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Investigating Constructive Interference for LoRa-based WSNs

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***Abstract*—LoRa-based Wireless Sensor Networks (WSNs) are typically operated in star topologies. Without the option to rely on multi-hop networking, the wireless transmission range is the limiting factor for the size of a LoRa network. Increasing the transmission power to extend the wireless range is not a viable option, however, due to national regulations. Other techniques thus need to be found that can help to maintain or even increase the wireless range, especially under harsh environmental conditions like heavy rain or hail, which are detrimental to the wireless signal propagation. In an attempt to increase the reliability of data transmissions in WSNs operated in such environments, we investigate the potential of constructive interference in LoRa-based WSNs. The concept of constructive interference is based on the simultaneous transmission of data frames with identical content, the superposition of which has been shown to significantly extended wireless transmission range in different network types. In this work, we present a testbed implementation to investigate the effects that occur when LoRa transmissions overlap. We document and interpret our results based on the analysis of the corresponding signal waveforms. Our results show the potential of constructive interference to increase the reception range of LoRa nodes, but also imperfections and difficulties that need to be addressed.**

I. Introduction

WSNs are often deployed in outdoor scenarios, where they are exposed to rough environmental conditions. Extremes are not only present in the ambient temperature, but also in precipitation and relative humidity. In order to enable reliable communication regardless of the ambient conditions, a high packet reception rate is essential. The reception of data can be hindered by permanent conditions, like long distances between nodes or dense build-up areas. Also temporary conditions, like severe weather events can lead to being no longer able to receive data from single or multiple nodes. Even temperature variations can have negative effects on Long Range (LoRa) links [1]. When the WSN is used in safety-relevant areas, like forecasting extreme weather conditions, or is part of an early warning system, this can have very serious or even catastrophic consequences.

To increase the reliability and reception rate in LoRa-based WSNs, multiple well-known methods have been already researched and applied. The LoRa Physical layer itself offers different configurations to increase the reception range and rate. Commercial off-the-shelf (COTS) transceivers like the Semtech SX1276 offer the possibility to configure the Spreading factor (SF), Bandwidth (BW) or Error correction rate (CR) [2]. But also methods on higher level have been developed and researched, like [3], where redundant information were used to successfully increase the reception rate of LoRa packets.

In our work, we will focus on the concept of constructive interference, analyse the signals of simultaneously transmitted LoRa packets and assess whether this concept can be used to reliably increase the reception rate and range in LoRa-based WSNs. For that, we first discuss related work in Section II. This is followed by the presentation of our evaluation setup in Section III. In Section IV we evaluate our implementation and discuss the results. Section V summarizes the key insights of our paper and gives an outlook of future work.

