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Outdoor IEEE 802.11ah Range Characterization using Validated Propagation Models

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***Abstract*—IEEE 802.11ah is the new sub-1 GHz Wi-Fi standard, targeting large-scale and dense deployments of low-power stations. One of its major improvements compared to previous 802.11 standards, is its ability to scale to thousands of stations per access point. Cost-effective evaluation at such a scale is only possible using simulation, which requires realistic path loss models and hardware parameters. In this paper, we evaluate seven path loss models, based on a large scale sub-urban measurement campaign, including macro line-of-sight (LoS), pico LoS, and pico non-LoS with different as well as equal antenna height deployments. For each of the four resulting scenarios, the most accurate model is determined and used in combination with radio transceiver parameters obtained from actual 802.11ah station hardware to determine MAC-layer throughput and packet loss as a function of distance. The standard promises a range of up to 1 km at 150 kbps. Our results paint a less optimistic picture. When using realistic hardware parameters ranges up to 450 and 130 m can be achieved for a near LoS macro and pico deployment scenario respectively. For the non-LoS pico scenario ranges of 80 and 150 m can be achieved for transmitter at height 12 m and transmitter at heights 1.5 m respectively. With an ideal hardware configuration that operates at the maximum allowed transmission power, this could ideally be increased to 1700, 490, 300 and 550 m respectively.**

***Index Terms*—802.11ah, propagation loss model, outdoor, measurements**

I. INTRODUCTION

The new IEEE 802.11ah standard, marketed as Wi-Fi HaLow, is a low-power wireless communication PHY and MAC layer protocol that operates in the unlicensed sub-1 Ghz frequency bands (i.e., 863–868 Mhz in Europe and 902–928 Mhz in North-America). It was designed to provide communications among densely deployed energy-constrained stations at ranges up to 1 km, while maintaining a data rate of 150 Kbps [1]. Moreover, its flexible data rate allows it to achieve up to 78 Mbps at shorter distances. This makes it especially suited for flexible Internet of Things (IoT) and Machine To Machine (M2M) communications. A major improvement of 802.11ah, compared to previous 802.11 standards, is its ability to scale to thousands of stations per access point (AP) by introducing restricted access window (RAW) feature. RAW allows AP to divide stations into groups, limiting simultaneous channel access to one group and therefore reducing the collision. Evaluating the scalability of new PHY and MAC amendments for 802.11ah on such a scale using real hardware is obviously infeasible. Simulation is consequently the preferred route. To this end, we previously developed an 802.11ah simulation module for the ns-3 event-based network simulator [2], which is available as open source software [1]. Realistic modeling of the underlying physical medium is of critical importance to obtain realistic results in terms of throughput and packet loss as a function of distance between transmitter and receiver.

The physical wireless medium is generally modeled using path loss (also referred to as path loss) models, which simulates the transmission loss between two antennas. The IEEE TGah working group, which standardizes 802.11ah, proposed empirical outdoor and indoor path loss models based on the 3GPP spatial channel model (SCM) and TGn (MIMO) model respectively [3]. The original models were devised for LTE and 802.11n respectively, operating at frequencies around 2 and 2.4 GHz. For use with 802.11ah, they have been transformed to the sub-1GHz frequency bands, but have not been validated using realistic and extensive measurements under varying conditions. Moreover, existing simulation studies use radio transceiver parameters (e.g., noise figure or transmission power) based on conjecture and non-validated assumptions. This combination of non-validated path loss models and radio transceiver parameters leads to inaccurate simulation results.

