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Crosstalk in modern software defined radio for the implementation of frequency modulated continuous wave radar

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Abstract

This study investigates crosstalk and leakage in the Software Defined Radio implementation of Frequency Modulated Continuous Wave (FMCW) radar systems. Empirical measurements of leakage power were conducted during the implementation of FMCW radar using National Instruments Universal Software Radio Peripheral (USRP) boards. Mono-static and bi-static/distributed Transmitter-Receiver configurations are compared for low power micro-Doppler applications. The impact of crosstalk on the dynamic range of the target is also investigated. The impact of electric noise generated by a windy source on the receiving USRP is also investigated. Furthermore, a simple splitter based approach is proposed to overcome the challenge of synchronisation or recovery of transmitted waveform in distributed configurations.

1 | INTRODUCTION

Software Defined Radios (SDRs) are increasingly being used for prototyping of modern Radio Frequency (RF) transmission systems. They are rapidly advancing and providing considerable benefits to both communications and RF sensing applications. In particular, the use of SDR for implementing low cost radar systems has been on the rise over the last decade [1]. Frequency Modulated Continuous Wave (FMCW) radar systems were first introduced many years ago however, due to their simple design and wide application area, they are still a popular RF sensing configuration. Thanks to the recent advancements, FMCW is the leading technology for low cost radar applications. National Instruments Universal Software Radio Peripheral (USRP) is one of the most popular SDR platforms [2]. There are various variants of these devices with different specifications that can be used for diverse applications. This study investigates the impact of crosstalk in such devices for implementation of the FMCW radar system. FMCW radars are used for a range of diverse applications [3], for example, Moving Target Detection radars, vital sign detection systems, Synthetic Aperture Radars and most recently in the automotive radars, all use FMCW signal transmission [4]. FMCW radars use linear frequency modulation (LFM) and its transmitted signal $s(t)$ is given as

$$s(t) = A\cos\left(2\pi f_{tx}t + \pi\frac{B}{T}t^2\right) \tag{1}$$

for $0 < t < T$, where A and f_{tx} are the amplitudes and start frequency of the reference LFM signal, B and T are sweep bandwidth and sweep period respectively [5–7]. The crosstalk is a phenomenon by which a signal transmitted from one circuit causes disturbance in the other circuit hence affecting the performance of the other circuit [8]. FMCW systems achieve vastly improved sensitivity by using careful antenna design,

active/passive leakage cancelation and shielding of electronics and transmission lines. Local Oscillator leakage in USRPs at times can cause systematic errors of the order of tens of dB's [9,10]. The term leakage will be used interchangeably with crosstalk for the remainder of this article. Crosstalk can be higher than echo signals as it depends on both the amplitude of echo signal and the crosstalk. Therefore, in certain configurations, crosstalk power can be higher than the backscattered radar signals. This high-powered crosstalk can saturate the low noise amplifier [11] adversely impacting Signal to Interference ratio at a nearby distance. Furthermore, since the radar is a continuous wave, this effect is experienced at all ranges making it more and more challenging to deal with the signals of furthest ranges as the interference level stays constant while the target returns scale at $\frac{1}{R^4}$. On the receiver side, the signal is deramped by mixing with the reference signal, to extract the beat frequency, which contains range and Doppler information [12]. If the receiver is affected by the crosstalk, the dereamped signal at Intermediate Frequency (IF) port $x(t)$ can be written as

$$x(t) = x_l(t) + x_t(t) \tag{2}$$

where $x_l(t)$ and $x_t(t)$ are the IF beat signals corresponding to leakage and target respectively. Depending upon the intensity of $x_l(t)$, the system performance is disturbed accordingly. Hence, the leakage between transmitter and receiver is an important problem to consider [13]. Therefore, even though FMCW radar has many advantages in near target distance, these benefits will be overshadowed if phase noise problem of leakage is not resolved. Although every USRP device has a separate port for transmission and reception, the close proximity of transmitting and receiving chains can cause signal leakage issue [14]. In a typical pulse based radar, the system is either transmitting or receiving, hence leakage of transmitting signal to receiving chain has much less impact during the reception process. However, in continuous wave signals, the transmitting signal does not get switched off during the reception process, therefore signal leakage can become very troublesome for radar system designers if it is not dealt with properly. Propagation of near-end crosstalk is the primary source of crosstalk noise in short un-terminated channels. The un-terminated ports of SDRs are also likely to be affected therefore, it is important to investigate the impact of crosstalk on un-terminated ports. In many applications, the receiver ends of the lines are left un-terminated to conserve power. Braunisch et al. [15] showed how theoretical crosstalk-free signalling on short un-terminated channels can be achieved. The near-end crosstalk propagating to the far end is the primary source of crosstalk noise in short un-terminated channels. It is therefore very important to mitigate this noise especially for indoor USRP-based Radar applications.

Most of the existing FMCW radar interference mitigation techniques rely on detection or identification of interference before mitigating it. The existing state of the art techniques use either detect-and-avoidance or detect-and-mitigate techniques to counter the interference effects. Hence, many existing techniques look into mitigating interference by repairing the interfered samples and possibly reconstruct the required signal. In the context of radars in general, the least-mean-square approach and CLEAN algorithms are used to filter out the direct signal interference for the passive radar system. It is known that the DOA estimation using CLEAN is inherently biased due to the sidelobe interference between the targets. The CLEAN algorithm is also implemented to facilitate the direction of arrival estimation of weaker targets [16]. Moreover, it also used in the beamforming set-ups to iteratively remove the sidelobe features of the strong targets [17]. It also allows for the correct detection of spectral line-of-sight-peaks in frequency-domain [18]. However, there is a significant overhead of this and related algorithms in terms of computation time. To estimate the unknown amplitude, frequency and phase of the short-range leakage IF signal, the method of least squares (LS) is widely used. Please note that the complexity of LS is dependent on a number of parameters. Moreover, it is efficient if we have prior knowledge of few of those parameters [19]. Apart from these, there are a number of techniques proposed in the literature to overcome the leakage issues. An artificial on-chip target can be used in the transceivers to mitigate the short-range leakage [13]. The leakage cancelation is carried out mainly in the digital domain enabling high flexibility and adaptivity. Lin et al. [20] present a digital leakage cancelation scheme for mono-static FMCW radars. A heterodyne scheme is used to generate an error signal modulated at a pre-selected reference frequency. Thus, the DC offset of the mixer can be separated from the modulated error signal using a band pass filter. Since the modulated error signal contains the amplitude and phase information of the leakage signal, controlling error vector is generated in DSP by comparing the reference signal and the modulated error signal. Then, the error vector is used to adjust the vector modulator. Although all such techniques can be effective in mitigating the leakage in FMCW systems, this study addresses a different dimension of crosstalk and leakage, that is to demonstrate the presence, variability and severity of crosstalk in FMCW radars implemented using USRP radios. Moreover, we can avoid the overhead of signal processing by using bi-static configuration of radars. Moreover, we have used three different types of USRP hardware (2922, 2943 and 2945) for implementation of FMCW radar systems and noticed the effects on the performance of the overall system. There have been many studies in the past to resolve leakage problem [21]. Most of these techniques are based on feedback algorithms affecting other radar parameters hence adding to the complexity of system. Moreover, different design techniques have been developed to eliminate the possibility of crosstalk on PCB boards but such techniques are not useful after manufacturing of the USRP device. From our study, we have shown that FMCW radar implementation on a single USRP device can create significant crosstalk which limits the hardware's ability to operate as a mono-static system, this can be avoided by using a spatially distributed solution. The challenge that such an implementation brings with itself is the synchronisation of the distributed network [22].

Our measurements and analysis include experiments on multiple sets of USRP-2922, 2943 RIO and the USRP-2945 RIO. We have shown the effect of crosstalk on the same and different channels of USRP RIOs. For that, we have

made use of both linear and triangular FMCW chirps. The near-end crosstalk propagating to the far end is the primary source of crosstalk noise in short un-terminated channels. It is therefore very important to mitigate this noise especially for indoor USRP-based radar applications. In this study, we have also shown a comparative analysis of crosstalk with un-terminated ports of five different USRPs of the same type and specifications. The results are produced using NI USRP-2922 which is a single channel (with separate Tx and Rx ports) USRP. We have also shown effects of crosstalks in two separate 2922 USRPs placed in a pseudo-mono-static configuration and shown the optimum distance in order to nullify the effect of crosstalk between the devices. We have also measured crosstalk for the MIMO based USRP-2945, which is different to MIMO based USRP-2943 in the sense that it has four channels, where Wi-Fi access point (AP) is used as the source to measure the difference. We have also shown the effects of leakage in pseudo-mono-static/bi-static configuration and its influence on the range-Doppler profile. It is shown how the dynamic range of the signal is affected by increasing crosstalk power. If we switch from mono-static system to a bi-static radar with a separation of few inches between transmitter and receiver, the maximum dynamic range shows an improvement of tens of kilometers. The influence of crosstalk on the range-Doppler profile is also shown. In addition, measurements have also been taken under environmental effects of wind and fog. A suitable technique to recover the transmitted waveform is also presented. Based on our findings, it is shown that crosstalk can badly impact the performance of USRP-based radar for applications with small radar signature, for instance Micro-Doppler analysis of low radar cross section (RCS) target like drone or bird.