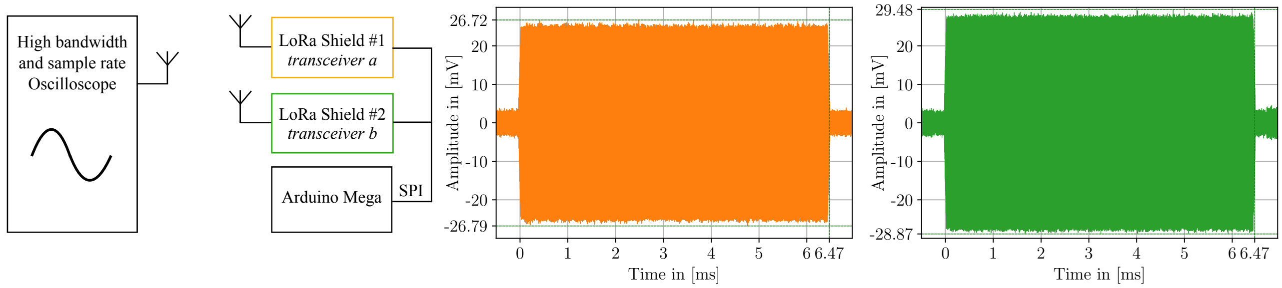
II. Related Work

The concept of constructive interference in WSNs is well known in research and literature [4]. “Glossy” was presented as a network flooding architecture for IEEE 802.15.4 networks that takes advantage of constructive interference, leading to high packet reception rates in excess of $99.99\,\%$ [4]. On the other side, Liao et al. investigated the effects of concurrent transmissions in IEEE 802.15.4 networks in [5]. They concluded that constructive interference is not reliably usable in real-world scenarios due to multiple reasons, which include the power and timing offset and especially the carrier frequency offset (CFO) that leads to unpredictable alternating destructive and constructive interference (referred to as the “beating effect”). Still, many practical protocols seeking to achieve highly dependable communication, rely on the concept of constructive interference[1]. Whether it can be reliably utilized in real-world LoRa networks to improve network communication is still under investigation.

A. Constructive Interference in LoRa-based WSNs

Due to the rising popularity of IoT devices and WSNs, LoRa has gained a lot of attention over the last years as a low-power and wide-range technology to transmit data wirelessly. Inevitably, this also leads to an increase in the number of deployed LoRa transceivers and thus a greater probability of packet collisions, especially in densely deployed ares. Therefore, a lot of research has been performed to

[1]See, e.g., the article “EWSN Dependability Competition: Experiences and Lessons Learned” in the March 2017 IEEE IoT newsletter, available at https://iot.ieee.org/newsletter/march-2017.html



(a) Schematic view of the testbed. (b) Signal emitted by transceiver a. (c) Signal emitted by transceiver b.

Figure 1. Graphical representation of the used testbed to investigate and analyze constructive interference in LoRa and time-domain analysis of the received voltage amplitudes for transceiver a and b.

investigate the effects of concurrent transmissions of LoRa packets and whether it is possible to decode collided packets [6]. For example, [7] investigated concurrent transmissions in multi-hop LoRa networks and came to the conclusion that LoRa can indeed tolerate collisions caused by concurrent transmissions. The authors also presented "offset-CT", a method to increase the receiver performance by adding random timing delays. Furthermore, the characteristics of collided LoRa packets were investigated in [8], and the "FTrack" communication paradigm that can demodulate collided LoRa frames and thus increase the throughput by up to $3\times$ was presented. Similar results were also achieved by [9], where "mLoRa" was presented as a protocol for decoding multiple collided LoRa packets, also increasing the throughput by about $3\times$. In [10], the authors presented "Choir", a system that is capable of decoding multiple interfering LoRa transmissions by making use of individual hardware imperfections of single nodes that characterize their transmitted signal. Also, in [10] the concurrent transmission of correlated and identical data was investigated, coming to the conclusion that an increase of nodes simultaneously transmitting the same data leads to a significantly higher throughput and reception range. Specifically, 30 concurrently transmitting nodes were able to increase the reception range by up to 2.65 times.

In summary, the usage of constructive interference in (LoRa-based) WSNs in order to increase the reception rate and range is a very promising approach and worthy of being researched further. In our contribution, we hence investigate the physical effects that occur due to constructive (and destructive) interference in concurrent LoRa transmissions and analyze the resulting signal and its properties.

