Radar Communications via Random Sequence Encoding

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Abstract: *In this paper we propose a novel approach to joint radar-communication waveform design with low probability of intercept characteristics. The data are encoded onto a certain parameter of a particular random distribution; using this distribution, random sequences are generated, which become amplitude weights for the orthogonal frequency division multiplexing (OFDM) sub-carriers. We assume and describe a worst-case scenario, in which an interceptor possesses a certain amount of knowledge about our approach and attempts to reconstruct the data from intercepted radar/communication signals – we then show, via simulations, that with more than 32 OFDM sub-carriers used in signal design, the interceptor cannot improve upon its bit error rate (BER) even with increasing number of intercepts.*

1. Introduction

The area of multi-functional RF sensor systems had received its start around the end of 1970's, when, e.g. a dual-use radar and communication sub-system was fielded in the Space Shuttle Orbiter by NASA [1]. While the sub-system had different signal processing components for each functionality, the radar and communication implementations shared a wideband transmitter, a two-channel receiver and an antenna – thus, providing for significant savings on weight, physical dimensions, power requirements and overall system complexity. Later, the topic of radar-communication functionality "fusion" had received further attention in both academia and industry, particularly, e.g. from the perspective of automotive-based design; see [2] for an excellent overview.

One aspect of radar-communications which has not been addressed as widely is the potential for covertness, especially in such scenarios when the data must be re-transmitted several times – e.g. when establishing ad-hoc communications among the platforms to be joined into a sensor network. One solution of this problem is radar-embedded communications, where a message is included in a specially designed noise-like radar waveform [3, 4]. Another approach to embedding communication symbols into a high-power radar signal on intrapulse basis is described in [5] – a specific scenario of non-line of sight (LOS), asynchronous communications enabled by backscatter of the radar waves was assumed. In our work we adopt the same situational setup; however, in contrast to the existing studies, we are not using the concept of radar-embedded communications at all – rather, we suggest to use exact same

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waveform for both purposes. The covertness is then addressed via a novel algorithm of radar-communication signal design in which the data is encoded as a parameter of a particular random distribution, whereas the signal is then created using samples of a random process with this distribution. We choose amplitude coefficients of the orthogonal frequency division multiplexing (OFDM) signal's sub-carriers as the signal parameters that carry the random process samples; the multi-functional ultra-wideband (UWB) OFDM radar-communication system prototype and its operation are described in our previous work, e.g. [6].
In the rest of the paper below we outline the basic algorithm of random sequence encoding for OFDM-based radar-communication fusion and preliminary simulation results along with an outline of the planned experimental verification.

2. Waveform Design with Random Sequence Encoding

Our goal is to transmit useful data with radar pulses, thus re-using the power and bandwidth of the multi-functional sensor system. The data to transmit may be our position, or other basic information, and as such we may want to re-transmit it multiple times. If intercepted by enemy, the data will be compromised – thus, we need to find a way to re-transmit same data in a random manner. We propose to solve this problem via the following approach: Transmit random samples taken from a certain distribution on OFDM sub-carrier coefficients; the structure of a typical OFDM signal spectrum is illustrated in Fig. 1.

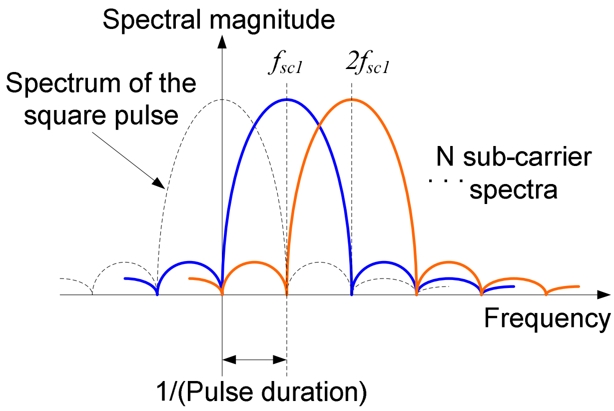


Figure 1. OFDM signal spectrum – the random sequence samples are to be coded onto spectral magnitudes associated with the sub-carriers

