Diversity Aspects of Radar-Embedded Communications

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Abstract **– This paper discusses aspects of *intra-pulse* radar-embedded communications whereby a tag/transponder illuminated by a radar converts the illumination waveform into one of a set of *K* communication waveforms with which to convey information to a spatially separated receiver. Initial work based upon an expansion of the radar spectrum has demonstrated the potential for significant data-rate improvement relative to previous *inter-pulse* approaches while still maintaining a low probability of intercept. In this work, a general mathematical formulation for *intra-pulse* radar-embedded communications is presented. This formulation provides insight into options for even higher data-rates by utilizing additional degrees-of-freedom.**

1 INTRODUCTION

The ability to communicate covertly is essential for defense-related operations where an intercepted message could be exploited by an adversary to reveal sensitive information and/or the existence and location of key resources. Traditional means of covert communication rely upon active signaling in unused portions of the spectrum in which the signal is designed to rapidly "hop" around the spectrum or to appear noise-like [1]. However, an alternative covert communication technique is to exploit the signal from existing transmitters by re-emitting the incoming signal after it has been modulated into some different signal. Detection of such a signal within the ambient electromagnetic environment is extremely difficult for an adversary, especially since the power level of the newly modulated signal can be much less than that of the surrounding clutter produced by natural scattering of the original signal.

Embedding information into radar scatter using RF tags/transponders is relatively well-established, though previous efforts have focused either on methods of *inter-pulse* modulation by mimicking a Doppler-shift sequence across a set of pulses [2-5] or on polarimetric modulation as a means of calibration [6]. As such, the application has been mostly limited to synthetic aperture radar (SAR) and requires a large number of pulses for the transmission of each data symbol, thus constraining the communication to such a low data-rate that, in some instances, the tags may only serve as identifiers for known tagged assets.

It has recently been proposed [7] to operate on an *intra-pulse* basis whereby the tag/transponder conveys information to some receiver on each individual pulse. Communication in this manner is accomplished by re-modulating the incident radar waveform (typically a frequency or phase modulation on the radar pulse) into one of some set of communication waveforms. The radar, which may be cooperative or not, provides a masking for the embedded signal via the local scattering around the tag/transponder and may also act as the power source in the case of a passive radio-frequency identification (RFID) tag. A conceptual illustration of intra-pulse modulated radar-embedded communication is depicted in Fig. 1. On the basis of phase modulation, it is discussed in [7] how to design the communication waveforms to jointly provide a low communication error rate at the receiver while maintaining a low probability of intercept by an eavesdropper.

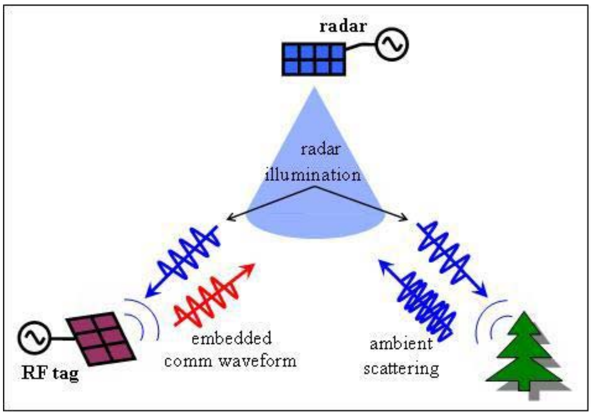

Figure 1. Intra-pulse modulation concept

In this paper, a general mathematical formulation is developed for use in the modeling, design, and processing of intra-pulse modulated communication waveforms embedded in ambient radar scattering. It is also discussed how additional degrees-of-freedom can be utilized as a means to further increase the data throughput and/or facilitate further obfuscation for the embedded signal (see [8]). Specifically, besides intra-pulse phase modulation we consider the additional diversity provided by polarization modulation, frequency hopping, delay (analogous to pulse position modulation), and joint inter-pulse phase modulation.

2 *INTRA-PULSE* RE-MODULATION

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A typical radar pulse (waveform) is characterized by a phase/frequency modulation over the extent of the pulse, which translates into some bandwidth about a given center frequency. The received reflections from this illumination are thus expected to be delayed versions of the same phase/frequency modulation and occupy the same bandwidth. Using the illumination waveform as a reference, a tag/transponder can covertly communicate with a spatially-separated receiver by re-modulating the reference illumination radar waveform into one of K possible communication waveforms, each of which acts as a communication symbol. The covert aspect is provided by the presence of the ambient scattering in the local region around the tag/transponder which acts as a masking interference signal.

