Evaluation of Maximum Range for Backscattering Communications Utilising Ambient FM radio signals

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***Abstract*—The objective of this article is to evaluate the maximum range of ambient backscattering communications (AmBC). FM radio signals operating at 100 MHz are selected as the ambient signal due to their large communication ranges. The FM radio signals operate in one of the lowest commercially available frequency bands that can be utilized for AmBC. Additionally, due to the extensive deployment of FM radio, this technology is readily available worldwide. Simulations are performed in a rural highway environment to analyse the suitability of FM radio as an ambient signal for backscattering communications. The FM transmitter and receiver antenna are located in approximately the same area representing a mono-static form of operation for backscattering communications. The sensors are located in more or less the line of sight (LOS) of the TX/RX antenna. The FM signal is reflected back from the sensor towards the receiver for detection. The ray-tracing technique and the radar equation are utilized to perform the simulations. Based on the ray-tracing simulations, a distance of 14.5 km was obtained between the TX/RX antenna and the sensor. The achievable distances utilising the radar equation depend significantly on the cross-section of the sensor and different sizes were utilised in the simulations.**

***Index Terms*—IoT, AmBC, FM, Sensor, RCS**

I. Introduction

Ambient backscattering communications (AmBC) is a wireless communication technology which utilises ambient RF signals to establish communication between devices. These ambient RF signals can originate from a variety of sources and some environments have a larger number of ambient signals than others. For example, in urban areas, ambient signals such as television broadcasts, FM radio signals, WLAN signals and cellular signals are predominantly found. However, in rural environments, there are significantly less number of ambient RF signals and those are restricted to only low frequency FM radio and television broadcast signals and intermittent cellular signals. AmBC is envisioned by researchers as a key technology for the internet of things (IoT) wireless communications. This is due to the fact that energy from the signals can be collected by the sensors utilizing the AmBC technology [1].

Sensors located in very secluded places are envisioned to be one of the key use cases of the AmBC technology. Additionally, as energy can be harvested from ambient RF signals, the AmBC technology can provide coverage to sensors located in places where maintenance is very difficult or not possible [2]. For example, sensors can be located inside walls of buildings to monitor various parameters. The installation of these sensors are integrated with the building construction, so changing batteries may prove to be difficult or even impossible once deployed. Therefore, in some cases these devices maybe permanently left inside the walls. Furthermore, the sensors may be deployed in remote locations such as in agriculture fields, highways and mountain villages to monitor environmental changes and other parameters as a result of climate change. Therefore, regular maintenance may prove to be a stumbling block as it may be very difficult and cumbersome to replace the batteries of the sensors in these locations. The AmBC technology eliminates the need for the periodic maintenance of these sensors by collecting energy from ambient RF signals [2]. This enables battery free and wireless operation of the sensors.

Radio backscatter is the fundamental backbone technology of ambient backscattering communications. The reflection of RF signals from different objects towards a receiver is the key operating principle of the radio backscatter technology. During the second world war, the radio backscatter technology was utilized to determine the identity of friendly or hostile air-crafts. The first article on radio backscatter was published by Harry Stockman in 1948 [3]. Radio frequency identification (RFID) technology works on the principle of radio backscatter. The signals are generated from a device and transmitted towards a sensor. After reflection from the sensor the signals are received and decoded by the same device [4]. RFID technology has its applications in areas such as identification and near field communication (NFC) payments. The research and development of RFID technology accelerated after the 1990s due to the reduction in cost of manufacturing sensors and readers [5].

Ambient television broadcast signals were utilised by the authors of [1] to power AmBC sensors. They were able to achieve communication distances of $0.46\,\mathrm{m}$ and $0.76\,\mathrm{m}$ in indoor and outdoor environments, respectively [1]. Data rates of $1\,\mathrm{kbps}$ were achieved for these ranges [1]. The throughput improved to a certain extent when WLAN was utilized as the ambient signal [6]. Two way communication was achieved between two tags by modifying the channel state information (CSI) and the received signal strength indicator (RSSI) of the WLAN signal [6]. Communication distances of $1\,\mathrm{m}$ and $2.2\,\mathrm{m}$ were achieved in indoor and outdoor environments with a maximum data rate of $0.5\,\mathrm{kbps}$. The throughput significantly improved in [7], as data rates of $1\,\mathrm{Mbps}$ were achieved for $5\,\mathrm{m}$ and $5\,\mathrm{Mbps}$ for $1\,\mathrm{m}$, respectively.

