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Spectral Signature Secured Retrodirective Array

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Abstract: A novel retrodirective array (RDA) architecture is proposed which utilises a special case spectral signature embedded within the data payload as pilot signals. With the help of a pair of phase-locked-loop (PLL) based phase conjugators (PCs) the RDA's response to other unwanted and/or unfriendly interrogating signals can be disabled, leading to enhanced secrecy performance directly in the wireless physical layer. The effectiveness of the proposed RDA system is experimentally demonstrated.

1. Introduction

A retrodirective array (RDA) is capable of re-transmitting signals back along the spatial direction along which the array was interrogated by the pilot signal without requiring a-prior knowledge of its direction of arrival [1]. This automatic tracking or beam-steering characteristic makes RDA technology suitable for a number of applications involving mobile wireless platforms, [2–4].

In order to achieve retrodirective re-transmit functionality, a phase conjugator (PC) is required [5]. Analogue PC solutions, particularly phase-locked-loop (PLL) based circuitry [6], [7], offer faster response and lower power consumption when compared with their digital counterparts [8]. RDAs suffer from the inability to distinguish the pilot-tone signal, originated from a desired direction, from an identical frequency signal, which may be radiated unintentionally or intentionally from different directions. The consequence of this is that the RDA's re-transmission pattern would form multiple main beams whose magnitudes are proportionate to the strengths of the corresponding interrogating signals (pilot tones) incident upon it [9–11]. This leads to reduced gain of the wanted transmission link, and, information leakage into unwanted spatial directions.

The only solution to this scenario found in the open literature uses the sub-array concept, which enables the entire array to form a power null along the direction where an extraneous pilot exists. This approach can only operate when there is one undesired pilot. Furthermore, it assumes that this unwanted source direction can be resolved and remains static, [12], [13]. This, however, cannot be guaranteed in most application scenarios. In addition, the sub-array architecture approach greatly reduces transmit and receive gains, especially when the desired target and other pilot source are close in angular separation.

In this paper an alternative solution is described. Instead of using a single carrier signal as a pilot tone as in the classical RDA approach, a modulated signal with a distinct frequency signature is chosen. This, with the help of a dual-PLL-based PC arrangement, can be exploited for spatial direction authentication. It should be noted that here we do not intend to design an RDA that projects null(s) along unwanted incoming pilot direction(s), but we wish to disable the RDA's response to such stimuli. The ultimate aim is to form array radiation pattern(s) steered only towards the wanted direction(s). Additionally, with the proposal in this paper, we can enhance security

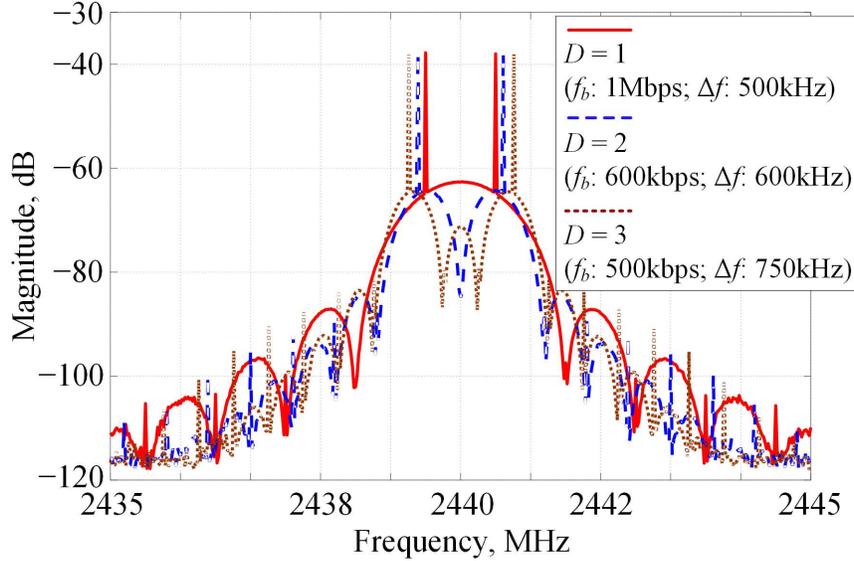


Fig. 1. Measured 2FSK frequency spectrum for D of 1, 2, and 3. f_c is fixed to 2440 MHz and f_b is the rate of PRBS data.

performance when compared with the classical RDA operation.