In this paper, the aforementioned limitations are addressed by proposing a realistic wireless channel model for 802.11ah. It incorporates outdoor path loss models validated using real measurements, as well as radio transceiver parameters based on actual 802.11ah radio hardware. As a first contribution, four sub-1 GHz path loss data sets for outdoor urban environments have been collected, a near line-of-sight (LoS) macro deployment, a LoS pico scenario, a non-LoS pico deployment with transmitter at height 12 m, and a non-LoS pico deployment with transmitter at height 1.5 m that includes interference of different buildings. The macro scenario has the transmitter antenna placed above rooftop level, while in the pico scenario it is placed below rooftop level [4]. Based on these measurements, seven widely used outdoor path loss models are compared and evaluated. As a second contribution, the most accurate models, which fits the best to our measurements, are implemented in the open source 802.11ah ns-3 simulator and evaluated in combination with the PHY and MAC implementation, using realistic radio transceiver parameters obtained from the radio prototype recently presented by Ba et al. [5]. This allows determining the maximum transmission range, throughput and packet loss for 802.11ah

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[1] https://github.com/MOSAIC-UA/802.11ah-ns3

under realistic conditions. The improvements to the path loss model implementation are made freely available as part of the open source 802.11ah ns-3 simulation module.

The remainder of this paper is structured as follows. Section II introduces related work in the area of path loss modeling and 802.11ah range characterization. Section III introduces the methodology used to gather the path loss data sets. Section IV introduces the different outdoor path loss models used in the evaluation. Subsequently, Section V compares and validates the path loss models and presents MAC-layer simulation results of the most accurate ones. Finally, Section VI provides conclusions.

II. RELATED WORK

Even though the IEEE 802.11ah standard has not been officially published, researchers have been investigating it for a few years, both in terms of PHY and MAC layer aspects. Several works provide a deep overview of the key mechanisms of the protocol [1], [6], including advantages and challenges in the design of physical layer and MAC schemes. Several studies have been performed to assess the feasibility and performance of 802.11ah for a variety of scenarios. Due to a lack of commercially available hardware, these studies are based on mathematical models or simulation results. Adame et al. [7] conducted a performance assessment of IEEE 802.11ah in four common machine-to-machine (M2M) scenarios, i.e. agriculture monitoring, smart metering, industrial automation, and animal monitoring, using theoretical models. Several recent works study physical layer aspects of 802.11ah and sub-1Ghz communications. Link budget, achievable data rate and optimal packet size of 802.11ah is studied by Hazmi et al. [3]. They evaluated the feasibility of using 802.11ah for IoT and M2M use cases, based on the 2 path loss models proposed by the IEEE TGah working group (i.e., the 3GPP spatial channel model (SCM) and TGn (MIMO) model). More recently, Baños et al. [8], [9] also evaluated the theoretical range of 802.11ah using the TGah proposed path loss models. Li and Wang [10] present indoor coverage performance and time delay comparison between IEEE 802.11g and 802.11ah for wireless sensor nodes in M2M communications. Aust and Prasad [11] proposed a software defined radio (SDR) platform for 802.11ah experimentation, operating at the 900MHz ISM-band, and used it to perform an over-the-air protocol performance assessment. Moreover, Aust, Prasad and Niemegeers [12] built a real-time MIMO-OFDM testing platform for evaluating narrow-band sub-1GHz transmission characteristics. Casas and Papaparaskeva [13] introduced an architecture for a programmable IEEE 802.11ah Wi-Fi modem based on Cadence-Tensilica DSP. Finally, Ba et al. [5] developed an 802.11ah fully-digital polar transmitter, this hardware prototype passes all the PHY requirements of the mandatory modes in IEEE 802.11ah with 4.4% error-vector-magnitude (EVM), while consuming only 7.1 mW with 0 dBm output power.

In summary, past research either focused on small-scale (i.e., up to 2 devices) evaluation using a simplified hardware prototype [11], [12], [13], or performed simplified simulation or modeling for large-scale network evaluation. In this paper, we aim to improve the accuracy of the latter, by thoroughly evaluating and optimizing the path loss models used for these simulations. Moreover, we propose a set of PHY and radio simulation parameters derived from actual 802.11ah hardware [5].

III. MEASUREMENT METHODOLOGY

In order to evaluate the accuracy of the different path loss models in different outdoor use cases, four data sets were collected at the University of Antwerp:

1) **Macro LoS** deployment scenario (20852 measurements) with the transmitter that uses a transmission power of 13 dBm and a transmitter antenna height at 30 m.
2) **Pico LoS** deployment scenario (874 measurements) with the transmitter that uses a transmission power of 2.4 dBm and a transmitter antenna height of 1.5 m.
3) **Pico non-LoS with transmitter at height 1.5 m** deployment scenario (1168 measurements) with the transmitter that uses a transmission power of 0 dBm.
4) **Pico non-LoS with transmitter at height 12 m** deployment scenario (26366 measurements) with the transmitter that uses a transmission power of 13 dBm.

