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Does Ambient Backscatter Communication Need Additional Regulations?

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Abstract—Ambient Backscatter Communication (AmBC) is an emerging ultra-low power communication scheme which enables smart devices to communicate by modulating ambient radio frequency (RF) signals without requiring active RF transmission. AmBC can be interpreted as a spectrum sharing system that AmBC devices share the spectrum with the incumbent wireless broadcast systems. In this paper, we study the impact of AmBC from the incumbent receiver perspective since AmBC introduces a new situation for regulators. In the analysis, we consider a generic Orthogonal Frequency Division Multiplexing based broadcast broadcast system that corresponds to digital audio or video broadcasting or downlink of a mobile communication system. Broadcasting spectrum can be used by unlicensed transmitters in television white space framework. Contrary to the television white space transmitters that always cause interference to the incumbent system, the impact of AmBC depends on the equalization interval of the receiver. The incumbent receiver sees an AmBC device as an additional fast fading multi-path component. AmBC can sometimes even contribute positively to the received signal quality. Our results suggest that in many practical scenarios AmBC systems can co-exist with digital broadcast systems without causing harmful interference.

Index Terms—Ambient backscatter communication, broadcast systems, interference, spectrum sharing

I. INTRODUCTION

The availability of energy has been one of the limiting factors of connecting things to the Internet using wireless technologies. Backscatter communication, e.g., radio-frequency identification, has become a solution that tags have no active radio frequency (RF) components, where the tags modulate their information onto a carrier generated by a reader, and the reader decodes the modulated information [1]. Although circuit power consumption can still be a serious problem in practice [2], [3], it is nevertheless much smaller than in case of active transmitters [4]. As an emerging new ultra-low power communication scheme, Ambient Backscatter Communication (AmBC) enables smart devices to communicate by utilizing ambient RF signals, which is first introduced in [5]. AmBC devices can be powered by the ambient RF signals including, for instance, digital television (DTV) [5], [6], cellular [6], [7], radio broadcast systems [8], [9], Bluetooth [10], [11], and WiFi [12]–[15]. AmBC offers a considerably more energy-efficient and increasingly practical alternative to active radio circuits on existing sensor systems [5], [16]. With proper designs, AmBC can also be seen as a means of improving the spectral

efficiency of the channel as the AmBC link can co-exist with the other wireless system with negligible interference as shown in [17], [18].

AmBC operates similarly to passive repeater that changes the signal reflection coefficient. The simplest form of a passive repeater consists of two directed antennas connected through coaxial cable. The passive repeater can be translated to an AmBC device by connecting the two antennas to each other through an RF switch or a controllable phase shifter. An AmBC device can also be built using single antenna connected to a controllable load. The simplest AmBC system performs on-off keying (OOK) by connecting the antenna either to a load impedance ("off" state) or short circuit ("on" state). The three discussed antenna configurations are shown in Fig. 1. In the off state, the AmBC antenna absorbs the RF energy which can be used, e.g. by an energy harvester, and in the on state the antenna is reflecting the received RF energy. More complicated designs are possible to achieve phase modulation, pulse amplitude modulation or even frequency modulation.

From an incumbent receiver perspective, the AmBC device modulated scattered signal paths appear as additional fast fading multipath components. The "fading" characteristics of that path depend on the modulation scheme utilized by the AmBC. If the incumbent receiver is not able to cope with fast fading the AmBC devices increase incumbent signal interference level. Some AmBC systems seek to use frequency modulation technique to shift the scattered signal away from the original signal band to avoid interference, such as [8], [19], [20]. This is possible if there exists an empty band adjacent to the signal band. In the OOK modulation case, significant portion of the scattered signal components still lay on the signal band. If the AmBC symbol duration is long and the propagation delay is short compared to the equalization interval length of the incumbent Orthogonal Frequency Division Multiplexing (OFDM) system, the receiver is able to track the channel variations and the AmBC can share the spectrum with the legacy system without causing any interference. If, on the other hand, the AmBC symbol duration is short, the equalizer at the incumbent receiver is not able to track the channel variations caused by the AmBC device, and the scattered signal components appear as interference (increased channel estimation error).