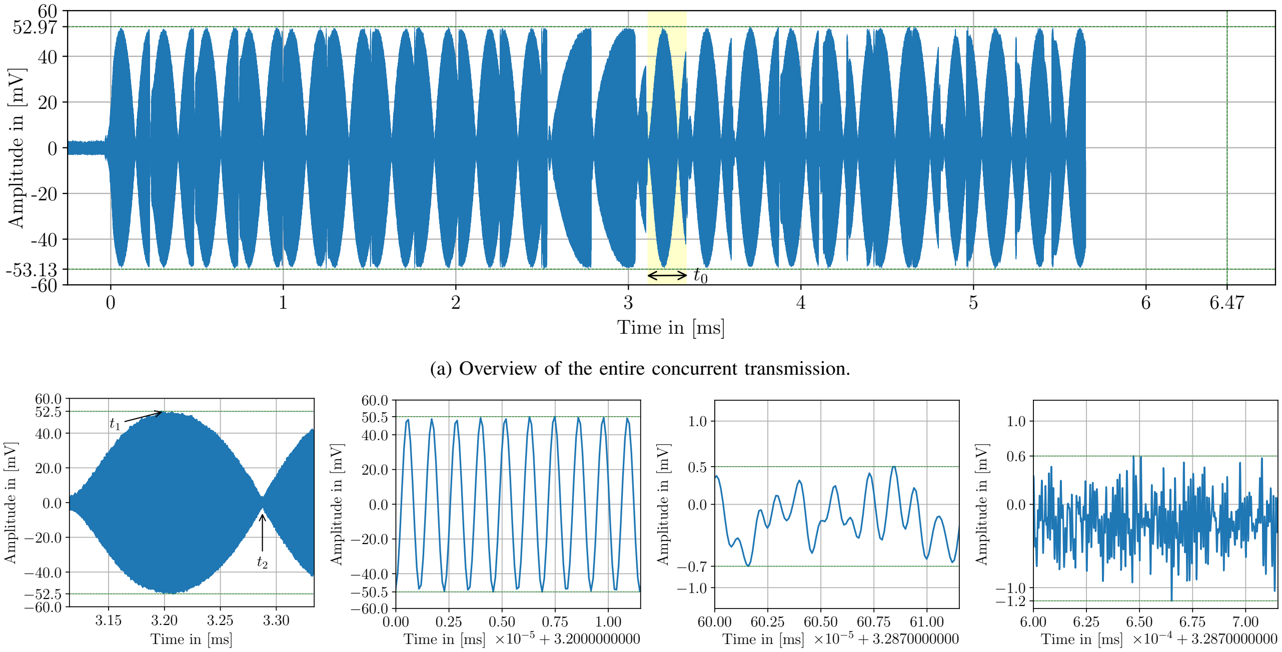
III. Setup

To investigate on the approach of constructive interference in LoRa-based transceivers, a testbed was designed. A schematic representation is shown in Figure 1a. On the transmitter side, we used two COTS LoRa shields, based on the Semtech SX1276 transceiver chip [2]. The LoRa Shields were controlled by an Arduino Mega microcontroller system. To achieve simultaneous transmissions by both transmitters, both shields were stacked on top of each other, so they shared the same Serial Peripheral Interface (SPI) bus. In order to also enable the analysis of different transmission configurations, we also made it possible to insert attenuators on the antenna output of the individual LoRa Shields. On the receiver side, an OmniLOG 30800 wide-band antenna [11] was connected to a Teledyne LeCroy WavePro HD 804HD-MS high-bandwidth oscilloscope [12]. This setup made an analysis of the LoRa signals in the time domain possible, thanks to the oscilloscope's $8\,\mathrm{GHz}$ bandwidth and its high sample rate of up to $20\,\mathrm{GS/s}$. To fit the entire LoRa test packet in the oscilloscope's available memory, the sample rate was set to $10\,\mathrm{GS/s}$ and the LoRa parameters were also configured accordingly (SF = 7, BW = $500\,\mathrm{kHz}$, CR = 4/5). For better signal analysis, an on-board $1\,\mathrm{GHz}$ low-pass filter was used.

IV. Evaluation

To get a first overview of the signal characteristics, a time domain analysis was performed. Therefore, we carried out three sequential measurements, one for each of the two LoRa transceivers a and b, and one for the simultaneous transmission of both. The results for the single LoRa transmissions are shown in Figures 1b and 1c, respectively. It can be seen that both transceivers achieve a quite similar maximum amplitude at the receiver antenna of about $26.72\,\mathrm{mV}$ and $29.48\,\mathrm{mV}$. Due to manufacturing and hardware tolerances, minor differences in output power cannot be eliminated totally between the individual transceivers. Nevertheless, it can be seen, that the individual amplitudes remain very constant throughout the entire duration of the packet transmission of about $6.47\,\mathrm{ms}$.