The useful information (data) is encoded onto a certain parameter of the distribution (e.g. variance). Upon reception, coefficients are estimated, from which the useful parameter estimation is also made, providing the information via simple mapping. An OFDM signal in time domain can be written as –

$$s_{TX}(t) = \sum_{n=1}^{2N+1} s_n \cdot \prod_{\tau=1/f_s} \left(t - \frac{n-1}{f_s} \right) \tag{1}$$

where $\prod_{\tau=1/f_s}$ represents a square pulse of duration ($1/f_s$), f_s is the sampling frequency of the digital-to-analog converter (DAC) in the OFDM transmitter chain [6], N is the total number of sub-carriers, and s_n are time-domain amplitude values determined as:

$$s_n = \frac{1}{2N+1}\sum_{k=1}^{2N+1} S(k)\cdot e^{j2\pi\frac{(k-1)(n-1)}{2N+1}}, \quad (2)$$

where *S(k)* is a real-valued amplitude coefficient of k^{th} sub-carrier onto which a sample of a random sequence is to be recorded. Then, assuming asynchronous, ad-hoc reception of this signal by a friendly platform via I/Q detection [7], we can represent the resultant output of both channels as:

$$\begin{aligned} s_{RX\_I}(t) &= \frac{1}{2}A\cdot s_{TX}(t-t_d)\cos(\underbrace{2\pi f_c t_d - \Delta\phi}_{\Theta_m}) + w_I(t) \\ s_{RX\_Q}(t) &= \frac{1}{2}A\cdot s_{TX}(t-t_d)\sin(\underbrace{2\pi f_c t_d - \Delta\phi}_{\Theta_m}) + w_Q(t) \end{aligned} \quad (3)$$

where A is amplitude factor associated with propagation and possible reflections from the target scene, t_d is time delay, $\Delta\phi$ is phase mismatch between the carrier frequency signal at up-conversion to the carrier frequency f_c (in the transmitter) and down-conversion (in the asynchronous receiver) and $w_{I,Q}(t)$ are cumulative representations of external disturbance and own system noise in I and Q channels. We notice that for the case of UWB systems and signals the quantities of A and $w_{I,Q}(t)$ are functions of frequency and, thus, after analog-to-digital conversion (ADC) and FFT operation the I and Q frequency-domain data vector coefficients will become, for the k^{th} sub-carrier:

$$\begin{aligned} \hat{S}_{RX\_I}(k) &= S(k)\cdot A(k)\cdot e^{-j2\pi\frac{k\cdot f_s}{2N+1}\cdot t_d}\cdot\cos(\Theta_m) + w_{k,I} \\ \hat{S}_{RX\_Q}(k) &= S(k)\cdot A(k)\cdot e^{-j2\pi\frac{k\cdot f_s}{2N+1}\cdot t_d}\cdot\sin(\Theta_m) + w_{k,Q} \end{aligned} \quad (4)$$

Finally, we combine the I/Q channel outputs into spectral magnitudes, from which the data are to be recovered:

$$\hat{S}_{RX_{IQ}}(k) = \sqrt{\left|\hat{S}_{RX\_I}(k)\right|^2 + \left|\hat{S}_{RX\_Q}(k)\right|^2} \approx \left|S(k)\cdot A(k)\right| + w_{k,IQ}. \quad (5)$$

To reconstruct the data we, therefore, need to perform the following:

i. Recover the samples of a random process, which are recorded onto *S(k)* – i.e. *S(k)* are the samples of a random process itself;
ii. Estimate the parameter of the distribution that was used to generate the random sequence (e.g. we can choose variance as such a parameter);
iii. Map the parameter estimate onto the data scale and, thus, produce an estimate of the resultant data symbol.

