# Range and Coexistence Analysis of Long Range Unlicensed Communication

Brecht Reynders*, Wannes Meert† and Sofie Pollin*
*Department of Electrical Engineering
†Department of Computer Science
KU Leuven
Heverlee, B-3001 Belgium
Email: brecht.reynders@esat.kuleuven.be, wannes.meert@cs.kuleuven.be, sofie.pollin@esat.kuleuven.be

***Abstract*—A broad range of emerging applications require very low power, very long range yet low throughput communication. Different standards are being proposed to meet these novel requirements. In this paper, the technical differences between a wideband spread spectrum (LoRa-like) and an ultra narrowband (Sigfox-like) network will be explained and evaluated. On the physical layer, simulation results show that an ultra narrowband network has a larger coverage, while wideband spread spectrum networks are less sensitive to interference. When considering the contention between nodes and interference between different networks, simulations show that adaptation of frequency and modulation is imperative for efficiently dealing with varying contention and interference in long range unlicensed networks. Depending on network load, size and distance, a device in a wideband network can send 6 times more packets to the base station when there is active rate and frequency management and an intra-technology control plane.**

***Index Terms*—Low Power Wide Area Networks, Coexistence, Range, Interference, CSS, UNB, PHY, MAC**

## I. Introduction

As the Internet of Things is gaining interest and more remote and battery powered sensors are getting connected to the cloud, there is a need to have long range low power communication. These networks enable connectivity for thousands of sensors with only one base station by sacrificing throughput and reliability. Recently, different standards are being proposed to fill this gap. LoRa [1] and Sigfox [2] are two examples that are getting a lot of interest, but other alternatives exist such as Weightless-N and -P [3] and Nwave [4]. While the design constraints in all those novel standards are similar, there are clear technical differences that we want to study in this paper. A first contribution of this paper is the study and comparison of two possible techniques. The first technique, inspired by LoRa, is the use of chirp spread spectrum (CSS), where each symbol is sent using a wide frequency band. The other approach, inspired by Sigfox, is an ultra narrowband (UNB) technique. We will refer to the first as *CSS* and the latter as *UNB* in the remainder of this work.

We further also notice that a lot of publications assume that the interference between multiple networks for long range communication can be neglected, as the number of messages that each node sends is typically low. Using our detailed physical layer model and MAC protocol (LoRaWAN for the CSS network and a modified ALOHA protocol for the UNB network), we then carry out a detailed intra-cell interference study and show that interference does matter when the number of nodes is high, which is predicted in [5] and by many others. Then, we study network scalability considering also collisions and interference between multiple cells, possibly using a mix of heterogeneous technologies. To the best of our knowledge, this is the first paper comparing both standards in depth or studying interference and coexistence for long range wireless networks. Some high level comparisons have already been done, e.g. [6] gives an introduction to Sigfox, LoRa and Ingenu [7]. They also obtained the reachable distance experimentally based on LoRa.

For unlicensed networks, many interference studies have been done before. For IEEE 802.15.4 networks for example, [8] showed that IEEE 802.11 has a significant impact on the throughput when transmitting close to the central frequency of the IEEE 802.11 interferer. The same results can be expected when considering different long range networks deployed at the same location. Also coexistence within the same technology is often challenging, as shown for IEEE 802.11 in [9]. [9] states that having only one single access point gives better results than having two individual cells, based on the packet error rate. The underlying reason is that rate adaptation leads to inefficient results when collisions are frequent, as selecting a lower data rate can only compensate for path loss. To improve this, collision-aware rate adaptation is needed in IEEE 802.11 networks, but expected to be even more important for long range networks. There, the link budget is significantly bigger than the link budget for IEEE 802.11 networks and therefore it will need the lower data rates to achieve the long range.

To summarize, the main contributions of this work are (a) a technical simulation study of an UNB and CSS protocol for long range communication, (b) a simulation and a measurement study of their interference sensitivity and then (c) a network scalability study to see how they cope with both inter and intra-cell collisions and interference. The main conclusions are that these networks are robust by design, yet, will benefit from active rate and frequency management and intra-technology control plane when usage starts to become really high.