The purpose of this paper is to evaluate the maximum range of AmBC. Due to the extensive worldwide availability and deployment, FM radio is selected as the preferred source of ambient RF signals. Additionally, the coverage area of FM radio signals is greater than conventional cellular systems or television broadcast signals as they operate at very low frequencies (between $88\,\mathrm{MHz}$ to $108\,\mathrm{MHz}$). FM radio signals operating at $100\,\mathrm{MHz}$ are used in the simulations. A rural highway (highway number 51) near Helsinki in southern Finland is chosen as the environment for the simulations as this area is generally free of significant obstacles and other interference. This ensures a more or less clear line of sight (LOS) path between the TX antenna and the sensors.

II. Ambient Backscattering Communications

AmBC is a wireless communication paradigm which works on the principle of energy and/or signal collection from ambient RF signals. These signals originate from a variety of sources such as television broadcasts, FM radio, cellular and WLAN signals to name a few. AmBC utilizes small devices (sensors) which have the necessary hardware to collect the energy from the ambient RF signals. The harvesting of the energy from the ambient RF signals enables wireless and battery free operation of the sensor.

Ambient backscatter is one of the three categories of backscatter systems [8]. Mono-static backscatter systems generate RF signals which are reflected back from a sensor for detection [8]. RFID is a typical example of a mono-static backscatter system. As the reader and the sensor needs to be in close proximity of each other, the range of operation is a limitation of mono-static backscatter systems. In bi-static backscatter systems, a carrier emitter generates the RF signals. The carrier emitter is located centrally (or, in different locations) and the sensors are placed within the coverage area of the carrier emitter. The signals generated by the carrier emitter are backscattered by the tags to a dedicated reader. The generation of a dedicated signal from the carrier emitter is a disadvantage of bi-static backscatter systems [9].

Ambient backscattering communications utilise ambient RF signals for its operation. Thus, a dedicated signal does not have to be generated. Furthermore, the utilization of low-frequency ambient signals overcomes the restriction of limited achievable communication range. In contrast to traditional wireless communication systems, AmBC operates by reflecting the ambient RF waves towards the receiver [2]. This operation is performed after the required information is added to the signal.

AmBC systems operate by transmitting '0' and '1' from the sensors by switching between the reflecting and non-reflecting states [1]. This functionality is achieved by modifying the electrical properties of the sensor. The receiver is able to distinguish the backscattered signals as they are transmitted at a lower data rate in comparison to traditional signals [1]. The authors in [1] also developed a prototype to demonstrate the bit-error rate (BER) in comparison with the distance between two passive AmBC sensors. The utilization of multiple antennas at the receiver helped in achieving a lower BER [10].

AmBC has certain disadvantages that needs to be addressed before this technology can be extensively deployed. Firstly, the receiver has to be able to distinguish between the traditional and the backscattered signals. Additionally, as the operating principle of AmBC is different in comparison with traditional wireless communications, separate channels for communication needs to be defined. Finally, the technology through which the energy and/or signal is harvested from ambient RF signals needs to be further developed in order to achieve seamless operation of the AmBC technology.

III. Propagation Models

The maximum achievable range of AmBC is analysed with the help of simulations. The ray-tracing technique and the radar equation are used for the simulations to investigate the feasibility of the approach.

