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# Feasibility Study of IEEE 802.11ah Radio Technology for IoT and M2M use Cases

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Abstract—In this paper we study the feasibility of IEEE 802.11ah radio technology for internet of things (IoT) and machine to machine (M2M) use cases. Devices in internet of things and machine to machine networks are foreseen to communicate wirelessly. Therefore, it is of foremost importance to have a reliable, low-energy wireless technology available that may be used anywhere and anytime without draining the device battery and could achieve satisfactory coverage and data rate. Here we study the link budget, achievable data rate and packet size design of the IEEE 802.11ah radio technology in different channel scenarios. System design and simulation results show that when using this technology the system parameters can be selected to satisfy in most of the cases a reliable communication link while providing better coverage and relatively comparable throughput when compared to other existing solutions like ZigBee.

#### I. INTRODUCTION

Advances in wireless technologies have altered consumer's communication habits. Wireless technologies have essentially affected users' daily life and it is expected to become an even more daily commodity in the future. World Wireless Research Forum (WWRF) has predicted that 7 trillion wireless devices for 7 billion people will be deployed by 2020 [1]. This will supplement a novel dimension to the world of information and communication technologies where connectivity from anytime, anyplace for anyone, will now encompass anything, hence introducing the Internet of Things (IoT) concept [2][3].

The definition of "things" in the IoT concept is very wide and comprises a variety of items. These items include personal objects we carry around such as smart phones, tablets and digital cameras. It also comprises elements in our environment as well as things having tags like RFID, or connected via a gateway device. Therefore, enormous number of things will be connected to the Internet, each providing data and information and some even services. In result, the IoT consists of heterogeneous sets of devices and heterogeneous communication strategies between these devices and different data servers. When these huge numbers of devices are connected to the Internet to form the IoT network, the first challenge is to adjust the basic connectivity and networking layers to handle the large numbers of end points.

There are new wireless technologies being developed for IoT purposes due to different demanding requirements, one of those being high energy efficiency. Cellular technologies for example, are being scaled to serve this kind of traffic [4]. Developing existing technologies to better meet the requirements of IoT is thus an important task.

In many scenarios, the wireless node must operate without battery replacement for many years. Energy efficiency is thus a very important constraint when designing an IoT network. The hardware, the link layer, the MAC layer, and all other higher layers should be jointly designed to minimize the total energy consumption [5]. Achieving an optimal joint design across all layers of the network protocol stack is quite challenging. Several existing proprietary solutions for machine to machine (M2M) and wireless sensor networks (WSN) use cases are available in the market [6]. The IEEE 802.15 standard family has also addressed the low-power use case issue earlier. For example, Radio-frequency identification (RFID) offers partly some of these functionalities. ZigBee and Bluetooth support other use cases [7][8].

In this paper we will focus mainly on the use of IEEE 802.11 OFDM radio technologies and their suitability in IoT and M2M context. IEEE 802.11 is known to be a de-facto standard for wireless Local Area Networks (WLAN) and one of the most deployed solutions for enterprise architecture. Although the major focus of the standard has been on deriving high user throughputs in a WLAN environment, there are many devices that require ultra-low power connectivity as in the IoT network. Recently a new amendment, the IEEE 802.11ah (802.11ah) [9] is being designed to fulfill this requirement, as an example of use case, while maintaining a certain user experience with old IEEE 802.11a releases.

Our main contribution in this paper is to study the feasibility of this new amendment for IoT and M2M

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 TABLE I

 Typical Ranges of some Low-Energy Technologies

System	Range
ZigBee	10100 m
Bluetooth	110 m
UWB	10 m
IEEE 802.11ah	$\geq 1000 \text{ m}$

use cases. The remainder of this paper is organized as follows. Section II describes the main parameters of the 802.11ah. Section III studies the link budget of the system given the path loss model and the transceiver typical settings, presents the system achievable data rate and investigates the packet size design in fast fading channel scenarios. Section IV draws the conclusions and proposes the directions for future work.

