On the Prospects of In-band Full-Duplex Radios as Monostatic Continuous-Wave Noise Radars

Mikko Heino[1], Jaakko Marin[1], Kai Hiltunen[2], and Taneli Riihonen[1]

[1]Tampere University, Finland
[2]Patria, Tampere, Finland
e-mail: firstname.lastname@{tuni.fi, patriagroup.com}

Abstract—**Future full-duplex (FD) radios simultaneously transmit and receive (STAR) on the same frequency band. This improves spectral efficiency and enables multiple new applications in the military context. One of such applications is the use of FD technology for a continuous-wave (CW) monostatic noise radar in which a wideband noise-like waveform is simultaneously transmitted and received. The main challenge in full-duplex communication systems is the strong self-interference (SI), i.e., direct leakage, between the transmitter and the receiver. In a noise radar, this problem is even more challenging as the required bandwidth is wider and transmit power levels are higher than in typical communications applications. This paper explores the feasibility of applying current full-duplex radio technology for a noise radar, targeting a system with a bandwidth of 500 MHz and transmit power in the kilowatt range. This is challenging compared to typical 5 to 80 MHz bandwidths and 0.1 to 2 W transmit powers supported previously in FD demonstrators. The obtainable SI suppression levels are estimated in terms of passive antenna isolation, analog cancellation and digital cancellation. In addition, the effect and tolerance of very-near environmental reflections are studied. It is concluded that, while high enough SI cancellation for a noise radar is feasible using state-of-the-art technology, the available transmit power limits performance.**

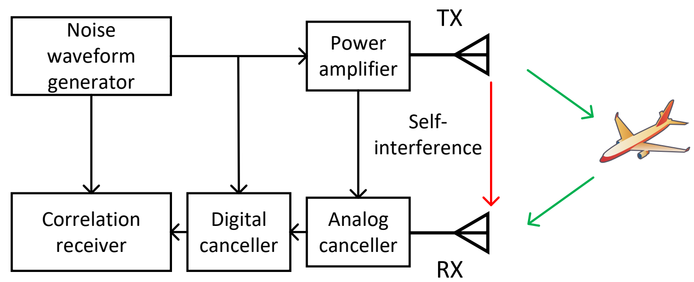

Fig. 1: Monostatic full-duplex/continuous-wave noise radar with self-interference suppression in three stages.

I. Introduction

Full-duplex (FD) communication has been intensively researched to increase the spectral efficiency of conventional communication systems. The main challenge in implementing full-duplex transceivers has been the strong interference between the transmitter and receiver of the device. However, applications in the security and military fields have not been widely researched [1], [2]. Conventional military radios utilize either frequency- or time-division duplexing. In addition to improving spectral efficiency, military full-duplex radios enable several new applications [3] such as simultaneous jamming detection [4] and communication under radio shielding [5]. One such potential emerging application is the use of full-duplex technology for novel monostatic noise radars.

The idea for a noise radar has been devised already 60 years ago, but it has gained increasing research interest during the last decade due to development of digital signal processing and increase in computational power [6]–[8]. As opposed to conventional radars utilizing deterministic signals, noise radars operate by transmitting a wideband pseudorandom signal providing high immunity to noise and a low probability of intercept (LPI). In addition, a wideband noise radar is able to operate in the presence of other radar or communication systems in the same frequency bands, when the transmitted signal's power spectral density is sufficiently low.

The performance of the noise radar depends on the available bandwidth and integration time. To fully take advantage of this, the continuous emission (CE) mode of operation of the radar is preferred making it essentially a full-duplex radio system [7]. However, this means that the leakage from the transmitter to the receiver becomes a severe problem. This is similar to the self-interference in full-duplex communication systems and similar techniques can be used for its mitigation. However, the very high transmit powers and dynamic range of the radar systems make this very demanding compared to communication systems. Especially in monostatic noise radars, where the transmitter is in the vicinity of the receiver, the transmit signal couples strongly to the receiver saturating it.

The successful cancellation of self-interference down to the receiver noise floor requires methods in the electromagnetic antenna domain, the analog RF domain in the receiver front-end, and finally in the digital baseband. In this paper, we analyze the feasibility of in-band full-duplex radios and self-interference cancellation methods for continuous-wave monostatic noise radars. By monostatic, we consider cases where the transmitter and receiver are within few meters of each other. We compare methods of self-interference cancellation in different domains, and assess limits for obtainable cancellation in this context. Finally, we analyze the radar performance obtainable with state-of-the-art full-duplex radios and study the effect of reflecting objects near the antennas.