It is clear from (5) that the two factors which must be considered before *S(k)* are estimated are: 1). Influence of *A(k)* on the parameters of the random sequence; 2). Effect of external additive noise w_k, which will corrupt the random sequence statistics. We proposed to resolve these concerns via the following approaches, assuming random process variance is used as the parameter from which the data can be estimated:

1. It is well known that the variance of a random process (or variable) X will change when the process (or variable) is scaled in amplitude by a constant factor m –

$$\sigma_{mX}^2 = VAR(mX) = m^2 VAR(X) \tag{6}$$

where, in our case, m is signal attenuation in free space between transmitter and receiver, plus any contribution from the reflections, i.e. m is $A(k)$. Therefore, to correct for the attenuation, we need to perform channel estimation, which can be achieved for either the case of flat frequency response or frequency-dependent attenuation, via a training procedure.

2. Again, there is a well-known relationship between variances of individual random processes and the sum of these processes. If there are two random processes that are received simultaneously as their sum, the relationship of variances is –

$$VAR(\underbrace{mX}_{\substack{\text{Original process } X \\ \text{scaled by } m}} + Y) = VAR(X) + 2mCOV(X,Y) + VAR(Y) \quad , \tag{7}$$

where $COV(X,Y)$ is covariance of the two processes. Therefore, to extract just the variance which contains our data, we propose to a). Estimate the variance of external noise prior to reception; and b). Evaluate the covariance between our random process and the noise – this can be either minimized by selecting an appropriate distribution of our own random sequence, or even ignored if we determine that such covariance is negligible.

While variance itself can be readily estimated from the random sequence, it is not a good candidate for encoding the data, since variance is distribution-independent and can be found easily. Rather, we propose to use distributions which depend on several parameters – then, if the receiver knows the value of one of the parameters (the "key") and estimates variance of the incoming random sequence, the other parameters – onto which the data is actually encoded – can be estimated using the "key" and the variance estimate. This is the approach we used to perform our simulation study, results of which are described below.

3. Simulation Results

We set up a simulation study to evaluate the efficiency of the proposed approach, particularly with the goal of estimating the amount of interceptor penalization (expressed in terms of bit error rate (BER) improvement of the friendly platform, compared with interceptor). We picked Weibull distribution from which random samples were drawn to create the random sequences for signal encoding:

$$f(x;\lambda,k) = \begin{cases} \dfrac{k}{\lambda}\left(\dfrac{x}{\lambda}\right)^{k-1} \cdot e^{-(x/\lambda)^k}, & x \ge 0 \\ 0, & x < 0 \end{cases} \tag{8}$$

where λ is the scale parameter and k is the shape parameter. If we choose to encode the data onto the scale parameter (and make shape parameter known to both the transmitter and receiver beforehand), then the receiver will reconstruct the data by estimating λ:

$$\hat{\lambda} = \sqrt{\frac{\hat{V}ar}{\left[\Gamma\left(1+\frac{2}{k}\right)+\left(\Gamma\left(1+\frac{1}{k}\right)\right)^{2}\right]}} \tag{9}$$

where $\hat{V}ar$ is the receiver's estimate of Weibull-distributed sequence's variance, made from the received samples of this sequence; and Γ is the gamma function.

We also made the assumption of a realistic worst-case scenario with regards to an interceptor, which are detailed below:

i. The interceptor knows that we are transmitting by encoding data onto some aspect of a Weibull distribution;
ii. We have a maximum variance cap we can transmit at (e.g. variance ≤ 100) and the interceptor is aware of what this variance cap is;
iii. The interceptor knows that we are encoding data onto the scale parameter of the Weibull distribution, but does not know the shape parameter we are transmitting with, or when/if we change the shape parameter used;
iv. The interceptor knows how many re-transmissions we are using, as well as how many and what sub-carriers we are transmitting on.

Finally, we assumed that the external noise had Gaussian distribution.

