# Reliable co-existence of 802.15.4e TSCH-based WSN and Wi-Fi in an Aircraft Cabin

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***Abstract*—In this paper we present the effects of Wi-Fi interference on a Wireless Sensor Network (WSN) in an aircraft. We use Time-Slotted Channel Hopping (IEEE 802.15.4e) as Link layer in the WSN network. We conduct measurements in an environment realistically representing an aircraft cabin. We provide the resulting application failure and packet drop rates with and without interference, for an exemplary deadline critical application. In order to outline the importance of hopping against interference in a controlled environment, we compare the results of individual channels, full channel hopping and clear channel hopping, where the TSCH only hops over channels free from WiFi interference. Results open further discussions for more sophisticated Link layer implementations resulting in increased reliability such as optimization of frequency allocation depending on the application deadline.**

## I. INTRODUCTION

The wiring required by the large number of applications in an aircraft creates several problems. Most important of them are the cost of the wires, their weight, a complicated testing process, and new design investments for each extra system that is built upon wired communication. On the other hand, an advantage of removing wires from the aircraft in the eyes of a system engineer is the increase in total safety due to one less failure element to model in the system fault tree. However, the increase in total system safety comes with a cost of a highly unreliable behavior for packet reception.

In order to make a wireless system a realistic replacement for the wired communication, high reliability of the application needs to be guaranteed. This can be achieved with two possible approaches. One approach is building the full system and exhaustively testing it to create the statistics, but this requires significant effort and time. Another approach is analyzing the full system reliability part by part to estimate the required levels of wireless communication. In order to provide such an insight, with the assumption of communication reliability matching system safety, we have introduced a reliability assessment in previous work [1] that outputs the maximum tolerable packet drop probability.

An intuition from this assessment is that the most increase in reliability is provided via the increase in flexibility of resource block allocation. In order to benefit from this factor, we select Time Slotted Channel Hopping (TSCH) as our candidate physical (PHY) and medium access control (MAC) layer. We aim to benefit from the time slot size modification to provide the flexibility needed for reliability increase. Compared to conventional Time Division Multiple Access (TDMA) systems, TSCH provides increased reliability with fast channel hopping mechanism by decorrelating bit error rate on subsequent channels as Watteyne *et al.* discussed in [2].

In previous work from Blanckenstein *et al.* [3] TSCH is implemented in an aircraft in order to provide the bit error rate and loss characteristics in the presence and absence of passengers to model the effect of a realistic flight environment. The interference effect of WiFi entertainment system on WSN is not included, but rather multiple access points are offered as a solution for reliability increase. In other works from Gonga [4] and Du [5], WiFi coexistence of TSCH based WSN is investigated in an office environment in order to extract the effect of interference and frequency diversity. The first conclusion was that packet drop rate was not directly correlated to WiFi interference due to uncontrolled environment. Several correlations between consequent packet losses on different channels is extracted, but no conclusion is deducted.

In this paper, we examine the allocation of frequencies in a controlled interference environment, while assessing the reliability and introducing an efficiency metric for frequency allocations with limited retransmissions. The contributions of this paper is threefold: (1) mitigation of WiFi interference in a controlled environment through whitelisting, is validated for TSCH based WSN with real implementation; (2) we demonstrate that the assumption of uncorrelated loss for subsequent packet drops against interference is a good approximation to calculate the application failure rate from individual packet drops with limited transmissions for application; (3) a novel metric, Whitening, is introduced for allocation of interference free channels in the frequency hopping sequence in order to increase the total reliability of the application.

The structure of the paper is as follows, the measurement setup and details on WiFi and WSN network are provided in Sec. II. Measurement results in terms of reliability are introduced in Sec. III. In Sec. IV standard hopping sequence is investigated against the novel metric Whitening in order to discuss the efficiency of channel allocation. A summary with possible future work concludes the paper in Sec. V.