2. Spectral Signature Secured Retrodirective Link

For discussion consider a binary frequency-shift keying (2FSK) signal. For a 2FSK signal the deviation ratio, D , is defined in [14] as $D = 2\Delta f/f_b$. When this satisfies

$$|\cos(\pi D)| = 1, \quad (1)$$

the frequency spectrum, $S(f)$, of the 2FSK signal transmitting Pseudo-Random Bit Sequence (PRBS) data, according to [14], contains two very distinct spectral peaks at $f_c \pm \Delta f$, (2), see Fig. 1.

$$S(f) = \frac{1}{4}\delta(X - D) + \frac{1}{4}\delta(X + D) + \frac{2}{f_b} \left[\frac{D}{\pi(D^2 - X^2)} \right]^2 (1 - \cos \pi D \cos \pi X) \quad (2)$$

$$X = 2(f - f_c)/f_b \quad (3)$$

Here f_c , Δf , and f_b denote the carrier frequency, the 2FSK frequency deviation, and the bit rate respectively.

The proposed RDA architecture is illustrated in Fig. 2, and its operation is described as follows;

1. The desired target radiates a pilot signal modulated for 2FSK with D set to be an integer.
2. Each PLL PC in each RDA receive chain pairing, shown in Fig. 2, respectively locks to each of the two discrete frequency spikes that are present in the frequency spectrum, Fig. 1, i.e.,

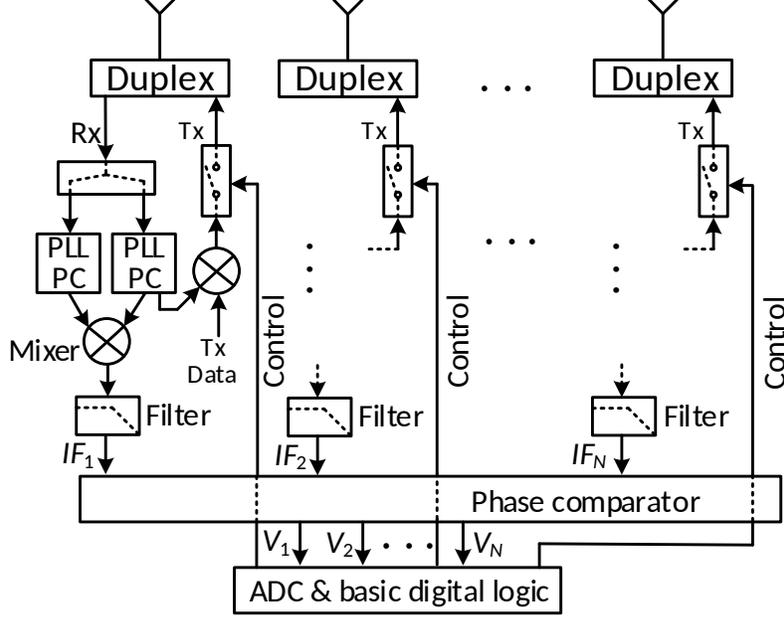


Fig. 2. Proposed dual-PLL PC RDA architecture.

$f_c \pm \Delta f$. The PLL PCs can be set up a priori, or the centre frequencies of the two PLL PCs can be tuned by changing the frequency divider coefficients in the feedback path in a programmable fashion. This can be achieved using divider coefficient information carried as part of the 2FSK data payload and demodulated in the conventional way, not shown. If required, the divider coefficient information itself can be encrypted by conventional mathematical means for additional security.

3. Since the two spectral spikes are at nearly the same frequency, the phase of the mixing intermediate frequency (IF) product of two PLL PC outputs is nearly identical for each receive chain in the array. When this is qualified as being the case, the RDA's re-transmission functionality is enabled by conjugating using a single PLL PC and multiplying up the PLL PC output with the required re-transmitted data stream applied, see Fig. 2.

