Power Budget for Wide Area Ambient Backscattering Communications

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***Abstract*—The objective of this article is to extend the range of Ambient Backscattering Communications (ABC). The ABC technology is a key enabling technology for Internet of Things (IoT) wireless communications. A rural open area towards Hanko, Finland is considered for the power budget calculations. FM radio waves are considered as the source of ambient RF waves as the FM radio waves have long communication range and the technology is readily available worldwide. The sensors are placed on a highway at an example distance of 30 km from the FM transmitter. There is a clear line of sight (LOS) connection between the FM transmitter and the sensors. The path loss is determined based on the sensor locations and the losses at the sensor occur due to diffraction and scattering. A power budget is calculated based on these aforementioned key system parameters. It is observed that there is around 44 dB of power margin available after the signal from the FM transmitter is backscattered (at the sensor) and the losses in the system are accounted for. This indicates that the receiver module is able to detect the signal as it is above the minimum reception level threshold for the system. Therefore, the radio waves are able to propagate further after the signal is backscattered at the sensor(s), utilizing the available power margin. Thus, the range of communication can be extended to a wider area.**

***Index Terms*—IoT, ABC, Power Budget, FM.**

I. Introduction

Ambient backscattering communications (ABC) is a relatively new wireless communication paradigm which enables devices to communicate by utilizing the energy from the ambient RF waves. These RF waves may be generated from a variety of sources such as television broadcasts, FM radio signals, cellular signals and wireless fidelity (WiFi) sources to name a few. The devices that enable ABC communications are small sensor-type elements which can power themselves with the ambient RF waves or be powered by an external source. By utilizing the ABC technology, battery-free devices can communicate between each other by using a technology which serves as the backbone of radio frequency identification (RFID) systems. This technology, termed as radio backscatter establishes communication by reflecting the RF waves. Radio backscatter was originally used during the second World War to determine the identity of different air-crafts. In 1948, Harry Stockman was the first researcher to publish a literature about backscatter communication [1].

Radio backscatter has been comprehensively studied during the last two decades. This was possible due to the fact that the cost of manufacturing integrated circuits (IC's) dropped drastically in the 1990s, leading to the mass development of the RFID technology and supporting devices. Research regarding the channel modelling [2], power budgets [3], coding methods [4] and multiple antennas [5] have been carried out for the RFID technology. Radio backscatter is thought of as a key enabling technology for the sensors used in the internet of things (IoT) wireless communications due to the very low power requirement and the relatively low cost of manufacturing such devices [6]. In classical backscatter systems, the reader radiates a carrier wave which is received by the sensor, relevant information is added and eventually backscattered to the reader. Therefore, systems operating with the classic radio backscatter principle suffer double the path loss. Additionally, RFID systems have very limited range (5-10 m) and the requirement of a dedicated reader has seen very restricted deployment of the technology. However, unlike the RFID technology, there is no requirement for a dedicated reader for devices utilizing the ABC technology.

The communication between two passive RFID sensors was first introduced in [7]. The tags communicate by modulating the field of the carrier signal. The backscattered signal is passed on to other tags which eventually decode the signal in order to retrieve the information [8]. According to Nikitin et al. [8], the strength of the carrier signal determines the passivity of the tag. Consequently, with ambient RF signals powering up the tags, the authors in [8] demonstrated a system where communication can take place between two passive/semi-passive tags.