## II. BACKGROUND

### A. 802.15.4e TSCH

The basic idea behind the TSCH amendment to the 802.15.4 is to introduce a MAC scheme, which (a) allows a determinis-

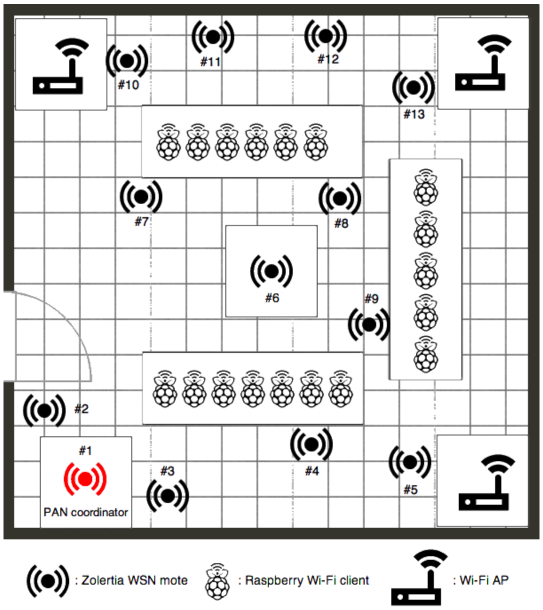

Figure 1. Scenario of Wi-Fi network and WSN co-existence in an aircraft environment. Room dimensions: $5.5m \times 6.35m$

tic behavior and (b) provides higher reliability by frequency diversity. 802.15.4e TSCH supports multi-hop topologies, however, in the scope of this paper, only single-hop is considered. The scheduling algorithm, as well as the length of the time slots, are design choices and not defined by the standard.

For network wide synchronization Absolute Slot Number (ASN), is propagated via a beacon to nodes, which is then used for the channel selection:

$$\mathsf{CH} = \mathsf{HS}[\mathsf{ASN}\%16], \tag{1}$$

where $\mathsf{HS}$ is the hopping sequence of channels, and $\mathsf{CH}$ is the resulting channel for a given ASN. For our measurements, we consider two different hopping sequences. Firstly, the full sequence, as defined in the minimal implementation of a 6tisch Network (with a slight modification of using the advertising channel as second on the list for ease of implementation)[6] of OpenWSN [7][1]: $\mathsf{HS}_{\mathsf{full}}$: [16, 20, 23, 18, 26, 15, 25, 22, 19, 11, 12, 13, 24, 14, 17, 21], and reduced sequence: $\mathsf{HS}_{\mathsf{wl}}$: [15, 20, 25, 26]. Reduced sequence takes into account only the channels free from Wi-Fi interference, and is referred to as whitelist hopping throughout this paper.

### *B. Measurements Setup*

Our setup entails a realistic aircraft environment, where the simultaneous communication of a Wi-Fi network and a Wireless Sensor Network occurs over the unlicensed ISM 2.4 GHz bandwidth. All the measurements were performed in an isolate environment where no external interferer was present. The final setup of our scenario is depicted in Fig. 1.

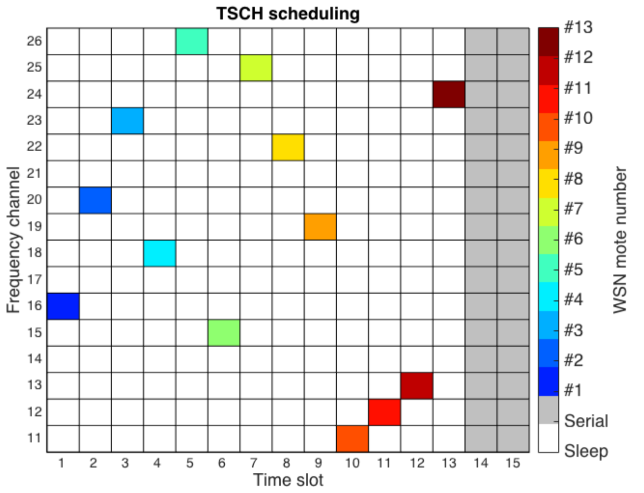

Figure 2. Scheduling grid in time/frequency domain deployed in the setup.