The study is organised in the following way. In Section 2, we have highlighted the effects of crosstalk on the USRP-RIO which is a dual channel re-configurable SDR with open-FPGA. The effect of crosstalk on both channels are considered. In Section 3, we have highlighted the importance of addressing crosstalks in un-terminated ports of SDRs and quantified that for USRP-2922 which is single channel SDR widely used in various applications. In Section 4, we have highlighted and quantified the crosstalk between two different USRPs. For that, we have considered USRP-2922, 2943R and 2945R. In Section 5, we have addressed the leakage issue in pseudo-mono-static/bi-static configuration and its influence on the range-Doppler profile. In Section 6, we have given suggestions on how distributed SDR based FMCW radars can synchronise/recover the transmitted waveform at the receiver. In Section 7, we have highlighted the impact of crosstalk on applications with small radar signature and Section 8 ends with a conclusion. Following are the main findings and contributions of this study.

- We have highlighted a very important issue of crosstalk and leakage associated with the implementation of FMCW radar system by using off-the-shelf National Instruments USRP boards that are increasingly been used in a large number of applications both in laboratory and commercial environments
- It has been shown that there are significant challenges in using a USRP device for a mono-static FMCW system due to crosstalk problems. Therefore, implementation of FMCW radars using NI USRP boards must incorporate the effect of crosstalk so that the results are not flawed
- It is shown that for a mono-static FMCW implementation, different channel of the SDR can be used if USRP has a MIMO capability. Each channel has a separate daughterboard which will imply greater separation between paths of transmitter of one channel and receiver of the other, inside the enclosure. Significant reduction in crosstalk, of the order of tens of dBs can be expected while using different channel (for transmitting and receiving) of the same USRP device
- We have provided a quantitative analysis of leakage power for various NI USRP devices
- It has been shown that the implementation of FMCW radar system in bi-static and multi-static configuration renders more benefits in terms of detection of targets and also in signal processing as it does not need a crosstalk elimination procedure. Therefore, for implementing an FMCW radar system for low power micro-Doppler analysis, bi-static or multi-static configuration is more suitable as it not only offers spatial diversity but also eliminates crosstalk
- We have shown that the crosstalk can have a huge impact (tens of kilometers) on the dynamic range of the target. It is shown that for a 1 m^2 RCS target like drone, separating two USRP units by a few inches can increase the potential detection range by tens of km's
- We have also shown the influence of electric noise generated by a windy source on the receiving USRP
- A naïve approach for recovering the transmitted waveform from multiple USRPs of different specifications has been proposed and implemented

2 | EFFECTS OF CROSS-TALK ON USRP-RIO HARDWARE

While SDRs have been used in the implementation of FMCW radar [23–25], the crosstalk between multiple devices have been entirely ignored. Therefore, the performance of these implementations can degrade severely depending on the crosstalk levels between these devices. We have emphasised leakage as performance metric for the implementation of FMCW radars that is specific to USRP SDRs and quantified this. From our experiments, it can range from few dBs to tens of dBs. Crosstalk is an inherent phenomenon in SDR implementations of radars. The crosstalk was empirically investigated for USRP devices in a mono-static configuration. The USRP devices are supported by a wide variety of software development systems, including LabVIEW, MATLAB and GNU Radio [26]. Following the capture of the IQ components, the USRP sends the collected samples to the host PC for offline MATLAB-based processing [27]. NI USRP-2943R was the main

hardware that was controlled by LabVIEW. The device supports centre frequencies from 1.2 to 6 GHz, with up to 120 MHz of instantaneous bandwidth [28]. PCIe cable and PCIe card were used for all measurements. The USRP SDR reconfigurable device is built on the LabVIEW re-configurable I/O (RIO) and USRP architectures. It has two channels with separate transmitter (Tx) and receiver (Rx) ports for each channel having a separate daughter board. Block diagram of USRP-RIO with two channels A and B is shown in Figure 1. Each channel has independent ports for transmission and reception of signals. Figure 1 shows a multiple channel USRP-RIO with two ports, one for the transmitter or receiver (T_{A_1}/R_{A_1}) and another port for the receiver (R_{A_2}). Other models of USRP radios have a single channel with one or both ports for the reception of the signal. Hence, in normal circumstances, if T_{A_1} is the transmitting port, then R_{A_2} would be the receiving port and R_{A_1} cannot be used because of the continuous transmission. However because of the multiple channels, R_{B_2} from the other channel (daughterboard) is used as the receiving port to maximise separation between transmitting and receiving ports.

Consider two traces of USRP running parallel to each other, if the signal in one trace has higher amplitude than the other, it can aggressively influence the other trace. The signal path in the victim trace will then begin to mimic the characteristics of the aggressor trace instead of its own signal. When this happens, we get the crosstalk in the corresponding receiving port of USRP. Different design techniques have been developed to eliminate the possibility of crosstalk on PCB boards but such techniques are not useful after manufacturing of the USRP device. For MIMO based USRPs which have multiple channels on the same device, the key reason of crosstalk is the internal leakages as transmission lines are in close proximity to each other. However, for USRPs in bi-static configuration, crosstalk is the effect of electromagnetic field of communication signal in victim's neighbouring area.

The measurements shown in this article include both same and different channels (for transmitting and receiving) of the USRP. The operating frequency is set to 2.4 GHz whereas IQ rate of 1 MHz has been used. Gain is set to 0 dB for all measurements to identify the crosstalk in minimum possible signal strength. Moreover, no antenna is used in any of the measurements unless stated as we aim to find the level of interference without antenna, that is, based on the coupling between adjacent USRP devices. In this section, chirp is swept from 20 to 200 kHz. Number of samples that are transmitted

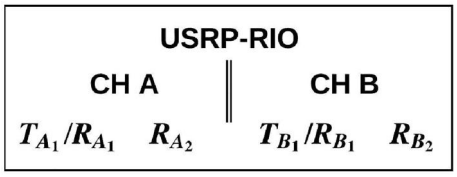

FIGURE 1 USRP RIO with two channels A and B

are 1000 whereas 5000 samples are received. The relation between fetch time and IQ rate is $t_f = \frac{N}{R}$, where t_f is the fetch time, N is the number of samples and R is the IQ rate. The sampling frequency of 50 MHz is used at the transmitting node that is $\frac{1000}{50x10^6} = 0.02$ ms of chirp length. On the receiver side, we sampled 5000 samples with an IQ rate of 1 MHz which gives us a fetch time of $\frac{5000}{1x10^6} = 5$ ms. By using this approach we acquired multiple pulses at the receiving end by levering the capabilities of the USRP hardware. The reference transmitted signal and the corresponding received waveform are shown in Figure 2, when the same channel is used for the transmission and reception (TA1 for transmission and RA2 for reception). Figure 2a,b show transmitted waveform and the received crosstalk signal $x_l(t)$ where duration of transmit and receive signal is 0.02 and 5 ms, respectively. For all the waveform graphs in the study, amplitude on y-axis is given in volts and that of x-axis is seconds. It can be seen that received voltage is approximately 0.0015 V, which with a 50 Ω load makes the received power of −43.47 dBm.

