Frequency-Modulated Continuous-Wave Joint Radar and Communications

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Introduction

Index Modulation definition:

Index modulation (IM) is a family of modulation techniques that rely on the activation states of some resources/building blocks for information embedding. The resources/building blocks can be either physical or virtual. Physical resources include antenna, subcarrier, time slot, and frequency carrier, while virtual resources include virtual parallel channels, signal constellation, space-time matrix, and antenna activation order .
A distinct feature of IM is that part of the information is implicitly embedded into the transmitted signal. This means that the information is not explicitly transmitted, but rather is embedded in the activation states of the resources used for transmission.
IM is a promising candidate for meeting the requirements of 5G wireless networks. It has the potential to provide immense bandwidth and much higher data rates with considerably lower latency.

Importance of Index Modulation:

In each type of modulation we saw in the course, storing data in a variable is the method of communication. For example, in frequency modulation, we store data in the instantaneous frequency. However, what if we store data in all the variables? If we store data in both amplitude and frequency, we can transmit double the data we could.
Let's imagine we are using digital communication as the primary form of communication. First, we quantize the signal and use different levels for data transmission. If we have 10 quantization levels for frequency and also 10 quantization levels for amplitude, we totally have $10 \times 10 = 100$ levels. Having more levels (transmitting more data) without using more power or bandwidth is our main concern in communication. That's why we use index modulation.

Definition of joint radar-communication systems

Joint Radar-Communication (RadCom) systems are a novel technology that combines radar sensing and communication functionalities in the same radio frequency hardware platform. This concept has been gaining interest due to the possibility of efficient spectrum management. In RadCom systems, additional components and processes are added to an existing standardized communication platform to enable radar functions. The same signal is used to communicate information to a receiver and to perform radar detection and estimation operations for a nearby target.
The modulation scheme plays a significant role in driving the performance of RadCom systems. The state-of-the-art modulation schemes for RadCom systems include chirp sequence, phase-modulated continuous wave, orthogonal frequency-division multiplexing, and orthogonal chirp-division multiplexing. For each of these schemes, a detailed system model is outlined, and parameters for quantifying both radar and communication performances are presented. A comparative analysis of the aforementioned RadCom modulation schemes is carried out to illustrate the presented discussion.