*1) **Wi-Fi network:*** The purpose of the Wi-Fi network is to provide an entertainment service to the passengers of the flight. The communication occurs between 59 Raspberry Pi clients and three different Access Points (APs) occupying non overlapping portions of the spectrum, in particular, the channels 1, 6 and 11. Every AP serves 20 or 19 clients simultaneously.

The network deploys the 802.11g standard at the MAC layer with CSMA-CA mechanism and backoff, and it is unaware of the underlying WSN. Every client emulates the behavior of a passenger's device streaming video during flight. Every client is mimicked via a Raspberry Pi streaming 1296kbit/s data continuously which results in $24-25$Mbit/s average traffic on each channel.

*2) **WSN:*** The WSN is deployed to replace the fixed wired aircraft communication network with a reliable and flexible infrastructure. For this reason, the network consists in 13 randomly deployed nodes, and it has a star topology configuration. Every node is programmed through OpenWSN open stack implementation of IEEE 802.15.4 for physical layer and IEEE 802.15.4e TSCH protocol, which is followed by the 6TisCH and IPv6 on network layer [7].

Each mote is running a 15 time slot schedule. The PAN coordinator is entitled to transmit the Enhanced beacon (EB) during the first time slot containing the scheduling of the entire network. Once synchronized, every mote is allowed to transmit on a single reserved time slot with transmission power equal to $-3$dBm, while during the other time slots it sleeps. Reliability is achieved by means of channel hopping and two additional MAC re-transmissions. A visual representation of the scheduling of the network is shown in Fig. 2. Due to this 15 slotted slotframe structure with 15ms slot size $T_s$, each slotframe lasts 225ms. This gives a transmission opportunity (TXOP) to each mote every 225ms.

Every mote is running an uplink application that generates a packet of 53 Bytes every 700ms. The packet generation rate from the application allows three TXOP per packet. When

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[1] Project's source code has been altered according to our setup. The repositories with our versions are available online (release vLKN1.0): https://github.com/mvilgelm/openwsn-fw and https://github.com/mvilgelm/openwsn-sw

a packet is generated it is transmitted on the next available TXOP, and AP answers back with an ACK in the same timeslot. If there is no ACK received back from the AP, it is re-transmitted on the next available TXOP.

We limit the maximum number of transmissions $N_p$ including retransmissions and initial transmission to 3 in a way that there will no buffer waiting time. The probabilistic sending and the waiting time between each TXOP are the only factors affecting a successful packet deadline. In other words, within each 700ms a packet is generated and either successfully sent or dropped due to maximum number of retransmissions.

### *C. Scenarios*

In order to evaluate the effects of different hopping strategies on the co-existence with Wi-Fi, we have performed the measurements with and without WLAN interference for three hopping options, resulting, in total, in six scenarios:

- **NINH**: **N**o Wi-Fi **I**nterference, **N**o **H**opping: all motes use one assigned frequency channel (#20).
- **NIFH**: **N**o Wi-Fi **I**nterference, **F**ull **h**opping: the motes hop over the full list of 16 available channels.
- **NIWH**: **N**o Wi-Fi **I**nterference, **W**hitelist **H**opping: since an aircraft is a controlled environment, we can determine in advance which channels are free from or less prone to the Wi-Fi interference. Thus, we have whitelisted these channels and defined a hopping sequence consisting only of them: {15, 20, 25, 26}.
- **WINH**: **W**ith Wi-Fi **I**nterference, **N**o **H**opping.
- **WIFH**: **W**ith Wi-Fi **I**nterference, **F**ull **H**opping.
- **WIWH**: **W**ith Wi-Fi **I**nterference, **W**hitelist **H**opping.

The duration of the measurements have been varied from 70 minutes to 900 minutes depending on the level of precision that is aimed for that measurement. A summary of the number of packets generated on mote and channel basis with the total number of packets can be seen in Tab. II.

