend, links are generally

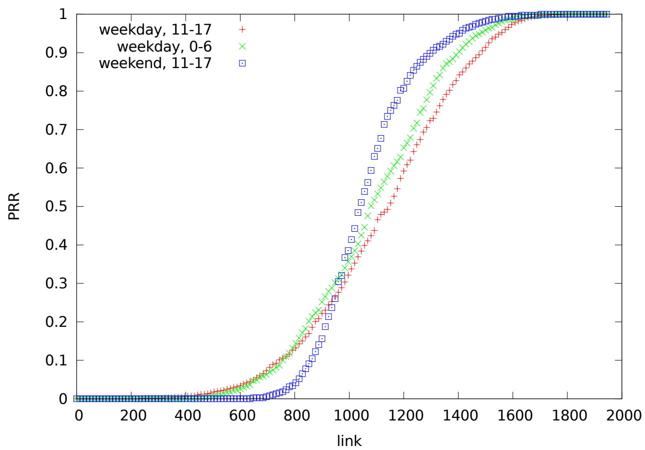

Figure 5. Mean PRR for different times of day.

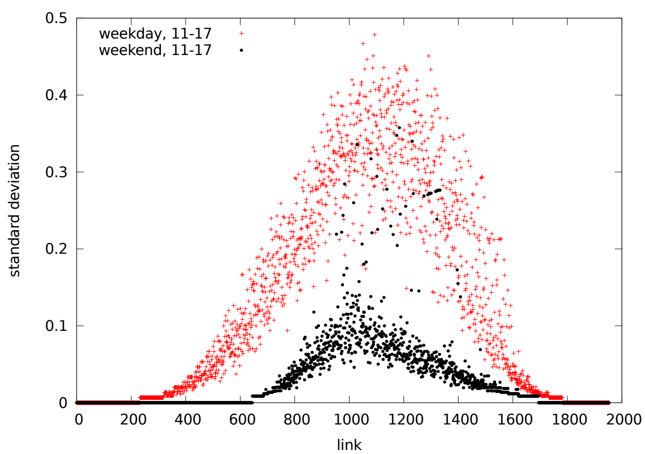

Figure 6. Standard deviation of PRR for different times of day.

the best as there is no activity in the building (e. g., HVAC is turned off); the gray zone is the smallest. During the week, the link distribution is fairly similar. Since there is no activity during the night, the link distribution improves, especially for links with a higher PRR (starting from a $PRR \geq 0.3$). Figure 6 additionally plots the corresponding standard deviation comparing weekday and weekend. We can see that the standard deviation on the weekend is considerably smaller and that the standard deviation for good links is rather low. Hence, we can conclude that there is a variation on links on a diurnal time scale. In the following we look at variations on smaller time scales.

To investigate short-term variations, we look at the burstiness of the channel w. r. t. losses and compare to Willig et al.'s experiments in the 868 MHz band [16] and the experiments by Meier et al. on 802.15.4 in the 2.4 GHz band [12].

As we can see in Figure 7 for –30 dBm, most packet bursts are rather short, i. e., bursts of errors occur on the order of a second. Good links have even shorter bursts, with 96.9 % of two or less consecutive packets corresponding to

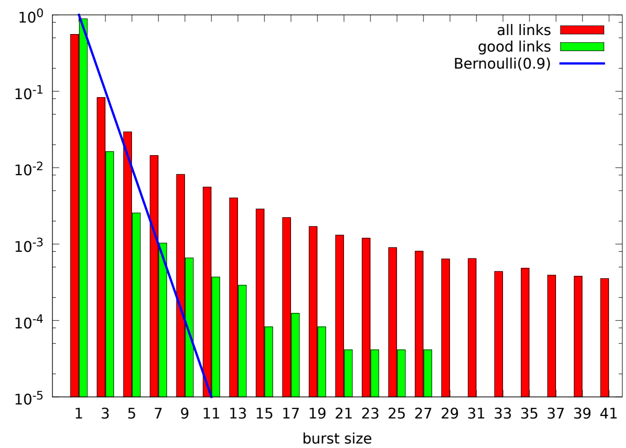

Figure 7. Burst errors for all and good links on a log scale.

Table IV
SINGLE BURSTS FRACTION COMPARISON. FOR OUR EXPERIMENTS, RESULTS FOR GOOD LINKS ONLY ARE IN PARENTHESES.