The ABC concept was first introduced (in 2013) by the researchers in [9]. As part of their research, two devices can communicate between one another by utilizing energy from television broadcast signals. These signals provide the only source of power for these devices. They were able to achieve data rates of $1\,\mathrm{kbps}$ by utilizing their prototypes for ranges of $45.7\,\mathrm{cm}$ in indoor and $76.2\,\mathrm{cm}$ in outdoor environments respectively. [9] Ambient WiFi signals were used in [10] to establish a two-way communication between the sensors and the WiFi device. This two-way communication was realized by altering the channel state information (CSI) and the received signal strength indicator (RSSI) of the WiFi channel. Therefore, such sensors were able to connect to the internet by utilizing the ambient RF waves. Thus, data rates of $0.5\,\mathrm{kbps}$ in uplink and $20\,\mathrm{kbps}$ in downlink were obtained for ranges of $1\,\mathrm{m}$ and $2.2\,\mathrm{m}$, respectively. The throughput was significantly improved in [11] where data rates of $5\,\mathrm{Mbps}$ and $1\,\mathrm{Mbps}$ are obtained for ranges of $1\,\mathrm{m}$ and $5\,\mathrm{m}$ [11].

Previous research results on ABC have obtained very small communication distances after the signal is backscattered by the sensor element. The typical values from existing research indicate that the communication ranges vary from a few centimeters to tens of meters. The aim of this article is to propose an increase in the range of ABC for wide area environments. The FM radio technology is chosen as the source for ambient RF signals as the longer wavelengths of FM radio waves enable wide area communications. Moreover, there are extensive FM radio networks available in most countries as the FM technology is standardized all over the world. In this paper, the power budget for ABC using the FM radio technology for wide area networks is presented.

II. Theory

A. Ambient Backscattering Communications

ABC sensors works on the principle of transmitting '0' and '1' bits by switching the antenna impedance states [9]. This can be achieved by transitioning between the reflecting and non reflecting states of the antenna. Consequently, the passive sensors can backscatter their own information at lower data rates to enable the receiver from distinguishing between these conventional signals and the ambient signals [9]. The authors in [9] devised a prototype to show the bit-error rate (BER) with respect to the distance for two passive devices communicating using ambient backscatter. In [12], multiple antennas are utilized at the reader (backscatter receiver) in order to receive signals from the sensors. The authors of [12] demonstrate that the increase in the number of antennas at the reader helps in achieving a lower BER.

Contrary to traditional wireless communication systems that use radiation, the ambient RF signal propagates (after backscattering) to the receiver module after scattering or diffracting from the sensor. Sensors utilizing the ABC principle have the necessary hardware to utilize or harvest the energy from the signal from a variety of ambient RF sources. The harvesting of energy from ambient RF signals help in the utilization of sensors which are free from batteries. However, ABC can also be applicable for sensors utilizing an external power source. The deployment of such sensors will enable IoT where sensors will be located at a variety of locations. In IoT, devices are expected to communicate with each other in order to exchange vital information such as real time traffic and weather updates.

The source for the ambient RF signals used for this work are the FM radio waves. The FM radio technology operates in the frequency range of $88\,\mathrm{MHz}$ to $108\,\mathrm{MHz}$ of the electromagnetic spectrum. The radio waves at the $100\,\mathrm{MHz}$ frequency band are utilized for the example power budget calculations. The available bandwidth at $100\,\mathrm{MHz}$ is $1\,\mathrm{kHz}$. The low frequency of operation of FM is the primary reason for choosing this technology as the source for the ambient RF signals. Consequently, the longer wavelengths of FM radio waves help in achieving wider communication ranges as the radio signals are able to propagate for tens of kilometers.

Despite some obvious advantages, some challenges remain in establishing ABC. First of all, extracting the power (for communication) from the ambient RF signal and their subsequent utilization at the sensor will pose a challenge for researchers. Secondly, ABC differs from traditional communications by transmitting '0' and '1'. Therefore, the channels used for the backscattered signal in ABC need to be different in comparison with regular communication technologies. Thirdly, the receiver has to discern between the ambient RF signal and the backscattered signal since the physical properties of the two signals are very similar. Furthermore, the backscattered signal from the sensor will cause interference for traditional communication systems as the two signals possess identical physical properties. Thus, studies need to be carried out in order to determine how the interference to legacy systems can be mitigated. Finally, the dynamic range of the receiver generally indicates the ratio of the strongest and weakest signals that can be decoded by the receiver module. As the received signal strength of the direct signal is greater than the backscattered signal, the dynamic range of the system needs to be studied before the receiver modules for ABC are designed.