This work is supported by IWT CELTIC O&O project ASUA/RoCCS.

The rest of this paper is organized as follows. The following section details the simulation study of the physical layer. Section III shows the comparison of the medium access layer. Finally, the performance of the standards mentioned above is evaluated when multiple networks coexist.

## II. Physical Layer

This section compares both technologies using two different performance metrics: the range and the coexistence. *Range* influences the costs as it determines the minimal number of base stations needed for the operator. Yet larger coverage means also larger collision domains. *Coexistence* is important, as the considered technologies operate in the crowded 868MHz ISM-band. Sec. II-A explains the details of the compared technologies and Sec. II-B introduces the simulation model. The various assumptions taken to determine the bit error rate (BER) for the CSS modulation are detailed in the same section, before the results are given in the last subsection.

### A. Long Range Low Power Physical Layer

The differences between UNB and CSS are detailed below.

*1) UNB:* The ultra narrow band technology uses BPSK, because of its spectral efficiency. The technology uses only $100Hz$. The bit rate is fixed to 100 bits per second.

*2) CSS:* The wideband technology uses chirp spread spectrum (CSS) as modulation, using a scalable bandwidth ($B$) of $125kHz, 250kHz$ or $500kHz$. As function of received SNR, a variable spreading factor (SF) can be chosen. This spreading factor adapts the length of a symbol, but also specifies the number of bits per symbol. So, changing the spreading factor results in a variable bit rate ($R_b$) between $366bps$ for the highest spreading factor (12) and $48kbps$ for the lowest spreading factor (6) as shown in Eq. 1.

$$R_b = B/2^{SF} * SF \tag{1}$$

### B. System Model

The system model used for the comparison relies on a AWGN channel model with only thermal noise with a noise temperature of $25^oC$. This is a lower bound, because lots of devices use this band increasing the ambient noise. In addition we assume a distance dependent path loss following the Hata model [10], where we focus on the urban model as the highest number of devices will occur in these areas. For this model, we assume the height of the base station to $30m$ and the height of the nodes to $1m$.

Here, only the uplink is considered, as the data in sensor networks generally flows in this direction. The data is modelled as packets of 160 bits or 20 bytes. Finally, the transmitter of the mobile device sends with a power of $25mW$, the maximal allowed power in most of the ISM-band. All these assumptions concerning the channel and noise will be used throughout the rest of this paper.

To compare BPSK in UNB networks with CSS symbols, we need closed form expressions for both. To encode data in a CSS symbol, M bits are translated to a specific starting frequency of the chirp signal. This frequency then chirps over the whole bandwidth, wrapping around to finish back at the starting frequency.

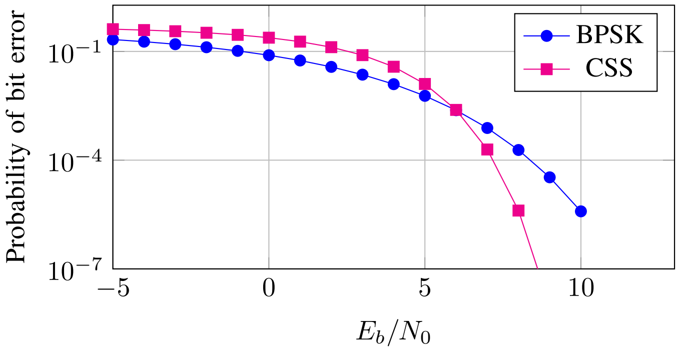



Fig. 1: Bit error rate of a BPSK and CSS symbol with bandwidth 125kHz and spreading factor 10. For lower values of $E_b/N_0$, BPSK gives better results, but for higher values, CSS is better.

To decode a CSS symbol, correlation with a copy of a base CSS symbol is used to extract the bits based on the phase shift of the signal. The CSS-decoder was implemented in MATLAB and the simulation results for a spreading factor of 10 and bandwidth of $125kHz$ are shown in Fig. 1.