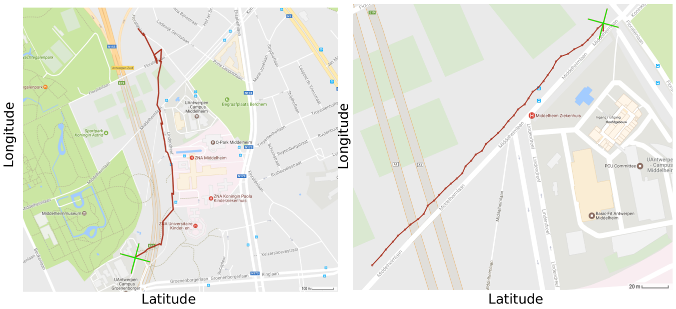
The receiver antenna height was 1.5 m for all scenarios. To properly compare these data set, all received link budgets will be normalized to a transmission power of 0 dBm and will be further explained in Section V. To fit each dataset with the different path loss models in a robust manner, many measurements were collected for each of them, as shown in brackets above. Each measurement was performed by receiving a packet with a payload of 2 bytes every 2 seconds at a center frequency of 868.1 MHz with a bandwidth of 150 kHz using the Silicon Labs Sub-GHz EZR32 Leopard Gecko Wireless Starter Kit. Furthermore, the receiver receives the packet from the transmitter and outputs the reception time, received signal strength and GPS coordinates (obtained from the mounted GPS) to a log file. During the measurement campaigns, the transmitter was kept static, while the receiver moved between different geographical locations (cf. Figure 1). Both the pico and macro deployment LoS scenarios have the occasional cars, pedestrians, bicycles, and trees as obstacles. Both non-LoS deployment scenarios have multiple buildings between the transmitter and receiver. According to the four data sets, a best-fit path loss loss model can be determined together with a realistic fade margin for the different use cases. This model and fade margin are used as a basis for the MAC-layer simulations presented in Section V.

IV. PATH LOSS MODELS

The received power or link budget between transmitter and receiver can be described using the following generic equation:

$$P_{rx} = P_{tx} + G_{tx} + G_{rx} - PL \tag{1}$$

where P_{rx} and P_{tx} are the received and transmitted power expressed in dBm, G_{tx} and G_{rx} are the transmitter and



(a) Macro LoS scenario

(b) Pico LoS scenario

(c) Pico non-LoS with transmitter height at 12 m scenario

(d) Pico non-LoS with transmitter height at 1.5 m scenario

Fig. 1. Transmitter (cross) and receiver locations (dots) of both LoS and non-LoS scenarios applied in a macro and pico deployment.

receiver gain, and PL is the path loss. The path loss PL is dependent on the environment, used frequency, and the distance between both devices. PL can be simulated with a path loss model, which can empirically or deterministically compute the signal loss. In this paper, seven widely used empirical outdoor path loss models for 802.11ah, that have been proven suitable given specific environments and constraints, are evaluated and compared [14]. The remainder of this section briefly summarizes the considered models.

a) Free Space path loss: The most naive and basic model that expresses the free space path loss as inversely proportional to the squared distance of a wave that is propagating in free space.

b) Two-ray path loss: This model includes at one hand the LoS signal and at the other hand the non-LoS signal. This non-LoS signal enables the inclusion of the ground reflection and is based on the calculation of the Fresnel reflection coefficients at reflection intersection with the soil. In order to use this path loss model, the heights of the transmitter and receiver antennas have to be known to calculate the reflection intersection.

c) COST-231 Hata: An outdoor path loss loss model that is used in urban and suburban environments. It has some restrictions that limit the heights and the frequency range of the used devices. This restriction will limit the height of transmitting devices from 30 meter to 200 m and 1 to 10 m for receiving devices. The frequency range of both devices should be below 1 GHz [4].