### *D. Reliability Analysis*

Different measurements for application failure and the packet drop rate enable us to assess the real measurements against the reliability assessment provided in [1]. The assumption in the paper was that we can neglect the correlation between subsequent packet drops in order to provide an estimation for the application failure requirement. We want to test this assumption against the real measurements to see if it holds and, furthermore, to determine the possible extension for more accurate modeling.

*1) Top-Down Limits:* We start with the assessment of reliability with the top bottom approach using medium access parameters from our application. It is common practice to assume five nines for the target reliability [8], and we use this assumption for the link layer loss rate $P_{app}$ of the star network as $P_{app} = 10^{-5}$. The assumption at this point is that higher layers have a reliability of one, since it is a one hop network. $N_p$ is set to 3 with the slotframe length and the deadline of the application. Then, this information is converted to the packet loss on physical layer $P_{comm}$ as in

$$P_{comm} = (P_{app})^{\frac{1}{N_p}} , \tag{2}$$

we can calculate the maximum tolerable packet drop rate as $P^{\max}_{comm} = 0.021$.

Table I

PARAMETERS AND NOTATION SUMMARY

| **Parameter** | **Explanation** | **Value** |
|---|---|---|
| $T_s$ | Time Slot Duration | $15ms$ |
| $SFS$ | Superframe size in timeslots | 15 |
| $N_p$ | Maximum number of allowed transmissions | 3 |
| $N_{cc}$ | Number of clear channels | 4 |
| $N_{tc}$ | Number of available channels | 16 |
| $ASN$ | Absolute Slot Number | |
| $HS[]$ | Hopping Sequence | |
| $HSS$ | Hoping Sequence Size | 16 |
| $CH_{j,i}$ | $i^{th}$ tx Channel after $CH_{j,1} = CH_j$ | 1 - 16 |
| $P_{comm_j}$ | Single packet loss probability on Channel j | |
| $P_{app_j}$ | Application failure probability on Channel j | |
| $W$ | Whitening Level | 1 - $N_p$ |
| $P_{IC}$ | Packet Loss probability on interfered Channel | |
| $\alpha$ | Interfered to Clear Channel loss ratio | 1 - $\infty$ |
| $L$ | Ratio of Whitened to Total Combinations | $\leq 1$ |

*2) Reliability Calculations with Frequency Hopping:* The channel hopping enables such that each retransmission is done on a different channel than the previous one. However, due to static superframe and static hopping sequence, each of the retransmission channels can be calculated beforehand when the initial transmission channel $CH_{j,1}$ is known. In order to use the reliability assessment with frequency hopping, we have to modify the way we approach the calculations. The modeling of drops with constant $P_{comm}$ is not feasible anymore since every channel has its own drop rate characteristics due to multiple effects.

To overcome this problem, after fixing the initial channel $CH_{j,1}$ selected for the first transmission with the hopping sequence, we relate the further frequencies used for the retransmissions after this frequency with

$$\mathrm{CH}_{j,i} = \mathrm{HS}[(\mathbf{ASN}_{\mathrm{CH}_{j,1}} + \mathrm{SFS} \cdot i)\%\mathrm{HSS}] \tag{3}$$

where $\mathrm{CH}_{j,i}$ is the channel for $i^{th}$ transmission after the selected initial channel $\mathrm{CH}_{j,1}$, HS[] is the Hopping Sequence, HSS is the Hopping Sequence Size, ASN is the absolute slot number used as hoping sequence index for channel $\mathrm{CH}_{j,1}$ and SFS is the slotframe size. $N_p$ is 3 in our application. Let's assume we have selected the channel 13, this means that we had an ASN of 12 after modulo 16, the SFS is 15, and the **ASN** will increase by 15 with each superframe, which will result in ASNs of $27, 42$ which outputs $11, 10$ as the result of modulo 16 for the first and second retransmission respectively so selected channel for 3 transmissions are $13, 12, 11$ respectively. The limited number of transmission model enables calculation of the combined error rates as