The analytical expression for the BER-curve of CSS is given in Eq. 3 with $E_b/N_0$ the energy per bit to noise power spectral density ratio and $Q(x)$ is the Q-function. Because any 2 CSS symbols are *nearly* orthogonal, the closed-form expression for correlation-based BER can not be used. For this reason, the curve fitting tool in Matlab was used to estimate Eq. 3 based on the obtained results for different spreading factor and bandwidths, where the energy per bit to noise power spectral density ratio is $E_b/N_0$ and the spreading factor is $SF$. Eq. 3 is used in the remainder of this paper for the BER of CSS. The equation shows that for higher spreading factor the BER curve is steeper. Fig. 1 also shows the performance of a BPSK symbol (Eq. 2) [11]. Fig. 1 shows that for lower $E_b/N_0$ BPSK gives a better BER, for higher $E_b/N_0$, CSS is better.

$$P_{e,BPSK} = Q(\sqrt{2\frac{E_b}{N_0}}) \tag{2}$$

$$P_{e,CSS} = Q(\frac{log_{12}(SF)}{\sqrt{2}}\frac{E_b}{N_0}) \tag{3}$$

### C. Simulation Results

*1) Range:* Fig. 2 shows the throughput of both physical layers as function of the distance between the device and the base station. The throughput is calculated as the product of the packet delivery ratio and the bit rate. Fig. 2 shows that UNB communication with BPSK is able to maintain a good throughput over larger distances. There are two reasons why CSS has a smaller range: a higher bit rate and a wider bandwidth. The measurement results in [6] show even a lower

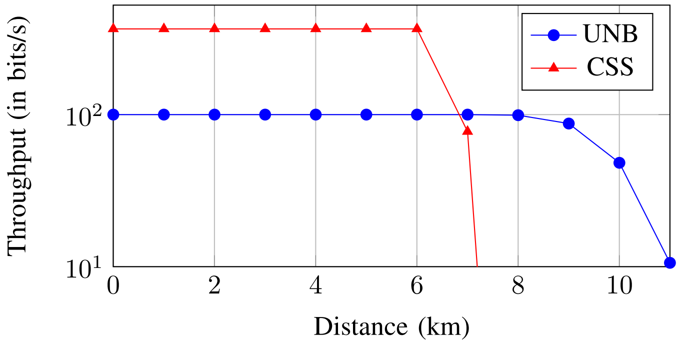



Fig. 2: Throughput of UNB and CSS network based on the range. The range of an UNB network is larger than the CSS network.

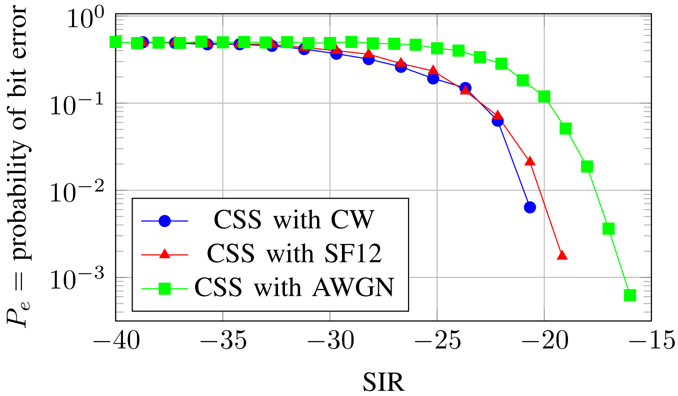



Fig. 3: BER for CSS symbol and LoRa symbol with spreading factor $SF = 10$ and bandwidth $B = 500kHz$.

range for CSS. The reasons are (a) higher ambient noise in reality and (b) receiver noise figure which is neglected here.

*2) Coexistence and Interference Sensitivity:* The coexistence of UNB BPSK has already been evaluated in [12], where it is shown that the error rate is dependent on frequency, phase and power of the continuous wave (CW). We confirmed their conclusions with our simulation model, which states that as long as the power of the UNB BPSK signal is 6dB higher than the interference, a CW interferer does not harm.