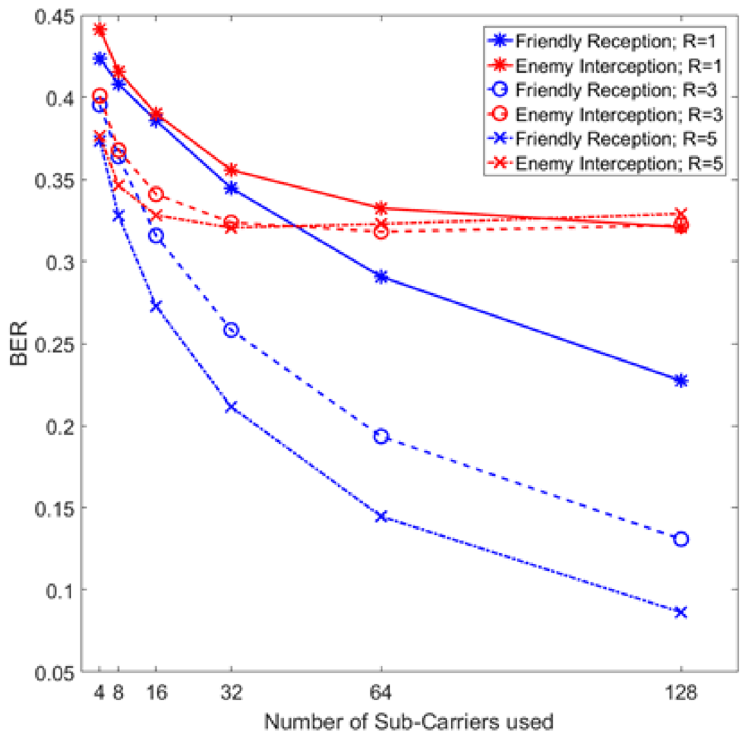


Figure 2. Interceptor penalization using Weibull distribution and scale parameter estimation from variance.

In Fig. 2 we illustrate the method's effectiveness in penalizing an interceptor with different numbers of OFDM sub-carriers used (where each sub-carrier would carry one sample of a random sequence); the parameter R in the plots denotes the effective length of the transmitted sequence – e.g. for the number of sub-carriers $N = 64$ and $R = 5$ we would transmit a random sequence of length $N \times R = 320$. It can be readily seen that after the number of sub-carriers is increased past approximately 32, the interceptor loses the ability to reconstruct the data better even with increasing lengths of the random sequence, whereas a friendly platform continues to improve its BER. At $N = 128$ the gap between the BER for the friendly platform and the interceptor reaches approximately 0.25 – or, to put it differently, the enemy will still reconstruct about every third bit incorrectly, while a friendly platform will only reconstruct about every thirteenth bit incorrectly, leading to much better reception rate under the worst-case scenario described above. In Fig. 3 below we also illustrate the method's performance under various levels of external Gaussian noise, i.e. BER versus SNR. It is seen that the method can perform well even in sub-zero dB of SNR conditions.