To analyse crosstalk while making use of different USRP channels, reference values corresponding to Figure 2 are used. Thereafter, we measure the strength of the received signal $x_l(t)$ when the reception is made on the farthest reception port of the other channel that is, T_{A_1} is used for transmission and R_{B_2} is used for reception. Because of the multiple channels, R_{B_2} from the other channel (daughterboard) is used as the receiving port because of the reasons explained above. From the waveform shown in Figure 3, we

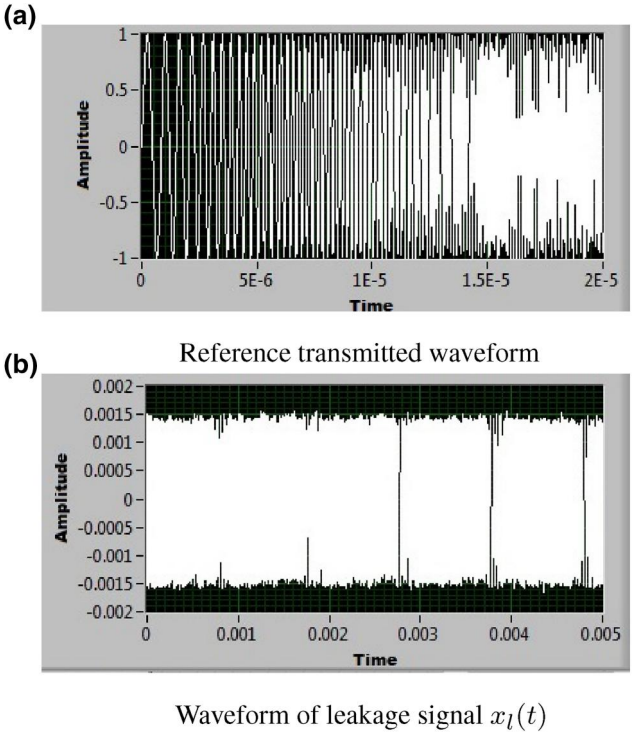

FIGURE 2 Waveform graphs using single channel of universal software radio peripheral (amplitude in volts vs. time in seconds)

can see that the received voltage is around 0.0004 V, which is around −54.951 dBm for 50 Ω termination. Thus, when two separate channels are used for transmission and reception, the crosstalk is reduced by 11.5 dB. After that, triangular chirp is implemented with sampling frequency of 9 MHz. The transmitted and received waveform spectrogram are given in Figure 4. If the same channel of USRP is used for transmission and reception, the amplitude of the received signal $x_l(t)$ is around 0.0012 V which scales to around −45.41 dBm with 50 Ω termination (see Figure 5). For different channels case, received power is reduced further to 0.00035 V equivalent to a power of −56.11 dBm with 50 Ω termination as shown in Figure 6. Hence as expected, crosstalk power is reduced by around 11.5 dBm.

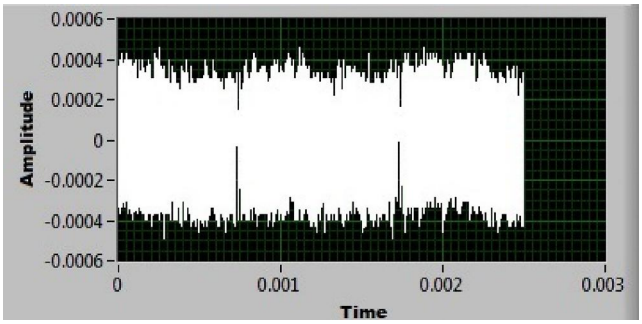

FIGURE 3 Waveform of leakage signal $x_l(t)$ using different channel of the same universal software radio peripheral

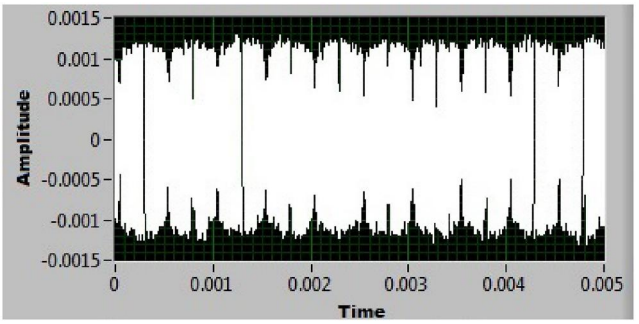

FIGURE 5 Waveform of leakage signal $x_l(t)$ for triangular chirp using the same channel of universal software radio peripheral daughter-board

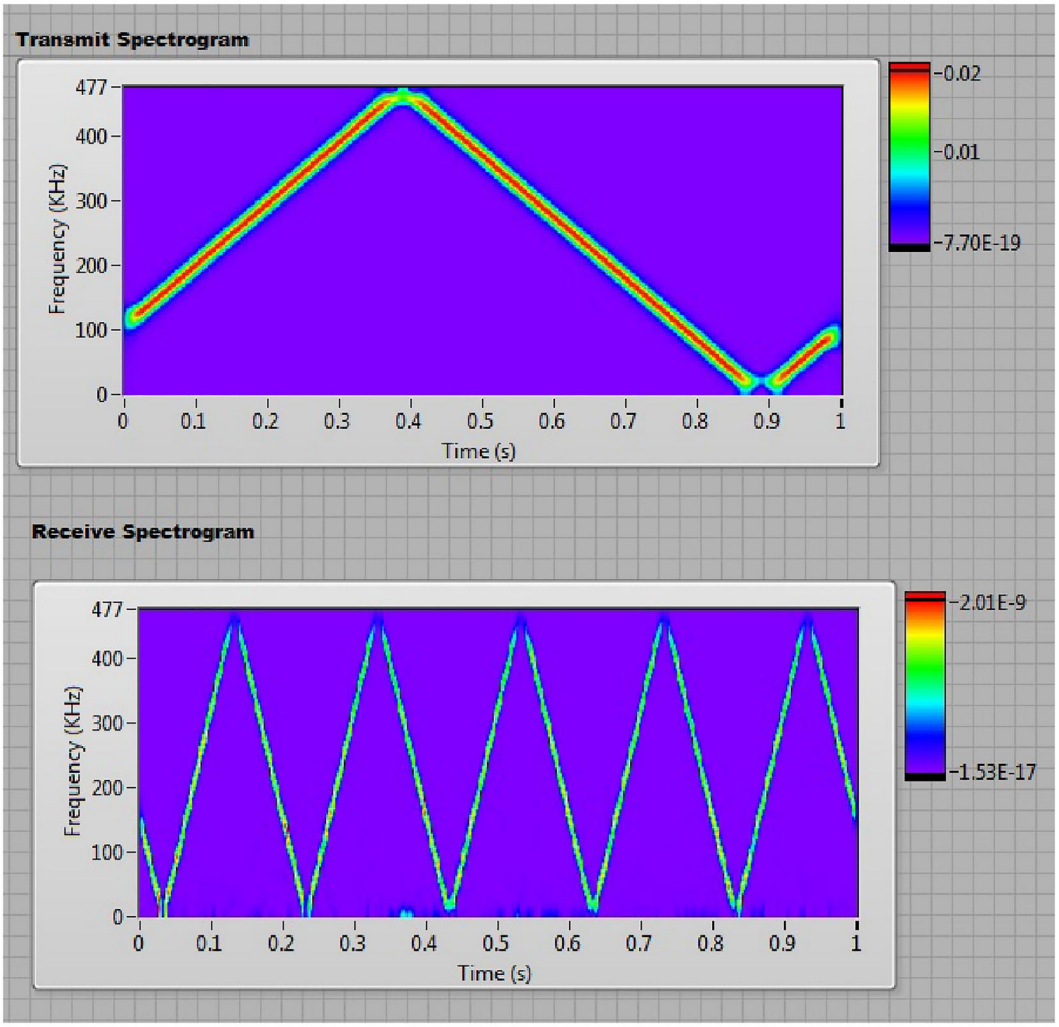

FIGURE 4 Spectrograms of triangular chirp

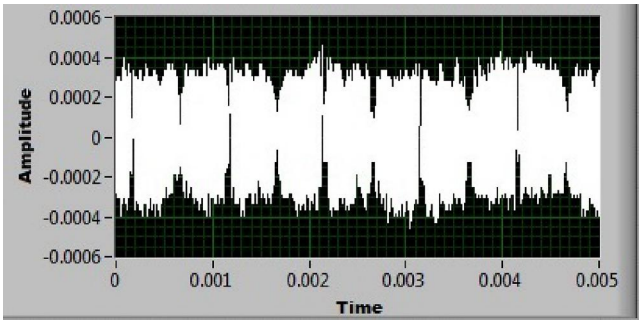

FIGURE 6 Waveform of leakage signal $x_l(t)$ for a triangular chirp using different channel of the same universal software radio peripheral

TABLE 1 Leakage/cross-talks with different configurations at 2.4 GHz

Case	t_{tx}	t_{rx}	BW	P_{rx} (dBm)
1-1	2×10^{-5} s	0.005 s	180 kHz	−43.47
1-1	1×10^{-5} s	0.005 s	90 kHz	−43.47
1-2	2×10^{-5} s	0.005 s	180 kHz	−54.91
1-1 Tri	2×10^{-4} s	0.005 s	1.8 MHz	−45.41
1-2 Tri	1.1×10^{-4} s	0.005 s	900 kHz	−56.11

Table 1 shows the comparison of the received crosstalk power with different cases at operating frequency, f_c, of 2.4 GHz. Case 1-1 refers to the observations on the same channel whereas 1-2 refers to measurements taken from different channels on the same USRP. Tri refers to measurements based on triangular chirp pattern. Time duration of the transmitted signal is denoted by t_{tx} whereas t_{rx} refers to time duration of the received signal $x_l(t)$. Furthermore, BW is the swept frequency or the bandwidth and P_{rx} is the received cross-talk power. From the table, it can be seen that as we switch to different channel for the simple linear chirp, the crosstalk decreases by around 11.5 dBm. Hence, for SDR implementation in USRP, it is imperative to use different channel for transmission and reception while using monostatic configuration.