This results in re-transmission antenna array radiation pattern steered towards the desired direction. An additional benefit of the approach is that the outputs from each of the mixers in the array are in-phase, so that they can be scalar summed to give a gain to the received signal which is equivalent to that of the receive array factor gain.

The 'phase comparator' module in Fig. 2 can be implemented using an array of phase detectors which compare the phase of IF_1 with each of the remaining IF signals, thus generating $N - 1$ voltage outputs, i.e., V_1 to V_{N-1} labelled in Fig. 2. A low speed analogue-to-digital-converter (ADC) then converts these into the digital domain, followed by basic digital logic units to check if the $N - 1$ voltages are 'identical' or not. In practical realization, a small voltage deviation should be allowed, the range of which is set to reject hardware noise. Thus according to the operating principle of the approach in this paper, when V_1 to V_{N-1} are virtually 'identical', the RDA re-transmission paths are enabled, otherwise, they are disabled.

It should be noted that when the special case condition, denoted by (1), does not occur the PLL PCs are unable to lock onto the 'normal' 2FSK spectrum due to the rapid phase fluctuations

between consecutive data bits, thus authentication fails.

The detailed explanation of the re-transmission enabling condition, i.e., the phase of the mixing IF product of PLL PC pairs being identical in every receive chain, is now presented;

- a) When two designated frequency components detected by the proposed N -element RDA are contributed only by a 2FSK pilot signal projected through a legitimate receiver, the two phase conjugated signals at the outputs of the two PLL PCs in the n^{th} receive chain, S_{n1} and S_{n2} , can be expressed as

$$S_{n1} = \exp[j2\pi(f_c - \Delta f)(t + r_n/c)] \quad (4)$$

$$S_{n2} = \exp[j2\pi(f_c + \Delta f)(t + r_n/c)] \quad (5)$$

Here r_n denotes the displacement between the desired target and the n^{th} RDA element, and c is the speed of light. Then the mixing IF product is

$$IF_n = \exp[j4\pi\Delta f(t + r_n/c)]. \quad (6)$$

From (6) the maximum phase difference of N mixing IF products can be derived as

$$\begin{aligned} P_{diff_max} &\leq \frac{4\pi\Delta f \max |r_m - r_n|}{c} \\ &= \frac{4\pi \max |r_m - r_n| \Delta f}{\lambda_c f_c}, \end{aligned} \quad (7)$$

where λ_c is the wavelength corresponding to the carrier frequency, and $\max |r_m - r_n|$ represents the maximum dimension of the RDA aperture ($m, n = 1, \dots, N$). Since a typical RDA array aperture normally has a size smaller than ten times of λ_c , and f_c is a thousand times greater than Δf , the resulting phase differences of the mixing IF product on each receive chain are negligible, assuming matched receive chain components. For example, for a 7-element $\lambda_c/2$ spaced linear array, when $f_c = 2440$ MHz, and $\Delta f = 500$ kHz, $P_{diff_max} \leq 0.45^\circ$.

- b) When a pilot is originated from a different direction to the 2FSK spectral signed pilot pair, at either of the two distinct frequencies that are contained within the 2FSK pilot pair, the S_{n1} and S_{n2} can be written as (8) and (5). Here it is assumed, without loss of generality, that the frequency of the interfering pilot is $f_c - \Delta f$, and it has the same power as that of the $f_c - \Delta f$ component in the 2FSK pilot signal.

$$\begin{aligned} S_{n1} &= \exp[j2\pi(f_c - \Delta f)(t + r_n/c)] \\ &\quad + \exp[j2\pi(f_c - \Delta f)(t + g_n/c) - j\varphi] \end{aligned} \quad (8)$$

g_n is the displacement between the interfering pilot and the n^{th} RDA element, and φ refers to the phase difference of the interfering pilot compared with the 2FSK pilot signal at their corresponding source points. In this case the phase P_n of the mixing IF product of the S_{n1} and S_{n2} is

$$P_n = 4\pi\Delta f r_n/c - \pi(f_c - \Delta f)(g_n - r_n)/c + \varphi/2. \quad (9)$$