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II. MONOSTATIC CONTINUOUS-WAVE NOISE RADAR

The noise radar (see Fig. 1) is based on a pseudorandom transmit signal which is typically digitally generated. Only the receiver has knowledge of this signal and uses it as the basis for the correlation analysis. The range resolution of the noise radar depends on the used physical bandwidth B and, together with the integration time T_i, it yields the processing gain BT_i for the radar detection. While also improving the radar range resolution, maximizing the bandwidth decreases power spectral density and, thus, decreases the probability of intercept. In this study, the wide bandwidth of 500 MHz is considered around 3 GHz center frequency.

One important aspect for the noise waveform in the noise radar is the peak-to-average-power-ratio (PAPR). Pure Gaussian noise has high PAPR and it can be inefficient for the transmitter by reducing the obtainable signal-to-noise ratio in the power budget as typically radar transmitters operate with a constant envelope. However, decreasing the randomness of amplitude in the signal can lead to increase in the probability of intercept leading to design trade-offs. [9]

In addition to reducing the dynamic range, the inherent transmitter–receiver coupling affects the radar operation at close distances due to the sidelobes of the autocorrelation function of the radiated waveform. The transmit waveform can be designed to have low range sidelobes to minimize this effect [7]. Typically, moving targets, i.e., Doppler-shifted targets, are of most interest in radar applications while self-interference and clutter have small Doppler shift.

III. SELF-INTERFERENCE CANCELLATION

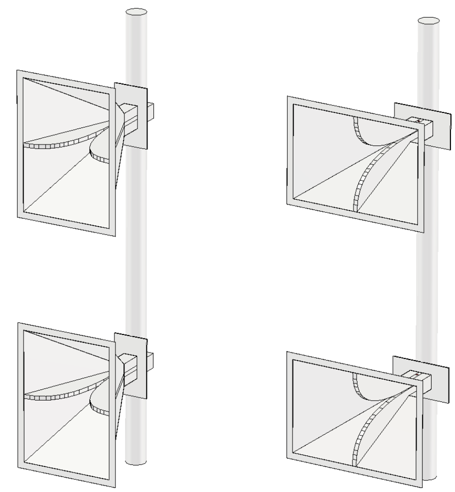
To successfully suppress the self-interference down to the noise floor and obtain total cancellation levels in the excess of 100 dB, we need to employ methods in the electromagnetic antenna domain, analog RF domain and the digital baseband domain. The main difference to full-duplex communications is that it is not necessary (or, in fact, not even desired) to cancel all of the reflected self-interference components as the actual targets are included in the reflected signal too. For a monostatic noise radar, the main considered options are to utilize the same antenna for the transmitter and receiver, or to use separate antennas relatively close to each other, i.e., within a range of few meters.

A. Single-Antenna Solutions

For the single-antenna case, there exist several methods on how to increase the isolation between the RX and TX. One common method is to use circulators, which are based on non-reciprocal ferromagnetic materials. In conventional circulators, the isolation is typically 20 to 30 dB between the receive and transmit ports. By cascading multiple circulators, up to 60 dB of isolation has been obtained [10]. However, imperfect antenna impedance matching decreases isolation and requires the use of impedance tuners, reducing benefits of passive components.

Another option are electrical balance duplexers (EBD). In EBDs, the reflection from the antenna is canceled with a matching reflection from a balance load by using a hybrid transformer. The challenge is that EBDs require careful matching of the balance load. For example, 36 dB of isolation has been achieved by using a real antenna as a load [11].

There exist also multiple CMOS- and metamaterial-based circulators [12]. Very high isolation levels, e.g., 45 dB, have been obtained between the transmitter and receiver [13]. However, the power handling of these solutions is only a few watts, making them unsuitable for long-range radar applications.



(a) H-planes aligned (b) E-planes aligned

Fig. 2: Two horn antenna setups for a monostatic noise radar.