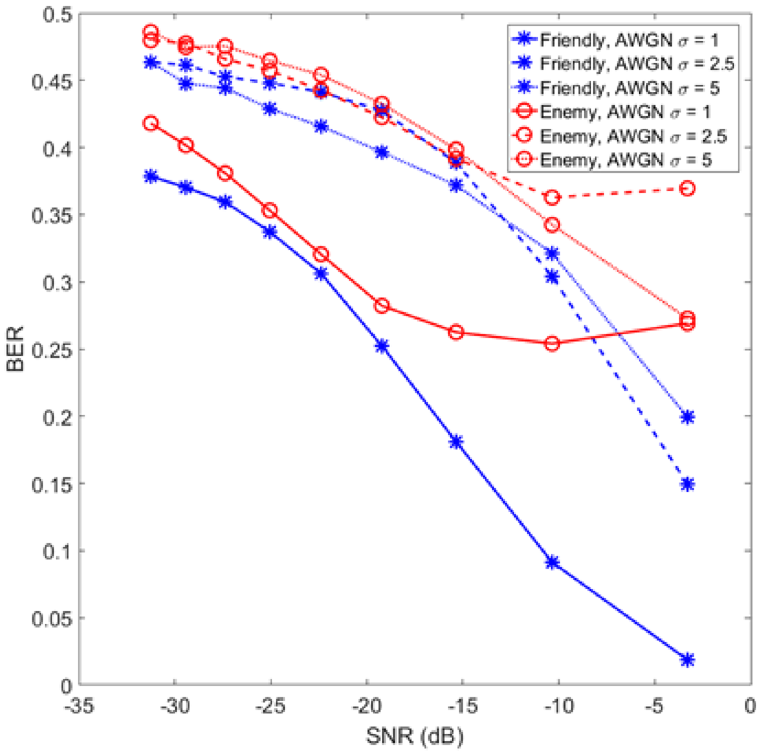


Figure 3. BER vs SNR.

4. Experimental System Calibration

In preparation for the experimental verification of the method's applicability, we performed the initial tests using the UWB OFDM software-defined radar system (SDRS), described in [6, 7]. The key feature of the system is its extremely low transmit power, which is provided by the carrier oscillator only (at +26 dBm), without a power amplifier. This is intentional and is aimed at maintaining compliance with the U.S. Federal Communications Commission's rules regarding UWB transmit power limits for time-gated indoor systems [8]. First, we collected the average noise profile – this was done by running the