In most countries, passive repeaters are allowed to be

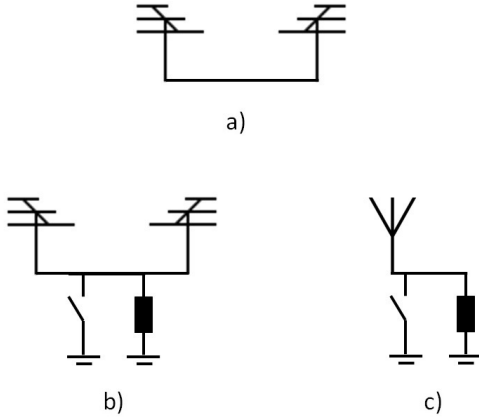


Fig. 1. a) Passive repeater; b) Passive repeater converted to AmBC device; c) Single-antenna AmBC device.

freely installed to enhance the coverage of wireless systems. However, AmBC modulates the signal. In addition, the Federal Communications Commission (FCC) in the United States allows low-power transmitters to operate without requiring a license in the amplitude modulation (AM), frequency modulation (FM), and TV broadcast bands [21]. AmBC introduces a new situation for regulators. AmBC is not traditional repeater but it also does not use any transmission power. How and whether such system has to be regulated depends on the interference conditions it generates to incumbent systems. Several works have been attempting to analyze the interference to the legacy systems. The interference analysis for AmBC on an existing system was conducted in [22] with respect to the bit error rate of the considered legacy system that the compound channel state information at the legacy receiver affects the effective interference range. The work in [23] studied a cognitive AmBC spectrum sharing paradigm. However, the interference to the legacy receiver was omitted. Based on stochastic geometry, [24] analyzed the coverage probability and achievable rate for both legacy and backscatter systems. Assumed that the channel state information is known, [25] proposed a spectrum sharing model for wireless-powered Internet of Things (IoT) devices with ambient backscatter communication capabilities such that the transmit power of the legacy transmitter and the reflection coefficient of the backscatter device are jointly optimized.

In this paper, we analyze the impact of the AmBC system sharing the bands with the OFDM broadcast system, for instance, DVB-T2, from the incumbent receiver perspective. Our analysis suggests that in case of fixed television reception, the impact of AmBC is negligible. In portable and mobile reception cases, the AmBC can cause harmful interference to the incumbent if the distance between the AmBC antenna and receiver antenna is short. Our results indicate that in many practical deployments, the scattered signal paths caused by the AmBC devices have several orders of magnitude smaller power. Hence, the tentative answer to our question, "Does

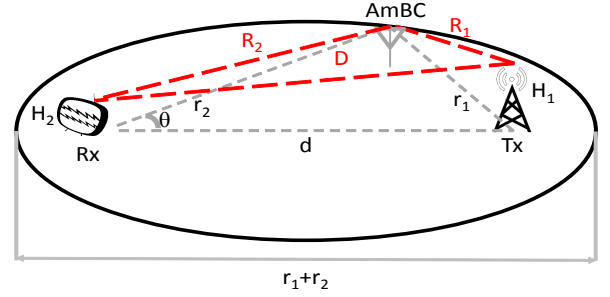


Fig. 2. System deployment.

AmBC need additional regulations?", seems to be that it does not need to be regulated. In fact regulating AmBC might be difficult as the devices do not actively transmit and no other multi-path components can be regulated anyway no matter how severe fading they cause.

The remainder of this paper is organized as follows. Sec. II presents the system model. We analyze the interference to the legacy system generated by AmBC in Sec. III. Simulated results are then presented in Sec. IV. The last section concludes this paper.

II. SYSTEM

We consider an OFDM-based broadcast system, for instance, DVB-T2, sharing the frequency band with an AmBC system shown in Fig. 2. The pilot structure and equalization method used by the OFDM receiver define the equalization interval \mathcal{E} , which is also called "equalization window". Thus a multipath component having arrival time $t \in \mathcal{E}$ can be at least partly utilized by the receiver. The useful signal power from the multipath components at the receiver can be expressed as [26, pp. 47]¹:

$$C = \sum_k w_k C_k,$$

where C_0 denotes the direct path, subscript k denotes the k -th signal at the receiver input, and w_k is a positive weight factor given by

$$w_k = \begin{cases} 0, & t \notin \mathcal{E}, \\ \frac{T_u+t}{T_u}, & t \in \mathcal{E}, t < 0, \\ 1, & t \in \mathcal{E}, 0 \leq t \leq T_g, \\ \frac{T_u+T_g-t}{T_u}, & t \in \mathcal{E}, t > T_g. \end{cases}$$

Parameters T_u and T_g denote the useful symbol time and the guard time, respectively. If a multipath component is not within the guard interval, then part of it constitutes interference due to channel estimation error:

$$I = \sum_k (1 - w_k) C_k.$$

¹We maintain the same notations used in [26].