B. Dual-Antenna Solutions

For the two antennas' case, the obtainable isolation depends on antenna type and the inter-antenna distance. To demonstrate the dual-antenna isolation, a ridged horn antenna was chosen as it has relatively high gain usable for radar applications and wide impedance bandwidth supporting the wideband radar signal. The gain of the horn antenna is 12 dBi and the system of two antennas is shown in Fig. 2. The antennas are mounted on a pole with varying distance between the antennas.

Figure 3 shows the simulated antenna coupling as a function of antenna distance on the pole with two possible orientations. It is seen that 10 to 20 dB better isolation is obtained when the H-planes of the antennas are parallel. This is due to a null in the H-plane radiation patterns of the antennas which can be used to further increase the isolation between the antennas.

It is seen that with the dual-antenna solution, 70 dB of isolation at 3 GHz can be obtained for antenna distances greater than 0.6 m and 80 dB isolation for distances greater than 1.7 m. Thus, it is possible to obtain greatly higher isolation with two antennas in a relatively compact form than with the single-antenna solutions discussed in the previous section. The isolation between the two antennas could be further increased, e.g., by using absorber materials to reduce the leaking energy, using electromagnetic band-gap materials between the antennas, or by further tuning of sidelobes of the antennas to deepen the nulls. Thus, it is probable that 90 dB

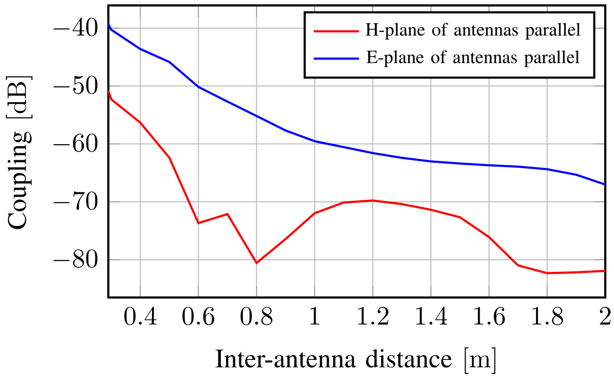


Fig. 3: Antenna coupling at 3 GHz with varying antenna distance and orientation.

Fig. 4: Radar measurement on a field.

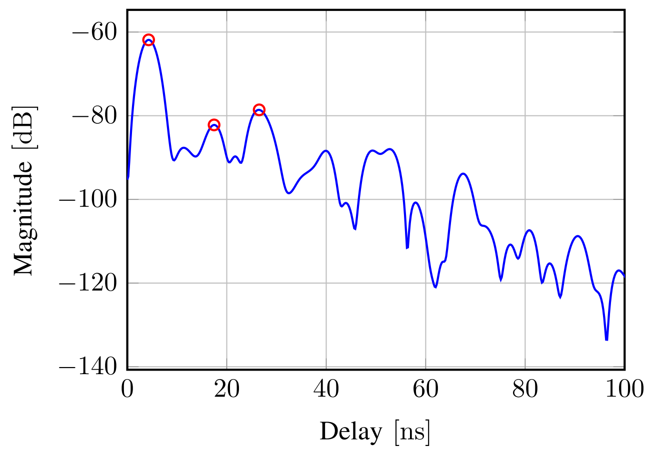


Fig. 5: Impulse response $h_{\mathrm{SI}}(\tau)$ between TX and RX antenna of the field measurement in Fig. 4.

of antenna isolation can be achieved in practice, even when the distance between the antennas is only one meter; ergo rendering a compact, really monostatic setup.

C. Analog Cancellation

To study the limits of obtainable analog cancellation, a simulation model was developed. Analog cancellers presented previously for full-duplex systems have been mainly designed for bandwidths under 100 MHz as this has been enough for communication applications [1]. The research considering wide bandwidths, e.g., 500 MHz, has been limited. For this reason, a realistic simulation of a multitap canceller was performed based on an existing prototype [14].

In the simulated model, power is coupled from the transmitted signal $x(t)$ and split with a power divider to multiple tap branches. Each tap then has a delay line of different length corresponding to a different component in the self-interference channel response, and a vector modulator. The vector modulator tunes the amplitude and phase of each tap to cancel the received interference. Finally, the signal from each tap is summed with the received signal $y(t)$. With baseband equivalent signals, this is expressed as

$$z(t) = y(t) + \sum_{n=1}^{N_{\mathrm{T}}} w_n x(t - \tau_n), \tag{1}$$

where N_{T} is the number of taps, w_n is adjustable vector modulator weight and τ_n is the fixed tap delay. The receive signal is obtained from the transmit signal by convolving it with the self-interference channel response $h_{\mathrm{SI}}(t)$ as

$$y(t) = \int_{-\infty}^{\infty} h_{\mathrm{SI}}(\tau) x(t - \tau)\, d\tau. \tag{2}$$

Band-limited Gaussian noise was used as the transmit waveform $x(t)$ as a basic case in this study.