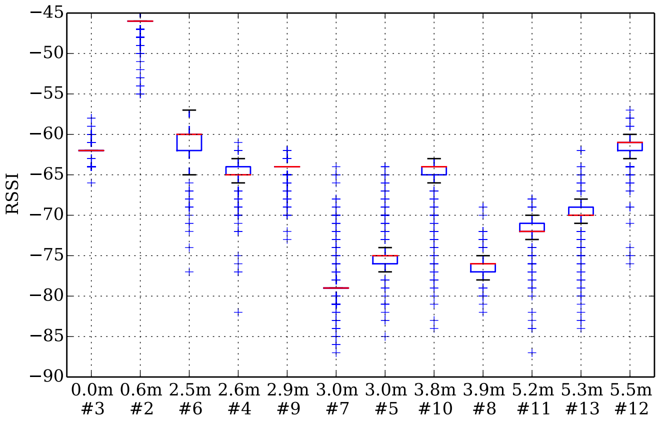

Figure 3. RSSI values of received packet vs. distance to PAN coordinator (# moteId) for NINH scenario.

$$P_{app_j} = \prod_{i=1}^{N_p} P_{comm_{\mathrm{CH}_{j,i}}}. \tag{4}$$

This structure allows the use of drop rate for each of the channels in order to calculate the application failure probability with all possible combinations. In Eqn.(4) the drop rate probability for initail channel $j$ is introduced. Since all of the $j$ initial channels are rotated for a transmission, we calculate the average application failure probability with

$$P_{app} = \frac{\sum_{j=1}^{\mathrm{HSS}} P_{app_j}}{\mathrm{HSS}}. \tag{5}$$

For worst case analysis, the drop rate should be limited to the worst $P_{app_j}$.

## III. MEASUREMENTS RESULTS

For every scenario, received packets are recorded together with the corresponding channel, Received Signal Strength Indicator(RSSI), sequence number, and MAC retransmission count. In Fig. 3, the values of RSSI for every mote are presented. Scenario NINH is taken as a base case. We observe that the distance alone is not sufficient to determine the channel quality. The fluctuations are very high, and there is no correlation to the distance within our environment. Also, RSSI values are recorded only for the successfully received packets, thus, a large portion of packets (not received due to the RSSI larger than a threshold, or discarded after the checksum check) is not included in the figure.

### *A. Reliability*

For assessing the reliability, two metrics are used and compared, as defined in Subsec. II-D: $P_{comm}$ as packet drop rate and $P_{app}$ as application failure probability. Figs. 4 and 5 illustrate these values for all six scenarios. Every box presents the distribution of the values for the set of motes, and the green line represents the averages weighted by the number of samples for every mote. We observe that, as expected, both application and communication failure rates are significantly lower for an interference-free scenario. It is also observed that the whitelist hopping reduces the average packet drop rate by 25%, whereas the application reliability is increased by 5%. Since the channel choice for no hopping scenario is 20 (among whitelisted channels), difference between WINH and WIWH is minimal.

As the effects of hopping sequence selection is drastic, we proceed with evaluating the drop rate on a per-channel basis. The statistics for per-channel measurements are presented in Fig. 7 for drop rate per single channel. Also the total drop rate per "channel combination" including the re-transmission are given in Fig. 6.

Now we check the compliance of the measurements with the analytical structure demonstrated in Subsec. II-D using per-channel measurements. First, we use the packet drop for NIFH scenario 0.1783 and plug it in Eqn. (6):

$$P_{app} = (P_{comm})^{N_p}, \tag{6}$$

with $N_p = 3$ transmissions, to obtain $P_{app}(ana) = 0.0057$. Then, we compare this result with the overall application failure measured for the scenario $P_{app}(meas) = 0.0062$.

Next, we compare the analytical and measured results for the interference scenario WIFH. The assessment with these calculations results in an application failure rate of $P_{app}(ana) = 0.0813$. When we compare this result with the overall application failure measured $P_{app}(meas) = 0.0940$. Estimation error is low for the application failure with full hopping and interfering scenario. Important observation here is that in both of the cases the failure probability estimation error is around $10\%$. This error, as explained in Subsec. II-D, is, in fact, showing that effect of correlation is small for full hopping list.