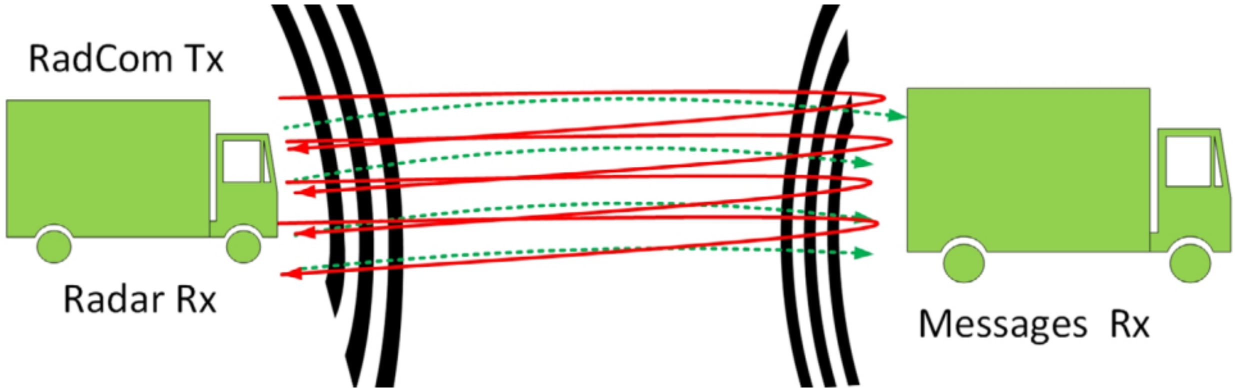

Figure 1: *System Model Scheme*

System Model

General view

Radar systems are used to detect the presence, location, and movement of objects in the surrounding area. However, this process consumes power and bandwidth, which can be a significant challenge in certain scenarios.
Joint Radar-Communication (RadCom) systems are a novel technology that combines radar sensing and communication functionalities in the same radio frequency hardware platform. This concept has been gaining interest due to the possibility of efficient spectrum management. In RadCom systems, data is embedded in the signals used for detection, thereby reducing the additional power and bandwidth consumption required for communication.
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In RadCom systems, the same signal is used to communicate information to a receiver and to perform radar detection and estimation operations for a nearby target. If the signal hits an object and returns, the system is used as a radar, and if it doesn't return, the system is used as a communication system. This way, the system can operate efficiently in both modes without any additional hardware or power consumption.

Transmitter

The signal sent from the radar carries information, and if it hits an object, it returns and enables us to detect the object (radar mode). If there isn't anything for detection, the signal doesn't hit an object, and we can use receivers to catch the signal transmitted from the radar and then interpret the embedded data.

Receiver

From the view of a receiver, what we see is a chirp, and it doesn't matter what it was used for (for detection or communication) 1. All we need to do at the receiver is to extract the data embedded in the chirp, so actually, the receiver is like all normal receivers.

Explanation of the receiver, its complexity, and proposal for a simpler receiver

Explanation of the receiver and its complexity

In radar systems, the received signal is a white Gaussian noise added to a chirp. Since we know all possible inputs of a chirp, we can create and store a dataset from all possible chirps and their fast Fourier transforms (FFTs). Having all possible FFTs, we iterate over the codebook and calculate the distance of the received signal with each existing element in the codebook using mean squared error (MSE). In this method, we are using the Maximum Likelihood estimator to extract the transmitted signal.
The Maximum Likelihood estimator is a mathematical algorithm used to extract useful data from a noisy data stream. For an optimized detector for digital signals, the priority is not to reconstruct the transmitter signal, but it should do the best estimation of the transmitted data with the least possible number of errors. The receiver emulates the distorted channel. All possible transmitted data streams are fed into this distorted channel model. The receiver compares the time response with the actual received signal and determines the most likely signal. In cases that are most computationally straightforward, root mean square deviation can be used as the decision criterion for the lowest error probability.

Disadvantages of the mentioned method:

1. An iteration over all elements of the codebook is needed.
2. FFT of the received signal and all possible FFTs are needed.
3. Calculating the distance of the received signal and possible receivings is time-consuming.

Our proposal for a simpler receiver

First proposal: In radar systems, data is embedded in the center frequency and bandwidth of the chirp. Instead of using a codebook and Maximum Likelihood (ML) estimator, it is more wise to use Short-Time Fourier Transform (STFT) and find the center frequency and bandwidth of the chirp.
STFT is a time-frequency method that is a valuable tool for estimating the parameters like start frequency, end frequency, bandwidth, pulse width, and chirp rate of a chirp signal. For doing parameter estimation, consider two scenarios: pure chirp signal and chirp signal embedded in noise. Generally, the parameter estimation in intercept sonar requires a minimal frequency resolution of 250Hz, but achieved a frequency resolution of 50Hz by using STFT technique which is much higher than the required frequency resolution. The simulation results show that in both scenarios, we achieved a lesser error value in pulse width estimation. STFT technique is found to be an efficient tool for the parameter estimation of noisy chirp signal with SNR varies from 0dB to -10dB.

What is STFT?

STFT is a tool used in signal analysis to observe the change of frequency behavior in time.
Since we are receiving a chirp, by using STFT we can find the instantaneous frequency. This means we can find all values of f_{start}, f_c and f_{end}.
These values give us the opportunity to find the bandwidth and the start frequency of the chirp.