On the right hand side in (9), the first and the third items for different n can be considered as constants, while the second item varies greatly because the two sequences g_n and r_n ($n = 1, \dots, N$) are uncorrelated due to their different directions of arrival. In order to illustrate interference rejection capability when interfering and interrogating tones are close in angular separation, consider again a 7-element $\lambda_c/2$ spaced linear array with, as previously, $f_c = 2440$ MHz, $\Delta f = 500$ kHz, if $r_{n+1} - r_n = \lambda_c/2 \times \cos(90^\circ) = 0$ and $g_{n+1} - g_n = \lambda_c/2 \times \cos(85^\circ)$, i.e., the angular separation between interrogating and interfering pilots is only 5° , the phase difference $|P_7 - P_1|$ is calculated to be greater than 47° . Hence signal authentication would fail and RDA re-transmission would be disabled.

- c) When there are two interfering pilots with frequencies of $f_c - \Delta f$ and $f_c + \Delta f$, respectively, located along two different directions, the two conjugated signals S_{n1} and S_{n2} take the forms in (8) and (10),

$$S_{n2} = \exp [j2\pi(f_c + \Delta f)(t + r_n/c)] + \exp [j2\pi(f_c + \Delta f)(t + l_n/c) - j\theta]. \quad (10)$$

Here l_n and θ have similar meanings to g_n and φ in (8), but are associated with the $f_c + \Delta f$ interfering pilot. In this scenario the phase P_n of the mixing IF product of the S_{n1} and S_{n2} can be derived as in (11),

$$P_n = 2\pi\Delta f(r_n + l_n)/c - \pi(f_c - \Delta f)(g_n - l_n)/c + \varphi/2 - \theta/2, \quad (11)$$

in which the term $(f_c - \Delta f)(g_n - l_n)/c$ results in different phases for different RDA receive chains. It is noted that when $l_n = r_n$ and $\theta = 0$, (11) becomes (9), which is the single interfering pilot case in b). In addition, when $l_n = g_n = r_n$ and $\theta = \varphi = 0$, (11) becomes $4\pi\Delta fr_n/c$, which is the interfering pilot-free case in a).

For scenarios where a wideband or multi-band interfering signal exists that contains both $f_c - \Delta f$ and $f_c + \Delta f$ frequency components of adequate power to simultaneously activate both PLL PCs, the phase P_n of the mixing IF product of the S_{n1} and S_{n2} is $2\pi\Delta f(g_n + r_n)/c$. This phase P_n , when, and only when, interfering tone pairs are phase locked to each other, can also be regarded as a constant for different n . As a consequence in order to ensure that the RDA has no response to such interfering pilot signals, identification data encoded into the required payload data, may be necessary. This scenario is beyond the scope of this paper, thus is not discussed.

When two, or more, valid 2FSK phase locked pilots are incident from different directions, and these two, or more, communication directions are required for re-transmission, then the proposed RDA could generate beams that point to each of the 2FSK pilot tone pair directions upon re-transmission [9]. It is also worth noting that the proposed RDA arrangement can also operate in multipath scenarios as long as the $2\Delta f$ is smaller than channel's coherence bandwidth.

3. Experimental Proof of Concept

In order to experimentally validate the proposed RDA system described in Section 2, four identical frequency-tunable PLL PCs were designed and fabricated, shown in Fig. 3. These were then used to construct two RDA receive chains. In order to simulate behaviour of RDAs with different sizes