For the whitelist scenarios, we repeat the calculation as shown in Subsec. II-D, since the effect of using different channels persists. For the calculations of NIWH and WIWH, we use the individual channel drop rates and combine them as it is done with full hopping. For the single channel scenarios NINH and WINH, we directly plug in the measured packet drop rate, 0.08 and 0.09 respectively.

The application failure rate for the analysis and the measurements are summarized in Table II. The assessment approximates the reliability with the assumption of no correlation between retransmission losses. However, in the real system,

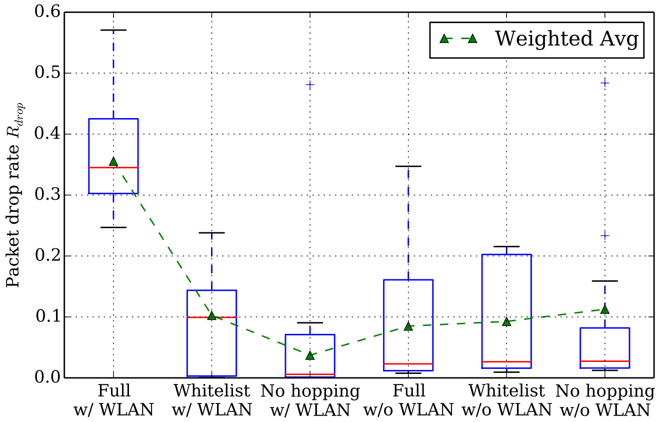

Figure 4. Packet drop rate for every scenario; weighted average considers number of packets every mote has generated.

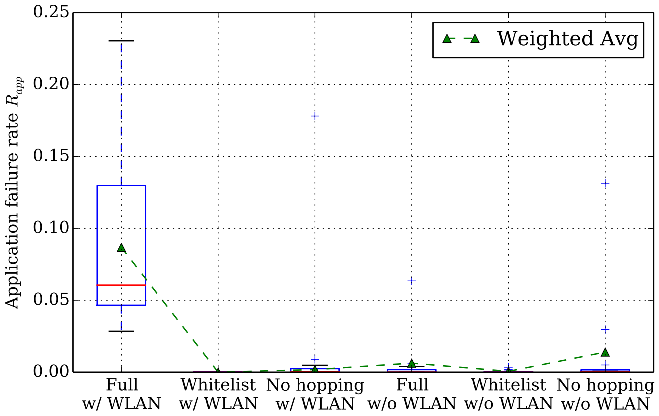

Figure 5. Application failure rate for all scenarios. Boxplot captures the distribution of the rate among all motes.

this is not the case and correlation has different effects. From the table it can be clearly seen that highest order of error is present for single channel measurements, which represents high correlation. We can notice that this effect decreases in whitelisted hopping where four channels are used and the assessment and measurement results are similar for full hopping.

As we can see from Fig. 6, only for channel 26 the measured packet drop rate is close to the required $0.021$, while the required application failure rate is not reached for any of the scenarios. On top of this, channel 26 is not usable in an aircraft since it is not part of ISM band in all of the countries. Even though the use of the only clear channel is not possible, this can be overcome with a better link layer design such as optimization of frequency hopping, use of coding and/or use of efficient time/frequency diversity.

## IV. WHITENING OPTIMIZATION

As the measurement results point out, whitelisting allows a dramatic reduction of interference effects. However, if using frequency multiplexing, it limits the slotframe length of a technology, which in our previous work [1] is pointed out as an important factor for reliability. Thus, we limit the possibility of employing multiple parallel networks by allocating only the interference-free channels for communication. First we define the term clear channel to create separate channel types.

We utilize an iterative binary clustering algorithm to separate clear and interfered channels. At the start of the algorithm all channels are treated as interfered. After a channel is selected as a clear channel it is taken out from the interfered channels list and the algorithm is restarted until no clear channel selection is possible.