B. Environment for ABC wide area communications

Although the communication distances achieved in the existing research are impressive, they are limited to indoor environments and have restricted range in outdoor environments. The reason is that, energy harvested from the ambient RF signals were utilized as the only power source. Fig. 1 is an illustration of the example environment that has been considered for the purpose of this article which enables communications on a wider scale utilizing ABC.

The area considered as an example for the power budget calculation is located near the Hanko region of southern Finland. A FM radio tower is located in the suburb of Kivenlahti, Espoo which serves as the ambient source of signals. The FM transmitter (T_X antenna) is located at a height (h_t) of $248\,\mathrm{m}$. FM radio waves can

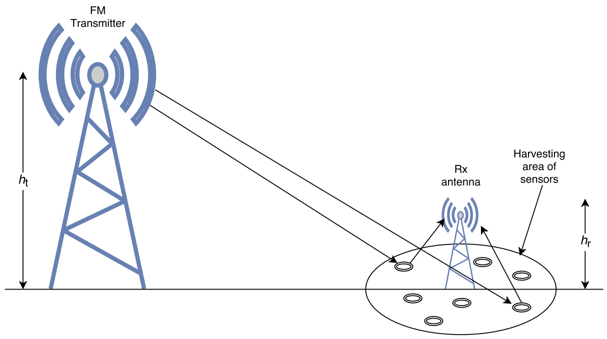

Fig. 1. Illustration of the propagation environment

Fig. 2. Propagation environment as shown in Google Maps.

propagate tens of kilometers due to their large wavelength and is therefore chosen as a source of ambient signals. The area towards Hanko is mainly a straight highway as is shown in the Google map view of the area in Fig. 2. The terrain is slightly undulating but there are no considerable losses due to this topography. There are also forests on both sides of the highway. However, there are adequate clearing of the forest on both sides of the highway. Furthermore, there are adequate arable lands located beside the highway which ensure a clear line of sight (LOS) connection between the T_{X} antenna and the sensors. The significant height of the FM radio tower helps in maintaining a LOS connection for most parts of the highway.

The area towards Hanko represents an open rural area and was selected because the propagation is excellent in this type of environment. Moreover, in order to maximize the range for the wide area communications, an environment like this is ideal. This is due to the fact that there is very little scope for interference in this type of environment. The sensors for the example power budget calculations are located on the highway 51 towards Hanko from Helsinki. The sensors are placed at some distance away from the FM radio tower at heights of approximately $1\,\mathrm{m}$ from the ground on top of dedicated poles (for sensors). In the example power budget calculations, the sensors are placed at a distance of 30 km from the T_{X} antenna. Although the FM radio technology enables the RF waves to travel nearly a hundred kilometers, the distance between the sensor and the T_{X} antenna is chosen in a cautious way so as to avoid an overestimation in the power budget calculations.

The receiver module (R_{X} antenna) is situated close to the sensor locations at a height of h_{r}. The available path loss after the signal is backscattered from the sensor helps to determine how far the signal is able to propagate. The sensors propagate the backscatterd signals towards the R_{X} antenna. The location of one or many sensors, propagating signals towards a R_{X} antenna can be termed as the harvesting area. The harvesting area is determined based on the location of the R_{X} antenna with respect to the position of the sensors. Therefore, the sensors can be placed in between the T_{X} antenna and R_{X} antenna and sometimes even beyond the R_{X} antenna as shown in Fig. 1, based on the use case.

III. Power budget

The power budget of a system represents the manner by which the total transmit power is utilized by different components that constitute the communication system. The target of the calculation is to indicate the total gains and losses in the system in order to illustrate the total power received at the R_{X} antenna. The calculation of the power budget is a very necessary segment of any wireless communication system design. As demographic and topographic features vary for different locations, radio propagation is also different for different environments. Therefore, to predict the coverage of the system and estimate the achievable data rates, it is crucial to represent the radio channel with respect to different key system parameters.