CSS on the other hand spreads the power over a wide band. Fig. 3 shows the robustness against interfering signals as function of the signal-to-interference noise ratio (SIR) for a symbol with spreading factor 10 and a bandwidth of $125kHz$. The figure shows that when the power of the signal is 20dB lower compared to the continuous wave interferer, errors occur in the implemented decoder. When comparing the BER performance with an AWGN interferer, a CW interferer has less effect, because the signal only correlates with the CSS symbol when the frequency of the CSS symbol is equal to the frequency of the CW interferer. Because CSS symbols with different spreading factor are orthogonal, symbols with different spreading factor can be received simultaneously. With a symbol with spreading factor 12 as noise and varying power, we see in Fig. 3 that this gives nearly the same performance as the continuous wave. So, we need a SIR of at least -18dB to correctly receive symbols while receiving the other stream of data.

## III. Medium Access Control Layer

A fair analysis requires also the study of the medium access control (MAC) layer, and how contention and interference between the many nodes in a cell or collision domain are handled. The rest of this section is divided as follows: first, Sec. III-A explains the two different MAC-layers. The second subsection describes the simulation environment in ns-3 [13]. And finally, in Sec. III-C, the results are discussed.

### A. Long Range Low Power MAC Layer

Both standards start from the unslotted ALOHA MAC-protocol, which implies that essentially all devices can access the channel whenever they want. Nevertheless, both technologies add some unique features to the MAC layer protocol, as described below.

*1) Ultra Narrow Band Contention:* The MAC layer in Sigfox limits the number of messages to the base station to 140 message a day or almost 1 message every 10 minutes. Here, we assumed 1 message every 10 minutes. Sigfox uses also multiple different parallel channels. For every transmission, the device picks a random channel (here: 400 channels). [14]

*2) CSS and ALOHA MAC:* The LoRa Alliance [1] has developed an open source MAC layer [15], which mandates devices to listen to the network after sending a message. This allows the network to control the transmission parameters such as spreading factor, power and bandwidth. In Europe, the network has 3 default channels for communication. The LoRaWAN MAC uses the default channel occupancy time limited by ETSI [16], and equals 1% of the time per device per channel in the 868MHz ISM band.

The LoRaWAN MAC accepts 2 types of traffic: acknowledged and unacknowledged data. In the acknowledged mode, the spreading factor is automatically adapted as function of the number of retransmissions. Concretely, every second, fourth and sixth retransmission, the MAC layer switches to more robust modulation, i.e. a higher spreading factor or a lower bit rate. Although the network has the capabilities to control the network, it is not obligatory. For this reason, two types of network control have been defined. First, a network with *passive control* is a network where devices decide locally on their rate adaptation, following the LoRaWan specification, which implies that they lower their rate every two consecutive lost acknowledgements. Second, a network with *active control* is a network where on top of the local rate adaptation in between successful acknowledgements, the network will embed rate adaptation requests in each acknowledgement. The implemented control algorithm is very simple: the devices are requested to reset the rate to the lowest spreading factor (i.e. the highest data rate). For both network control algorithms, all devices start with the maximal data rate or the lowest spreading factor as described in the LoRaWAN specifications (i.e. spreading factor 7 and bandwidth $125kHz$) .

### B. Simulation Model

The topology for the simulation model in ns-3 consists of uniformly distributed nodes over an area of $1000m$ by $1000m$, served by 1 central base station. We assume saturated traffic, which means nodes send data as much as possible and adapt flexibly to the available bandwidth and network control. The channel conditions are kept identical to the previous section.