Netw-A [12]	Netw-B [12]	Willig[16]	0 dBm	–30 dBm
91.2	95.0	98.4	83.9 (93.2)	82.2 (98.5)

400 ms. By comparing the good links to a Bernoulli process with $p = 0.9$, we can also see that packet losses are not independent. We analyzed the data for 0 dBm and the results are very similar to Figure 7: burst errors are even shorter, however the difference between good and all links becomes less as the largest number of links are good links as shown before. Finally, for reference we compare our burst results to the previously mentioned experiments in Table IV. While burst length across all experiments have the same trend, the bursts in our experiments last slightly longer. As an example, 98.4 % of all bursts for all links are within about 1 s for our experiments.

We investigate this further by performing longer experiments for specific nodes. In particular, we select 6 specific nodes and send $44,000$ packets at an IPI of 62.5 ms, i. e., for approximately $45\,\text{min}$. We evaluate these links using the conditional packet delivery function (CPDF) as described by Srinivasan et al. [14]. In a nutshell, the CPDF is a measure how packet delivery success is dependent on previous consecutive delivery successes and losses. As an example, if a link is independent it will exhibit a constant conditional packet delivery probability. We focus here on good links as these are most interesting to protocol developers. Figure 8 shows a good link with a high mean PRR shown as a horizontal line; the bars show the CPDF. The link is fairly constant when considering consecutive successes. Once, more than one packet was successful, the successive transmission are most likely to succeed as well. We can also see that transmission are not independent. As a packet is lost, the successful delivery becomes less likely. Note however that only a few packets are lost at a time;

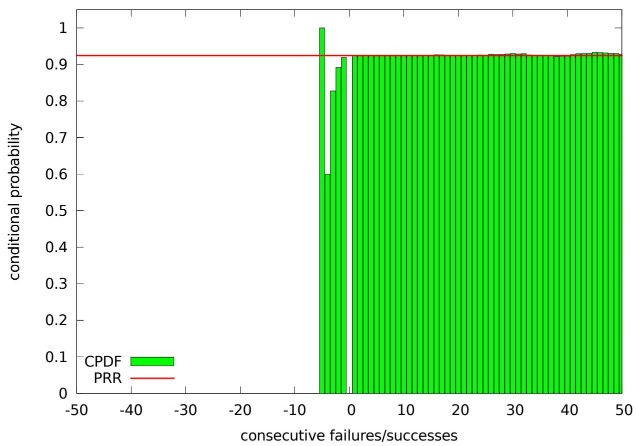

Figure 8. CPDF of link from node 56 to node 76 in a week night.

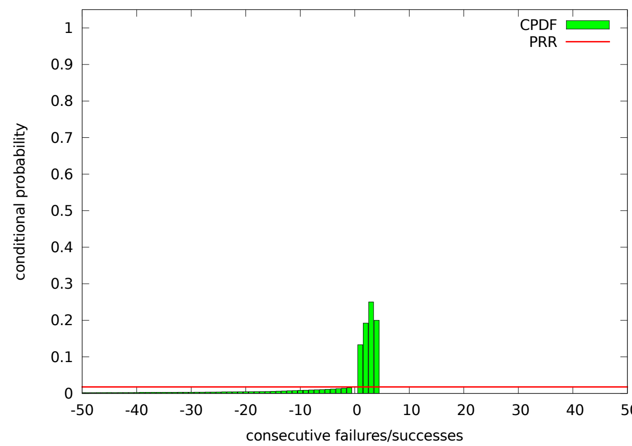

Figure 9. CPDF of link from node 56 to node 76 during a week day.

this confirms our burst loss results above. This is just one example showing that good links are over a short- and medium-term quite stable with short bursts. Figure 9 shows the same link at a different time of day. We can see the effect of our observation in the beginning of the section: links perform better during nights. The link has low mean performance and the CPDF shows us that only few packets can be sent successfully in a row. Additionally, this link is very dependent on its history. Note that this underlines the fact that links are variable on a large time scale and may turn from very good to very bad depending on the time of day.

Observations and comparison: In this section we investigated temporal link characteristics on different time scales. On short time scales, good links maintain a high PRR such that mechanism such as packet trains, i. e., sending consecutive packets in a burst, become attractive. We see that burst errors may occur within one or two second intervals. Although 868 MHz does not suffer from WiFi interference, our results are similar to previous experiments with 802.15.4 [12], where the authors propose to avoid aggressive retransmission strategies to waste energy. However, on a long-time scale links cannot be assumed to be stable. We identified that there are patterns in the link distribution over time of day: weekends with low activity are good and weekdays with high activity have a negative influence. This is very similar to the observations by Baccour et al. [1], in that we can see from the experiments that the temporal variations of link quality is mainly influenced by characteristics of the environment, and in particular by the movement of people in our office setup.