3 | EFFECT OF CROSS-TALK ON UN-TERMINATED CHANNELS OF USRP-2922

In many applications, the receiver is left un-terminated to conserve power. Braunisch et al. [15] showed how theoretical crosstalk-free signalling on short un-terminated channels can be achieved. The near-end crosstalk propagating to the far end is the primary source of crosstalk noise in short un-terminated channels. It is therefore very important to mitigate this noise especially for indoor USRP-based radar applications.

In this section, comparative analysis of crosstalk with un-terminated ports of five different USRPs of the same type and specifications has been presented. The results are produced using NI USRP-2922 which is a single channel (with separate Tx and Rx ports) USRP having a bandwidth of 20 MHz and it can operate from 400 MHz to 4.4 GHz. USRPs are named as A,B,C,D and E. In the interest of space, we have shown received waveforms for those two USRPs that have the greatest difference in measured cross-talk power and named them as A and B. The difference in the crosstalk of the same type of devices could be observed because of wear and tear of the device or because of changes in the internal hardware of older devices. Therefore, it is imperative to calibrate older devices before any measurements where crosstalk can play its part. Please note that although we are comparing here the un-terminated received signals but all power calculations in this study have assumed a load of 50 Ω. Since un-terminated crosstalk is not compared with terminated crosstalk, these calculations will give us a fair comparison. First, we analyse the crosstalk for USRP-A with reference parameters. Figure 7 shows the waveform graph for the USRP-A. It can be seen that the received voltage is around 0.004 V which corresponds to a power of −34.95 dBm.

Figure 8 shows the waveform graph for the USRP-B. It can be seen that the received voltage is around 0.0003 V which is around −57.45 dBm of power, which is substantially less than the received power of USRP-A. Although both USRP radios have the same specifications and are of the same type and model, still the crosstalk measured for each of them is much different. Hence, each device should be carefully calibrated for expected crosstalk before taking any measurement. Table 2 shows the recorded numbers in tabular form. In practical applications, these factors should be taken into account in order to figure out the true power levels. Please note that Table 2 illustrates un-terminated crosstalk between two ports in USRP-2922 devices. Crosstalk of five different devices (all USRP-2922) has been taken into account. It is shown that devices with the same specifications can have significant different crosstalk, hence each device should be checked for how much crosstalk it produces for correct measurements.

4 | CROSS-TALK BETWEEN TWO USRPs

The noise characteristics include random distribution of noise among frequencies and distortions caused by the receiver's limitations [9]. For comparison, it is important to know the noise floor of the hardware when measuring crosstalk that is received power in case of no transmitted power. Figure 9 shows the waveform graph for the noise signal as received on the USRP receiver. This shows average noise power of around −65 dBm (0.00012 V) for 50 Ω load, hence −65 dBm is the noise floor with no crosstalk effects.

After doing initial set of experiments with no antennas, now in order to mimic the practical use, experiments have been conducted using 3 dBi omni directional Wi-Fi antennas. The indoor radar applications are more likely equipped with an omni-directional antenna due to the cost and size. Radar applications like detection of moving personnel targets using Wi-Fi has been studied in great detail in recent indoor applications of radars [29]. H. Griffiths et al [30] present the use of Wi-Fi

APs as illuminators of opportunity in passive bi-static radars. Wi-Fi transmission units as a low cost surveillance tool has widespread applicability [31].

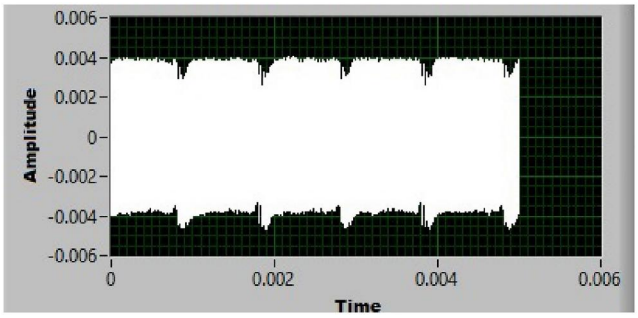

FIGURE 7 Waveform of leakage signal $x_l(t)$ for universal software radio peripheral -A

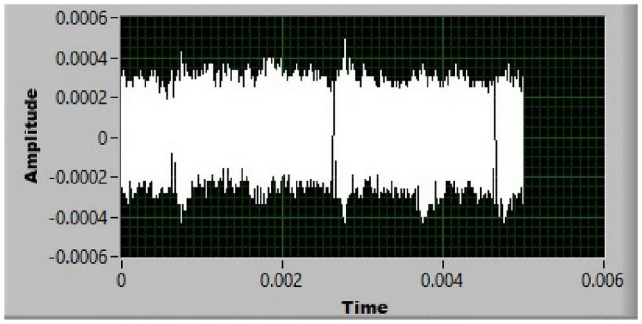

FIGURE 8 Waveform of leakage signal $x_l(t)$ for universal software radio peripheral -B

TABLE 2 Effect of cross-talks in the same channel for five different USRPs

USRP-2922	f_C (GHz)	P_{rx} (dBm)
A	2.4	−34.95
B	2.4	−57.45
C	2.4	−56.1
D	2.4	−54.95
E	2.4	−40.97

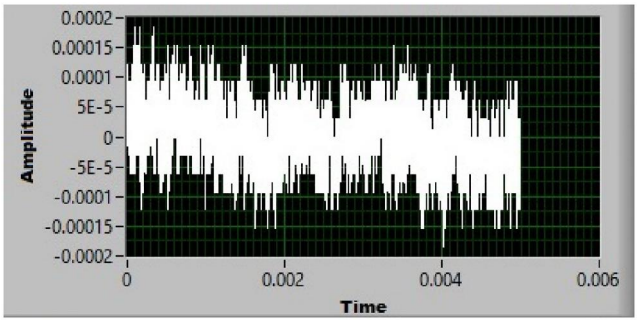

FIGURE 9 Rx noise waveform graph for no transmitted signal

USRP-C and USRP-D (USRP-2922) have been used in bi-static configuration for measurements in this section as they showed identical results in terms of measured cross-talk power. Table 3 shows different antenna configurations with distances and crosstalk power. C0 in the table corresponds to the case where USRP-C (as Tx) is connected with antenna and no antenna is attached to USRP-D (as Rx). The same analogy is applied with D0. CD1 refers to the case when both USRPs are connected with antennas and are placed vertically one after the other, which is around 1 inch of distance. CD2 refers to the case when adjacent USRPs are placed right next to each other, which is around 3 inches of distance. Figure 10 is the illustration of case CD1 where both USRPs (aggressor and the victim) are connected to omni directional antennas and are placed vertical to each other. Figure 11 shows the illustration of the same USRPs placed horizontally to each other. There is a high level of crosstalk in such configuration as both devices are in close proximity to each other. The corresponding waveform graphs are given in Figures 12 and 13 where y-axis represents $x_l(t)$, that is, crosstalk signal's amplitude in volts corresponding to each case. It can be seen that in order to avoid crosstalk from a USRP with an antenna, a distance of at least 42 inches should be maintained for any Rx circuitry. Similarly, there is a considerable crosstalk for adjacent USRPs.

TABLE 3 Crosstalks with Wi-Fi antennas in pseudo-mono-static configurations

Case	Distance (inch)	P_{rx} (dBm)
C0	41.5	−65
D0	42	−65
CD1	1	−13.01
CD2	3	−15.39

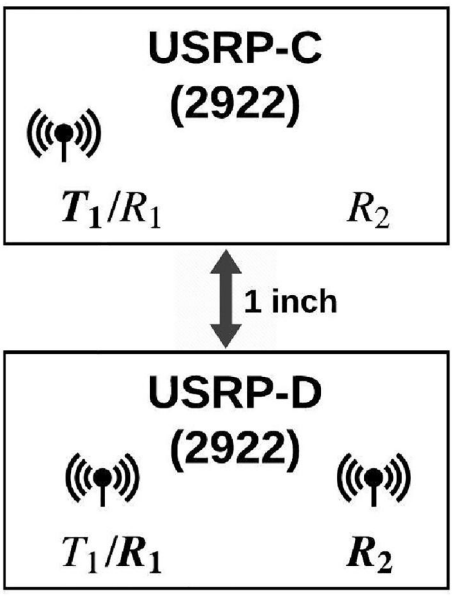

FIGURE 10 Illustration of case CD1 for USRP-C and USRP-D. USRP, universal software radio peripheral

We have also measured crosstalk for the MIMO based USRP-2945, which is different to MIMO based USRP-2943 in the sense that it has four channels. Two of the four channels are used for the measurement where noise floor for RX1 is around −57 dBm, whereas for RX2, it is around −64 dBm. Thus, noise floor of USRP-2945 is comparable to −65 dBm floor of USRP-2922. Figure 14 illustrates the set up where Wi-Fi AP is used as the source to measure the difference. One receiving port (RX1) is connected to the Wi-Fi AP through a cable, therefore it maintains constant energy. Whereas, the other receiving port (RX2) is used to measure the effect of crosstalk. The result for the crosstalk as a function of distance for the USRP-2945 is shown in Figure 15.