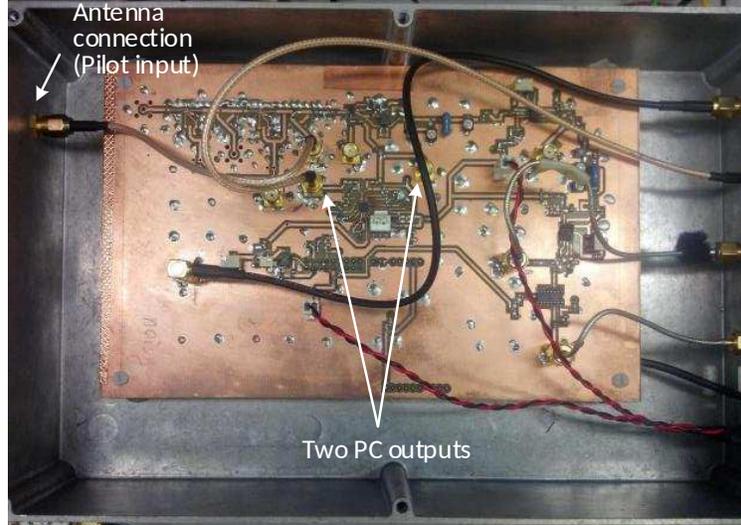


Fig. 3. Photo of fabricated frequency-tunable PLL PC.

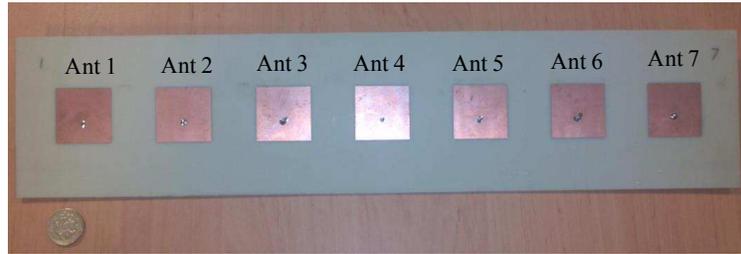


Fig. 4. Photo of fabricated 7-element 2.4 GHz patch antenna array.

of array apertures, the two receive chains were connected to the 1st and the 2nd or the 1st and the 7th elements in a 2.44 GHz patch antenna array which has uniform $\lambda_c/2$ spacing between elements, see the photo in Fig. 4. The S-parameters and the normalised active element patterns, associated with the 1st, the 2nd, and the 7th elements in the fabricated array, were measured and these are presented in Fig. 5 and Fig. 6, respectively. It can be seen that at 2.44 GHz the antennas are well matched and isolated, and the radiation patterns are relatively broad in half space.

The block diagram of the experimental setup for proof of concept is plotted in Fig. 7. The 1st and the 7th antennas are connected in the graph for illustration purpose. In the RDA experiment a 2FSK signal centred at $f_c = 2440$ MHz with $f_b = 1$ Mbps and $\Delta f = 500$ kHz was generated as the pilot signal and was radiated by a horn antenna in the far-field. The 2FSK signal has two discrete frequency components at 2439.5 MHz and 2440.5 MHz, see Fig. 1, at which frequencies the two implemented PLL PCs in each receive branch operate. The frequencies of their phase conjugated output signals were set to be 2443.69 MHz and 2444.69 MHz, from which a 1 MHz IF mixing product was obtained in each receive branch. The choice of the PLL PC output frequency is determined by the 4.19 MHz IF filters adopted in the PLLs.

Firstly, it was verified that two PLLs were able to be phase locked to the two discrete frequency spikes present within the 2FSK spectrum. At the received 2FSK signal power level as low as -113 dBm, each PLL PC could generate spectrally pure phase conjugated output signal at a constant output magnitude of -3 dBm. These two 2443.69 MHz and 2444.69 MHz signals were extremely