radar system in listen-only mode at random times during several trials and recording 1000 samples of data; Fig. 4 shows the resultant profile after the down-conversion to baseband and normalization to average sub-carrier magnitude. It is seen that, while there is a spike (of yet unknown origin) consistently occurring at 300 MHz – half the sampling rate of the DAC – it is quite small compared to expected signal receptions (only about 3% of the magnitude seen at 300 MHz when transmitting 16 sub-carriers uniformly). Thus, it appears noise is a negligible, or a secondary concern.

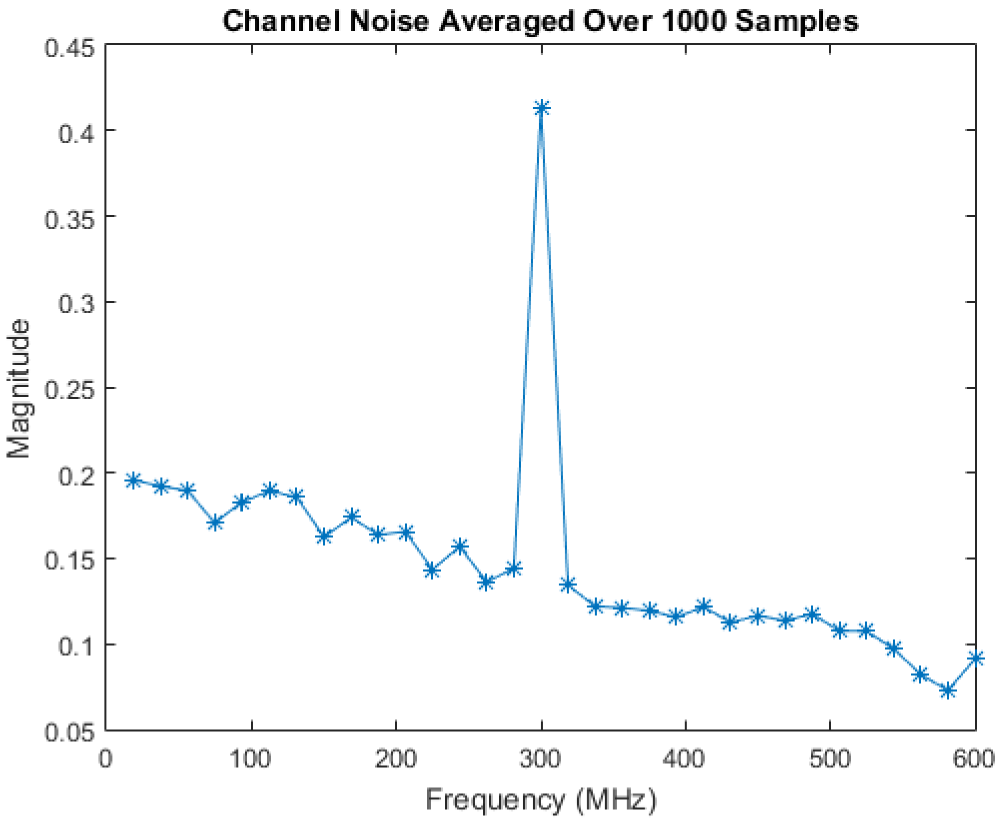
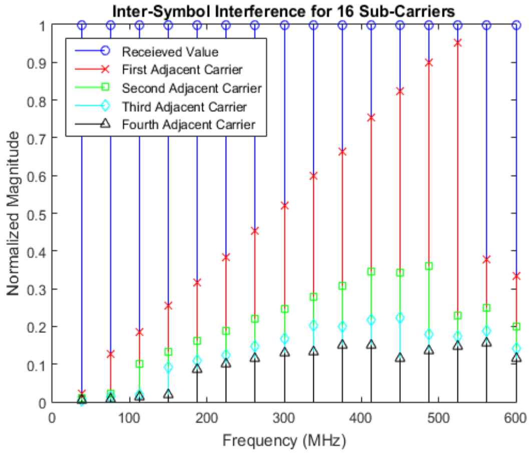
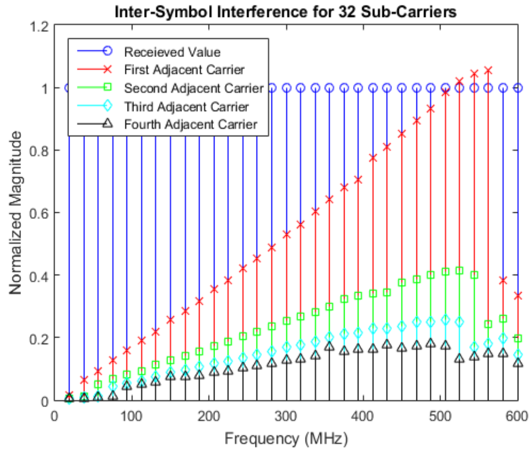