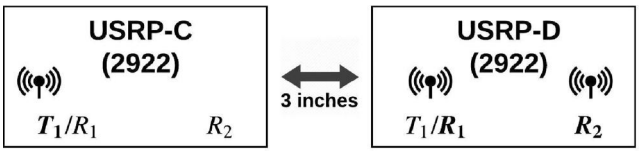

FIGURE 11 Illustration of case CD2 for USRP-C and USRP-D. USRP, universal software radio peripheral

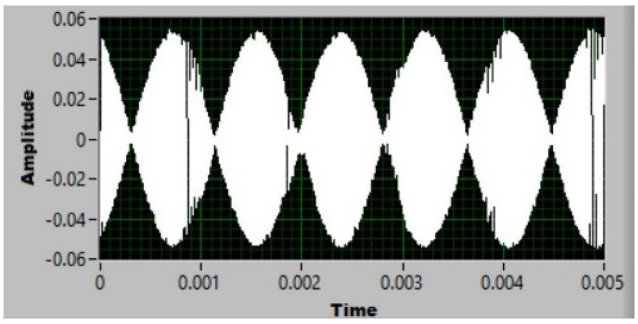

FIGURE 12 Waveform of leakage signal $x_l(t)$ for adjacent universal software radio peripherals: Case CD1

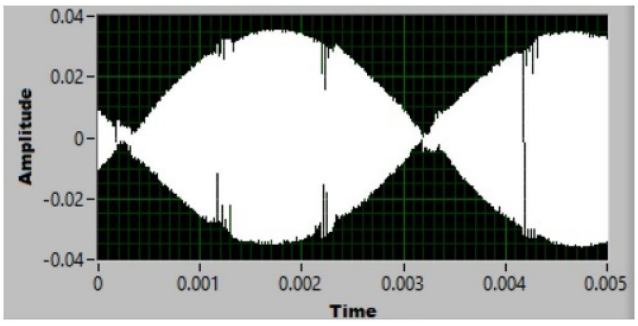

FIGURE 13 Waveform of leakage signal $x_l(t)$ for universal software radio peripherals placed next to each other: Case CD2

5 | LEAKAGE IN PSEUDO-MONO-STATIC/BI-STATIC CONFIGURATION AND ITS INFLUENCE ON THE RANGE-DOPPLER PROFILE

IEEE defines bi-static radar as a radar system that uses antennas at different locations for transmission and reception [32]. The distance of separation between the two is referred to as the baseline range. However, there is no stipulation as to how far apart the two antennas should be. However, generally, baseline distance should be comparable to the target range in order to classify a bi-static configuration. For that matter, we will be using the terminology pseudo-mono-static for the measurements that involve transmitter and receivers not collocated with each other but generally close enough.

In this section, no antenna is used, hence leakage of RF signal transmitted into free space is measured. To mimic the practical use for two devices with greatest difference in measured crosstalk, we have again used USRP-A and B for measurements in this section. In the following measurements, USRP 2922-A was set as transmitter and USRP 2922-B as receiver. Both were set in a pseudo-mono-static configuration such that there was a certain distance between them. The distance is measured from the SMA connectors of each USRP. Figure 16 shows received voltage for bi-static baseline distance of 3 inches between the SMA connectors of the transmitter and receiver. The voltage as shown in the figure is around 0.00017 V, which is around −62.38 dBm. Figure 17 shows the received waveform graph for a bi-static baseline distance of 6 inches. The figure shows the received voltage of around 0.00012 V, which is around −65 dBm, which is almost equal to the threshold for noise signal alone. Hence, there should be at least 6 inches of separation between transmitter and receiver in order to avoid the crosstalk completely.

An important point to note is how bi-static baseline is measured. If we set apart the two USRPs so that they are side-on to each other, such that the transmitter and receiver are not pointing towards each other, even then we get quite a considerable crosstalk as shown in Figure 18 for a bi-static baseline distance of 5.5 inches. From Figure 19, we can see

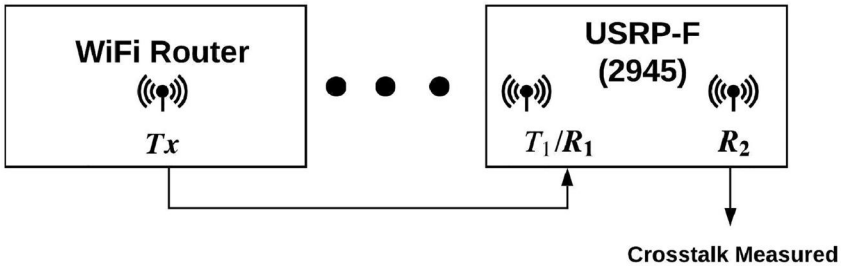

FIGURE 14 Illustration of measurements taken from USRP-2945. USRP, universal software radio peripheral

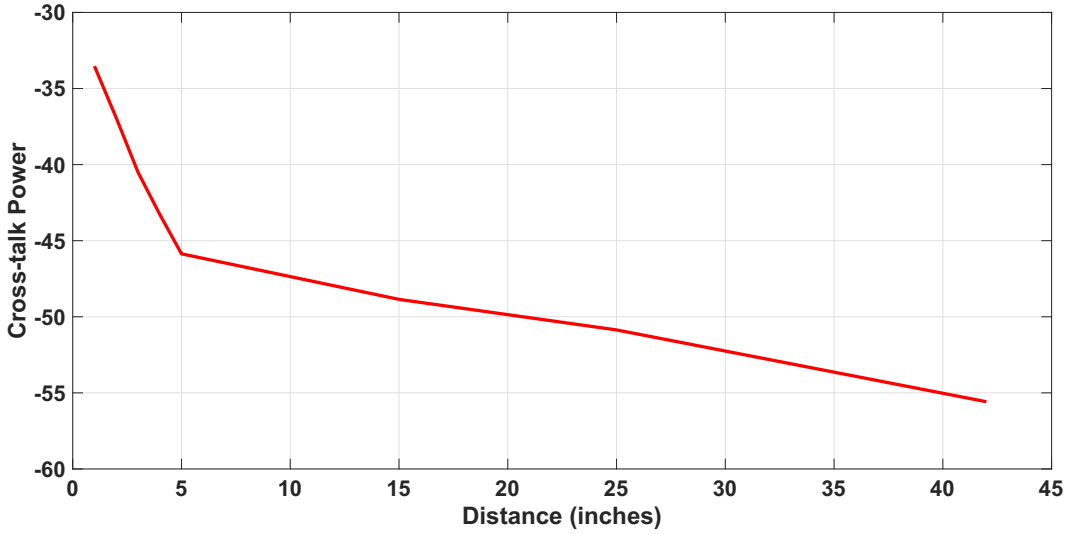

FIGURE 15 Bi-static crosstalk power versus bi-static distance for universal software radio peripheral-2945

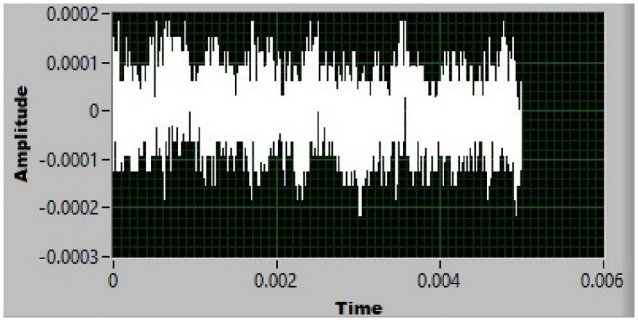

FIGURE 16 Waveform of leakage signal $x_l(t)$ for the 3-inch baseline distance

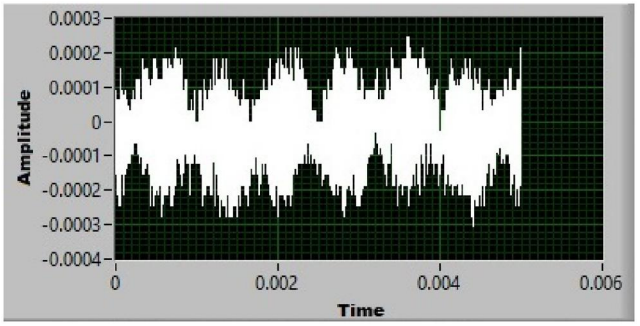

FIGURE 18 Waveform of leakage signal $x_l(t)$ for 5.5 inch sideways baseline distance