Mathematically, we can represent the proposed method for radar-embedded communications in the following manner. Let $s(t)$ be the transmitted radar waveform which illuminates a collection of discrete, linear *time-invariant* scatterers. The response at the radar receiver (or at some other intended receiver) can thus be described by:

$$y_s(t) = \int_V \int \psi_{rx}(t,t';\bar{r}) \int \gamma_s(\bar{r})\,\delta(t'-t'')\,dt' \int \psi_{tx}(t'',t''';\bar{r})\,s(t''')\,dt''dt'''d\bar{r} \tag{1}$$

where the functions ψ_{tx} and ψ_{rx} describe the propagation from the radar antenna to a particular scatterer at position $\bar{r}$ and back, respectively, and $\delta(\bullet)$ is the dirac delta. The complex value γ_s likewise indicates the scattering coefficient of this discrete scatterer. Therefore, $y_s(t)$ is the ambient scattered signal incident at a given receiver that shall act as a masking interference for the embedded communication signal.

In contrast to the phenomenology of ambient scattering, the tag/transponder is essentially a discrete, linear *time-varying* scatterer. If located at position $\bar{r}$, the received response $c_k(t)$ from this object is

$$c_k(t) = \int \psi_{rx}(t,t';\bar{r}) \int \Phi_k(t',t'')\,dt' \int \psi_{tx}(t'',t''';\bar{r})\,s(t''')\,dt''dt''' \tag{2}$$

where the kernel $\Phi_k(t,t')$ describes the k^{th} re-modulation operation upon the incident waveform $s(t)$ thus yielding the k^{th} communication waveform $c_k(t)$ for $k = 0, 1, \cdots, K-1$. As such, the received response $y_r(t)$ resulting from a single tag/transponder located within a collection of scattered objects is

$$y_r(t) = c_k(t) + y_s(t) + v(t) \tag{3}$$

with $v(t)$ being additive noise.

From the standpoint of optimal estimation of the embedded communication waveform, the k^{th} re-modulation operation would ideally "rotate" the illuminating function $s(t)$ into a subspace orthogonal to the responses from the surrounding scatterers, *i.e.*

$$\int c_k(t)\,y_s^*(t)\,dt = 0\,, \tag{4}$$

while likewise producing a communication waveform that is mutually orthogonal to the other $K-1$ communication waveforms such that

$$\int c_j(t)\,c_k^*(t)\,dt = 0 \quad \text{for} \quad j \neq k\,. \tag{5}$$

where * denotes complex conjugation. However, to preserve the obfuscation capability of the set of communication waveforms, they must in fact remain partially correlated with the radar scatter so that an eavesdropper cannot simply project away the radar illumination from the received signal $y_r(t)$ and thereby uncover the embedded communication signal. From the perspective of optimizing the estimation of the correct embedded communication waveform given that some degree of correlation with the radar scatter is necessary, an optimization problem for communication waveform design can be expressed as:

$$\begin{aligned} &\arg\min_{c_j(t)} \int c_j(t)\,c_k^*(t)\,dt \quad \text{for } j \neq k \text{ and } \forall j,k \\ &\text{such that } \int c_j(t)\,y_s^*(t)\,dt \approx \int c_k(t)\,y_s^*(t)\,dt = \lambda(y_s) \\ &\qquad \int c_j(t)\,c_j^*(t)\,dt = E_c. \end{aligned} \tag{6}$$

In other words, minimize the communication waveform cross-correlation while maintaining the energy of each communication waveform to be E_c and the cross-correlation between each communication waveform and the radar backscatter to be nearly constant across the K communication waveforms. Note the functional dependence on the radar scatter in the $\lambda(y_s)$ term of (6) which determines the degree of correlation between the communication waveforms and the radar scatter.

Because in practice it is more accessible to both the tag/transponder and any intended receiver(s), the illumination function $s(t)$ may be better suited to determine the communication waveforms than the ambient scatter signal $y_s(t)$. As such, the first constraint in (6) becomes a function of $s(t)$ for the purpose of communication waveform design and necessarily becomes a constraint to be met "on average" as the local scattering phenomenology may fluctuate. The ambient scatter $y_s(t)$ can thus be used to establish the power level of the embedded signal at a given time instant. Of course, a second non-modulating tag/transponder could alternatively be employed to provide a controlled level of scattering power so that the embedded signal does not unintentionally surpass the power level of the scattered signal and possibly become more visible to an eavesdropper.

Under the assumption that the communication waveforms meet the above requirement, exact knowledge of the set of K possible communication waveforms $c_0(t), \cdots, c_{K-1}(t)$ is required to extract the embedded signal from the radar scatter. In the presence of the radar scatter interference and noise, this extraction necessitates coherent processing of the received signal. Based on straight-forward matched filtering, this can be expressed mathematically as

$$\hat{k} = \arg\max_k \int c_k(t)\, y_r^*(t)\, dt \tag{7}$$

where $\hat{k}$ is the index of the communication waveform most likely to be present (according to matched filtering) and corresponds to some binary sequence according to a pre-established encoding scheme.