d) COST-231 Walfisch-Ikegami: This model adds the average rooftop heights of nearby buildings, and the antenna heights to compute the path loss. It is mostly used in urban environments [4].

e) AH Macro deployment: The first outdoor model proposed for use with 802.11ah by the IEEE TGah working group, based on the 3GPP SCM for LTE [3]. It assumes an antenna height 15 m above rooftop level.

f) AH Pico deployment: The second outdoor model proposed for use with 802.11ah by the IEEE TGah working group, based on the 3GPP SCM for LTE [3]. It assumes an antenna height at rooftop level.

g) ITU-R street canyon: This model is characterized by two slopes defined by two individual models and a break point. This break point has a dependency on the used wavelength and the different antenna heights. The first slope is defined by the Free Space path loss model for distances smaller then the break point. Beyond the break point, the LoS path loss model with a different path loss exponent is used, which represents the worst case path loss [15].

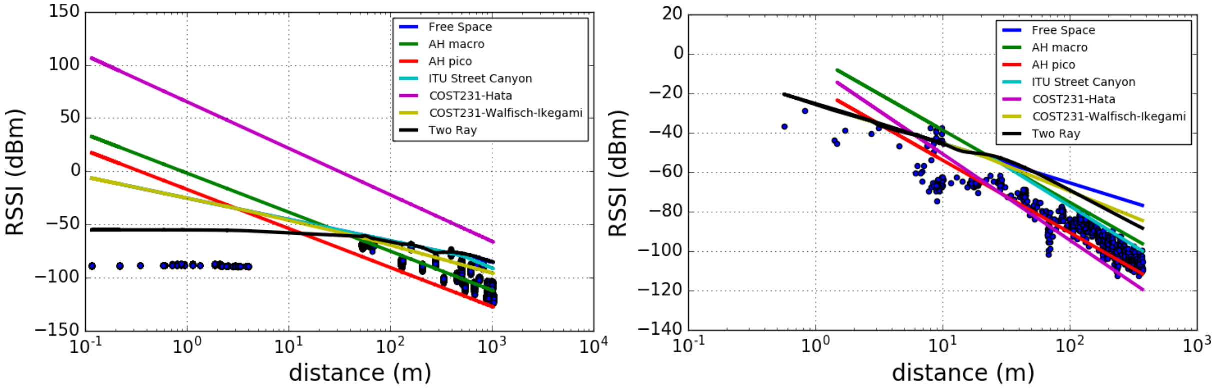
V. EVALUATION AND RESULTS

The goal of this section is twofold. First, the seven path loss models described above are fit to the four data sets, in order to determine the most accurate one for each scenario. Second, the 802.11ah ns-3 simulator [2] is used to calculate accurate throughput and packet loss values as a function of distance, using the best fitting path loss models, as well as realistic fade margins and radio parameters for a typical and an ideal IEEE 802.11.ah use case.

A. Path loss model comparison

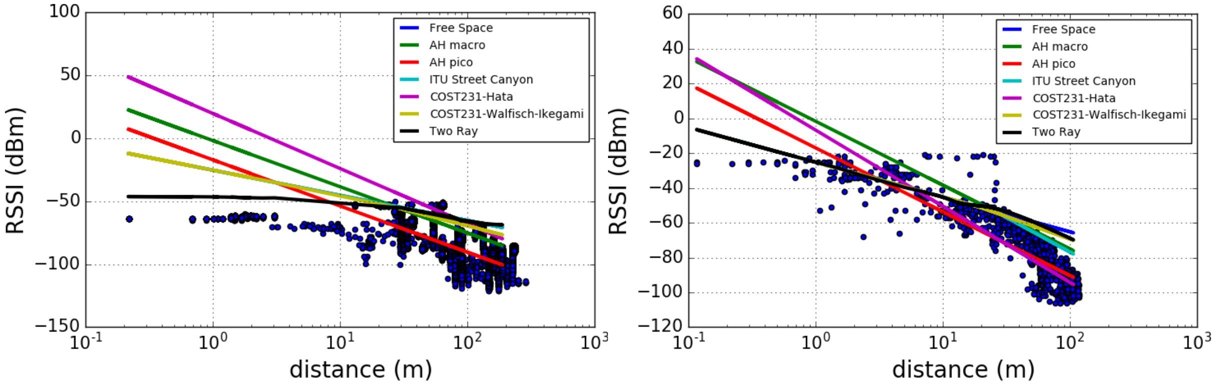
In order to determine the optimal path loss loss model for each of the four outdoor scenarios under study, the seven models are fit to all data sets and compared in terms of the normalized root-mean-square error (NRMSE). Figure 2 compares the seven models to the different dataset measurements in terms of the normalized received signal strength (RSS) as a function of distance. This normalized received signal strength is the actually received signal power subtracted with the transmitted output power. Each path loss model is simulated with a transmission power of 0 dBm, a center frequency of 868.1 MHz, and an antenna gain of +3 dBi that is applied for transmitter and receiver.