VI. Asymmetries

Another important characteristic of wireless links is whether they are symmetric or not. Various studies have shown that in general we cannot assume that links are symmetric [10]. We analyze our extensive link data, in particular the 96 hours used for Figure 4, investigating (a)symmetry by determining the absolute difference of link pairs. More specifically, we look at the set of links $\mathcal{L}$. Each link $(u, v) \in \mathcal{L}$ connects two nodes u, v. We quantify each links with the measured PRR, $PRR_{u,v}$ In turn we define symmetry s as:

$$s = |PRR_{u,v} - PRR_{v,u}|, \ \textit{where} \ PRR_{u,v} > 0 \ \vee \ PRR_{v,u} > 0$$

Note that we only determine symmetry for link pairs where packets were exchanged in at least one direction.

Figure 10 displays an overview of the CDFs of link symmetry over all link pairs for both transmission levels. We can see that a large fraction of nodes is completely symmetric. Symmetry improves for a higher transmission power. We also show detailed number of symmetry in Table V. Most of the nodes are fairly symmetric over time, i. e., 85 % of the links are within $s = 0.1$ for 0 dBm, or 73 % for –30 dBm respectively. For link estimation we are typically only interested in good links, i. e., $PRR_{u,v} > 0.9 \ \vee \ PRR_{v,u} > 0.9$. We see in the figure that symmetry is considerably better for good links irrespective of transmission power. In particular, when we look at Table V, we can see that for both transmission powers all links (100 %) are within $s = 0.1$.

Observations and comparison: Our experiments show that most links are quite symmetric over a longer time span, in particular the good ones. Nevertheless, we cannot generally rely on link symmetry similar to 802.15.4. As such protocol designers need to account for asymmetry but still may benefit from low asymmetry for a large set of links. Further experiments are needed to characterize asymmetry over time and investigate the source of asymmetry.

VII. Discussion

A. Threats to validity

All of our experiments were performed on the Rack, our local testbed, i. e., in a single indoor environment. As we saw in the experiments, the environmental effects (e. g.,

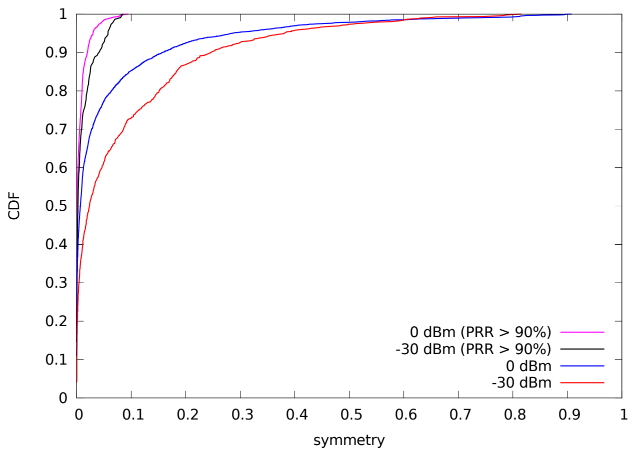

Figure 10. Distribution of the symmetry of the links

noise) are quite heterogeneous and the environment changes and challenges our testbed, e. g., temporal characteristics compared between weekday and weekend. Additionally our testbed is quite large and as such we expect it to be representative for a larger class of indoor testbeds. Our study here relies on a single 868 MHz radio. Hence, further studies are needed to confirm our results for a wider range of (current) 868 MHz radios. In particular, we have seen in the differences to previous studies, hardware advances, e. g., in modulation, improve radio performance and as such may further facilitate protocol design in the future. In our study we relied on a single (standard setting) for the 868 radio using 2-GFSK modulation and Manchester encoding. However, Zhao et al. [18] show that encoding can have a considerable impact on link performance. As such results will differ using another radio setup. Nevertheless, by using a standard configuration selecting a newer modulation technique (in comparison to OOK and ASK used before), we measure very little noise in all our experiments. Note that we favor reliability over performance by relying on Manchester encoding. We performed additional experiments without Manchester encoding using the same baud rate as before. This results in a higher bit rate and therefore shorter transmission times. These experiments show that there are fewer links in total, yet these are primarily the bad links. The number of good links stays approximately the same. As such, it would be interesting to further investigate the trade-off between the reliability (with Manchester encoding) and bit rate (without it) for our noise-free environment. Similarly, we performed most of our experiments using a single frequency and confirmed our results using a second frequency where appropriate. Additionally, we performed experiments using a larger packet size. Larger packet sizes slightly decreased link qualities, in particular for bad links, but the overall properties remain the same. As we could see in our study, the environment changes considerably dependent on time-of-day. Hence, we performed extensive

