Analysis of Phase Noise Performance in Spatially Separated Backscatter Systems

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***Abstract*—Backscatter radio systems are generally considered to be suitable only for short range transmission limited by the two-way path losses and receiver sensitivity. Using a simple model of the receiver noise due to the leakage of the carrier signal into the receiver, we show that by spatially separating the transmit and receive antennas to increase isolation while sharing a single local oscillator such that the phase noise is correlated, a 6m antenna separation can achieve 10,000m² area of coverage, 3 times greater than a monostatic system. This can be increased a further 10 times if a delay is introduced to the path of the LO-Rx to match the propagation delay to within 1ns. Such a system could be implemented with a distributed antenna system or dedicated LO cable channel between the Tx and Rx nodes.**

***Keywords*—Backscatter, separated system, detectable area, phase noise, range correlation effect**

I. Introduction

The internet of things is predicted to cause a vast increase in the number of wirelessly connected devices. In many cases the devices will be severely power constrained so the power used for wireless communication must be minimized. For low data rate applications, backscatter communication is attractive, having a power consumption of 100-1000 times lower than conventional radio devices, however to date the range has been restricted.

In backscatter communication a carrier wave is transmitted to the backscatter device, where it is reflected and modulated to a receiver. As a result of the mode of operation, free space propagation losses are incurred in both the forward (carrier transmitter to backscatter device) and return (backscatter device to receiver). Hence for a monostatic reader where the carrier transmitter and backscatter receiver share a common antenna or are co-located, assuming free space propagation the received power scales as R^4 where R is the separation of the reader and backscatter device.

The ultimate range of a backscatter communication system is determined by the sensitivity of the receiver. Since, the carrier must be transmitted continuously during the backscatter, and the achievable frequency offset of the backscatter communication is generally small. The carrier leakage from the transmitter to the receiver is often the limiting factor in the receiver sensitivity.

A bistatic arrangement of the reader antennas as shown in Fig. 1 gives a wide spatial separation of the carrier transmitter and receiver and has the potential to mitigate both problems to an extent. Where the backscatter device is in the region between the transmit and receive antennas, free space propagation losses can be reduced compared to the monostatic case [1,2], and the free space losses between the transmit and receive antennas can provide a large isolation of the receive antenna to the transmitter reducing the noise entering the receiver.

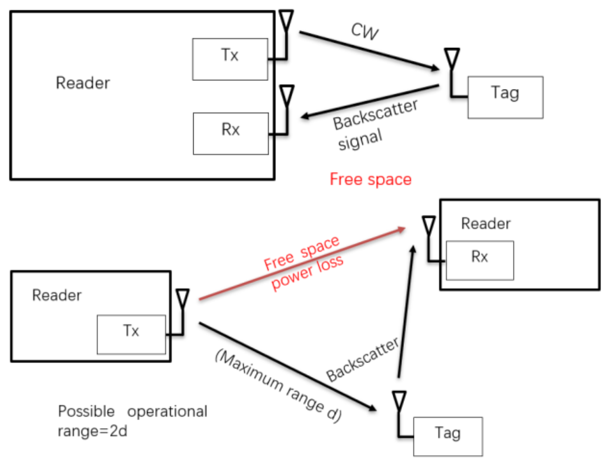


Fig. 1. Structure of bistatic reader and spatial separated system

However, in the case of a monostatic system, a commonly local oscillator is usually employed for the transmit and receive chains, greatly reducing the phase to amplitude converted noise in the receiver. Thus, to date, monostatic systems have generally been preferred for backscatter systems [3,4].

Long range backscatter systems have been investigated in [5] where a reflective amplifier is employed in the tag to improve the reflected power and hence link budget achieving a range of several kilometers. The other approach to improving the range is to reduce the influence of the phase noise on the receiver. Methods include cancellation of the leakage signal with an out of phase component [6], range correlation effect to reduce the phase noise impact for collocated antennas [7] and [8]. An alternative approach to mitigate phase noise is to place the backscatter communications signals away from the noise. Commonly this is achieved though miller modulation and a high backscatter frequency. In [9] a coding approach was developed to account for the non-white characteristic of the self-mixed noise. This paper focuses on how phase noise cancellation together with a separated structure could improve the detectable range for backscatter communications. Since the power consumption at the backscatter device will be determined by the backscatter switching frequency, it will be advantageous for low power devices to be able to use low backscatter frequencies.

The contribution of this work is to model the impact of phase noise on bistatic backscatter systems both for the case of independent local oscillators and the case where the LO is shared by some means (e.g. a dedicated wired channel or a distributed antenna system) such that the range correlation effect can be exploited. We show that significant range enhancement can be achieved compared to the monostatic case through the use of bistatic reader antennas and a common LO.