The self-interference channel response is obtained from the measurement of the horn antennas in the field setup in Fig. 4. The delay line lengths τ_n were chosen based on the impulse response in Fig. 5 to be around the major multipath components which are circled in the figure. The tap weights w_n were run through an optimizer to obtain the best possible total cancellation in the receiver. The number of taps N_{T} was limited to eight for practical reasons as more taps would become increasingly impractical to manufacture and operate. Eight taps are already quite much because previous canceller prototypes have used only three taps [15], for instance.

The cancellation results are seen in Fig. 6. It it seen that the obtainable cancellation drops greatly when the bandwidth is increased. For the 500 MHz bandwidth, about 15 dB of analog cancellation is obtained with eight taps in the canceller which was considered as a practical maximum. After eight taps, the benefit of adding taps starts to decrease. Thus, 15 dB can be considered as a feasible analog cancellation value obtainable in the wideband radar application at best.

D. Digital Cancellation and Total Cancellation

Digital cancellation is based on using a computational model to subtract the self-interference from the received signal in the digital baseband. The effectiveness of the cancellation is based on how well the used signal model corresponds to the real received signal including the nonidealities of the transmitter and the receiver. The nonidealities include the

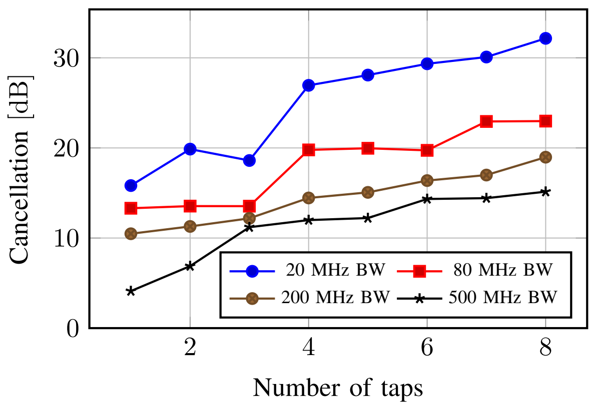


Fig. 6: Simulated analog cancellation obtained with different bandwidths.

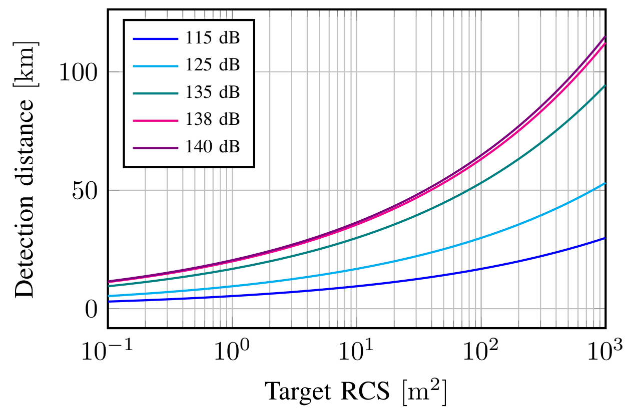


Fig. 7: Target detection distance with different total cancellation values when $T_i = 100\,\mathrm{ms}$ and $P_{\mathrm{tx}} = 890\,\mathrm{W}$.

nonlinearity of the transmitter and receiver, carrier frequency offsets, phase noise and IQ imbalance. In addition, if the self-interference signal is significantly stronger than the desired signal at the digital baseband, the quantization noise can surpass the thermal noise floor of the receiver and decrease the sensitivity of the detection. The quantization noise is random by nature so it cannot be removed by the digital cancellation. Therefore self-interference needs to be sufficiently cancelled in the previous stages of the receiver [16].