In the next step, both transceivers were configured to transmit data simultaneously. The resulting amplitude measured at the receiving antenna is shown in Figure 2a. Here, a quite different amplitude curve is visible. In contrast to the clean signals received from the individual transceivers, interference effects can be observed. Especially a "beating effect" with randomly alternating amplitude valleys and peaks can be seen. The amplitude oscillates around maximum amplitude



(a) Overview of the entire concurrent transmission.

(b) t_0 detailed. (c) t_1 detailed (10 T_{LoRa}). (d) t_2 detailed (10 T_{LoRa}). (e) t_2 detailed (100 T_{LoRa}).

Figure 2. Time domain analysis of the received voltage amplitudes for simultaneous transmission of both transceivers a and b. Figure 2a shows an overview over the entire transmission. The highlighted part t_0 is analyzed in more detail in Figure 2b clearly showing the "beating effect". Figure 2c shows the effect of constructive interference while Figure 2d and Figure 2e show excerpts with predominantly destructive interference in different time scales.

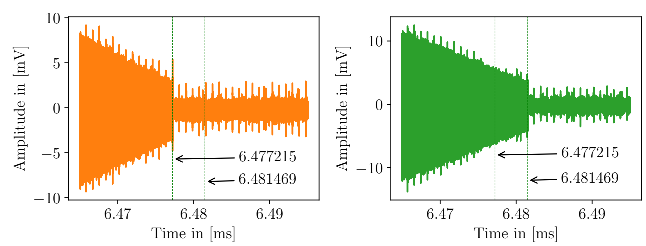
values of about $53\,\mathrm{mV}$, which is about $94\,\%$ of the sum of both maximum amplitudes of the individual transceivers ($26.72\,\mathrm{mV} + 29.48\,\mathrm{mV} \approx 56.2\,\mathrm{mV}$).

For a more detailed analysis, different parts of the interfered signal were analyzed and visualized in Figures 2b to 2e, using different time scales. The duration of one period of the LoRa frequency, T_{LoRa}, is calculated as follows:

$$f_{LoRa} = 868 \cdot 10^6\,\mathrm{Hz} \tag{1}$$

$$T_{LoRa} = \frac{1}{f_{LoRa}} \approx 1.152\,\mathrm{ns} \tag{2}$$

Figure 2b shows an excerpt of $190\,000$ LoRa periods (i.e., $190\,000 \cdot T_{LoRa} \approx 218.89\,\mu\mathrm{s}$) of the interference measurement, taken at an offset of $3.115\,\mathrm{ms}$ from the start of the transmission. The "beating effect" that shows up in form of an amplitude peak and valley combination is clearly visible. In Figure 2c, a $10 \cdot T_{LoRa} \approx 11.52\,\mathrm{ns}$ excerpt of the transmission is shown, where a good example of constructive interference can be observed, with both individual signals adding up, resulting in higher amplitude values in the range of $50.5\,\mathrm{mV}$. On the other side, Figure 2d shows an excerpt of the same length with mostly destructive interference, resulting in alternating, very small amplitude values below $1\,\mathrm{mV}$. Finally, Figure 2e shows a larger, $100 \cdot T_{LoRa} \approx 115.2\,\mathrm{ns}$ time frame, where destructive interference is also the dominant effect, leading to reduced amplitudes over the entire section.



(a) Transceiver a. (b) Transceiver b.

Figure 3. The end of the transmissions differ by $4.25\,\mu\mathrm{s}$

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Furthermore, we investigated the packet durations of both transceivers and found, that both transceivers had minor but measurable differences in their packet durations. Figure 3 shows the end of the received packets, revealing a time difference of about $4.25\,\mu\mathrm{s}$, partly deriving from timing behavior, phase and frequency offsets of both individual transceivers. The diverging durations of frames with identical contents also explain why the initial advantages of constructive interference vanish over time.

To quantify the benefits of constructive interference, an analysis of the Root Mean Square (RMS) amplitudes of the signals was performed. In the first step, the measured amplitude time series x_n of $10\,\mathrm{ms}$ duration was divided into $n_f = 1000$ frames. With a sample rate of $f_s = 10\,\mathrm{GS/s}$, this resulted in the number of samples n_s, frame size n_{fs} and frame duration T_{frame} as given in Equations (3) to (5).