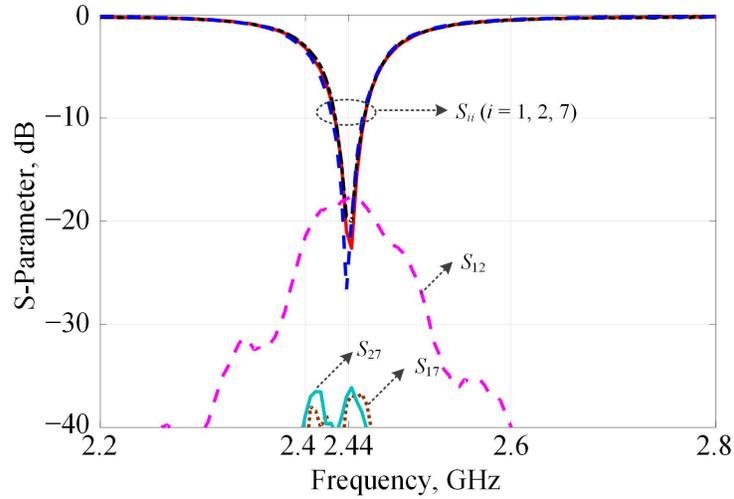


Fig. 5. Measured S -parameters of the 1st, the 2nd, and the 7th elements in the fabricated 7-element array.

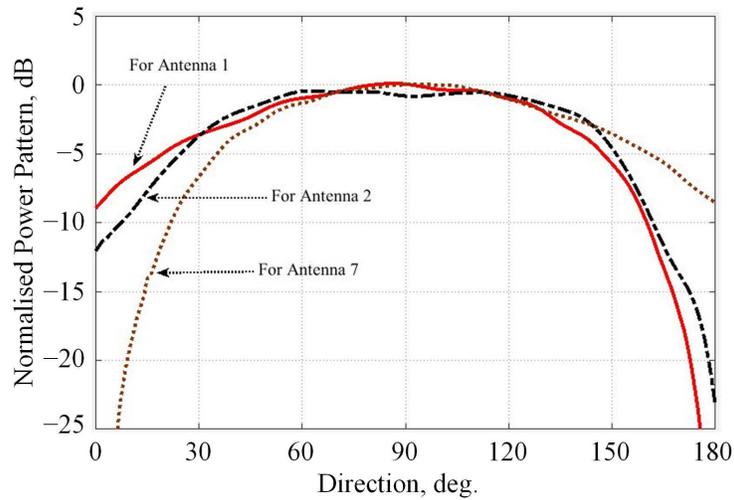


Fig. 6. Measured normalised active element patterns of the 1st, the 2nd, and the 7th elements in the fabricated 7-element array. Boresight is along the direction θ of 90°.

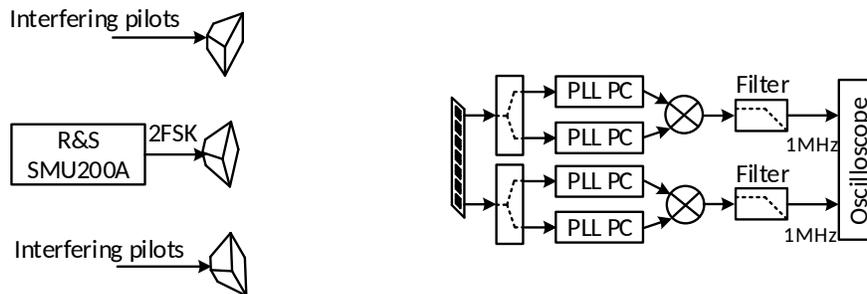


Fig. 7. Block diagram of the experimental setup.