A. Ray-tracing

The ray-tracing technique is based on the detailed simulation of the entire propagation environment. The simulations are performed based on the path each individual signal travels between the transmitter and the sensor. If there are obstructions such as trees or buildings between the transmitter and the sensor then each individual signal is divided into line-of-sight (LOS) links. The free space path loss (FSPL) equation is utilized in order to calculate the path loss encountered for each LOS link of the signal. The FSPL is calculated based on eq. 1 where "d" represents the distance in kilometers and "f" represents the operating frequency in megahertz (MHz).

$$FSPL = 32.45 + 20 \cdot \log_{10}(d_{\mathrm{km}}) + 20 \cdot \log_{10}(f_{\mathrm{MHz}}). \quad (1)$$

The signal may also have a variety of multi-path components between the transmitter and the receiver. Each individual signal may experience reflection, scattering or diffraction from various objects in the environment while propagating from the transmitter to the sensor. Additional losses are factored in the simulations to account for the losses caused due to any such phenomenon. However, the environment and the location of the sensor and the receiver (with respect to the transmitter) has an important role in determining the strength of the multi-path components. In this work, the sensors are assumed to be in more or less the direct LOS of the TX/RX antenna.

B. Radar Equation

The total range of communication can also be calculated utilizing the radar equation. The operating principle of the radar equation is based on the reflection of the transmitted signal from a target (or, sensor) towards the receiver. The location of the TX and RX antenna determines the type of radar system. In mono-static radar, the TX and RX antenna are co-located. For bi-static radar systems, the TX and RX

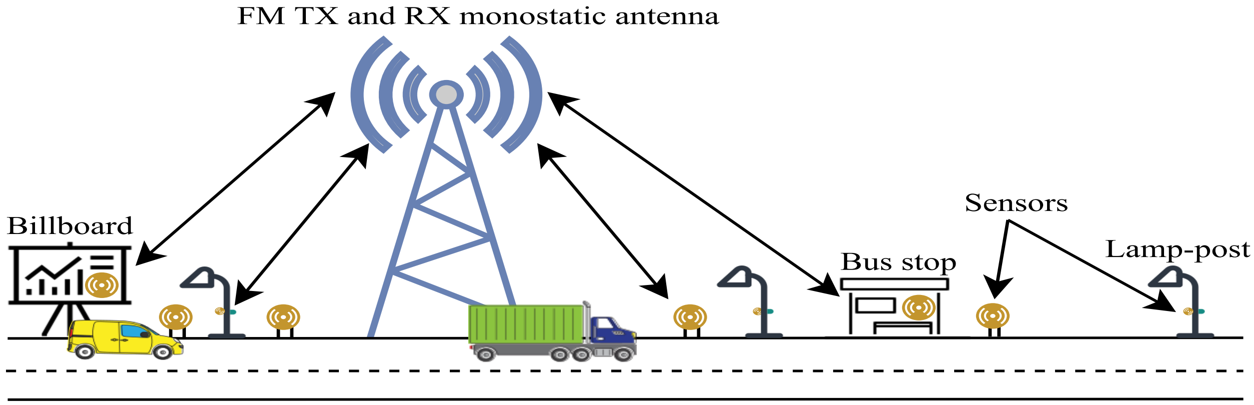

Fig. 1. Illustration of the deployment scenarios for AmBC sensors in rural highway environment.

antenna are located at different positions. The simulations in this work are performed using mono-static radar systems.

The radar equation (for mono-static systems) in represented by eq. 2. The range of the radar is represented in kilometers. In bi-static radar, the range term (R) in eq. 2 is divided into two parts to represent the distance between the transmitter and sensor (R_t) and the distance between the sensor and the receiver (R_r). For the mono-static operation of radar systems, the range terms R_t and R_r are equal and combined into R.

$$R = \sqrt[4]{\frac{P_t G_t G_r \lambda^2 \sigma}{(4\pi)^3 P_r L}}. \tag{2}$$

In eq. 2, P_t represents the power of the transmitted signal and P_r represents the power of the received signal. The units for both these terms is watts (W). The wavelength (in meters) of the signal is represented by λ. The G_t and G_r represent the antenna gains for the TX and RX antenna, respectively. The parameter L factors in the additional loss of the system. The radar cross section (RCS, σ) is expressed in square meters and is the sensor from where the ambient signal is reflected back to the RX antenna. In [11], σ is considered as a half-dipole antenna and is represented by the formula in eq. 3.