However, given that the embedded signal is masked by and partially correlated with the higher power radar scatter signal, matched filtering will generally be inadequate as some suppression of the received radar return signal will likely be required to accurately extract the embedded signal. Thus, given knowledge of the communication waveforms and utilizing interference cancellation in the receive processing, the desired receiver would be able to effectively estimate the correct embedded signal while any non-coherent attempts to eavesdrop are substantially inhibited by the masking interference.

3 HIGHER DIMENSION MODULATION

To achieve even higher data rates, multiple tags/transponders may be utilized with each being modulated such that they each occupy a different communication "channel". These channels can be formed by utilizing the additional diversity provided by polarization, frequency hopping, delay, and inter-pulse phase modulation. Essentially, each tag/transponder performs intra-pulse modulation of the radar waveform into one of the K communication waveforms for a particular polarization, a particular frequency shift relative to the illumination center frequency, a particular temporal delay associated with the radar range dimension, and applies a scalar phase-shift to the communication waveform that changes over some pre-determined number of pulses. In so doing, the embedded signals from the distinct tags/transponders can be made sufficiently independent thereby enabling a multiplicative increase in overall information capacity.

Of course, to continue to exploit the ambient scattering to mask the presence of the covertly embedded signals, some properties of the scattering must be taken into account. Specifically, if the ambient scattering is predominantly characterized by a particular polarization (*e.g.* horizontal), then a different polarization on the embedded signal (*e.g.* vertical) would make it more visible to an eavesdropper. Likewise, a frequency shift away from the radar illumination center frequency would place the embedded signal in the lower spectral sidelobes of the radar scattering. However, if accounted for properly, both of these aspects can be managed by appropriately setting the power of the embedded communication signal. Also, as previously mentioned, artificial ambient scattering can be inserted for the desired polarization and frequency as long as it is reasonable for the given illumination.

Unlike polarization and frequency, using delay shift to separate the communication waveforms from different tags/transponders generally does increase visibility to an eavesdropper as long as the amount of delay is not overly large. The amount of possible delay must be bounded such that the covert transmission is still masked by the surrounding ambient scatter so that an eavesdropper cannot utilize bi-static receive angle to discriminate the radar scatter from the embedded signal. Also, depending upon the amount of delay shift, the embedded waveforms from different tags/transponders may interfere with one another thus necessitating additional measures of interference suppression processing to accurately estimate the embedded information at the intended receiver. In addition, note that delay may be generalized to convolution such that each tag/transponder further encodes its communication waveform by convolving with a specific identification sequence. This approach may alleviate some of the mutual interference between tags/transponders by enabling receiver filtering "tuned" to particular convolution schemes.

Performing joint intra-pulse and inter-pulse phase modulation can either provide a higher data rate or further obscure of the embedded communication signal. Not unlike BPSK or QPSK, a scalar phase shift can be modulated onto a given communication waveform such that, after determination of particular embedded waveform at the receiver, the given phase of that waveform can provide additional bits of information. In contrast, a sequence of known inter-pulse phase shifts can be applied in a similar manner as [2-5] in conjunction with intra-pulse modulation such that the power of the embedded communication waveform can be made smaller without detriment to symbol estimation accuracy at the intended receiver. Of course, this further obfuscation is achieved at the cost of reducing the data rate.

Finally, note that the polarization, frequency offset, delay shift, inter-pulse and intra-pulse phase modulations can be considered from an overall high-dimension perspective whereby a very high number of combinations are possible. As such, the tag/ transponder could arbitrarily select the values of these parameters for each pulse or set of pulses. Thus the eavesdropper is forced to non-coherently search for an unknown signal within a high-dimensional space while the intended receiver, which presumably has prior knowledge of the signal parameters, must only determine which of the known possibilities is most likely.

4 CONCLUSIONS

Radar-embedded communications on an intra-pulse basis can provide a substantial increase in data-rate relative to previous inter-pulse approaches that necessitate hundreds of pulses. A general mathematical framework has been devised to model the reception of an intra-pulse modulated signal in the presence of ambient radar scattering and noise. The intra-pulse modulation model also enables the utilization of higher degrees of diversity in terms of polarization, frequency offset, delay shift, and inter-pulse phase modulation. The combination of all these modulation schemes can be used to further increase the data-rate and/or further obscure the embedded communication signal from an eavesdropper.

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