II. SYSTEM MODEL

We consider a simple backscatter system operating at 915MHz. For simplicity all antennas are assumed to be omni-direction and of matched polarization. The carrier transmitter emits a continuous wave (CW) carrier with phase which is modelled on the recorded phase noise as a piecewise linear fit (-70@1kHz, -87@4kHz, -87@80kHz, -140@800kHz) as shown in Fig. 2. The backscatter device is considered to be perfectly linear such that the modulation loss is independent of the incident RF signal. Phase modulation between open and short states is used to minimize the modulation loss. At the receiver we consider noise contributions arising from the leakage of the transmitted carrier and its phase noise. Any carrier leaking into the Rx antenna will be mixed by the LO to DC, which can be filtered and rejected, however the phase noise will be converted into amplitude noise at a frequency equal to the carrier offset by the mixing process. Where the Tx and Rx LOs are independent oscillators, the phase noise of each will be independent (although it may share a common characteristic shape as in Fig. 2) and reciprocal mixing (RM) will occur. In the case where a single LO is shared between the Tx and Rx, the noise will no longer be entirely independent, and the correlation of the noise becomes a function of the time delay. This gives rise to the range correlation (RC) effect which reduces the noise seen at the output of the mixer.

The Power Spectral Density (PSD) of received phase noise under the range correlation effect is:

$$S_{\Delta\varphi}(f) = 2S_{\varphi}(f)[4sin^2(2\pi\Delta t\Delta f)] \qquad (1)$$

where Sφ (f) is the PSD of phase noise send from the LO. Δf is the offset frequency in phase noise spectrum. Δt is the time difference between LO signal and receiving signal [7,8]. It can be seen from equation (1) that the suppression of the phase noise is a function of both the relative time delay and the offset frequency. For frequencies close to the carrier, the phase noise is supressed, although as the relative delay increases, both the level of suppression and the bandwidth over which suppression is effective decrease. Due to the low frequency offsets used in backscatter systems, range correlation can be very effective as shown in Fig. 3. Here a time delay of 0.33ns is applied with LOs phase noise shown in Fig. 2 when considering RC. Thermal noise is neglected to give clearer results.

A comparison of the phase noise of a bistatic system with independent oscillators and a monostatic system exploiting the range correlation effect is illustrated in Fig. 4. Both system have 30 dB isolation. In this case, thermal noise is included and the phase modulated backscatter has been emulated at an offset frequency of 50kHz. The blue curve, representing range correlation in a monostatic system, clearly has noise level in the frequency range of the modulation than a bistatic system with reciprocal mixing.

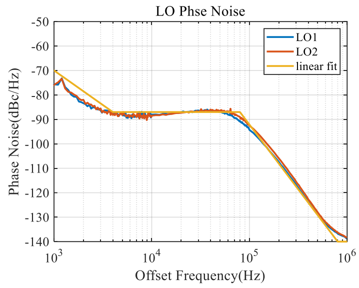


Fig. 2. Phase noise from local oscillators and linear fit

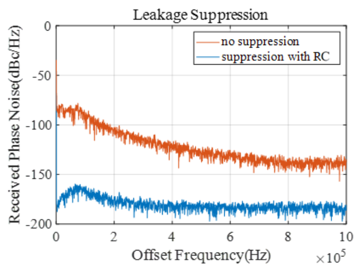


Fig. 3. Phase noise from leakage after down converting with or without range correlation

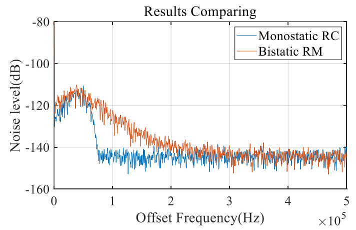


Fig. 4. Simulation on receive information in bistatic system without range correlation and monostatic system with range correlation

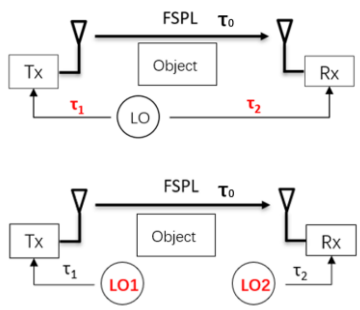


Fig. 5. Two types of LOs on separated setup

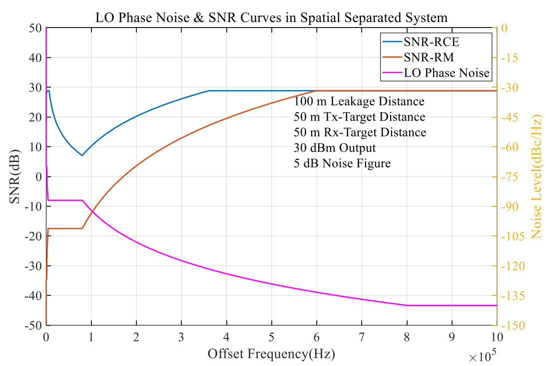


Fig. 6. Received SNR when range correlation and reciprocal mixing take place at receiver side under certain conditions