$$\sigma = 0.88 \times \lambda^2. \tag{3}$$

In the simulations, different values are considered for σ to compare how the cross-section of the sensor affects the achievable range of communication. Moreover, the cross section of the sensor in comparison to the wavelength of the signal has a significant role in determining if scattering or reflection occurs at the sensor [12]. The value of x in eq. 4 determines the phenomenon happening at the sensor.

$$x = (\frac{2\pi r}{\lambda}), \tag{4}$$

where r represents the size of the sensor and λ represents the wavelength of the signal. If the value of $x < 1$, the signal is scattered at the sensor. A clear reflection happens when the value of $x > 1$. [12]

IV. Simulation Setup

A. Simulation environment

The simulations in this work are performed beside a rural highway as shown in Fig. 1. This type of environment helps in determining the maximum achievable range of communication due to the absence of significant obstacles such as multi-storied buildings. The map of the simulation environment is obtained from Google Maps and is shown in Fig. 2. Highway 51 is mainly a straight highway and the area (beside the highway) is clear of obstacles and consist of mainly arable lands. This area is located towards the direction of Hanko in southern Helsinki, Finland. The FM TX antenna is located in the suburb of Kivenlahti and there is almost a clear LOS to highway 51. The minor obstructions are due to tree foliage located beside the highway. The typical effective isotropic radiated power (EIRP) of this FM radio TX antenna is $60\,\mathrm{kW}$ or $77.78\,\mathrm{dBm}$ [13].

The FM radio TX antenna at Kivenlahti is at a height of 248 meters. The receiver is assumed to be co-located with the FM TX antenna in approximately the same area. The ambient FM radio signals are reflected back to the receiver from the sensors. The schematic diagram of the simulation environment is illustrated in Fig. 1. The sensors are located in more or less the LOS of the TX/RX beside the highway to monitor different parameters as shown in Fig. 1. For example, the sensors can be utilized to determine the number of vehicles passing through a certain point for traffic monitoring. Additionally, some sensors installed on lamp-posts can also be utilized to determine the level of snow on highways by measuring the depth. Furthermore, sensors can be deployed on the walls of bus stops or on billboards to monitor different parameters. The deployment scenarios for AmBC sensors are shown in Fig. 1.

B. Simulation parameters

The ray-tracing technique and the radar equation are utilized to determine the maximum achievable communication range between the TX/RX antenna and the sensor after the signal impinges on it. Consequently, the noise floor

Fig. 2. Propagation environment from Google Maps.

(or, the receiver sensitivity) of the system is calculated to determine the maximum achievable range of communication. The noise floor gives an indication of the signal level that can be decoded by the receiver and is calculated based on eq. 5. The parameters represent the typical values used for the noise floor calculation for FM radio systems. The Boltzmann constant (k) is 1.38×10^{-23} J/K and the operating temperature (T) is $290\,\mathrm{K}$. The bandwidth (B) is $1\,\mathrm{kHz}$ and represents the standard bandwidth for FM radio signals.

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

The receiver sensitivity (P_{r}) of the system is calculated to be $-123.97\,\mathrm{dBm}$ utilising eq. 5. The noise figure (NF) is $10\,\mathrm{dB}$ and the signal to noise ratio (SNR) is $10\,\mathrm{dB}$. Therefore, if the power of the backscattered signal is higher than the noise floor, the signal can be decoded by the RX antenna. The value of the receiver sensitivity is utilised as an input parameter for the received power (P_r) term in eq. 2. This helps to determine the maximum achievable communication range by using the radar equation. Moreover, based on the EIRP of the FM radio tower ($77.78\,\mathrm{dBm}$) and the receiver sensitivity ($-123.97\,\mathrm{dBm}$), the total available path loss for the system is $201.75\,\mathrm{dB}$.