AmBC devices appear as components generating additional multipaths. If the AmBC symbol duration is short, the equalizer is not able to track them and $w_k = 0$. That is, the AmBC-induced signal paths appear as additional interference. If the AmBC symbol duration is in the same order of magnitude as the length of the equalization interval, part of the AmBC signal contributes positively to the received signal $0 < w_k < 1$. If the AmBC has the same symbol duration as the original OFDM system without being synchronized, the time offset Δt between the systems is added to the propagation delay $t := t + \Delta t$.

The receiver is able to successfully decode the broadcast signal if the signal-to-interference plus noise ratio (SINR) $C/(I + N)$ is larger than a given threshold γ , i.e.,

$$\frac{C}{I + N} = \frac{\sum_k w_k C_k}{\sum_k (1 - w_k) C_k + N} \geq \gamma,$$

where N denotes the noise power. This can be equivalently be written as

$$\sum_{k \in \mathcal{K}_+} (w_k(1 + \gamma) - \gamma) C_k \geq \sum_{k \in \mathcal{K}_-} (\gamma - w_k(1 + \gamma)) C_k + \gamma N, \quad (1)$$

where $(w_k(1 + \gamma) - \gamma) > 0$ for $k \in \mathcal{K}_+$ and $(w_k(1 + \gamma) - \gamma) \leq 0$ for $k \in \mathcal{K}_-$. The notations \mathcal{K}_+ and \mathcal{K}_- denote the set of the wanted signals and the unwanted ones, respectively.

III. INTERFERENCE ANALYSIS

Consider a system setup operating on DVB-T2, illustrated in Fig. 2, we, in this section, first analyze the impact of a single AmBC device, and then study the case that AmBC devices are distributed following a Poisson Point Process (PPP) with a density ρ . The victim receiver situated at $(0, 0)$ in polar coordinates and the transmitter is situated at $(0, d)$. The AmBC device is located at $(\theta, r_2(\theta))$ with distance $r_2(\theta)$ away from the receiver and distance $r_1 = \sqrt{r_2^2 - 2d \cos(\theta)r_2 + d^2}$ from the transmitter. We assume that the AmBC device antenna height is 0, the transmitter antenna height is H_1 , and the receiver antenna height is H_2 . We further assume that d is large such that the impact of H_1 and H_2 on the overall path length l is negligible, i.e., $l \approx r_1 + r_2$. Hence, all signal paths having the same length form an ellipse having eccentricity $e = d/l$. Let l_{max} denote the maximum path-length so that the signals are received within the equalization interval. The signal components having path length less than equal to l_{max} are received with weight $w_k = w$, and the longer paths are received with $w_k = 0$ that contribute to the interference. Consequently, the SINR condition in (1) can be written as

$$C_0 + (w(1 + \gamma) - \gamma) \sum_{k \in \mathcal{K}_{l_{max}}} C_k \geq \sum_{k \notin \mathcal{K}_{l_{max}}} C_k + \gamma N,$$

where $\mathcal{K}_{l_{max}}$ is the set of radio paths that have length less than l_{max} . If the AmBC symbol duration is much larger than the equalization interval of the OFDM symbol, we have $w \approx 1$. On the other-hand, if the AmBC symbol duration is shorter than the equalization interval, we have $w \approx 0$.

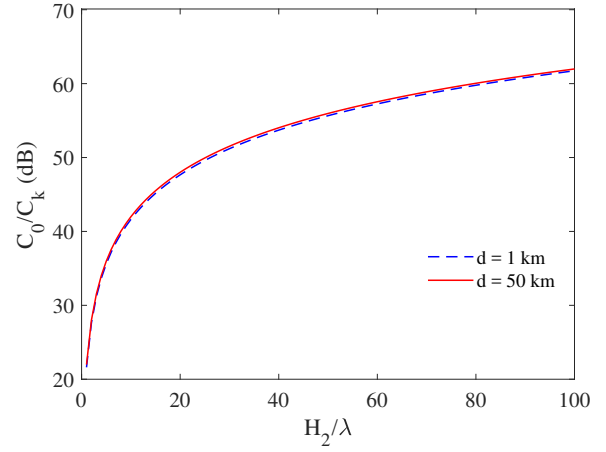


Fig. 3. C_0/C_k as a function of H_2/λ

In free-space the direct path power transfer between the transmit and the receive antennas is given by the Frii's equation as