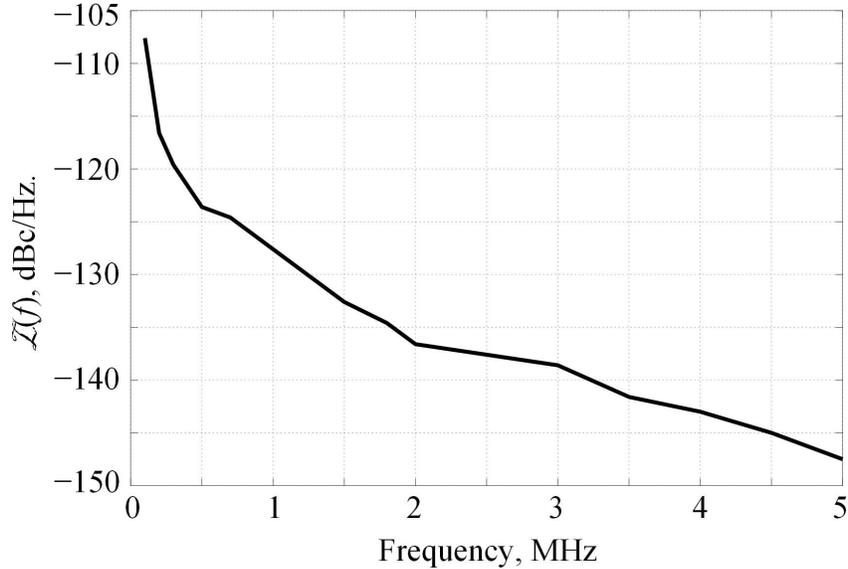


Fig. 8. Measured single sideband phase noise $\mathcal{L}(f)$ of the phase conjugated 2444.69 MHz signal.

‘clean’, since they were directly generated by multiplying up a temperature compensated crystal oscillator (TCXO). The measured single sideband phase noise $\mathcal{L}(f)$ of the reconstituted phase conjugated 2444.69 MHz signal is plotted in Fig. 8.

The two 1 MHz IF signals obtained in the 1st and the 2nd (or 7th) receive branches were observed on an oscilloscope. They stayed in-phase and did not vary in magnitude or phase while altering the angle of arrival of the incoming 2FSK pilot signal radiated by a horn antenna at the pilot source in the far-field. The measured screen-shot for the choice of the 1st and the 7th antenna pair is shown in Fig. 9. Here no variation in the Lissajous figure with respect to that shown in the diagram was observed as the angle of arrival (or path length) of the 2FSK pilot was varied, validating the enabling condition for RDA re-transmission stated in the previous section. The non-ideal straight line of the Lissajous curve in Fig. 9 was caused by the imperfect response of the low-pass-filters.

Further experiments were conducted when additional interfering pilots were applied, using the arrangement in Fig. 7. Three types of interfering pilots were used: a) signals with no frequency spikes at $f_c \pm \Delta f$; b) a single tone at either $f_c + \Delta f$ or $f_c - \Delta f$; c) two tones at $f_c + \Delta f$ and $f_c - \Delta f$, respectively, which were radiated by two interfering sources along two spatial directions. For case a) no IF phase variation was observed, indicating that the RDA was immune to this type of interfering pilots. For cases b) and c), corresponding to the scenarios b) and c) discussed in Section 2, the phase differences between the 1 MHz IF signals obtained in two receive branches did change noticeably, i.e., signal authentication failed and RDA re-transmission was disabled. A screen-shot of the resulting waveforms in the scenario b) is shown in Fig. 10, while the results for the scenario c) are similar, thus are omitted here.

The ability of the PLL PC pair to preserve input phase for an applied 2FSK signal was tested by applying a two-tone signal centred at 2440 MHz with 1 MHz spacing. Fig. 11 shows the measured phases of the 1 MHz IF signals with respect to the phase differences between the two tones. It can be seen that the PLL PCs are able to operate at a received power as low as -122 dBm, indicating their applicability for 2FSK signal detection at -113 dBm.

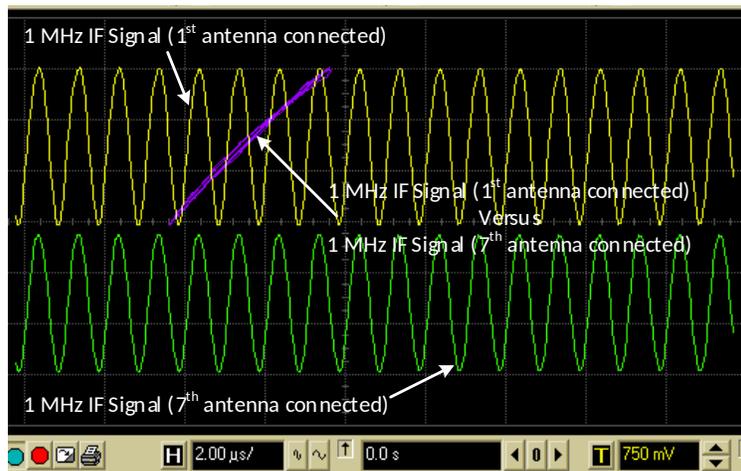


Fig. 9. Screen-shot of measured waveforms of 1 MHz IF signals when the 1st and the 7th antennas were connected. No interference pilots were radiated.