#### II. IEEE 802.11AH OVERVIEW

The development of 802.11ah is still in its early stages. 802.11ah is currently in the process of collecting system design proposals. The final standard is expected to be finalized by year 2014. The target is to enhance the designs of the physical and MAC layers of IEEE 802.11ac (802.11ac)[10] so that it operates in free sub-1-GHz bands [9]. Due to lower center frequencies, the path loos at sub-1-GHz provides longer distances when compared to typical WLAN frequencies around 2.4 GHz and 5 GHz. Also, power consumption of the devices can be pushed down at these frequencies, because of the propagation properties and simpler needed device components. Therefore, the expected low-cost and large coverage make 802.11ah radio technology highly attractive for deployment in rural areas compared to WiMAX [11] technology. In [9], the functional requirements and the evaluation methodology for .11ah were described. The main requirement can be summarized on the following three points:

- Transmission range up to 1 km.
- Data rates > 100 kbps.
- Maintaining the 802.11 WLAN user experience for fixed, outdoor, point to multi point applications.

As can be seen in the first point, the target range is relatively high when compared to the range of the existing technologies that consider low-energy applications as in ZigBee, Bluetooth, Ultra-Wide band (UWB) [7][8][12], etc. Table I shows an example of the typical ranges of these technologies. The data rate however is relatively low, as the main focus here is on those use cases that consider a relatively low speed data transfer. The third point on the requirement states that the 802.11ah should keep a certain compatibility with older IEEE 802.11 standards, like the 802.11ac. This means that the PHY and MAC layers in the .11ah may not be very different than the 802.11ac standard.



Fig. 1. A generic communication system with gains and losses.

Technically 802.11ah has taken the 802.11a OFDM technologies as baseline. It is mainly using 802.11ac [10] Physical layer. It will be centered at the sub-1-GHz bands (S1G) band. The 802.11ah operating bands include one or more of the following: 863-868.6 MHz (Europe), 950.8 MHz -957.6 MHz (Japan), 314-316 MHz, 430-432 MHz, 433.00-434.79 MHz (China), 917 -923.5 MHz (Korea) and 902-928 MHz (USA). By downclocking, i.e., increasing the symbol duration, suitable bandwidths can be obtained. Novel 802.11ah amendment supports the following channel bandwidths: 1 MHz, 2 MHz, 4 MHz, 8 MHz, and 16 MHz and all 802.11ah stations shall support 1 and 2 MHz (rests are optional). The 2 MHz PHY transmission shall be an OFDM based waveform consisting of a total of 64 tones. The same tone spacing will be used in all other bandwidth modes. MAC and PHY layers need to be adapted to support a variety of different use cases.

#### III. 802.11AH LINK BUDGET ASSESSMENT

In a communication system, the link budget considers all the gains and losses from the transmitter, through the medium (free space, cable, etc.) to the receiver. The gains and losses variables are shown in Fig. 1. The principal link budget equation for the system illustrated in Fig. 1 is given by

$$P_{RX} = P_{TX} + G_{TX} - L_{TX} - PL(d) + G_{RX} - L_{RX},$$
(1)

where  $P_{RX}$  and  $P_{TX}$  model the receiver and the transmitter power, respectively.  $G_{RX}$ ,  $G_{TX}$ ,  $L_{RX}$  and  $L_{TX}$  are the antenna gains and system losses at the receiver and the transmitter. PL(d) is the path loss in dB at distance *d*. Channel model in 802.11ah case consists of outdoor and indoor scenarios. Outdoor channels typically experience higher delay spread than is typically occurring for indoor conditions.

#### A. Outdoor Path Loss Model

The path loss models for 802.11ah outdoor scenarios are based on [13] and include two options:

1) Macro Deployment: The antenna height is assumed 15m above rooftop and the path loss in dB is given by the formula:

$$PL(d) = 8 + 37.6 \log_{10}(d).$$
 (2)

2) Pico/Hot Zone Deployment: The antenna height is assumed at roof top level and the path loss is given by:

$$PL(d) = 23.3 + 37.6 \log_{10}(d), \tag{3}$$

where d is in meters and the RF carrier frequency is assumed to be at 900 MHz. For an other frequency f different than 900 MHz, a correction factor of  $21log_{10}(f/900)$  should be added.