$$C_0 = \left(\frac{\lambda}{4\pi}\right)^2 G_r G_t p_t \frac{1}{d^2 + (H_1 - H_2)^2},$$

where λ denotes wavelength, p_t is the transmit power, G_t is the transmitter antenna gain, and G_r is the receiver antenna gain. The received power of the k -th scattered path is given in [27] as

$$C_k = \left(\frac{\lambda}{4\pi}\right)^4 G_r G_b^2 M G_t p_t \frac{1}{(r_{2,k}^2 + H_2^2)(r_{1,k}^2 + H_1^2)},$$

where M is the modulator loss and G_b is the AmBC antenna gain. The scattered power has a maximum value when $r_2 = 0$ and $\theta = 0$ so that the power ratio can be written as

$$\frac{C_0}{C_k} = \frac{(4\pi)^2}{G_b^2 M} \left(\frac{H_2}{\lambda}\right)^2 \frac{H_1^2 + d^2}{(H_1 - H_2)^2 + d^2} \geq \frac{(4\pi)^2}{G_b^2 M} \left(\frac{H_2}{\lambda}\right)^2. \quad (2)$$

The inequality holds when $H_2 < H_1$, which is generally always valid, and it becomes asymptotically tight as $d \rightarrow \infty$.

According to the Recommendation ITU-R BT.1368-13 [28], for TV signals the wanted-to-unwanted signal ratio D/U for co-channel interference is 39 dB. This protection criteria can be written as

$$\frac{C_0 + wC_k}{(1 - w)C_k} \geq \frac{D}{U}, \quad (3)$$

which can be equivalently written as

$$\frac{H_2}{\lambda} \geq \frac{G_b}{4\pi} \sqrt{[(1 - w)D/U - w]M}.$$

In fixed reception, the receiver antenna is typically located at the rooftop of a building resulting tens of meters distance between an AmBC device and the receiver antenna. However, in case of mobile reception, this D/U criteria cannot be always assured. Fig. 3 shows C_0/C_k as a function of the protection distance with $\lambda = 0.6\text{m}$, $H_1 = 300\text{m}$, and $G_b = M = 1$.

Having established that the impact of a single AmBC device on incumbent receiver is small, the question arises what is the aggregate effect of a large number of AmBC devices.

From the regulation aspect, we are interested in the scenarios consisting of a large number of backscatter device. We assume that the AmBC devices are distributed in the space according to a PPP with density ρ , i.e. the number of AmBC devices per square meter. A scatter located at $(\theta, r(\theta))$ contributes to the received power following

$$c(\theta, r) = \left(\frac{\lambda}{4\pi}\right)^4 \frac{G_r G_b^2 M G_t p_t}{(r^2 + H_2^2)(r^2 - 2d \cos(\theta)r + d^2 + H_1^2)}.$$

Consider an integral of the form

$$c_R(\theta) = \int_0^R c(\theta, r) r dr \quad (4)$$

for $R > 0$. This integral has a closed-form solution given in (5) through using integration by parts. Also its limit $\lim_{R \rightarrow \infty} c_R(\theta) \triangleq c_\infty(\theta)$ has a closed form given by (6). It can be easily verified that for all $0 \leq \theta < 2\pi$, $0 < c_\infty(\theta) < \infty$.

The mean scattered power received from devices having path length at most l_{max} is obtained by integrating the scatter power over an ellipse having eccentricity $e = d/l_{max}$:

$$\bar{C}_{l_{max}} = \int_0^{2\pi} \int_0^{r_2(\theta; l_{max})} c(\theta, r) r dr d\theta = \int_0^{2\pi} c_{r_2(\phi; l_{max})}(\theta) d\theta,$$

where

$$r_2(\theta; l_{max}) = \frac{l_{max}}{2} \frac{1 - e^2}{1 - e \cos(\theta)}$$

and the AmBC device density ρ was scaled to one. The total received power from scattered components can be obtained by integrating over the whole plane as

$$\bar{C}_\infty = \int_0^{2\pi} \int_0^\infty c(\theta, r) r dr d\theta = \int_0^{2\pi} c_\infty(\theta) d\theta.$$

A simple upper bound in (7) can be obtained by setting $\theta = 0$.