In the literature, digital cancellation levels of 30 to 50 dB have been achieved. For example, 38 dB of cancellation has been obtained for the bandwidth of 300 MHz [17] and 48 dB for the bandwidth of 80 MHz [18]. There are no references available for digital cancellations for wider bandwidths such as 500 MHz. Nevertheless, we can estimate based on the previous literature that 40 to 50 dB of digital cancellation could be obtained presuming vast computational resources. Additionally, in the radar application, digital cancellation is potentially easier as then there is no need to cancel all reflected multipath components and the undesired static radar reflections can typically be filtered out from the radar response. This has been noted with OFDM radars [19].

The estimated antenna isolation in Section III-B is 70 dB for two antennas within 0.6 m distance from each other increasing to 80 dB for a distance larger than 1.6 m, and it is assumed that at least 90 dB could be achieved with more complicated antenna design methods while keeping the compact size. In Section III-C, 15 dB of cancellation is justified based on modeling of the analog canceller with a reasonable number of delay taps. In this section, it is estimated based on previous literature that 50 dB of digital cancellation could be obtained. Together, these values combine to 135 to 155 dB of total cancellation. This number exceeds the total cancellation numbers obtained in previous literature, mainly because the transmit power has been limited therein.

If a typical noise floor of -115.5 dBW is considered for the radar receiver for a bandwidth of 500 MHz, the 135 dB total cancellation would already enable the use of 89 W of transmit power, further increasing to 890 W and 8.9 kW with total cancellations of 145 dB and 155 dB, respectively. It is seen that actually the available transmit power becomes the limiting factor, and that the obtainable total cancellations enable very high transmit powers to be used. In addition to cancellation capability, the sheer power tolerance of transceivers and antenna structures becomes a significant issue to solve.

IV. Implementation and Performance Analysis

A. Radar Detection Performance

In this section, the performance of the modelled radar system is studied considering the obtainable total cancellation and transmit power levels. The received power is calculated with the classic radar equation and considering the processing gain BT_i as

$$P_r = \frac{P_t G_t G_r \lambda^2 \sigma B T_i}{(4\pi)^3 r^4}, \tag{3}$$

where P_t is the transmit power, G_t and G_r the transmitting and receiving antenna gains, λ wavelength, σ radar cross-section (RCS) of the target and r the distance to the target. Thermal noise floor of the receiver is estimated with $P_n = kTB$, where k is Boltzmann constant and T the noise temperature of the receiver. Thus, the signal-to-noise ratio (SNR) is calculated as

$$\mathrm{SNR} = \frac{P_t G_t G_r \lambda^2 \sigma T_i}{(4\pi)^3 r^4 kT}. \tag{4}$$

Maximum target detection distance is presented in Fig. 7 with transmit power of 890 W. The noise figure of the receiver is assumed to be $NF = 8\,\mathrm{dB}$, thus $T = T_0(F-1) \approx 1540\,\mathrm{K}$, where $T_0 = 290\,\mathrm{K}$. The detection threshold is considered to be $\mathrm{SNR} = 14\,\mathrm{dB}$ and $G_t = G_r = 12\,\mathrm{dBi}$. It is seen that at around 138 dB to 140 dB of total cancellation, the detection distance does not increase anymore and the system becomes transmit power limited instead of cancellation limited.

B. Impact of Environment

To obtain as good isolation as presented in Section III, the vicinity of the antennas needs to be free from reflecting objects, i.e., eliminating the very near reflections so that the reflections do not decrease the dynamic range of the receiver.