### C. Simulation Results

The packet delivery ratio of an UNB network in Fig. 4 illustrates that the UNB MAC is slightly better than ALOHA MAC. The ALOHA MAC discards both colliding packets at reception, while the UNB network enables reception of the strongest packet, the so-called capture effect. The results for the ALOHA MAC are based on the exact formulas provided in [17]. These formulas show that the maximal throughput of the network occurs when $10^5$ devices are using the network, nevertheless resulting in a packet loss of 63%. Because of the capture effect, nodes closer to the base station experience fewer collisions as their power is more likely 6dB stronger than devices further from the base station.
Fig. 5 shows the packet delivery ratio for the CSS network when only the highest spreading factor (12) is used (*CSS high*). The packet delivery ratio is defined as the number of acknowledgements received to the number of transmissions of a device. In the CSS network, the effective throughput has increased with a factor 3 compared to the UNB network, because of the higher bit rate and a less strict channel occupancy limitation compared to the UNB network. The packet delivery ratio is slightly worse than the pure ALOHA MAC because acknowledgements increase the channel occupancy time and cause more collisions. When more devices are in the same cell, the packet delivery ratio improves compared to ALOHA MAC, due to the capture effect discussed before: only few devices are transmitting close to the base station. So, on average this gives a relatively better packet delivery ratio. Fig. 5 also shows that the number of devices is a factor 1000 less than in the UNB network.
We can improve the throughput by adapting the rate or spreading factor. The main challenge is however how to implement this rate control as function of the network conditions. In the next simulation, a CSS network with active control is used. Fig. 5 shows that when using multiple spreading factors (*CSS active*), the packet delivery ratio also improves. This adaptation has two benefits: first, nodes with a lower spreading factor can transmit faster, which means less channel occupancy time and second, collisions with different spreading factors are orthogonal. The results shows that adaptation of the spreading factor can improve the network reliability. Also in Fig. 5 the capture effect plays an important role: devices close to the base stations have a better packet delivery ratio (see also Sec. IV-B).

The MAC layers of these 2 long range networks show clear differences in throughput and number of devices in a network.

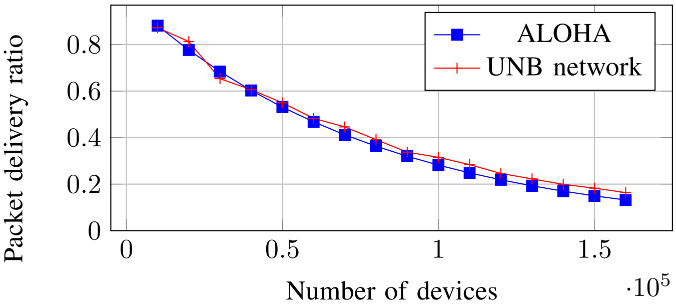



Fig. 4: Packet delivery ratio averaged over an UNB cell in function of the number of devices in the network. This figure shows the resemblance with ALOHA MAC.

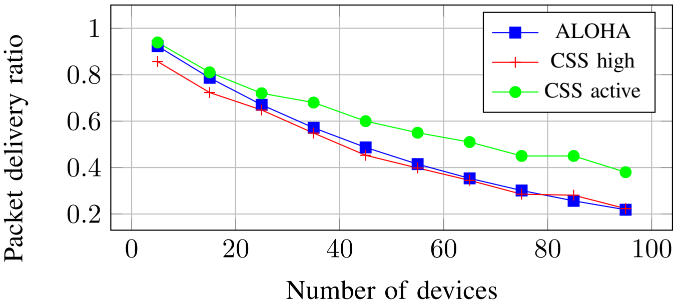



Fig. 5: Packet delivery ratio in a CSS-cell in function of the number of devices in one cell. A packet is considered delivered if the acknowledgement is received.

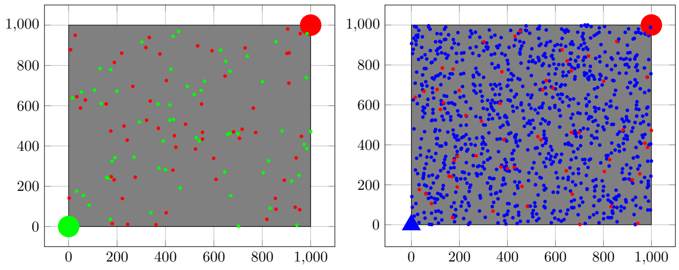
It is the application layer that defines which standard is more suited. Many devices with low data rate requirements suit a UNB network well. For higher throughput, the proposed CSS network is better. This section also showed that limiting the number of messages to send increases the possible number of devices in the network and rate control improves the network reliability and throughput in a CSS network.