### B. Indoor Path Loss Model

The 802.11ah indoor path loss model can be modelled by directly scaling down the frequency operation of the IEEE 802.11n (802.11n) [14] model which consists of the free space loss (slope of 2) up to a breakpoint distance  $d_{BP}$  and slope of 3.5 after the breakpoint distance. This is given in equations (4) and (5), respectively.

$$PL(d) = L_{FS} = 20 \log_{10}((4\pi df)/c) \quad for \quad d \le d_{BP},$$
(4)

$$PL(d) = L_{FS} + 3.5 \log_{10}(d/d_{BP}) \quad for \quad d > d_{BP},$$
(5)

where d, f and c are the transmit-receive separation distance in meters, carrier frequency (set to 900 MHz) and speed of light, respectively.

#### C. Shadowing and Fast Fading Effects

The above formulas (2-5) represent the median path loss. Deviations around this median to account for shadowing is typically modelled by adding a random Gaussian variable with zero mean and non-zero standard deviation. Equation (1) can be modified to include the shadowing effect. In the following, for the sake of simplicity we will neglect the losses  $L_{TX}$  and  $L_{RX}$ . The received power in dBm can be then given as follows:

$$P_{RX} = P_{TX} + G_{TX} - PL(d) + G_{RX} - \varphi_{dB}, \quad (6)$$

where  $\varphi_{dB}$  is the Gaussian distributed random variable with mean zero and variance  $\sigma^2_{\varphi_{dB}}$  accounting for shadowing effect. In the case of outdoor channel case, standard deviation of 8 dB for Macro deployments and 10 dB for Pico deployments are considered. For indoor channel case, variable standard deviation values are used depending of the breakpoint and the indoor channel model.

The combined effect of path loss and shadowing have some implications on the wireless system design. Typically in any wireless communication system, it is possible to define a target minimum received power level,  $P_{min}$ , below which the system performance becomes unacceptable. Usually the target  $P_{min}$  is assessed by the outage probability  $p_{out}(P_{min}, d)$  defined as the probability that the received power at a given distance d,  $P_{RX}(d)$ , falls below  $P_{min}$ . As can be noticed from (6) and because of the distribution of the shadowing, the

TABLE II Fade Margin for a Given Link Reliability: Outdoor Channel Case

Rel. in %	Macro Deployment		Pico/Zone Deployment	
	Shad.	Shad. + Fast Fad.	Shad.	Shad. + Fast Fad.
99.0	18.6	25.6	23.3	28.9
90.0	10.3	15.1	12.8	17.0
80.0	6.7	10.7	8.4	11.9
70.0	4.2	7.5	5.2	8.3
60.0	2.0	4.8	2.5	5.2
50.0	0.0	2.3	0.0	2.3

received power at any given distance from the transmitter is log-normally distributed. Therefore the outage probability can be easily evaluated by the following equation:

$$p_{out}(P_{min}, d) = p(P_{RX}(d) \le P_{min}) = 1 - Q\left(\frac{P_{min} - (P_{TX} + G_{TX} - PL(d) + G_{RX})}{\sigma_{\varphi_{dB}}}\right)$$
(7)

where Q-function is the complementary cumulative distribution function of a standardized normal zero mean, unit variance random variable. Knowing the target minimum received power level  $P_{min}$  at the output of the receiver antenna, we can then simply determine the outage probability. An outage probability of 1 % is a typical target in wireless system design.

In addition to the shadowing effect, and given the lognormally attenuated signal power at a given distance from the transmitter, the signal may experience fast fading in which the envelope of the signal is multiplied by a Rayleigh random variable accounting for the fast fading effect. The log-normally received signal power is multiplied by a fading factor that has unit mean and exponential distribution. In practice a positive fade margin (FM) in dB need to be guaranteed with respect to the target  $P_{min}$ . The FM at a given distance d can be defined as follows:

$$FM(dB) = P_{RX}(d) - P_{min}.$$
(8)

Using (7) and (8) we can determine the reliability of the wireless link, for a specified FM, i.e., the percentage likelihood that the FM is above a certain value for given channel scenario. In Table II, values of the FM need to be assured to guarantee a corresponding reliability link are shown. For example FM equal to 18.6 dB is needed to assure a reliable link 99% of the time when only shadowing is taken into account.