As shown in Table I, the AH-macro model proposed by the TGah working group fits best to the macro LoS dataset, while the AH-pico model proposed by the TGah suits best for the pico LoS and non-LoS datasets. A very noteworthy observation is the fact that the data of the macro scenario dataset and the pico non-LoS with transmitter height at 12 m scenario dataset has a significant offset with the path loss models when the distance is small. This observation can be explained to the fact that the path loss models consider a perfect isotropic antenna, while our antenna has a monopole radiation pattern. The AH-macro deployment model, which



(a) Macro LoS scenario

(b) Pico LoS scenario



(c) Pico non-LoS with transmitter height at 12 m scenario

(d) Pico non-LoS with transmitter height at 1.5 m scenario

Fig. 2. Correlation between the measurements and path loss models in terms of RSS and as a function of distance

TABLE I
NORMALIZED RMSE COMPARISON OF THE PATH LOSS LOSS MODELS FOR ALL SCENARIOS

Model	NRMSE			
	Pico LoS	Pico NLoS with transmitter height at 1.5 m	Pico NLoS with transmitter height at 12 m	macro LoS
Free space	0.26	0.006	0.05	0.29
AH macro	0.14	0.004	0.01	**0.01**
AH pico	**0.04**	**2.15e-5**	**0.001**	0.27
ITU-R street canyon	0.10	0.006	0.05	0.26
COST231-Hata	0.09	0.027	0.044	0.82
COST231-Walfish Ikegami	0.21	0.003	0.029	0.16
Two Ray	0.20	0.003	0.052	0.28

is the optimal choice for the macro LoS scenario, can be characterized as follows:

$$PL = 8 + 36.7\log_{10}(d) \tag{2}$$

where d is the distance between the receiver and the transmitter. Next, the AH-pico model is the optimal algorithm for pico LoS and pico non-LoS scenarios and is defined with the formula:

$$PL = 23.3 + 36.7\log_{10} d + c_{pico} \tag{3}$$

Where c_{pico} is the correction function for suburban environments and is defined as:

$$c_{pico} = 21\log_{10}\frac{f}{900} \tag{4}$$

Subsequently, the fade margin needs to be computed to enable realistic simulations and packet loss calculations. This fade margin is calculated as the root mean square error of the differences between the simulated and real reception power P_{rx}. The resulting fade margin for each scenario is listed among the other simulation parameters in Table II.

B. MAC-layer performance

This section characterizes the packet loss and throughput of IEEE 802.11ah for the four scenarios, based on the best fitted path loss models and realistic fade margins that were previously determined, as well as realistic radio transceiver parameters. Two different radio transceiver configurations are used to analyze the 802.11ah MAC-layer performance: (i) prototype and (ii) ideal. The prototype configuration is based on the 802.11ah radio hardware prototype developed by Ba