The power budget can be calculated based on the simple formula in (1). The transmit power (P_{Tx}) and the received power (P_{Rx}) are expressed in decibel-milliwatts (dBm). The system gains and losses are expressed in the decibel (dB) scale. The system gains are calculated based on the transmit and receive antenna gains. The system losses are due to the feeder and connector losses at the transmitter and receiver. The propagation losses arise from diffraction and scattering. Additionally, the attenuation of the signal varies as a function of distance between the T_{X} and R_{X} antenna.

$$P_{\mathrm{Rx}} = P_{\mathrm{Tx}} + gains - losses. \tag{1}$$

The effective radiated power (ERP) of the FM radio tower located in Kivenlahti is $60\,\mathrm{kW}$ or $77.78\,\mathrm{dBm}$ [13]. As an example, the sensors are placed at a distance of $30\,\mathrm{km}$ from the T_{X} antenna for the power budget calculations. The free space path loss (FSPL) [14] between the transmitter and the sensor is $102\,\mathrm{dB}$ as represented by the path loss graph in Fig. 3. The curve for the FSPL is calculated based on (2).

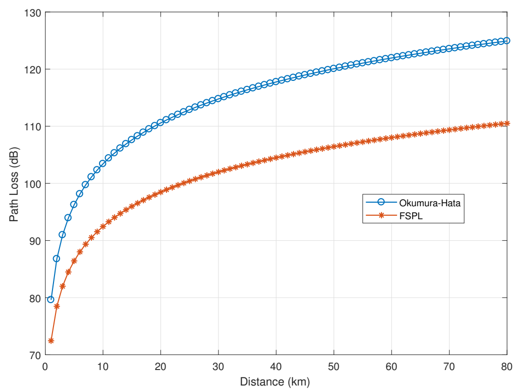

Fig. 3. Path loss

$$FSPL = 32.45 + 20 \cdot \log_{10}(d_{\text{km}}) + 20 \cdot \log_{10}(f_{\text{MHz}}). \quad (2)$$

The Okumura-Hata model [14] can be compared with the FSPL model in order to provide a more accurate or realistic estimation of the propagation between the FM transmitter and the sensor. This can be observed from the path loss graph in Fig. 3. Few parameters of the Okumura-Hata model may cause some negligible errors. For example, the range of transmit antenna heights specified for the Okumura-Hata model are in the range of $30\,\text{m}$ to $200\,\text{m}$. As the height of the transmit antenna is $248\,\text{m}$ in this work, it exceeds the upper bound of the specified range. Additionally, the lower range of the operating frequency for the Okumura-Hata model is in the range of $150\,\text{MHz}$ to $1000\,\text{MHz}$. Thus, some minor errors in the propagation may be observed as the frequency band used for the power budget calculations ($100\,\text{MHz}$) is below the lower bound of the operating frequency. The mathematical form of the model is represented in (3).

$$L = A + B \cdot \log_{10}(f_{\text{MHz}}) - 13.82 \cdot \log_{10}(h_{\text{t}}) - a(h_{\text{ms}}) + (C - 6.55 \cdot \log_{10}(h_{\text{t}})) \cdot \log_{10}(d_{\text{km}}) + C_{\text{m}}, \quad (3)$$

where $a(h_{\text{ms}})$ is calculated as,

$$a(h_{\text{ms}}) = (1.1 \cdot \log_{10}(f) - 0.7) \cdot h_{\text{r}} - (1.56 \cdot \log_{10}(f) - 0.8). \quad (4)$$

The path loss (L) from the Okumura-Hata model is calculated to be $114.8\,\text{dB}$ at a distance of $30\,\text{km}$ from the FM transmitter. The path loss curve for the Okumura-Hata model is displayed in the graph in Fig. 3. The model specific parameters, A and B are chosen to represent the low frequency of operation. The values selected for A and B are 69.55 and 26.16, respectively. The value of $a(h_{\text{ms}})$ is chosen to represent a small city. The value of C is 39.5 and is tuned to ensure the path loss exponent for the system is less than 2.5 (which represents rural area). The area correction factor (C_m) is set to $-10\,\text{dB}$ which is a very typical value for an open area. This is in coherence with the area considered in Hanko, Finland for the power budget calculations. The values selected for C and C_m are considered to be realistic or slightly even pessimistic.