In the ray-tracing approach, the path loss in the LOS links between the TX and the sensor is calculated based on eq. 1. Consequently, based on the principle of reciprocity, the path loss between the sensor and the RX has the same value. The total available path loss provides an estimation of the maximum achievable distance the signal can travel between the TX/RX and the sensor.

Furthermore, losses are experienced in the system due to the obstruction of the Fresnel zone (due to the close proximity of the sensor to the ground) and the reflection loss that is experienced at the sensor. An additional loss (L) of $10\,\mathrm{dB}$ is accounted for in the simulations. The simulation parameters are summarized in Table I.

V. Results and Analysis

The maximum achievable range of communication between the TX/RX antenna and the sensor is calculated utilizing the ray-tracing technique and radar equation.

TABLE I
Simulation parameters.

Parameters	Unit	Value
Frequency	MHz	100
FM TX EIRP	kW	60
TX antenna height	m	248
Temperature (T)	K	290
Bandwidth (B)	kHz	1
Noise figure (NF)	dB	10
Signal-to-noise ratio (SNR)	dB	10
Additional loss	dB	10

The ray-tracing technique provides an optimistic value for the maximum achievable communication range as the size of the sensor is not factored in the calculations. The total available path loss for round trip communication between TX-sensor-RX is $201.75\,\mathrm{dB}$. After the additional loss ($10\,\mathrm{dB}$) is factored in, the available path loss decreases to $191.75\,\mathrm{dB}$. Thus, for one-way communication between the TX-sensor (or, sensor-RX), the total available path loss is $95.87\,\mathrm{dB}$. Therefore, a maximum distance of $14.5\,\mathrm{km}$ in one direction can be achieved and the signal experiences a path loss of $95.67\,\mathrm{dB}$ at this distance. Consequently, based on the principle of reciprocity, a maximum round trip communication range of $29\,\mathrm{km}$ can be achieved. This distance represents the longest achievable range of communication where the sensor is located $14.5\,\mathrm{km}$ from the TX/RX antenna.

The range of the radar equation is calculated utilizing eq. 2 and represents the total range of communication (between the TX-sensor and sensor-RX). In the simulations, the size of the cross-section of the sensor (σ) is altered to observe the change in the achievable range. The size of the sensors utilized for IoT wireless communications varies based on the use case.

The sensor size of $0.001\,\mathrm{m}^2$ ($3\,\mathrm{cm}\times 3\,\mathrm{cm}$) represents the worst case scenario. It is observed that the total communication range achieved with such sensor sizes is about $2.8\,\mathrm{km}$. Sensors with such a small cross section may be difficult to locate and can be placed $1.4\,\mathrm{km}$ from the TX/RX antenna. A distance of $2.5\,\mathrm{km}$ is achievable between the TX/RX and the sensor having a cross section of $10\,\mathrm{cm}\times 10\,\mathrm{cm}$ ($0.01\,\mathrm{m}^2$). A distance of $5.1\,\mathrm{km}$ can be achieved when the size of the sensor is $0.16\,\mathrm{m}^2$ ($40\,\mathrm{cm}\times 40\,\mathrm{cm}$). The distance increases to $5.9\,\mathrm{km}$ when the size of the sensor is $0.3\,\mathrm{m}^2$ ($54\,\mathrm{cm}\times 54\,\mathrm{cm}$). Furthermore, when the cross section of the sensor is increased to $0.7\,\mathrm{m}^2$ ($83\,\mathrm{cm}\times 83\,\mathrm{cm}$) the achievable distance increases to $7.38\,\mathrm{km}$. A radar cross section of $7.92\,\mathrm{m}^2$ ($2.8\,\mathrm{m}\times 2.8\,\mathrm{m}$) is calculated based on the eq. 3 and represents a half dipole antenna for the intended carrier frequency [11]. The achievable distance utilizing such a sensor is $13.5\,\mathrm{km}$. The different values utilized for σ and their corresponding distances are summarised in Table II.