## IV. Interference and Coexistence Analysis

This section analyses the coexistence of multiple (heterogeneous) networks.

### A. Simulation Environment

Two different coexistence scenarios are given in Fig. 6. The first network topology (Fig. 6a) is a network with 2 CSS competing networks (red and green). More precisely, the network topology consists of two base stations: one at location $(0m, 0m)$ for the red nodes and the other one at location $(1000m, 1000m)$ for the green nodes. Every network has 60 nodes spread in between the two base stations and does not acknowledge data from the other network. In this network topology, 3 different scenarios are simulated: an isolated network with passive control, an isolated network with active control and two coexisting networks with active control. The second topology (Fig. 6b) is a CSS network with active control and a competing UNB network with 1000 devices. This simplifies to only one device per 1000 square meter, which is




(a) Topology 1 (b) Topology 2

Fig. 6: An example of the 2 topologies. Topology 1 shows two CSS competing networks (green and red) with for each network 1 base station (green and red circle). Topology 2 shows an UNB network in blue, with base station (blue triangle) and a competing CSS network in red with its base station (red circle).

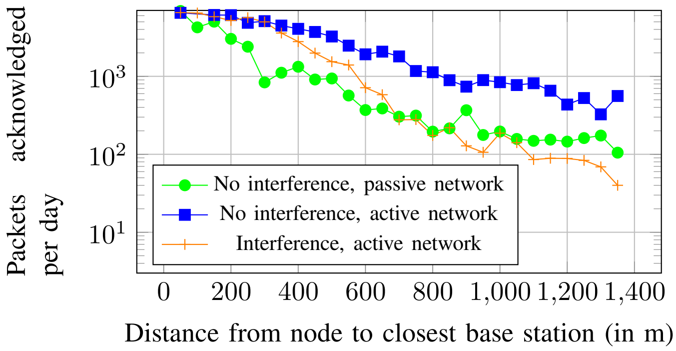



Fig. 7: Number of acknowledged packets per device per day based on the distance in topology 1. A network that actively controls the transmission parameters of every device, performs better than one that does not. When another competing network is introduced, the throughput far from the base station decreases to less than 150 messages.

a low number for urban areas. Two different scenarios are simulated for this topology. First, the two networks are simulated when working in the same band. The second simulation shows both networks without interference, i.e. assuming network planning ensured they use non-overlapping frequencies.

In these simulations, the traffic, the channel and positions are similar to Sec.III-B. The data in the CSS network is acknowledged data while the UNB network uses unacknowledged data. It should be noted that the simulations only consider one channel for a CSS network. The packet lengths used in these simulations are 70 bytes for the CSS network and 20 bytes for the UNB network. The length of the packets is different because the data rate is different for both technologies.

No simulation has been done for two competing UNB networks, because of the origin of both networks. The UNB network originates from SigFox, where all base stations are deployed by one company and collaborate, while the CSS network originates from LoRa, where private networks are allowed and interfere with each other.

### B. Simulation Results

*1) Topology 1:* Fig. 7 shows the number of packets for each device at a given distance from the base station that got acknowledged. It is clear from the figure that, when the network is passive, i.e. nodes adapt their spreading factor locally, the performance degrades quickly as function of the distance to the base station, even without interference. All the devices further than 150m suffer from the fact that they use a higher spreading factor because they need multiple retransmissions. The end-to-end packet error rate (PER) goes up to $20\%$ for devices at $1000m$, which results in only 200 arriving packets per day. If we use a network with simple active control, the number of acknowledged packets increases significantly with a factor 6 for nodes far away ($1000m$) from the base station and the PER decreases to only $7\%$. Larger gains are expected if we would do this control with more network context information.

When the interfering network is introduced, it is clear that performance drops, because nodes close to the competing base stations suffer from high collision probabilities. The amount of packets acknowledged by the system at 1000m is reduced by $80\%$ to only 200 packets per day, while there is no difference close to the base station. The PER at $1000m$ from the base station is close to $50\%$. Better control of this network by choosing spreading factor, power and channel, could improve the reliability and fairness of this system further. Because of symmetry in this topology, the other network shows identical results and an analysis is omitted here.