The potential area of coverage of a backscatter system is simulated by considering the locus of potential backscatter device positions where the SNR at the receiver will be equal to a required SNR level. The noise level considers noise attributed to the Tx leakage modified by either reciprocal mixing or range correlation along with a receiver noise figure (5dB is used in the following examples). In our consideration of the range correlation effect we consider τ_1 and τ_2 to be the delays between a common LO and Tx and Rx mixers respectively and τ_0 to be the propagation delay in free space between the Tx and Rx mixers (including antenna feed cables etc.) experience by the leakage signal as shown in Fig. 5.

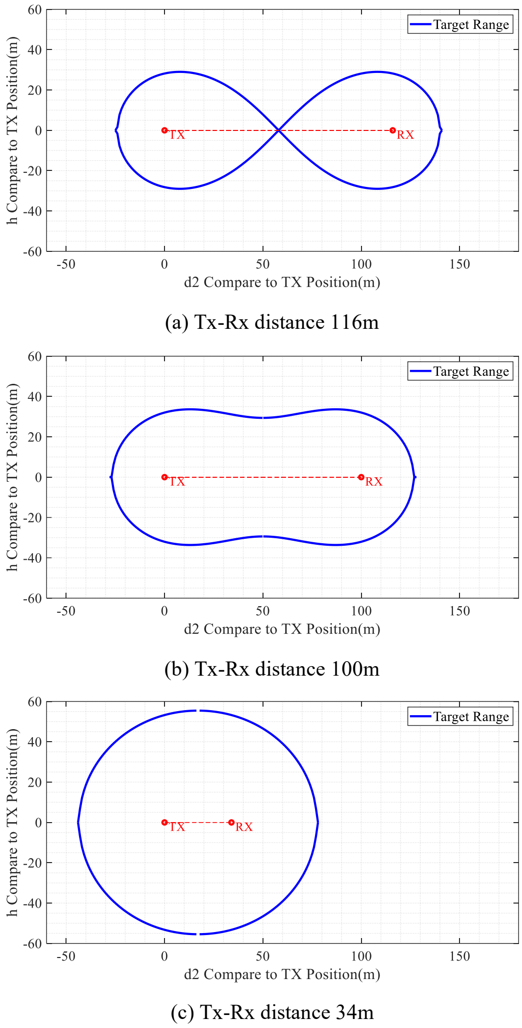
Fig. 6 shows the expected SNR as a function of the offset frequency for the two schemes. The modulation bandwidth is assumed to be 10kHz. τ_1 and τ_2 are set to be the same value to represents a situation where the connection cables of LO-Tx and LO-Rx are identical. At the offset frequency of 85kHz which results in the minimum SNR in this case the range correlation results in 7.8dB SNR at the receiver. The red curve in Fig. 6 shows reciprocal mixing. It can be seen that the performance is worse at all frequency offsets until the offset is sufficiently large that thermal noise dominates. For the monostatic case, range correlation will always outperform reciprocal mixing and also represents a hardware simplification as it is trivial to share the Tx and Rx LO.

III. RESULTS

Using the model outlined above, we first illustrate the effect of altering the transmitter to receiver separation in a bi-static system on the area and shape of coverage. Here we consider a required SNR of 5dB and an offset frequency of 85kHz (the worst case for the range correlated noise in Fig 6) and a Tx power of 36dBm EIRP. All other parameters are the same as for Fig 6. The results are shown in Fig. 7. Fig 7. (a) has a Tx to Rx separation of 116m, chosen by assuming equal losses in the forward and reverse links, where the maximum transmission distance would be 58m. Although this provides the maximum separation between Tx and Rx it is unlikely to be of practical use as the shape is pinched to a single point midway between the Tx and Rx. Decreasing the separation broadens the area of coverage between the Tx and Rx until it becomes ellipsoid. However, decreasing separation also decreases the Tx to Rx isolation having the potential to increase the noise level in the receiver. As a result, it is not trivial to optimize the Tx to Rx separation to maximize the area covered.

To find the optimum separation of the Tx and Rx, Fig 8 shows the available coverage area as the Tx to Rx separation is varied. In this case we assume that the LO is arranged to have the same cable delay between the LO and Tx and LO and Rx mixer, so the Δt term in equation (1) represents the free space time of flight from the Tx to Rx mixer. Therefore, with increasing Tx to Rx separation the isolation increases as the distance squared while the range correlation decreases according to (1). Under the condition that $\Delta t \Delta f$ is small, the effects approximately cancel resulting in little change in coverage area with increasing separation. The largest coverage area of 10500m^2 is achieved with a 34m separation distance. However, smaller separations may be preferable for the convenience of sharing the LO and the more circular coverage area which would be achieved.