It is observed that with the increase in the cross section of σ the communication range increases as there is more area available for the ambient FM radio signal to reflect back from. Additionally, a study is also carried out to determine

TABLE II
DIFFERENT DISTANCES FOR AMBC WITH RT AND RE PROPAGATION MODELS.

Propagation model	RCS (σ, m^2)	Distance between TX/ RX and sensor (km)	Total distance (km)
Ray-tracing	-	14.5	29
Radar equation	0.001	1.43	2.87
	0.01	2.55	5.10
	0.16	5.10	10.21
	0.3	5.97	11.94
	0.7	7.38	14.76
	7.92	13.54	27.08

how the additional loss affects the range of communication. A graph illustrating the different communication ranges for different cross section of σ is shown in Fig. 3. Additional loss values of $10\,\mathrm{dB}$ to $30\,\mathrm{dB}$ are utilized to observe how the communication range is affected. It is observed that with the increase in the additional loss, the range of communication reduces for different σ sizes.

The value of x in eq. 4 determines the boundary condition for scattering or reflection to occur after the signal impinges on the sensor. The minimum required cross section of the sensor is $47\,\mathrm{cm}\times 47\,\mathrm{cm}$ for the ambient signal to reflect towards the RX antenna. Sensors with a smaller cross section cannot be utilised as the ambient FM radio signal will scatter instead of reflecting. Therefore, only sensors having a cross section greater than $47\,\mathrm{cm}\times 47\,\mathrm{cm}$ (or, $0.22\,\mathrm{m}^2$) can be utilised to determine the maximum achievable range of communication.

VI. CONCLUSION

The purpose of this article was to evaluate the maximum range of mono-static AmBC technology. A rural highway near Helsinki in southern Finland was chosen as the environment where the simulations were performed. The AmBC sensors were deployed beside the highway for monitoring different parameters in more or less the LOS of the FM TX antenna in Kivenlahti. The selected area is free of obstacles and therefore, the amount of interference is least in such an environment. The ambient FM radio signals (at $100\,\mathrm{MHz}$ frequency) were utilised in the simulations. Two propagation models, the ray-tracing technique and the radar equation were utilized to perform the simulations. It was observed that utilising the ray-tracing technique the sensors could be deployed $14.5\,\mathrm{km}$ from the TX/RX antenna. Utilising a mono-static radar, it was observed that the sensor could be located $5.9\,\mathrm{km}$ from the TX/RX antenna for sensor sizes of $54\,\mathrm{cm}\times 54\,\mathrm{cm}$. Sensors of such cross sections can be deployed in billboards or bus-stops located beside the highway. A significant limiting factor for reflection to occur is based on the cross section of the sensor in comparison with the wavelength of the ambient signal. Consequently, for reflection of the ambient FM radio signals, the cross section of the sensor has to be a a minimum of $47\,\mathrm{cm}\times 47\,\mathrm{cm}$. Therefore, the size of the sensor has an essential role in the achievable range of communication. Furthermore, it can

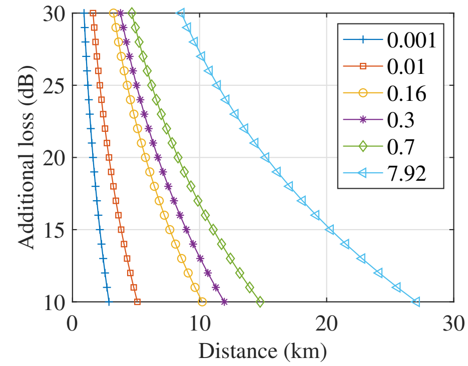

Fig. 3. Achievable distances for different additional losses for varying RCS (σ).

be inferred that the achievable range utilising the radar equation is more realistic in comparison with the ray-tracing technique as the cross section of the sensor is factored in the simulations. Also, it was observed that the communication range decreases with the increase in the additional loss. In conclusion, ambient FM radio signals could offer a wide range of opportunities for monitoring purposes in rural or highway areas utilising the AmBC technology.

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