Advantages:

1. No codebook is needed.
2. No iteration is needed.
3. time efficiency is much higher in this method.

Second proposal: In radar systems, the instantaneous frequency of the received chirp can be obtained by using a differentiator and an envelope detector. The differentiator is used to obtain the phase of the signal, and the envelope detector is used to obtain the amplitude of the signal. The instantaneous frequency is then calculated by taking the derivative of the phase with respect to time.

$$r(t) = A\cos(\omega(t)t) + n \to \omega(t) = at + br'(t)$$

$$= \frac{d}{dt}(A\cos(\omega(t)t) + n) = A(2at + b)(\cos(\omega(t)t)) + n'$$

After envelope detector what we have is $A(2at + b) + envelope(n)$.
The rest is like the last proposal, we can find all values of f_{start}, f_c and f_{end} and then extract the data.

Advantages:

1. No codebook is needed.
2. No iteration is needed.
3. time efficiency is much higher in this method.

Disadvantages

1. High noise vulnerbility.

one-bit transmission and displaying simulation figures

Explanation of how one-bit transfer is achieved using upchirp/downchirp and on-off keying.

In upchirp/downchirp transmittion we interpret increasing frequency (upchirp) as a sign of bit 1 and interpret decreasing frequency (downchirp) as a sign of bit 0.
In on-off keying method we can interpret the existence of a chirp as 1 and its absence as 0.

Include a simulation figure in the report displaying the transmitted and received chirps (two or three consecutive chirps) in the STFT domain.

Transmitted Chirp: We're currently generating random chirps, and we'll display the STFT of the first randomly transmitted chirp. The STFT provides insights into how the frequency content of the chirp evolves over time.
In the following sample, initial frequency is $3.33 \times 10^7 Hz$ and the bandwidth is $7.43 \times 10^8 Hz$.

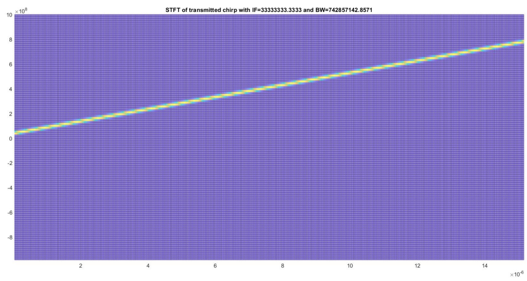

Figure 2: *Transmitted Chirp*

Received Chirp:

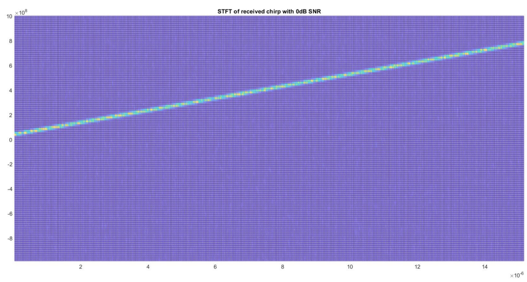

Figure 3: *Received Chirp with $SNR = 0db$*

Received Chirp:

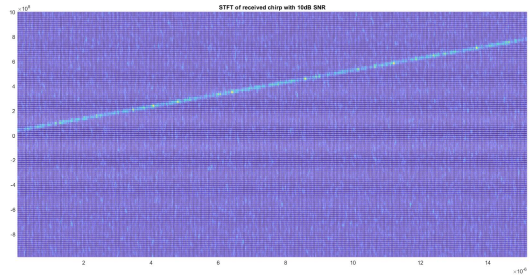

Figure 4: *Received Chirp with $SNR = 10db$*

Received Chirp:

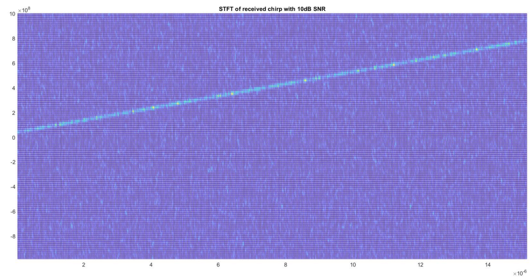

Figure 5: *Received Chirp with $SNR = 20db$*