For a general AmBC device density ρ , we can write the SINR constraint as using the mean values as

$$C_0 + (w(1 + \gamma) - \gamma)\rho\bar{C}_{l_{max}} \geq \gamma(\rho(\bar{C}_\infty - \bar{C}_{l_{max}}) + N)$$

or equivalently as

$$C_0 + w(1 + \gamma)\rho\bar{C}_{l_{max}} \geq \gamma(\rho\bar{C}_\infty + N). \quad (8)$$

The maximum AmBC device density that can co-exist with the incumbent OFDM system is thus

$$\rho \leq \frac{C_0 - \gamma N}{\bar{C}_\infty - w(1 + \gamma)\bar{C}_{l_{max}}} \quad (9)$$

if $w \leq \bar{C}_\infty / (1 + \gamma)\bar{C}_{l_{max}}$; otherwise ρ is not bounded above.

Besides $C/(I + N)$, we may also consider the $D/U = C/I$ constraint discussed above. In that case, the AmBC density is bounded by

$$\rho \leq \frac{C_0 U / D}{\bar{C}_\infty - w(1 + U/D)\bar{C}_{l_{max}}} \quad (10)$$

if $w \leq \bar{C}_\infty / (1 + U/D)\bar{C}_{l_{max}}$; otherwise ρ is not bounded.

IV. SIMULATIONS

Figures 4 and 5 show the allowed AmBC density for $C/(I + N)$ and D/U protection criteria when the useful signal power factor is $w = 0$ and $w = 0.5$. In portable reception case $\gamma = 9$ dB and $H_2 = 2$ m protection distance are assumed. In fixed reception case $\gamma = 20.9$ dB and $H_2 = 21$ m. In both cases, the coverage area radius was assumed to be 50 km and maximum length $l_{max} = 67.2$ km. Compared to the D/U criterion, the $C/(I + N)$ criterion allows larger densities of AmBC devices except at the very edge of the coverage area. In both deployment scenarios (portable/fixed) the conservative D/U criterion allows approximately 1000 simultaneously active AmBC devices per square kilometer.

We analyzed the impact of AmBC transmissions from the incumbent performance point of view on the worst case, in which the AmBC modulated signal component lies on the same band as the original signal. The receiver sees this signal component as an additional fast fading path. The interference generated by the AmBC to the incumbent depends on its modulation scheme. If the AmBC would be perfectly synchronized with the incumbent OFDM system having the same symbol duration, interference would only be caused by those AmBC devices that are far away. On the other-hand if the AmBC symbol duration is much shorter than the OFDM symbol duration, the AmBC modulated signal paths cannot be tracked by the equalizer resulting in interference. Our results indicate that in many practical deployments, the scattered signal paths caused by the AmBC devices have several orders of magnitude smaller power. Interference problems may happen when the AmBC device is very close to the victim receiver. In fixed reception this hardly ever happens.

V. CONCLUSIONS

We used the Poisson Point Process to capture dense random deployments of AmBC devices. Two different incumbent protection criteria were discussed. The first one sets a strict limit on the desired to undesired power ratio and the second one sets a limit on the required carrier-to-interference+noise ratio. The first one is typically much more strict than the latter one - except on the very edge of the coverage area. Our results indicate that in many practical deployments, the scattered signal paths caused by the AmBC devices have several orders of magnitude smaller power, so that the DVB-T2 systems can tolerate more than 1000 active AmBC devices per square kilometer even if very conservative protection criteria is used. Thus, the answer to "Does AmBC need additional regulation?" is "no", unless we expect extremely high deployment densities. If it were to be regulated, the regulation would need to consider also the passive relaying capability of these devices. The future work will study the regulation policies on AmBC operating with, e.g., the FM broadcasting, LoRa, and WiFi systems.

ACKNOWLEDGMENT

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$$\begin{aligned}
c_R(\theta) &= \int_0^R c(\theta, r) r dr \\
&= \left[2\sqrt{2}d \cos(\theta) (d^2 + H_1^2 + H^2) \tan^{-1} \left(\frac{\sqrt{2}d \cos(\theta)}{\sqrt{d^2(1 - \cos(2\theta)) + 2H_1^2}} \right) \right. \\
&\quad + \sqrt{d^2(1 - \cos(2\theta)) + 2H_1^2} \left((d^2 + H_1^2 - H_2^2) \log \left(\frac{(d^2 + H_1^2)(H_2^2 + R^2)}{H_2^2(d^2 - 2dR \cos(\theta) + H_1^2 + R^2)} \right) - 4dH_2 \cos(\theta) \tan^{-1} \left(\frac{R}{H_2} \right) \right) \\
&\quad \left. - 2\sqrt{2}d \cos(\theta) (d^2 + H_1^2 + H_2^2) \tan^{-1} \left(\frac{\sqrt{2}(d \cos(\theta) - R)}{\sqrt{d^2(1 - \cos(2\theta)) + 2H_1^2}} \right) \right] \\
&\quad \times \frac{\left(\frac{\lambda}{4\pi}\right)^4 G_r G_b^2 M}{2\sqrt{d^2(-\cos(2\theta)) + d^2 + 2H_1^2} (d^4 + 2d^2H_1^2 + 2d^2H_2^2 \cos(2\theta) + (H_1^2 - H_2^2)^2)} \tag{5}
\end{aligned}$$