The algorithm works as such, a selected channel $k$ is compared to every interfered channel $P_{IC_l}$ to ensure $P_{IC_k} = \frac{P_{IC_l}}{\alpha_{k,l}}$ holds $\forall k, l \ \alpha_{k,l} > \alpha$ where $\alpha$ is the channel quality separation criterion. If $\alpha$ is selected as $1$ it will result in a single interfered channel and if it is selected too high it will result in no clear channel. We will use $\alpha = 2$ for our separation.

In order to clarify the multiplexing trade-off, we start by defining whitening.

**Definition IV.1.** Whitening is the provision of a clear channel to any of $i^{th}$ transmission channel $CH_{j,i}$ by the $HS[]$. If the $HS[]$ enables multiple clear channels for multiple transmissions for the same initial channel $CH_j$, this is referred as multiple levels of whitening.

We define the overall whitening level of transmission combinations as $W = (N_{cc} \cdot N_p) \mod N_{tc}$. This is followed by the definition of $L$ as the ratio of whitened combination that are above the overall whitening level to the total number of combinations. This definition leads to following relation

$$L \leq \frac{(N_{cc} \cdot N_p) \mod N_{tc}}{N_{tc}}, \tag{7}$$

where $N_{cc}$ is the total number of clear channels in a network, the whitenening ratio is $L$, the total number of channels is $N_{tc}$ and the number of allowed transmissions is $N_p$. Increasing $N_p$ gives more opportunities to get a clear channel. This inequality always holds and we prove why the equality is the optimum for overall system reliability. We refer to whitening that allows the equality as Symmetric Whitening and others as Asymmetric Whitening.

We aim to define overall reliability of Symmetric Whitening in the following calculations. First, we define a general channel

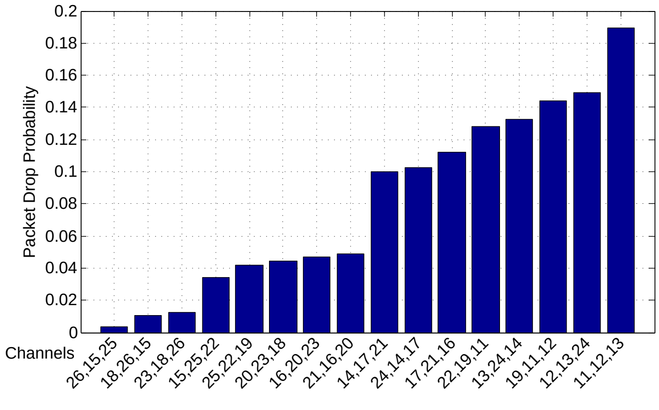

Figure 6. Combined Packet Drop Rate $P_{app}$ including retransmission in IEEE 802.15.4 channels against Wifi interference in channels 1,6 and 11

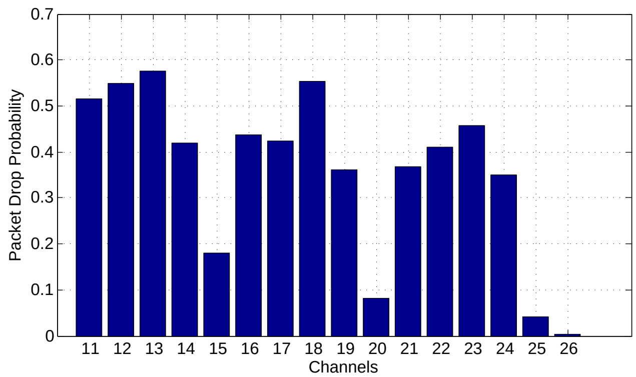

Figure 7. Single Packet Drop Rate $P_{comm}$ in IEEE 802.15.4 channels against Wifi interference in channels 1,6 and 11