TABLE II

Physical layer parameters used for simulation

Common parameters		Value
Frequency (Mhz)		868
Modulation scheme		BPSK
Bandwidth (MHz)		1
Data rate (kbps)		300
Coding method		BCC
Error rate model		YansErrorRate
Packet size (bytes)		256
Transceiver parameters	Prototype	Ideal
Transmission power (dBm)	0	14
Transmission antenna gain (dBi)	0	0
Reception antenna gain (dBi)	0	3
Noise figure (dB)	6.8	3
Scenario parameters	Macro LoS	Pico LoS
Path loss model	AH Macro	AH Pico
Transmitter antenna height (m)	30	1.5
Receiver antenna height (m)	1.5	1.5
Fade Margin (dB)	0.99	3.60
Scenario parameters	Pico non-LoS with transmitter at height 12 m	Pico non-LoS with transmitter at height 1.5 m
Path loss model	AH Pico	AH Pico
Transmitter antenna height (m)	12	1.5
Receiver antenna height (m)	1.5	1.5
Fade Margin (dB)	7.67	2.62

et al. [5], and has a transmission power of 0 dBm, a gain of 0 dBi for both antennas and noise figure of 6.8 dB. The ideal configuration is based on the maximum recommended transmission power values as proposed by the CEPT Electronics Communications Committee (ECC) [16], and has a transmission power of 14 dBm, a 0 dBi transmit antenna gain, a 3 dBi receiver antenna gain and noise figure of 3.0 dB [3]. Table II gives a complete overview of the different PHY parameters that are used in the simulation to evaluate the packet loss and throughput. The evaluation is performed using the 802.11ah ns-3 simulation module [2], which includes both a MAC and PHY implementation of 802.11ah. Concerning the MAC layer analysis, the channel time is ensured to be fully utilized by allowing a single station to constantly send packets to the AP over a period of 60 seconds using a 1 MHz bandwidth (MCS0) . The results are averaged over 10 simulation runs, and are depicted in Figure 3.

Figure 3 shows the 802.11ah transmission range separately for the four data sets. Each graph visualizes the results for the prototype and ideal radio transceiver configurations. From Figure 3a, it can be derived that for the prototype hardware configuration, stations in the macro LoS scenario can transmit up to 445 and 480 m at 1.29% and 9.63% packet loss respectively. In contrast, the ideal configuration can achieve up to 1640 and 1780 m respectively at 1.21% and 10.7% packet loss. The maximum transmission range for the other 3 scenarios is much lower. The results of the pico LoS scenario are shown in Figure 3b and show that a transmission range of 120 and 150 m can be achieved with a prototype hardware configuration, with a packet loss of 1.24% and 9.89% respectively. Additionally, 440 and 550 m can be achieved at 1.18% and 9.5% packet loss with an ideal hardware configuration. For the pico non-LoS with transmitter at height 12 m scenario, as shown in Figure 3c, the prototype hardware configuration only achieves distances of 65 and 105 m at 1.14% and 9.41% packet loss respectively. The ideal configuration achieves up to 240 m and 400 m at 1.0% and 10.31% packet loss respectively. Finally, Figure 3d depicts the result of the pico non-LoS with transmitter at height 1.5 m scenario. It suggests that stations can transmit messages up to 136 and 162 m at 1.0% and 9.8% packet loss respectively with a prototype hardware configuration. This transmission range can be increased to 500 and 600 m at 1.02% and 10.19% packet loss by using an ideal hardware configuration. The control frames and data frame are both used in IEEE 802.11ah, while only data frames are counted as throughput. This result in a super-linear inverse relationship between throughput and packet loss. These results show that the macro LoS and pico LoS scenarios, using state-of-the-art low-power hardware, have a maximum range of 450 and 130 m, while maintaining a throughput of 150 kbps. On the other hand, for the pico non-LoS with transmitter at height 1.5 m and 12 m scenarios the maximum range is 80 and 150 m. These results need to be interpreted as a worst case situation that can be improved at the cost of a higher power consumption. An ideal hardware configuration could achieve 1700, 490, 300 and 550 m for the four scenarios respectively. The results also reveal that with the same hardware configuration, packet loss increases dramatically at a specific tipping point. This can be seen in the macro LoS scenarios due to the small fade margin, while the packets loss increases more slowly in the other three scenarios.