#### D. Achievable Data Rate

For the purposes of data and error rate analysis, the most important aspect of a given modulation technique is the Signal-to-Noise Ratio (SNR) necessary for a receiver to achieve a specified level of reliability in terms of bit error rate (BER). The  $E_b/No$  is a measure of the required energy per bit relative to the noise power

density. In order to convert from  $E_b/N_o$  to SNR, the data rate and system bandwidth must be taken into account as:

$$(S/N)_{dB} = (E_b/N_o)_{dB} + 10 \log_{10}(R/B),$$
 (9)

where S is the received signal power referred as  $P_{RX}$ in equation (1). Additionally, N is the received noise power and  $E_b$  is the energy required per information bit. Thermal noise power density is given by  $N_o$ , R is the bit rate and B the system bandwidth, respectively. In the following, the bandwidth will be set to 2 MHz. The received noise power, N, can be given as follows:

$$N = N_o B = k_b T_o F B, \tag{10}$$

where  $k_b$  is the Boltzmann's constant (Joule/Kelvin),  $T_o$  is the receiver temperature in Kelvins (K) typically set to  $T_o = 293$  K and F is the receiver noise figure (NF) in linear form.

Usually we set the target packet error rate (PER) for a given data packet length in bits L. For IoT use case we will assume that the target PER = 10% as generally set in the IEEE 802.11a standard. In order to convert PER to BER we can use the following equation,

$$PER = 1 - (1 - BER)^L.$$
 (11)

The above equation assumes implicitly that the errors within the packets are independent and are equally likely to occur. In AWGN channel, the BER perfromance of BPSK modulation is given [15] as follows:

$$BER = Q(\sqrt{2E_b/N_o}). \tag{12}$$

We can then find the corresponding BER and the required un-coded  $(E_b/No)_{dB}$  for a given modulation. If for example L = 4096\*8 bits then BER = 3.2e-06 and for BPSK,  $(E_b/No)_{dB} = 10$  dB. Substituting the corresponding value in equation (6), and using equation (1) to replace S by  $P_{RX}$  and taking into account the fade margin FM we have

$$R_{dB}(d) = P_{TX} + G_{TX} - PL(d) - FM(d) + G_{RX} - (E_b/N_o)_{dB} + N_o.$$
 (13)

Equation (13) finally relates the maximum bit rate that the system can achieve, the system parameters and the distance d in meters separating the transmitter and the receiver.

Typical 802.11ah parameters are shown in Table III, and used in the data rate assessment as depicted in Fig. 2. We considered both downlink (access point to user station) and uplink (user station to access point) cases. Consideration of both scenarios is motivated by the fact that the available transmit power and the antennas gains are relatively different when comparing the access point and the station. For example, the transmission power of the access point can be around 20-30 dBm, but for

TABLE III Typical IEEE 802.11ah Parameters

802.11ah parameters	Uplink	Downlink
Carrier Freq.	900 MHz	900 MHz
$P_{TX}(dBm)$	0	30
$G_{TX}(dBi)$	0	3
$G_{RX}(dBi)$	3	0
Noise Figure, F (dB)	3	5
Modulation	BPSK	BPSK
Packet size(bytes)	4096	4096
FadeMargin(dB): Macro/Pico	10.3/12.8	10.3/12.8
Uncoded EbNo@PER=10%	10 dB	10 dB
Coded EbNo@PER=10%	2 dB	2 dB



Fig. 2. 802.11ah uncoded bitrate for variable range: Outdoor channel scenario with uplik and downlink cases, both shadowing only and shadowing plus fast fading effects cases are considerd with fixed reliability of 90%, the packet size is 4 Kbytes.

a battery powered station targeted for long stand by times, transmission powers of 0dBm are expected. As mentioned in Section II, the target range and data rate of the 802.11ah are 1 km and larger than 100 kbps, respectively.

Fig. 2 shows the data rate that we can achieve versus range in meters for the 802.11ah parameters depicted in Table III. For downlink case, ranges above the required 1 km at data rate larger than 100 kbps can be achieved. However for the uplink case, and due to the limited transmit power, the required data rate can be achieved only for ranges smaller than 400 m. These ranges can be improved by considering coding. In 802.11ah system, as in 802.11ac, convolutional coding and LDPC are possible forward error correction (FEC) schemes. Due to the coding gain, the required  $E_b/N_o$  for a target PER of 10% can be decreased. In BPSK case, about 8 dB coding gain can be achieved with LPDC decoder when 1/2 code rate is used [17]. By taking this into account in equation (12), ranges for the uplink case can be improved by about 150 meters for data rate larger than 100 kbps. The achieved range is still under the 802.11ah requirement. In addition to FEC schemes, a