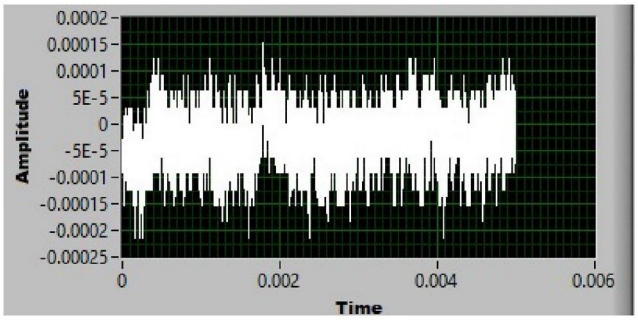

FIGURE 17 Waveform of leakage signal $x_l(t)$ for 6-inch baseline distance

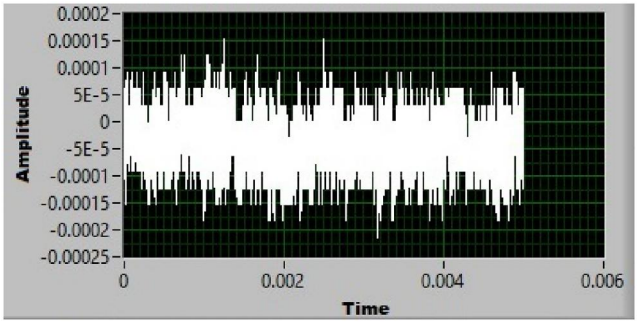

FIGURE 19 Waveform of leakage signal $x_l(t)$ for 11-inch sideways baseline distance

that the crosstalk is almost totally eliminated from the system for a bi-static baseline distance of 11 inches unlike the vertical orientation case where crosstalk was eliminated at 6 inches of separation. Hence, orientation of the USRPs also influence the crosstalk, depending on how far the victim and aggressor ports are. Here although no antenna is used, the effective antenna patterns would dictate how the transmitted signal is propagated in space. Table 4 shows the results in tabular form where it can be seen that bi-static separation of 11 inches has eliminated the effect of cross-talk on the receiver. An interesting point to note is that the crosstalk is also dependent on the bi-static geometrical configuration as it can be seen that the orientation of the USRPs did have an effect on the resultant cross-talk. We can see that 4-inch bi-static straight line distance has the same cross-talk as 5.5-inch sideways bi-static baseline distance. An illustration of sideways placement can be seen from Figure 11 where USRPs are placed horizontally next to each other.

Figure 20 shows the effect on crosstalk power with increasing distance in bi-static configuration. It can be seen that there is a linear relationship between leakage power with baseline distance. Hence, care should be taken in evaluating the safe distance to avoid the crosstalk completely.

To see the effect of crosstalk power on the dynamic range R, we should make use of the bi-static radar equation. The signal to noise ratio for a bi-static radar has a minimum value at $R_T = R_R = R$. For normalized noise level of 1 (0 dB), we can make use of following radar equation.

$$R^4 = R_T^2 R_R^2 = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 K T_0 B F L P_r} \tag{3}$$

TABLE 4 Effect of crosstalks with bi-static configurations at 2.4 GHz

Baseline distance	Prx (dBm)
3-inch	−62.38
4-inch	−63.47
6-inch	−65
5.5-inch sideways	−63.47
11-inch sideways	−65
Noise	−65

where we have assumed that gain of transmitter G_T is equal to the gain of receiver G_R and equals $G_T = G_R = G = 0$ dB. The maximum input power of USRP is around 1 mW and for considering the mimimal effect on the distance, we are taking this as a figure of merit for the transmit power. Moreover by assuming a drone target [33] with RCS of 1 m^2 and considering a noise figure of $F = 6$ dB, $K = 1.38 \times 10^{-23}$ J/K, $T_0 = 290K$, and wavelength $\lambda = 0.125$ m, Equation (3) reduces to

$$R = \frac{836.66}{Pr^{1/4}} \tag{4}$$

Figure 21 shows how the dynamic range of the signal is affected by increasing the crosstalk power. Crosstalk power has a direct influence on the maximum target range of the target. Refer to Table 2, if we consider worst case crosstalk power (−34.95 dBm) of USRP-A (2922), the maximum target range comes out to be 35.2 km. If we switch from mono-static system to a bi-static radar with a separation of 3-inch and 6-inch between transmitter and receiver (refer to Table 4), the maximum dynamic range comes out to be 198.4 and 170.62 km respectively that is an improvement of around 30 km in range by a mere change of bi-static distance to few inches.

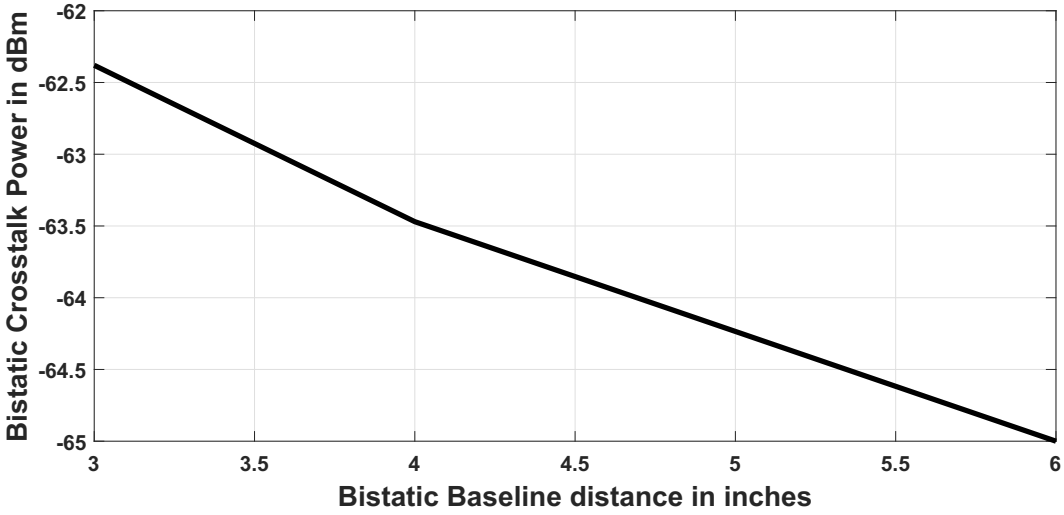

FIGURE 20 Bi-static crosstalk power versus bi-static distance

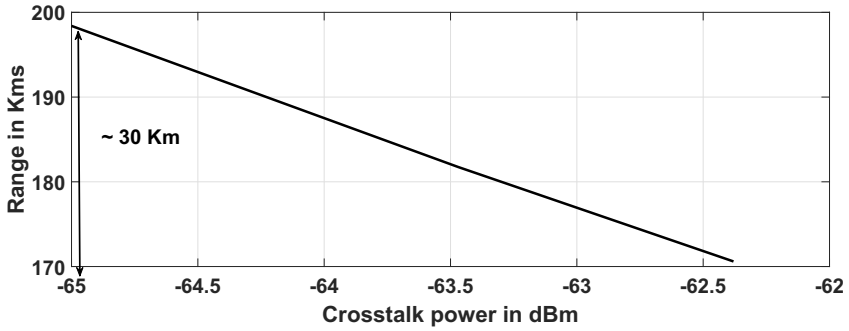

FIGURE 21 Dynamic range versus crosstalk power

5.1 | Influence of cross-talk on range-Doppler profile

If a directional antenna were used, then the crosstalk would also be reduced as the energy would be directed away from the second USRP and towards the target. For range-Doppler profile, the measured data is taken from USRP into LabVIEW and later imported into MATLAB. Figure 22 shows the range-Doppler profile that we measured inside the laboratory environment at University College London (UCL) using USRP-2943R (RIO) and directional Yagi antennas. The operating frequency of 2.4 GHz and an IQ rate of 38 MHz is used for this measurement. Moreover, gain of 30 dB is used for the USRPs that were set in the bi-static configuration at a distance of around 85 inches that is around 2 m. This gives a result showing a static target (the ceiling in our case) at a distance of 9000 mm that is 9 m, under the influence of crosstalk, which in certain cases can get totally shadowed. The strong reflection that is seen at 9 m can get faded away if the bi-static baseline distance is reduced because of stronger crosstalk effect.