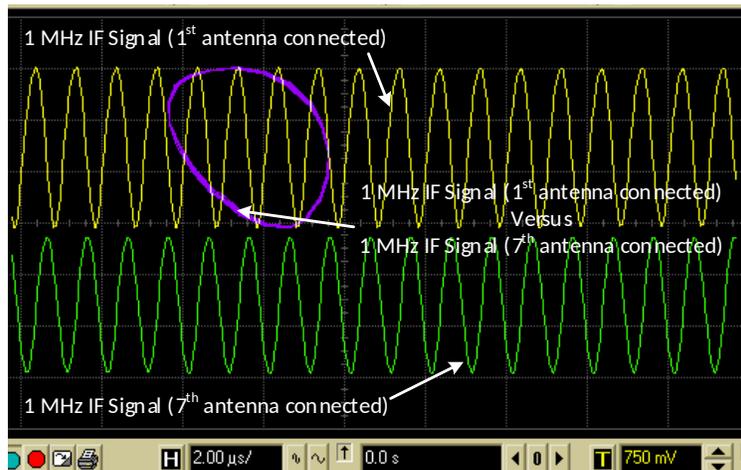


Fig. 10. Screen-shot of measured waveforms of 1 MHz IF signals when the 1st and the 7th antennas were connected. An Interference pilot at 2439.5 MHz was radiated along a spatial direction other than that of the 2FSK pilot.

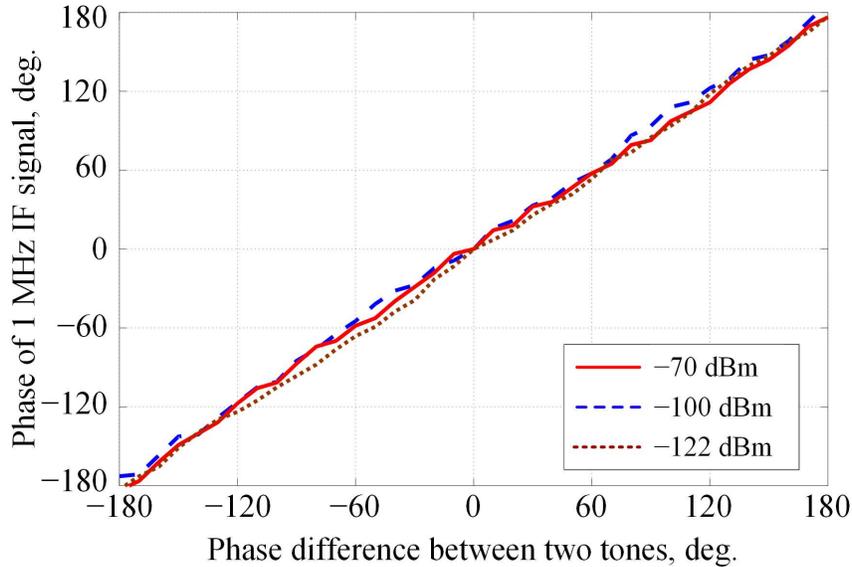


Fig. 11. Measured phases of the 1 MHz IF signals versus the phase differences between two tones for various input power levels in one receive chain.

4. Conclusion

This communication presented a real time analogue means by which an RDA can be configured in order to reject single frequency pilot tone beam stealing irrespective of the pilot tone direction. This was achieved by using the spectral signature characteristics of a 2FSK pilot signal under certain very specific modulation conditions. The proposed approach should also work using an amplitude shift keying (ASK) derived spectral signature. The approach significantly reduces the classical RDA problem of unwanted signal interception by beam stealing. This results in enhanced RDA performance with respect to both the security and the gain of the desired re-transmission link that can be obtained.

5. Acknowledgments

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