TABLE I
RECEIVER SENSITIVITY PARAMETERS.

Parameter	Unit	Value
Boltzmann's Constant (k)	J/K	1.38×10^{-23}
Temperature (T)	K	290
Bandwidth (B)	kHz	1
Noise Figure (NF)	dB	10
Signal-to-Noise ratio (SNR)	dB	10

The sensitivity of the receiver is the minimum strength of the RF signal which can be decoded by the receiver module. Some different parameters play a key role in determining the sensitivity. The signal-to-noise ratio (SNR) and noise figure (NF) are some of the fundamental parameters that are utilized. Additionally, Boltzmann's constant (k), the temperature of operation (T) and the bandwidth (B) of the system are essential parameters used for calculating the minimum reception level of the system. The temperature of operation for the system is the room temperature or $290\,\text{K}$. The bandwidth of FM radio waves is $1\,\text{kHz}$. The values of the different parameters used for the calculation of the receiver sensitivity are summarized in Table I. The computation is performed based on the mathematical expression given in (5).

$$RX_{\text{sensitivity}}(\text{dBm}) = 10 \cdot \log_{10}(\frac{kTB}{0.001}) + NF + SNR. \quad (5)$$

The sensitivity of the receiver is calculated to be $-123.97\,\text{dBm}$. This value represents the minimum reception level of the system. Therefore, the signal can be decoded by the receiver module and the system can operate efficiently if the received signal strength is greater than $-123.97\,\text{dBm}$.

When the FM radio signal strikes the sensor, the signal gets split into different components which propagate to a variety of directions. This occurs due to diffraction and/or scattering. Therefore, the energy of the EM wave reduces after the signal is backscattered and subsequently propagates to the R_{X} antenna. Propagation losses due to diffraction and/or scattering at the sensor module add to the system losses and this adds up to approximately $30\,\text{dB}$. The power budget for the propagation from the transmitter to the sensor is calculated based on the aforementioned system parameters. The power budget of the system when the signal is backscattered (at the sensor) is presented in Table II.

Based on the power budget calculations there is approximately $55\,\text{dB}$ to $70\,\text{dB}$ of path loss available (Fig. 3) at the sensor location ($30\,\text{km}$) before the signal

TABLE II
POWER BUDGET.

	Parameter	Unit	Value
Transmission	Transmit power	dBm	77.78
Propagation Losses	FSPL/Okumura-Hata	dB	102/115.3
Sensor Losses	Diffraction/Scattering	dB	30
R_{X}	Receiver sensitivity	dBm	-123.97
Available Path Loss	FSPL/Okumura-Hata	dB	69.77/56.45

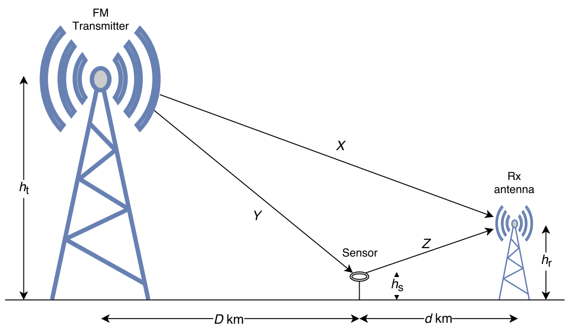

Fig. 4. Dynamic range

cannot be distinguished from the background noise. This is dependent on the minimum reception level of the system ($-123.97\,\mathrm{dBm}$). After the necessary information is added to the signal from the sensor, the backscattered signal can propagate to the R_{X} antenna. The available path loss (shown in Fig. 3) ensures that the signal is able to propagate to nearby R_{X} antennas. These R_{X} antennas are able to receive the backscattered signal from a variety of sensors located in their vicinity.