*2) Topology 2:* The results for topology 2 are shown in Fig. 8 and Fig. 9. The first figure shows the number of packets which were correctly received by the network in a CSS network. Although the interference is narrowband and a spreading gain can be used, the network degrades similarly as in the first topology: no performance loss close to the base station, but severe throughput degradation far from the base station. For devices at $1000m$, each device can send only 50 packets per day with a PER of more than $50\%$.

The UNB network on the other hand performs better than the wideband network. To corrupt a packet from the UNB network, a CSS transmitter should be close to the base station, which is not likely with only 60 devices spread over one square kilometer. Fig. 9 shows a decline in throughput, because the higher noise floor in this scenario. These results show that UNB networks are better suited for long range, but also that interference planning is needed to share the unlicensed spectrum with competing and heterogeneous networks.

## V. Discussion

This paper considers interference and coexistence for long range unlicensed networks, assuming interference from only a single interfering technology and assuming ideal, saturated traffic conditions. We shortly discuss these assumptions in this section. First, it needs to be realised that coexistence with other, older or even upcoming technologies (e.g., IEEE 802.11ah) is important. The 868 MHz ISM band is the second

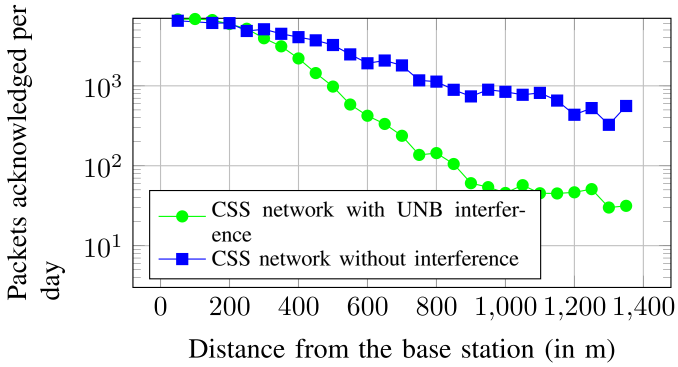



Fig. 8: The wideband network from topology 2 shows a clear decrease in throughput per day. The narrowband interferers make communication difficult far from the base station.

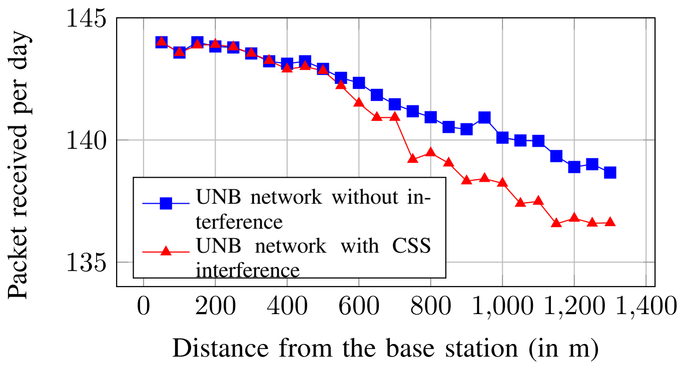



Fig. 9: The UNB network from topology 2 can cope well with the interfering network. Only few packets are lost due to the interfering CSS network and collisions.

most popular ISM band and therefore other technologies are important to consider. The CSS network sees all the other networks as narrowband and the UNB network sees all the other networks as wideband. So, it can be assumed that the impact of other sources of interference will be similar. Secondly, we assumed saturated traffic concerning CSS networks, which is not typical for sensor networks. Changing this traffic pattern or changing the channel occupancy time to less than 1% results in less collisions. The results given in Sec. III would be analogous only the horizontal axis would be scaled linearly, as a first order approximation. In Sec. IV, the results would improve network reliability as less collisions happen, but inequality between the far nodes and the close nodes concerning packet error rate will remain.