In order to add the effects of Doppler, new measurements have been taken using a moving target (human moving inside the laboratory). The range-Doppler profile of the moving target has been shown in Figure 23. An effect of micro-Doppler (with less intensity) can also been seen.

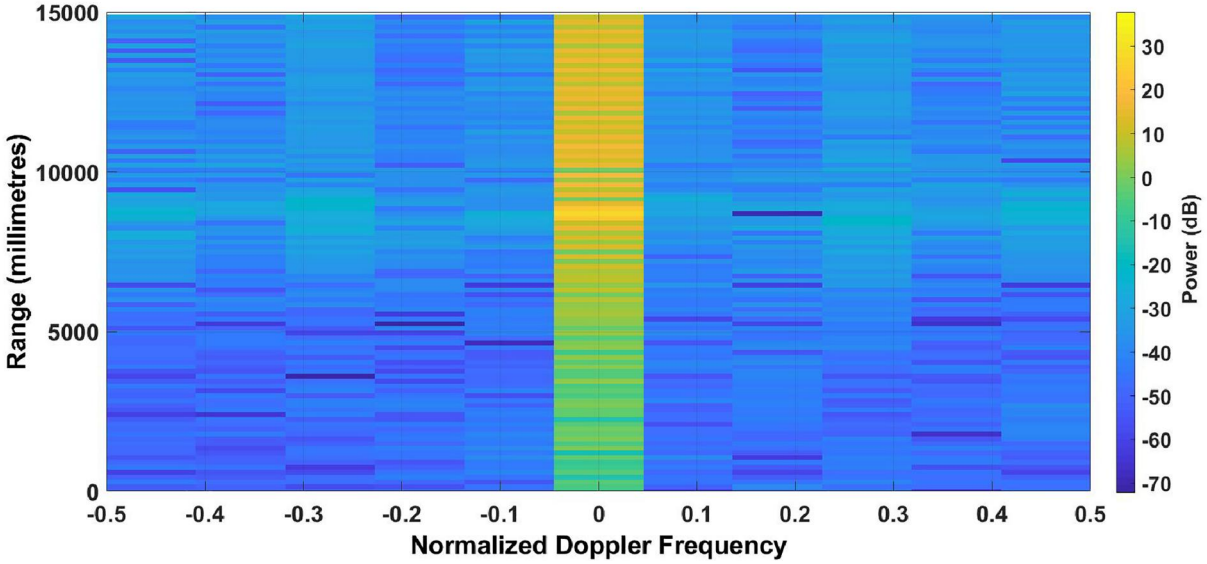

FIGURE 22 Range-Doppler profile under crosstalk

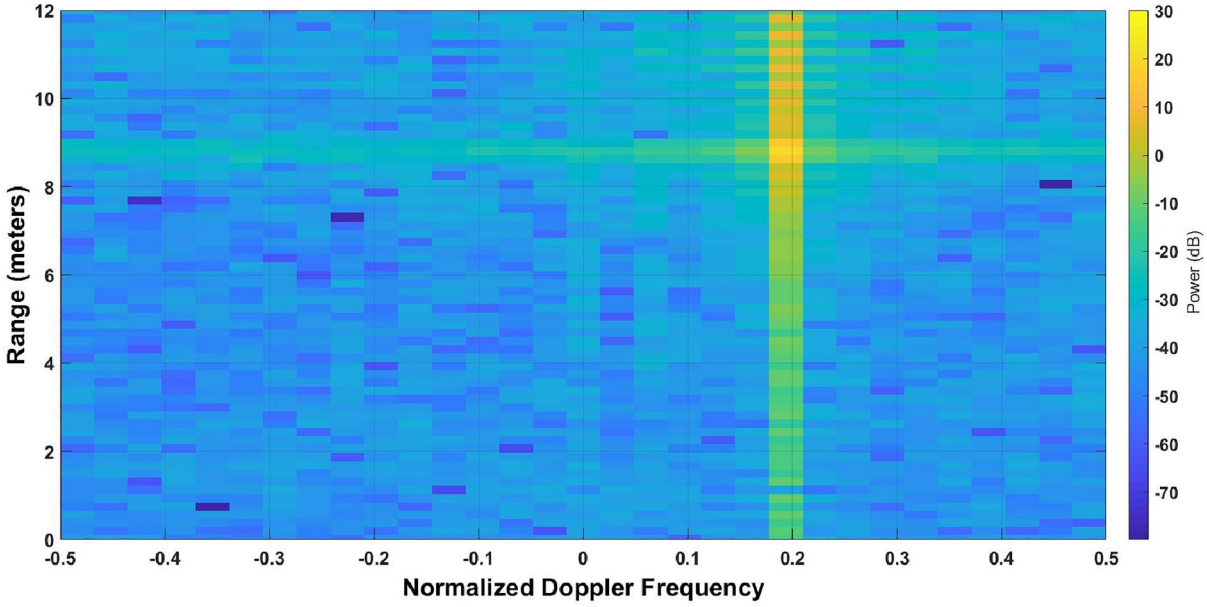

FIGURE 23 Range-Doppler Profile of a moving target under crosstalk

In addition, measurements have been taken under environmental effects of wind and fog. To mimic the practical windy environment on airborne platform, a pedestal fan moving at a velocity of 8 miles per hour (at 1 m distance) is used. Figure 24 shows illustration of windy environment using pedestal fan. Here, we are talking about a set-up of two USRPs at a distance of 2 m from each other and the stimulus of strong wind is applied from a distance of 1 m. For a Wi-Fi antenna of length 0.003 m, our far field distance comes out to be 0.00014 m, whereas the distance between the two USRPs is 2 m. An airborne platform like a drone having two SDRs for independent communication can exhibit additional noise created by wings on top of crosstalk. As it is a moving platform, there would be a substantial involvement of air between the two devices. The purpose of this experiment is not to quantify the impact of wind on radio signal receptions. Although it is well known that strong wind tends to bend and also scatter radio signal beam [34], which will in effect create more multiple signals that will either lower or increase the strength of received network signal at a point [35], the aim of this experiment is to rather show the effects of electrical noise that is introduced by the fan being turned on. Hence, the basic idea of using the pedestal fan is to investigate the effects of electrical noise on the USRP devices. It is well known that motor fans used for cooling electric motors have long been recognized as one of the major noise sources [36]. Especially in our case, where crosstalk noise already has an influence in the overall measurements, noise reduction at source is very important to cater and therefore a critical task. The noise generated in motor fans is mainly due to aerodynamic noise [37]. There are many examples where fan noise has been diagnosed to see the overall effect on the aerodynamic performance [38]. In real fan noise applications, total noise often radiates from the blades and fixing elements. The blade-pass-frequency and its harmonics act as stationary sources radiating an electrical noise [39]. Figure 25 shows the waveform graph for the effect of crosstalk under windy environment for two USRPs at distance of 1 m (around 30 inches) from each other. The measurements reveal that power of around −57.5 dBm is observed for 50 Ω load. Referring to Equation (2), electrical noise created here would contribute on top of the additional crosstalk power $x_I(t)$. The aim of this experiment is to show that windy sources (for example-wings of drones) do have an influence on received signal strength and hence the crosstalk in USRPs. It does not quantify the impact of wind on radio signal receptions. In addition, experiments have also been done under non-windy foggy environment. No substantial difference has been observed under foggy environment; however, it can vary for aerial platforms and provides interesting direction for future works.