Fig. 3. 802.11ah coded bitrate for variable range: Outdoor channel scenario with uplink case, only shadowing effect is considered with variable link reliability, the packet size is 256 bytes.

repetition of two technique is also introduced in the robust 802.11ah mode, i.e., the BPSK with 1/2 code rate. The repetition of two scheme will provide optimally an extra 3 dB gain. Uplink range can still be improved by considering smaller packet size. For IoT sensors traffic model, packet size of 256 bytes is assumed. Additionally if link reliability smaller than 90% is allowed, smaller FM is then required and consequently larger coverage can be achieved. As depicted in Fig. 3, for link reliability smaller than 60% the required coverage of 1 km can be achieved even in the Uplink scenario. Clearly, reducing the reliability requirement will have a negative effect to the stations energy consumption. In the Fig. 2 and 3, only shadowing effects were considered. If fast fading is taking into account, higher transmit power and antennas gains need to be used in the 802.11ah transceiver. Fast fading effect caused by mobility of the terminal stations in the 802.11ah network and its effect on the packet size design is studied further in the next section.

#### E. Packet Size Design

Devices using 802.11ah radio technologies in an IoT or M2M networks can be static or mobile. In mobile radio environment, the received signal is characterized by rapid signal level fluctuations known as fast fading. Generally, these amplitude fluctuations are assumed to be Rayleigh-distributed causing the signal to fade [16]. The link performance deteriorates rapidly when the received signal level fades below some systemdetermined threshold or fade margin. The distribution of the temporal duration of these signal fades is thus useful in system design and evaluation, mainly when selecting the packet size. The packet need to be transmitted within the available transmit time duration, i.e., in those portion of the time where the received signal level is above



Fig. 4. Packet size design for variable Doppler frequencies: Outdoor channel with macro deployment, shadowing and fast fading are considered and corresponding link reliability is used as in Table II.

the system-determined threshold. Closed form formulas are available for the mean rate of occurrence or level crossing rate (LCR) of fades and for their mean duration or average fade duration (AFD) [16]. Here we will use these formulas to study the packet size versus the system mobility, usually characterized by Doppler frequency. In our case the carrier frequency is again  $f_c = 900$  MHz, the Doppler frequency,  $f_d$ , due to terminal mobility and the interference of the many scattered radio paths between the access point and the vicinity of the mobile station is assumed to be a variable parameter. Based on [16] the AFD,  $\eta$  and LCR,  $\zeta$  are given respectively as follows:

$$\eta = \frac{exp(\rho^2) - 1}{\rho f_d \sqrt{2\pi}},\tag{14}$$

$$\zeta = \frac{1 - exp(-\rho^2)}{\eta},\tag{15}$$

where  $\rho = \sqrt{2/FM_l}$ , and  $FM_l$  is the fade margin in linear form. The average available time for transmission is finally given in seconds as follows:

$$\tau_{TX} = \frac{1}{\zeta} - \eta. \tag{16}$$

Knowing the target data rate of the 802.11ah (100kbps), and the available time for transmission  $\tau_{TX}$  we can easily calculate the number of bytes needed for a packets. In Fig. 4 we show the packets size in bytes for variable Doppler frequencies. For example at  $f_d$ = 20 Hz, in Outdoor channel scenario with macro deployment, the packet size can be selected from about 200 bytes to 350 bytes depending on the link reliability.

#### **IV. CONCLUSIONS AND FUTURE DIRECTIONS**

In this paper, we studied the feasibility of the 802.11ah radio technology for IoT and M2M use cases. Based on the link budget assessment we showed that the .11ah technology can be used efficiently to establish reliable communication mainly in the downlink scenario. Some link budget limitations have been however noticed for the uplink case. Fortunately, if more transmit power and higher antenna gains are available, the uplink case can be also successfully established. We also proposed packet design in different channel scenarios when fast fading is mainly characterizing the system environment. In future work, we plan to study further the feasibility of the 802.11ah radio technology from the energy efficiency point of view as this feature is one of the core assumptions when designing IoT and M2M networks.

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