## VI. Conclusion and Future Work

This paper showed the main differences between a CSS (LoRa-like) and an UNB (Sigfox-like) network. The choice to use one of them depends mainly on the application. The UNB network performs better for long range communication, where the amount of data is small and the number of devices is high. A CSS network is well suited for applications with higher throughput, where smaller ranges are needed. These results were obtained by simulation in MATLAB and ns-3 for respectively the physical layer and the medium access layer. This paper also observed that an active network is needed to keep the settings of a CSS network up to date to counteract the need to go to a higher spreading factor. This increases the throughput of devices far from the base station. Finally, this paper also showed that there is an impact on network performance when other long range networks are deployed in the same area. On the border of the network, heterogeneous networks will suffer most, because of the lower signal power, the higher probability of collisions and the increased noise floor. This work relies on a very simple active control scheme, and improved versions that rely on radio environment maps of the interference and competing base stations could be very useful to provide more context information and create better control instances for these networks.

## Acknowledgement

The authors would like to thank Bertold Van den Bergh for the discussions about LoRa.

## References

[1] "Lora alliance," http://lora-alliance.org, 2015, accessed: 2015-09.
[2] "Sigfox," http://www.sigfox.com/en, 2014, accessed: 2015-09.
[3] "Weightless sig," http://www.weightless.org, 2015, accessed: 2015-09.
[4] "Nwave," http://www.nwave.io, 2015, accessed: 2015-09.
[5] A. Biral, M. Centenaro, A. Zanella, L. Vangelista, and M. Zorzi, "The challenges of m2m massive access in wireless cellular networks," *Digital Communications and Networks*, vol. 1, no. 1, pp. 1 – 19, February 2015. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S235286481500005X
[6] M. Centenaro, L. Vangelista, A. Zanella, and M. Zorzi, "Long-range communications in unlicensed bands: the rising stars in the iot and smart city scenarios," *arXiv preprint arXiv:1510.00620*, 2015.
[7] "Ingenu," http://www.ingenu.com, 2015, accessed: 2015-09.
[8] M. Petrova, L. Wu, P. Mähönen, and J. Riihijärvi, "Interference measurements on performance degradation between colocated ieee 802.11 g/n and ieee 802.15. 4 networks," in *Networking, 2007. ICN'07. Sixth International Conference on*. IEEE, April 2007, pp. 93–93.
[9] M. A. Ergin, K. Ramachandran, and M. Gruteser, "An experimental study of inter-cell interference effects on system performance in unplanned wireless lan deployments," *Computer Networks*, vol. 52, no. 14, pp. 2728–2744, October 2008.
[10] M. Hata, "Empirical formula for propagation loss in land mobile radio services," *Vehicular Technology, IEEE Transactions on*, vol. 29, no. 3, pp. 317–325, Aug 1980.
[11] L. W. Couch, II, *Digital and Analog Communication Systems*, 6th ed. Upper Saddle River, NJ, USA: Prentice Hall PTR, 2000.
[12] R. Axford, "Effects of cw-and bpsk-signal interference on a standard bpsk digital communications system," DTIC Document, Tech. Rep., February 1992.
[13] "Ns-3," http://www.nsman.org, 2015, accessed: 2015-09.
[14] *LE51-868 S RF Module User Guide*, Telit, Apr. 2014, rev. 1.
[15] *LoRaWAN Specification*, LoRa Alliance, Inc, Jan. 2015, rev. 1.
[16] ETSI, "Electromagnetic compatibility and Radio spectrum Matters: Short Range Devices: Radio equipment to be used in the 25 MHz to 1.000 MHz frequency range with power levels ranging up to 500 mW," ETSI, ETSI EN 300 220-1, February 2010. [Online]. Available: http://www.etsi.org/deliver/etsi_en300200_300299/30022001/02.04.01_40/en_30022001v020401o.pdf
[17] A. S. Tanenbaum and D. J. Wetherall, "Aloha," in *Computer Networks: Pearson New International Edition: University of Hertfordshire*. Pearson Higher Ed, 2013, pp. 280–283.