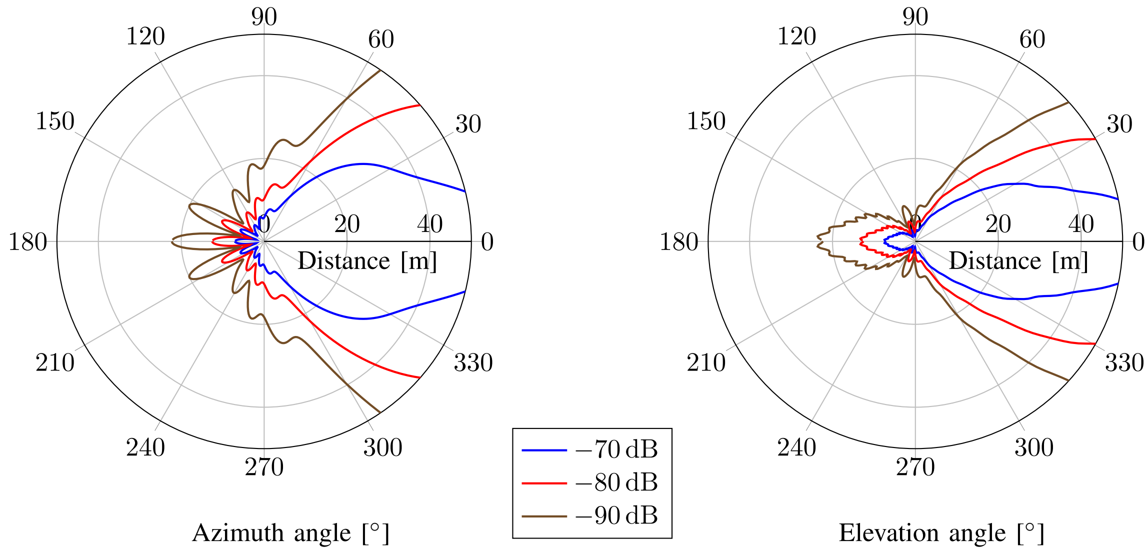


Fig. 8: Distance limits for reflector in the near vicinity of the antennas for certain coupling levels.

The goal is to have the reflected power below the power level of inherent direct coupling between the antennas. This way the antenna isolation and analog cancellation can be designed in a more controllable way and independently from installation environment if suitable clearance distances are enforced.

Figure 8 shows the distance to reflecting objects corresponding to certain reflection levels in the azimuth and elevation planes. A worst-case reflecting object is considered: a $1 \times 1\ \mathrm{m}^2$ square metal plane oriented perpendicular to the antennas with the specular reflection being directed back towards the antennas. Oriented this way, the plate has an RCS of 1200 m^2 towards the antennas.

It it seen that the system is sensitive for reflections towards the main lobe direction as it is supposed to be. The minimum reflection distances in the main lobe are 62 km, 110 km and 196 km, for reflection levels of -70 dB, -80 dB and -90 dB, respectively. However, the areas behind and below the antenna are interesting as the antenna mounting structures affect in these directions. It is seen that the clearance below the antenna needs to be under 6 meters for -90 dB reflection level. This is due to antenna pattern nulls being directed towards ground. The antenna receives somewhat more significant reflections from the back lobe. The clearance distance for the back lobe is 20 meters for -90 dB coupling level decreasing to 7 meters for -70 dB coupling level. These clearances can be challenging to fulfill especially for the -90 dB limit, if the radar is deployed on a vehicular platform. The antenna design could be modified to further minimize the back lobe and the sidelobes.

C. Power Handling

The most demanding aspects for power handling are for the transmitter chain of the radar. The transmit antenna and the transmit front-end components need to handle the high transmit power. For example, the N-connectors of the measured horn antennas can tolerate 1000 W of CW power at 3 GHz. For higher powers, waveguide components are needed, e.g., a waveguide feed for the antennas, and a waveguide component for the analog canceller coupler in the transmitter. For example, the power handling of a 50 dB WR340 waveguide power sampler is 3500 W on average at 3 GHz.

With two antennas and high antenna isolation, the power handling requirements for the analog canceller and the receiver chain are not very high. In particular, if the antenna isolation is 70 dB, roughly a 60 dB coupler or power sampler is needed to couple power to the analog canceller branch. Even if the transmit power is 890 W, the power entering the canceller is only 0.89 mW, and with 8.9 kW only 8.9 mW. Thus, the maximum power is limited essentially by the available power amplifier and the transmitter components after the amplifier.

However, if some decoupling components, e.g., absorbers or bandgap structures are near the antennas, the power handling for those can limit the transmit power. For example, the typical power handling limit of absorber material is 0.15 $\mathrm{W/cm^2}$ which can be easily reached if placed close to an antenna with 890 W of transmitted power.

V. Conclusion

This paper studied the limitations of applying full-duplex radio communication technology to monostatic noise radars. It was concluded that roughly 135 to 155 dB of total self-interference suppression could be obtained over 500 MHz bandwidth. This suggests that the state-of-the-art 110 decibels demonstrated in full-duplex communications is not actually limited by the cancellation technology per se, but there just has been no room to reach higher cancellation before reaching noise floor when using low transmit powers of few watts. At high cancellation, the availability of transmit power becomes the limiting factor for the performance. In order to fully utilize the highest achievable cancellation under typical receiver sensitivity, the transmit power would need to be kilowatts.

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