6 | RECOVERY OF THE TRANSMITTED WAVEFORM

In FMCW system, the transmitted waveform is important, whereas the bi-static geometry needs a way to obtain the transmitted waveform. Distributed devices need to be synchronised in order for the receiver to recover the transmitted waveform. Synchronisation is necessary in communication networks like USRPs to enable coordination among spatially distributed nodes. In order to have a radar system that works correctly in USRP-based bi-static configuration, it needs a good level of synchronisation. USRP-2922 can be synchronised using MIMO cable as shown in Figure 26. The MIMO expansion cable is a 0.5 m length cable that is used to link a pair of USRP systems together. One of the USRP device is configured to accept frequency and timing reference of the master USRP from the MIMO cable. As MIMO cable usually has a limited length, it can only be used for synchronising two nearby SDR devices. On the other hand,

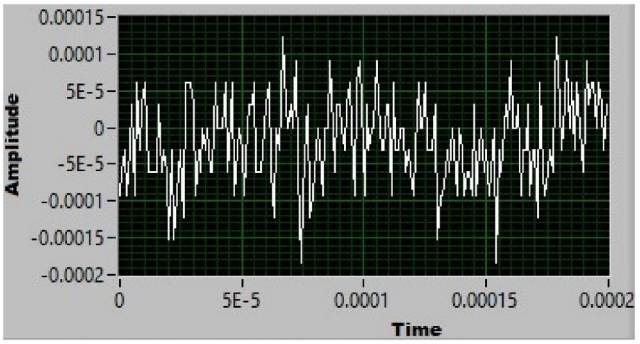

FIGURE 25 Waveform graph depicting the effect of crosstalk under windy environment across the universal software radio peripherals

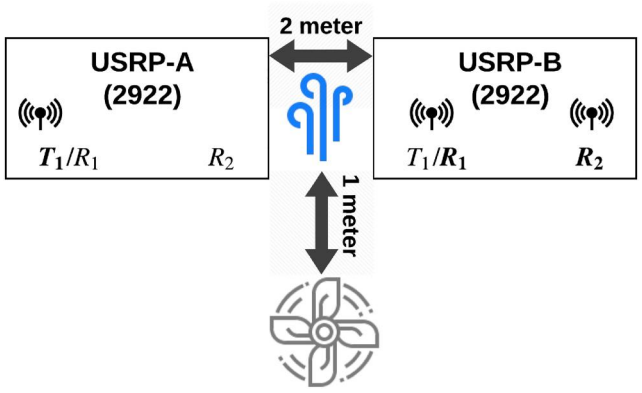

FIGURE 24 Illustration of windy environment using pedestal fan that cause electrical noise. USRP, universal software radio peripheral

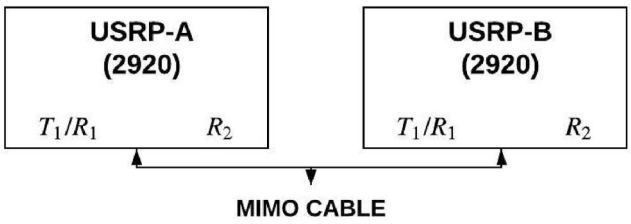

FIGURE 26 Synchronisation of USRPs using MIMO cable. USRP, universal software radio peripheral

USRP RIOs can be synchronised using octoclock [40]. Apart from that, usually Patton's approach is followed for time synchronisation in which a 50 Ω coaxial cable is used to connect transmitter and receivers of the daughter boards [41]. Most synchronisation approaches require a significant amount of overhead [42] and hence they are not suitable for USRPs used in rugged applications. In G. Aloi et al. [43], a preamble is transmitted with various pulses. This approach is not only complex but also applicable to pulsed radars only. In this work, we have used a naïve approach for recovering the transmitted waveform, that is, synchronisation of spatially distributed USRPs using RF splitter. If we have to synchronise two different types of USRPs we can use a splitter as shown in Figure 27. One output is connected to the antenna and the other can be inserted with the receiver terminal of other USRP device. Similarly, the other terminal of USRP receiver can be configured for target echo reception. As MIMO cable usually has a limited length, it can only be used for synchronising two nearby SDR's whereas by using a splitter based configuration, we can synchronise two 2922 USRPs at greater distances from each other. Use of splitter can serve additional advantages of protecting the receiver from high-powered transmitting signal. Using this approach, we can synchronise multiple USRPs in multi-static configuration as well, given that delay of the cable is acceptable. For example, we can avoid using costly octoclock for synchronising multiple USRPs by using splitter-based approach as shown in Figure 28.

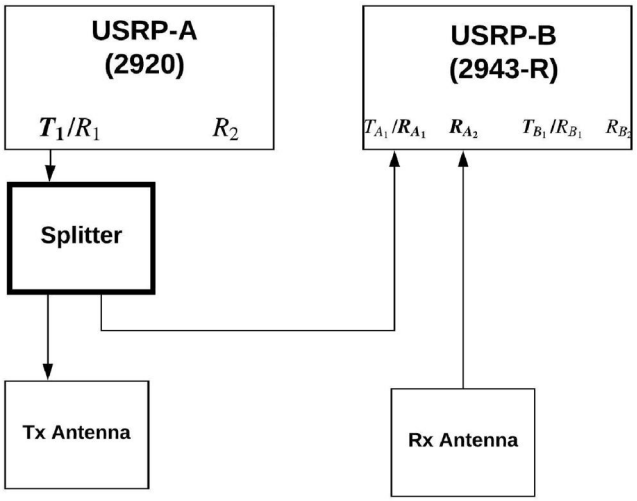

FIGURE 27 Proposed method of synchronising USRPs. USRP, universal software radio peripheral

7 | IMPACT OF CROSS-TALK ON APPLICATIONS WITH SMALL RADAR SIGNATURE

Based on our findings in previous section, it is shown that crosstalk can badly impact the performance of USRP-based radar for applications with small radar signature, for instance Micro-Doppler analysis of low RCS target like drone or bird. Micro-Doppler is referred to those Doppler components that arises from the non-rigid part of the target. These non-stationary components are used in detection, tracking and classification of such targets [44, 45]. If we focus our attention to micro-Doppler analysis of targets using USRP, our findings prove that mono-static implementation of FMCW on USRP is not feasible. A detailed performance analysis of different bi-static/multi-static configurations for micro-Doppler classification is an open problem and yet to be investigated [46]. The time varying nature of the signature requires time frequency analysis technique because of low power of micro-Doppler components in the signal [47]. In addition, the signature varies with target aspect angle [48], which is an additional challenge during target detection process. The drone exhibits visible micro-Doppler with strength of about {−40 dBm} [49] which is very close to our measured crosstalk power in mono-static configuration. If this is added with additional crosstalk power, the overall system would get highly affected resulting in inaccurate measurements which are taken from the SDR. Moreover, micro-Doppler classification requires large amount of data to be recorded [50] which demands interference free hardware. Hence, for micro-Doppler classification doing USRP, it is imperative to resolve the issue of crosstalk as discussed in this study.

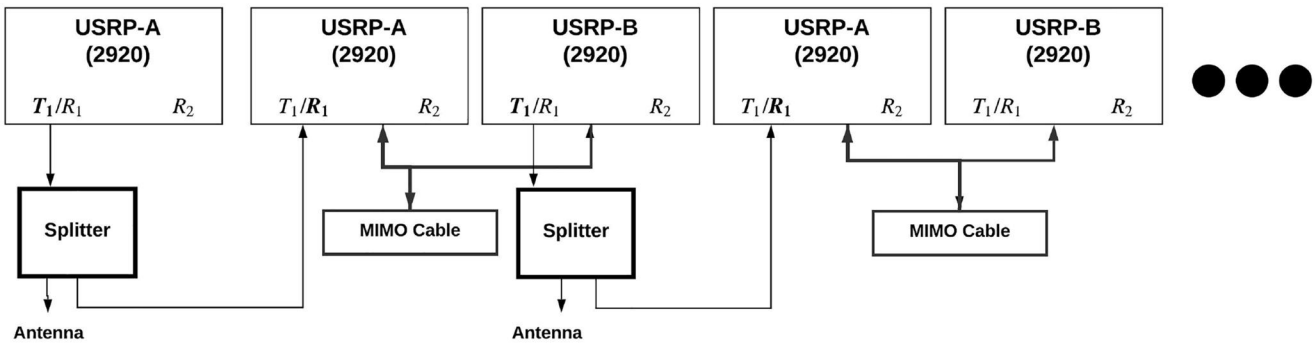

FIGURE 28 Generic Synchronisation using splitter based approach. USRP, universal software radio peripheral

8 | CONCLUSION

In this study, crosstalk in modern USRP-based SDRs is investigated for the implementation of FMCW based radar systems. The crosstalk measured during this empirical investigation proves that it can badly impact the performance of USRP-based applications with small radar signature, for instance Micro-Doppler analysis of low RCS target like drone or bird. Using the empirical analysis, it is shown that an SDR based FMCW system could experience considerable crosstalk if implemented in mono-static configuration. Therefore, implementation of FMCW radar system in bi-static/distributed configuration renders more benefits in terms of detection of targets and also in signal processing as it does not need a crosstalk elimination procedure. It is shown that the dynamic range can be increased by tens of kilometers by increasing baseline distance to few inches. If mono-static configuration is to be used, use of different channels (for transmitting and receiving) results in significant reduction in crosstalk, of the order of tens of dBs. Moreover, crosstalk power differs for multiple devices with the same specifications; therefore, a calibration of each specific device should be performed for implementation of FMCW systems. Finally, to synchronise different types of USRPs, a simple splitter based approach is proposed for recovering the transmitted waveform by multiple USRPs at the same time.

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CONFLICT OF INTEREST

None.

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