Table II
ANALYSIS AND MEASUREMENT COMPARISON

| | NINH | NIWH | NIFH | WINH | WIWH | WIFH |
|---|---|---|---|---|---|---|
| Duration(min) | 89 | 73 | 900 | 96 | 135 | 136 |
| Packet gen. per mote | 7628 | 6257 | 77143 | 8228 | 11657 | 11571 |
| Packet gen. per channel | 91543 | 18771 | 57857 | 98743 | 34971 | 8678 |
| Packet gen. total | 91543 | 75086 | 925710 | 98743 | 139890 | 138860 |
| $P_{app}(ana)$ | $0.74 \times 10^{-3}$ | $0.14 \times 10^{-3}$ | $0.57 \times 10^{-2}$ | $0.63 \times 10^{-3}$ | $0.74 \times 10^{-3}$ | $0.81 \times 10^{-1}$ |
| $P_{app}(meas)$ | $0.14 \times 10^{-1}$ | $0.23 \times 10^{-3}$ | $0.62 \times 10^{-2}$ | $0.20 \times 10^{-2}$ | $0.10 \times 10^{-3}$ | $0.94 \times 10^{-1}$ |

failure rate such that $\forall l \; P_{IC_l} \leq P_{IC}$ and $\forall l,k \; \alpha_{k,l} \leq \alpha$ in terms of drop rate of interfered channels $P_{IC}$ and clear channels $\frac{P_{IC}}{\alpha}$ and plug it in Eqn. (4) resulting in

$$P_{app_j} \leq \frac{P_{IC}^{N_p}}{\alpha^W}. \tag{8}$$

We average the application failure rate over all $j$ channels since selection of any starting channel is arbitrary:

$$P_{app} \leq \frac{\sum_{i=1}^{N_{tc}} \frac{P_{IC}^{N_p}}{\alpha^W}}{N_{tc}}. \tag{9}$$

Due to the limited number of clear channels, increasing the whitening level of a channel combination, in order to decrease the failure probability, results in increasing the failure probability of another channel combination. We use Eqn. 9 to prove that such an exchange never increases the overall system reliability. We apply this exchange to two channel combination as in Eqn. (10):

$$2\frac{P_{IC}^{N_p}}{\alpha^W} > \frac{P_{IC}^{N_p}}{\alpha^{W-1}} + \frac{P_{IC}^{N_p}}{\alpha^{W+1}}. \tag{10}$$

All of the elements in the inequality are positive, simplification is done further as in Eqn. (11):

$$\alpha^2 - 2\alpha + 1 = (\alpha - 1)^2 < 0. \tag{11}$$

These results shows that such inequality never holds and they are equal if $\alpha$ is one, which means that the clear and the interfering channels are not different. So it can be concluded that such a trade-off is never favorable and Symmetric Whitening is always better than Asymmetric.

As seen in Fig. 7 in our network we have 4 clear and 16 total channels with 3 total transmission for each packet. This results in overall whitening level of 0 and a overall whitening ratio of 0.75. However, due to inefficient structuring of frequency hopping sequences, we have 8 whitened out of 16 combination, which results in a overall whitening ratio of 0.5. It is also observed in Fig. 6 that the 8 whitened channel combination on the left part of figure are at least two times better than the non-whitened channel combinations on the right.

In case of the co-located operation, multiple WSNs are necessary to support high number of reliable critical deadline based applications, and defined above results can be used to optimize network frequency planning. The variation of $N_p$ for different applications can be used to optimally select the number of clear channels allocated to a cell in order to maximize reliability.

## V. CONCLUSION

In this work we have presented a reliability analysis of the co-existence of IEEE 802.15.4e TSCH Wireless Sensor Network with Wi-Fi in closed and controlled environments, such as an aircraft. We have evaluated the expected application and communication reliability levels for an exemplary application using the previously introduced reliability assessment. Then, we have conducted measurements on a real testbed for interference-free and interference scenarios, and evaluated packet drop rates and application failure rates. The measurements were compared to the analytical results.

Moreover, we introduce Whitening as a metric for frequency allocation optimization and discuss the the trade-off between the reliability and frequency multiplexing opportunities.

## ACKNOWLEDGMENT

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