Table V
SYMMETRY FOR DIFFERENT POWER LEVELS

TX power	All links		Good Links	
	$s < 0.1$	$s < 0.2$	$s < 0.1$	$s < 0.2$
0 dBm	85 %	92 %	100 %	100 %
–30 dBm	73 %	87 %	100 %	100 %

experiments at different times of day and show in our study mean performance of long experiments. In most cases, we focus on the link characteristics on a typical weekday, since at these times links are exposed to the most challenging conditions.

B. *What we can learn*

The 868 MHz band exhibits little noise across several channels. Additionally, the distribution of links is similar to 802.15.4 radio, i. e., the gray region is rather small such that there are good links available for protocol designers. While the fraction of good links is fairly constant over time, there still is variation of links over time. In particular, we see on our testbed large variations between active periods on weekdays and inactive periods on weeknights and weekends where channel conditions are considerably better. Hence, we see that links are not generally good and stable and therefore necessitate link estimation techniques. As an example we investigated burst errors, where we could see that the results on 868 MHz closely resemble the ones for 802.15.4. Thus, we can expect that many of the techniques for link estimation for 802.15.4 [1] can be largely applied to 868 MHz radios.

VIII. Related work

In the following we present related work for both 802.15.4 radios as well as related work on radios using 868/916 MHz.

A. *802.15.4*

We compare all of our work to the previous comprehensive empirical study on 802.15.4 low-power links by Srinivasan et al. [14] to show interesting differences as well as to provide guidance to protocol designers focussing on 868 MHz radios. Baccour et al. [1] survey radio link quality estimation. To this end, they also detail on low-power links, focussing in particular on 802.15.4 in the 2.4 GHz band. We compare our results to their observations throughout the paper. Link properties of 802.15.4 sensor nodes are also investigated by Meier et al. [12]; different to their work our primary focus is link characterization and not estimation. Nevertheless, we compare the burstiness reported in their work with measurement from our testbed in Section V.

B. *868/916 MHz radios*

Radios that operate in the 868 MHz band have been used in various sensor nodes, e. g., [4], [7] and in several deployments and with varying success, e. g., [2], [3], [11].

Hence the question that we wanted to address with our study is: how good is the 868 MHz band for WSN systems?

Most of the studies on 868 MHz have been performed with previous generations of radio hardware such as the TR1001 [13], [16]. There are also several studies on TR1000 radios where experiments were performed in the 916 MHz range [6], [18], [17]. A considerable difference in these older radios is that most of them use Amplitude-Shift Keyed (ASK) or On-Off Keyed (OOK) modulation techniques which are different to the 2-GFSK employed here and usually more sensitive to noise.

Most of these early works focus on spatial characteristics of wireless links and in particular the gray zone [13], [18] and its impact on multi-hop routing [17]. Similar to our work, Cerpa et al. [6] consider temporal properties of links. Inspired by the work of Willig et al. [16] we studied packet failure bursts in Section V.

IX. Summary

This paper presented a study on low-power wireless links of 868 MHz radios. Based on extensive experiments on a 108-node testbed we investigated various properties of links. The major findings are that the 868 MHz band is basically noise free, but multi-path and human activity result in time-varying lossy and asymmetric links. Moreover, we compared our observations to previous studies for 802.15.4. Additionally, our work can be used to guide protocol developers when designing and testing of protocols for 868 MHz radios.

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X. References

[1] N. Baccour, A. Koubaa, L. Motolla, M. Zuniga, H. Youssef, C. Boano, and M. Alves. Radio link quality estimation in wireless sensor networks: a survey,. *ACM Transactions on Sensor Networks*, 8(4):(to appear), 2012.

[2] G. Barrenetxea, F. Ingelrest, G. Schaefer, and M. Vetterli. The hitchhiker's guide to successful wireless sensor network deployments. In *6th ACM Conf. Embedded Networked Sensor Systems (SenSys 2008)*, 2008.

[3] J. Beutel, S. Gruber, A. Hasler, R. Lim, A. Meier, C. Plessl, I. Talzi, L. Thiele, C. Tschudin, M. Woehrle, and M. Yuecel. PermaDAQ: A scientific instrument for precision sensing and data recovery in environmental extremes. In *8th ACM/IEEE Int'l Conf. on Information Processing in Sensor Networks (IPSN 2009)*, pages 265–276, San Francisco, CA, USA, 2009.