Figure 4. Experimental noise profile.

Secondly, we collected the data on inter-carrier interference (ICI). This was done in the following way: The amount of energy spill from one sub-carrier into another was evaluated by successive turn-on/turn-off of the sub-carriers; thus, values were obtained by transmitting each sub-carrier independently, averaging the received weights; 500 samples were used for division of the baseband spectrum into 32 sub-carriers and 1000 samples were used for division of the spectrum into 16 sub-carriers. The following two graphs – Fig. 5 (a, b) – show the amount of ICI as detected on the first, second, third and fourth adjacent sub-carrier. It appears to be the most significant form of interference. By the 3rd adjacent sub-carrier and beyond, ICI starts to flat-line in magnitude. The most straightforward resolution of this issue is by nulling (dropping) every other sub-carrier, which would reduce ICI, but also reduce the data rate as a trade-off.



(a)



(b)

Figure 5. Experimental ICI evaluation: (a) – With $N = 16$; (b) – With $N = 32$.

Finally, we collected the data to analyze the impact of the channel itself, as a transfer function. Fig. 6 illustrates the result.

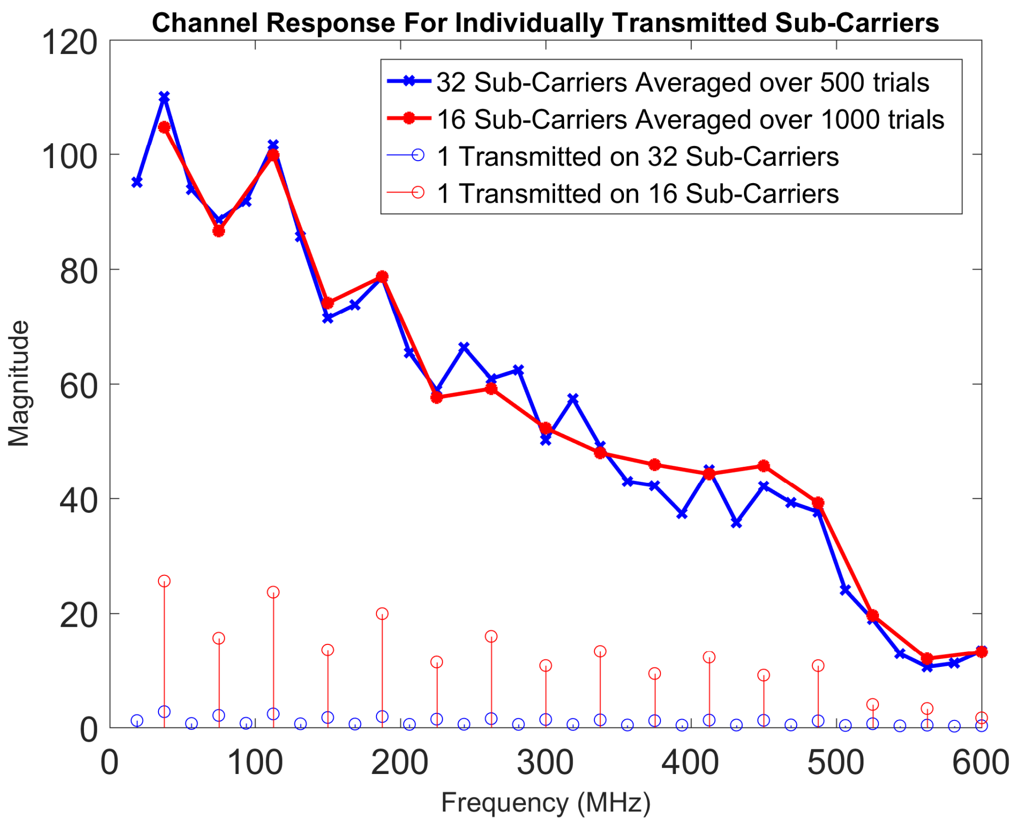


Figure 6. Experimental channel response.

Graphs in Fig. 6 show the magnitude received for each sub-carrier averaged over 500 trials for division of bandwidth into 32 sub-carriers and 1000 trials for division into 16 sub-carriers. In general, a decreasing response is seen, with sharp drops after 112.5 MHz (6th and 3rd sub-carrier of 32 and 16 divisions respectively) and 487.5 MHz (25th and 12th sub-carrier respectively). Stem plots on the bottom are for uniform magnitude transmitted on all available sub-carriers. It appears that there is insufficient energy to support transmission on 32 sub-carriers. For 16-sub-carriers, magnitude of received sub-carriers past 487.5 MHz is small enough to be mistaken for noise. However, by eliminating transmission on the last 2 sub-carriers, we may be able to adequately receive on 506.25 MHz. In general, transmitting uniformly on all 16 sub-carriers reduces energy by about 80% compared to individual transmissions of the same sub-carrier weight – which is, again, a common feature of multi-carrier systems, where transmit energy is sacrificed for spectral expansion.

5. Conclusion

In this work we proposed a method of radar-communication fusion for multi-functional sensor systems. The method does not embed communication data into the radar waveform; rather, it allows for the design of a single waveform which addresses both functions. The data are encoded onto a parameter of a particular random distribution, which is then used to generate random sequences. Values of random sequence samples are used to encode sub-carrier amplitudes of radar/communications OFDM pulses. This approach allows for covert, non-LOS, asynchronous communications in establishing ad-hoc sensor networks. Our simulation study showed that with more than 32 sub-carriers the interceptor loses the ability to improve upon its BER, even with increasing number of intercepted re-transmissions. We also described three major considerations for an experimental study of this method with UWB OFDM SDRS: Indoor noise profile, ICI impact and channel response estimation. Future work will include consideration of other distributions and scenarios, as well as experimental validation of the proposed approach.

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