The signals follow two paths from the transmitter to the receiver module as illustrated in Fig. 4. The direct signal from the transmitter to the receiver module ('*X*') and the backscattered signal via the sensor ('*Y*') to the receiver ('*Z*'). The sensors are located at a distance of D kilometers from the T_{X} antenna with heights (h_s) from the ground. In the example power budget calculations, the value of D is $30\,\mathrm{km}$ and the value of h_s is $1\,\mathrm{m}$. The dynamic range of the system is defined as the ratio between the strongest and weakest signals measurable by the receiver module. This is a major parameter for the design of the receiver module. It is assumed to be $70\,\mathrm{dB}$ for the system used for the power budget calculations. Therefore, the difference in the received power levels of the two signals ('*X*' and '*YZ*') should not be more than $70\,\mathrm{dB}$. This enables the receiver module to distinguish between the two signals. The received signal strength of '*X*' at the R_{X} antenna, located at an example distance of $50\,\mathrm{km}$ (from the T_{X} antenna) is $-28.65\,\mathrm{dBm}$ (FSPL). '*X*' represents the strongest (direct) signal received by the R_{X} antenna. Consequently, the backscattered signal '*YZ*' can be detected by the R_{X} antenna if the received signal strength is greater than $-98.65\,\mathrm{dBm}$ (based on the FSPL model). In comparison with the minimum reception level of the system, the dynamic range of the system limits the available path loss for the transmission from the sensor to the R_{X} antenna. Therefore, the available path loss is reduced by approximately $25\,\mathrm{dB}$ after the dynamic range of the system is taken into account. Thus, the final available path loss is computed to be $44.43\,\mathrm{dB}$ for the FSPL model. So, the signal is able to propagate further to the R_{X} antenna if the power of the backscattered signal is greater than $-98.65\,\mathrm{dBm}$ (for an example distance of $50\,\mathrm{km}$). Furthermore, the communication links of d kilometers may be established between the sensor and R_{X} antenna based on the available path loss.

IV. CONCLUSION

ABC is considered as an enabling technology for IoT wireless communications. ABC utilizes ambient RF waves to provide power for the sensor-type devices or to simply assist in the forward propagation of the signal. The previous research on ABC have managed to accomplish communication distances of a few centimeters in indoor locations. In outdoor environments, the communication distances of tens of meters were achieved by researchers. In this article, the power budget for wide area communications using the ABC technology has been proposed. The FM radio waves at $100\,\mathrm{MHz}$ frequency, with a transmit power of $60\,\mathrm{kW}$ were utilized as the source of ambient RF waves. The sensors were placed at an example distance of $30\,\mathrm{km}$ from the transmitter on the highway which is primarily an open area. Thereafter, the power budget for the system was computed. Additionally, the dynamic range of the system limits the range of the backscatterd signal. It is observed that the reduction in the available path loss (due to the dynamic range) is approximately $25\,\mathrm{dB}$. After the signal is backscattered and additional losses (at the sensor module) are accounted for, there is around $44.43\,\mathrm{dB}$ of available path loss for the communication from the sensor to the R_{X} antenna. Therefore, the radio wave can propagate to the R_{X} antenna after diffracting or scattering from the sensor. Many such sensors located in the vicinity of the R_{X} antenna can propagate their signals to the receiver for signal detection keeping the dynamic range of the system in mind. In the future studies, the measurements will be performed in the real environment and based on the analysis of the results the propagation from the sensor to the receiver will be studied.

ACKNOWLEDGMENT

The authors would like to thank the Academy of Finland and European Communications Engineering (ECE) Ltd for supporting this research work.

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