In order to compare this bistatic separated system to a monostatic system with a similar coverage shape, the



(a) Tx-Rx distance 116m

(b) Tx-Rx distance 100m

(c) Tx-Rx distance 34m

Fig. 7. Target available range with same required SNR and different distance between Tx and Rx antennas for range correlation

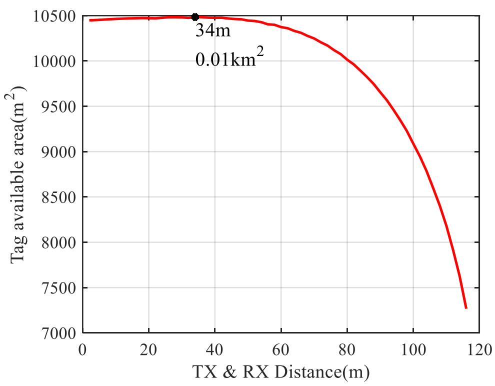


Fig. 8. Target available area with time different distance between Tx and Rx terminals

separation distance between Tx and Rx terminals is set to 6m as shown in Fig. 9 and compared to a monostatic system with the single antenna at the midpoint. The monostatic system is assumed to have antenna delay error of 3ns as a result of the path length difference between the LO to Rx and the delay of the leaked LO entering the Rx as well as a Tx Rx isolation of 35dB between mixing signals. A second leakage path due to antenna mismatch is also considered with an isolation of 40dB

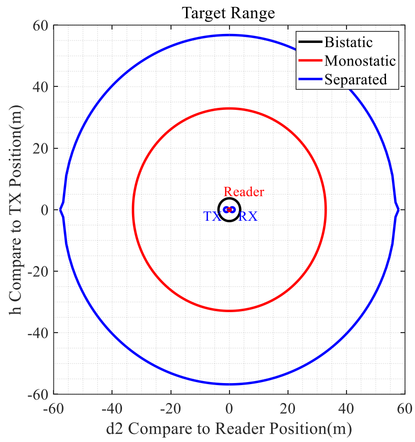


Fig. 9. Target available area of bistatic system with reciprocal mixing, monostatic system with range correlation and separated system with range correlation

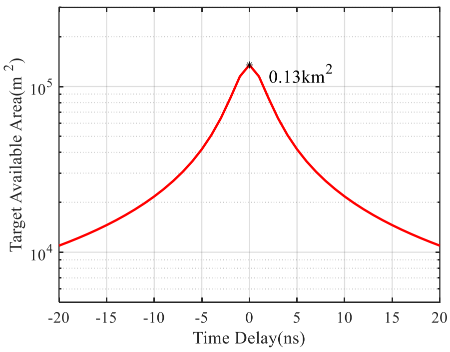


Fig. 10. Target available area with time difference between links ($\tau_1+\tau_0-\tau_2$)

and a total 25ns delay. It can be seen that the area covered by the monostatic system is about 3300m^2 while the area of separated system could reach about 10000m^2, which is 3 times larger. A bistatic system with reciprocal mixing is also illustrated in Fig. 9 due to the LO phase noise this, results in a small coverage area of only around 43m^2.

While the separated system with range correlation has been shown to significantly outperform monostatic, the system where $\tau_1 = \tau_2$ is not the optimum since better range correlation can be achieved if $\tau_0 = \tau_2 - \tau_1$ such that the difference in the Rx and Tx LO delays matches the free space path delay. This is considered in Fig. 10 where the area of coverage is plotted compared to delay mismatching (again for the 6m antenna separation). It can be seen that in the perfect case, a further 10 times improvement in the coverage area compared to Fig 8 is achieved, although a delay accuracy on the order of a few nanoseconds is required. With good range correlation wider antenna separations can be expected to further improve on this performance, although in practical systems, multipath effects on the Tx to Rx leakage which are not considered in this simple model may limit the performance.

IV. Conclusion

Using a simple model, the performance of monostatic and bistatic backscatter systems has been considered under the condition of range correlation. It is shown that even with a non-optimized system where the delay of the LO at the transmit and receive nodes is matched, the area of coverage greatly exceeds a monostatic system. If the delay of the LO is well matched, over 30 times improvement in coverage area could potentially be achieved.

Future work of this project will investigate methods to distribute the LO in separated systems and achieve precise delay accuracy for phase noise range correlation, as well as the impact of multipath on the Tx to Rx leakage for bi-static systems.

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