VI. Conclusion

This paper provides a realistic characterization of outdoor IEEE 802.11ah MAC-layer throughput and packet loss as a function of distance based on sub-1GHz radio transmission measurements and realistic radio transceiver parameters. The measurements are used to classify seven popular path loss models for near-LoS macro, near-LoS pico, non-LoS pico with transmitter at height 1.5 m and 12 m scenarios. The results showed that the path loss models proposed by the IEEE TGah working group for 802.11ah indeed provide a good fit to the real data. However, while the standard promises a range of up to 1 km at 150 kbps, the results paint a less optimistic picture when using realistic low-power station hardware parameters. Simulation results indicate a maximum range of 450, 130, 80 and 150 m at 150 kbps for these four scenarios. For more ideal hardware with the maximum allowed transmission power, this range could be increased up to 1700, 490, 300 and 550 m respectively for the four different scenarios. Furthermore, the retrieved results are found optimal for this specific geographical location and therefore context dependent.

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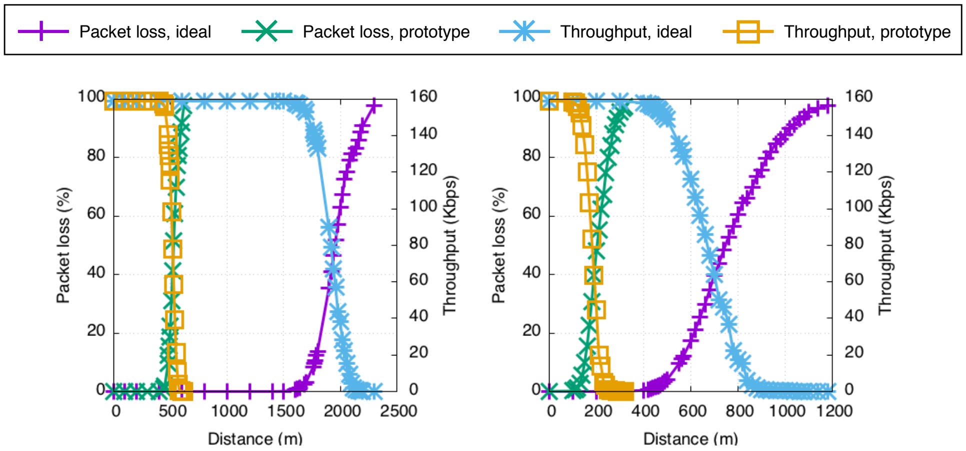
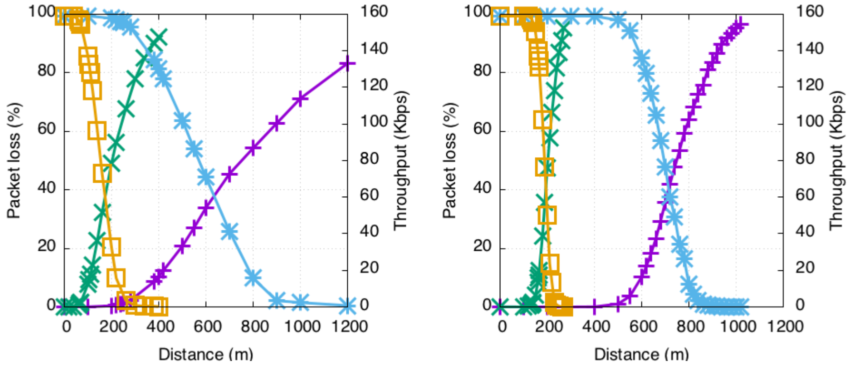


(a) Macro LoS scenario

(b) Pico LoS scenario



(c) Pico non-LoS scenario with transmitter height at 12 m

(d) Pico non-LoS with transmitter height at 1.5 m scenario

Fig. 3. Packet loss and throughput as a function of distance for the actual radio hardware as well as ideal case

REFERENCES

[1] E. Khorov, A. Lyakhov, A. Krotov, and A. Guschin, "A survey on IEEE 802.11ah: An enabling networking technology for smart cities," *Computer Communications*, vol. 58, pp. 53–69, mar 2015. [Online]. Available: http://linkinghub.elsevier.com/retrieve/pii/S0140366414002989

[2] L. Tian, S. Deronne, S. Latré, and J. Famaey, "Implementation and Validation of an IEEE 802.11Ah Module for Ns-3," in *Proceedings of the Workshop on Ns-3*, ser. WNS3 '16. New York, NY, USA: ACM, 2016, pp. 49–56.