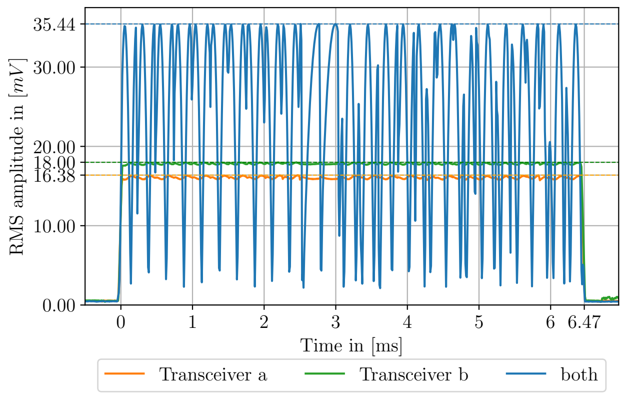

Figure 4. Analysis of the received RMS amplitudes for transceiver a, b and the simultaneous transmission of both.

$$n_s = 10^{-2}\,\mathrm{s} \cdot 10^{10}\,\mathrm{Hz} = 10^8 \tag{3}$$

$$n_{fs} = \frac{n_s}{n_f} = \frac{10^8}{10^3} = 10^5 \tag{4}$$

$$T_{frame} = \frac{n_{fs}}{f_s} = \frac{10^5}{10^{10}\,\mathrm{Hz}} = 10\,\mu\mathrm{s} \tag{5}$$

In the next step, all frames were analyzed regarding their RMS amplitude values $U_{RMS}[i]$, cf. Equation (6).

$$U_{RMS}[i] = \sqrt{\frac{1}{n_{fs}} \cdot \sum_{frame_i} x_n^2} \quad with \quad i \in [0, n_f - 1] \tag{6}$$

The results for this investigation are shown in Figure 4. First of all, it can be clearly seen, that the RMS amplitude values are very constant for the single transceiver transmissions. This applies for both transceivers a and b. It can also be seen, that both transceivers provide slightly different RMS amplitudes, this is expected, due to slightly different output powers of the individual transceivers. Furthermore it can be observed, that the RMS amplitude starts to vary a lot when both transceivers transmit data simultaneously. In this case, the RMS amplitude has its maximum well above the single transceivers, but also a much lower minimum. Specifically, a maximum value of $35.44\,\mathrm{mV}$ was achieved, whereas both individual signals max out at $16.38\,\mathrm{mV}$ (a) and $18\,\mathrm{mV}$ (b). Here, an even slightly higher RMS value (by $3\,\%$) than the sum of both individual signals was achieved, which can be explained by the high vulnerability of the sequential experiments to ambient influences on the wave propagation. The minimum RMS value lies in the range of the noise floor level of about $2\,\mathrm{mV}$.

This observations can be explained by constructive and destructive interference. Due to imperfections in the phase, amplitude, and frequency stability of the transceiver devices, a combination of constructive and destructive interference occurs. Whenever the two signals superimpose constructively, the RMS amplitude increases. Whereas it decreases, if the two signals overlay destructively. Nevertheless, the potential of constructive interference is visible in the evaluation in the form of a partial increase of the RMS amplitude, potentially leading to an increased reception range of the signal.

V. Conclusion and Outlook

In this paper, we have presented real-world measurements of the signal interference when two LoRa transmitters send identical data frames synchronously. We have set up a testbed to enable the simultaneous transmission of LoRa signals, and captured the waveforms of the resulting signal. Our evaluation has shown that the total signal's RMS amplitude experiences strong fluctuations when two simultaneous LoRa signals interfere, alternating between constructive and destructive interference. This is due to timing behavior, phase, and frequency offsets of the individual LoRa transceivers.

In our future work, we plan to get a better understanding of the underlying physical aspects and optimize the transmitter's (LoRa parameter) settings, in order to increase the amount of time during which interference is constructive. We also plan to validate our findings in real-world outdoor settings, in order to prove their usability and especially reliability in practice.

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