[4] J. Beutel, O. Kasten, F. Mattern, K. Römer, F. Siegemund, and L. Thiele. Prototyping wireless sensor network applications with BTnodes. In *1st European Workshop on Sensor Networks (EWSN 2004)*, volume 2920 of *Lecture Notes in Computer Science*, pages 323–338, 2004.

[5] C. Boano, T. Voigt, C. Noda, K. Romer, and M. Zúñiga. Jamlab: Augmenting sensornet testbeds with realistic and controlled interference generation. In *Information Processing in Sensor Networks (IPSN), 2011 10th Int'l Conference on*, pages 175–186. IEEE, 2011.

[6] A. Cerpa, J. L. Wong, M. Potkonjak, and D. Estrin. Temporal properties of low power wireless links: modeling and implications on multi-hop routing. In *6th ACM int'l symposium on Mobile ad hoc networking and computing*, MobiHoc '05, pages 414–425, New York, NY, USA, 2005.

[7] H. Dubois-Ferriere, R. Meier, L. Fabre, and P. Metrailler. Tinynode: a comprehensive platform for wireless sensor network applications. In *5th Int'l Conf. Information Processing Sensor Networks (IPSN '06)*, pages 358–365, 2006.

[8] V. Iyer, M. Woehrle, and K. Langendoen. Chamaeleon - exploiting multiple channels to mitigate interference. In *7th Int. Workshop on Networked Sensing Systems (INSS 2010)*, pages 65–68, 2010.

[9] V. Iyer, M. Woehrle, and K. Langendoen. Chrysso – a multi-channel approach to mitigate external interference. In *8th IEEE Conference on Sensor, Mesh, and Ad Hoc Communications and Networks (SECON 2011)*, pages 422–430, 2011.

[10] D. Kotz, C. Newport, R. S. Gray, J. Liu, Y. Yuan, and C. Elliott. Experimental evaluation of wireless simulation assumptions. In *7th Int'l symposium on Modeling, analysis and simulation of wireless and mobile systems (MSWiM 2004)*, pages 78–82, 2004.

[11] K. Langendoen, A. Baggio, and O. Visser. Murphy loves potatoes: Experiences from a pilot sensor network deployment in precision agriculture. In *20th Int'l Parallel and Distributed Processing Symposium (IPDPS 2006)*, pages 8–15, 2006.

[12] A. Meier, T. Rein, J. Beutel, and L. Thiele. Coping with unreliable channels: Efficient link estimation for low-power wireless sensor networks. In *5th Intl Conf. Networked Sensing Systems (INSS 2008)*, pages 19–26, Kanazawa, Japan, 2008.

[13] N. Reijers, G. Halkes, and K. Langendoen. Link layer measurements in sensor networks. In *1st IEEE Int. Conf. on Mobile Ad-hoc and Sensor Systems*, 2004.

[14] K. Srinivasan, P. Dutta, A. Tavakoli, and P. Levis. An empirical study of low-power wireless. *ACM Trans. Sen. Netw.*, 6:16:1–16:49, 2010.

[15] L. Tang, Y. Sun, O. Gurewitz, and D. B. Johnson. Em-mac: a dynamic multichannel energy-efficient mac protocol for wireless sensor networks. In *12th ACM Int'l Symposium on Mobile Ad Hoc Networking and Computing*, MobiHoc '11, pages 23:1–23:11, New York, NY, USA, 2011.

[16] A. Willig and R. Mitschke. Results of bit error measurements with sensor nodes and casuistic consequences for design of energy-efficient error control schemes. In *3rd European Workshop on Wireless Sensor Networks*, Zürich, Switzerland, 2006.

[17] A. Woo, T. Tong, and D. Culler. Taming the underlying challenges of reliable multihop routing in sensor networks. In *1st int'l conference on Embedded networked sensor systems*, SenSys '03, pages 14–27, New York, NY, USA, 2003.

[18] J. Zhao and R. Govindan. Understanding packet delivery performance in dense wireless sensor networks. In *1st int'l conference on Embedded networked sensor systems*, SenSys '03, pages 1–13, New York, NY, USA, 2003.

[19] G. Zhou, J. A. Stankovic, and S. H. Son. Crowded spectrum in wireless sensor networks. In *3rd Workshop on Embedded Networked Sensors (EmNets)*, 2006.