[3] A. Hazmi, J. Rinne, and M. Valkama, "Feasibility study of IΕΕΕ 802.11ah radio technology for IoT and M2M use cases," in *2012 IEEE Globecom Workshops*. IEEE, dec 2012, pp. 1687–1692. [Online]. Available: http://ieeexplore.ieee.org/document/6477839/

[4] COST Action 231, "Digital Mobile Radio Towards Future Generation Systems," 1999.

[5] A. Ba, Y.-H. Liu, J. van den Heuvel, P. Mateman, B. Busze, J. Gloudemans, P. Vis, J. Dijkhuis, C. Bachmann, G. Dolmans, K. Philips, and H. de Groot, "26.3 A 1.3nJ/b IEEE 802.11ah fully digital polar transmitter for IoE applications," in *2016 IEEE International Solid-State Circuits Conference (ISSCC)*. IEEE, jan 2016, pp. 440–441. [Online]. Available: http://ieeexplore.ieee.org/document/7418096/

[6] M. Park, "IEEE 802.11ah: sub-1-GHz license-exempt operation for the internet of things," *IEEE Communications Magazine*, vol. 53, no. 9, pp. 145–151, sep 2015. [Online]. Available: http://ieeexplore.ieee.org/document/7263359/

[7] T. Adame, A. Bel, B. Bellalta, J. Barcelo, and M. Oliver, "{IEEE 802.11ah}: the {WiFi} approach for {M2M} communications," *IEEE Wireless Communications*, vol. 21, no. 6, pp. 144–152, 2014.

[8] V. Baños-Gonzalez, M. Afaqui, E. Lopez-Aguilera, and E. Garcia-Villegas, "IEEE 802.11ah: A Technology to Face the IoT Challenge," *Sensors*, vol. 16, no. 11, p. 1960, nov 2016. [Online]. Available: http://www.mdpi.com/1424-8220/16/11/1960

[9] V. Baños-Gonzalez, M. S. Afaqui, E. Lopez-Aguilera, and E. Garcia-Villegas, "Throughput and range characterization of IEEE 802.11ah," p. 7, apr 2016. [Online]. Available: http://arxiv.org/abs/1604.08625

[10] M. Li and D. Wang, "Internet of Vehicles Technologies and Services," in *Proceedings of the 1st International Conference on Internet of Vehicles*, ser. Lecture Notes in Computer Science, R. C.-H. Hsu and S. Wang, Eds., vol. 8662. Cham: Springer International Publishing, 2014, pp. 211–217. [Online]. Available: http://link.springer.com/10.1007/978-3-319-11167-4

[11] S. Aust and R. V. Prasad, "Advances in Wireless {M2M} and {IoT}: Rapid {SDR}-prototyping of {IEEE} 802.11ah," in *IEEE Local Computer Networks Conference*, 2014.

[12] S. Aust, R. V. Prasad, and I. G. M. M. Niemegeers, "Performance study of {MIMO-OFDM} platform in narrow-band sub-1 {GHz} wireless {LANs}," in *11th International Symposium on Modeling & Optimization in Mobile, Ad Hoc & Wireless Networks (WiOpt)*. IEEE, 2013, pp. 89–94.

[13] R. A. Casas, V. Papaparaskeva, R. Kumar, P. Kaul, and S. Hijazi, "An {IEEE} 802.11ah programmable modem," in *IEEE 16th International Symposium on A World of Wireless, Mobile and Multimedia Networks (WoWMoM)*, 2015.

[14] T. K. Sarkar, Zhong Ji, Kyungjung Kim, A. Medouri, and M. Salazar-Palma, "A survey of various propagation models for mobile communication," *IEEE Antennas and Propagation Magazine*, vol. 45, no. 3, pp. 51–82, jun 2003.

[15] ITU, "{ITU-R} Recommendation P.1411.8," 2015.

[16] CEPT ECC, "{ERC} Recommendation 70-03," 2016.