$$\begin{aligned}
c_\infty(\theta) &= \lim_{R \rightarrow \infty} c_R(\theta) \\
&= \left[2\sqrt{2}d \cos(\theta) (d^2 + H_1^2 + H^2) \tan^{-1} \left(\frac{\sqrt{2}d \cos(\theta)}{\sqrt{d^2(1 - \cos(2\theta)) + 2H_1^2}} \right) \right. \\
&\quad + \sqrt{d^2(1 - \cos(2\theta)) + 2H_1^2} \left((d^2 + H_1^2 - H_2^2) \log \left(\frac{d^2 + H_1^2}{H_2^2} \right) - 2\pi d H_2 \cos(\theta) \right) \\
&\quad \left. - \pi \sqrt{2}d \cos(\theta) (d^2 + H_1^2 + H_2^2) \right] \\
&\quad \times \frac{\left(\frac{\lambda}{4\pi}\right)^4 G_r G_b^2 M}{2\sqrt{d^2(-\cos(2\theta)) + d^2 + 2H_1^2} (d^4 + 2d^2H_1^2 + 2d^2H_2^2 \cos(2\theta) + (H_1^2 - H_2^2)^2)} \tag{6}
\end{aligned}$$

$$\bar{C}_\infty \leq \pi \frac{H_1 (d^2 + H_2^2 - H_1^2) \log \left(\frac{d^2 + H_1^2}{H_2^2} \right) + 2d (d^2 + H_1^2 + H_2^2) \tan^{-1} \left(\frac{d}{H_1} \right) + \pi d (d^2 + (H_2 - H_1)^2)}{H_2 (d^2 + (H_2 - H_1)^2) (d^2 + (H_2 + H_1)^2)} \left(\frac{\lambda}{4\pi}\right)^4 G_r G_b^2 M. \tag{7}$$

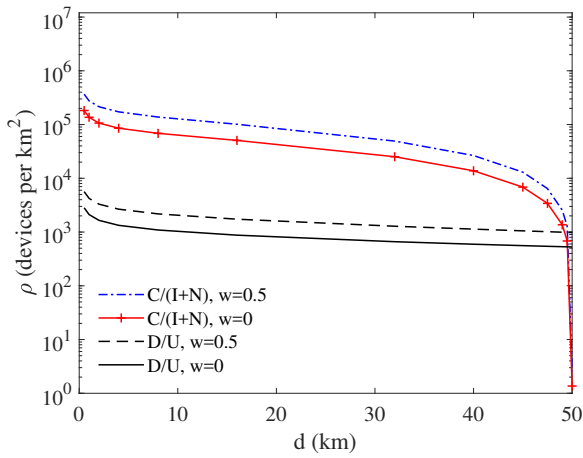


Fig. 4. AmBC density as a distance from transmitter for Fixed TV reception.

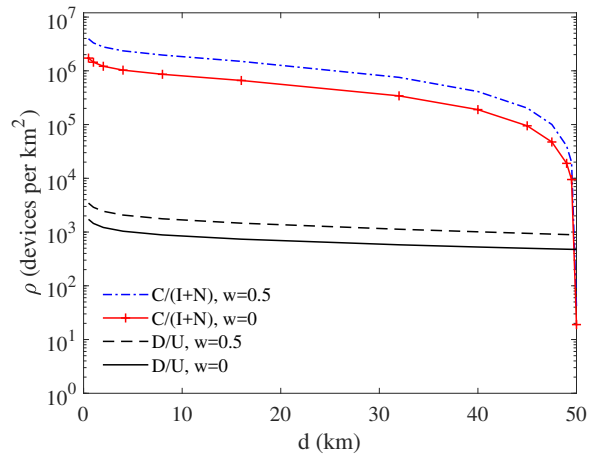


Fig. 5. AmBC density as a distance from transmitter for Portable TV reception.

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