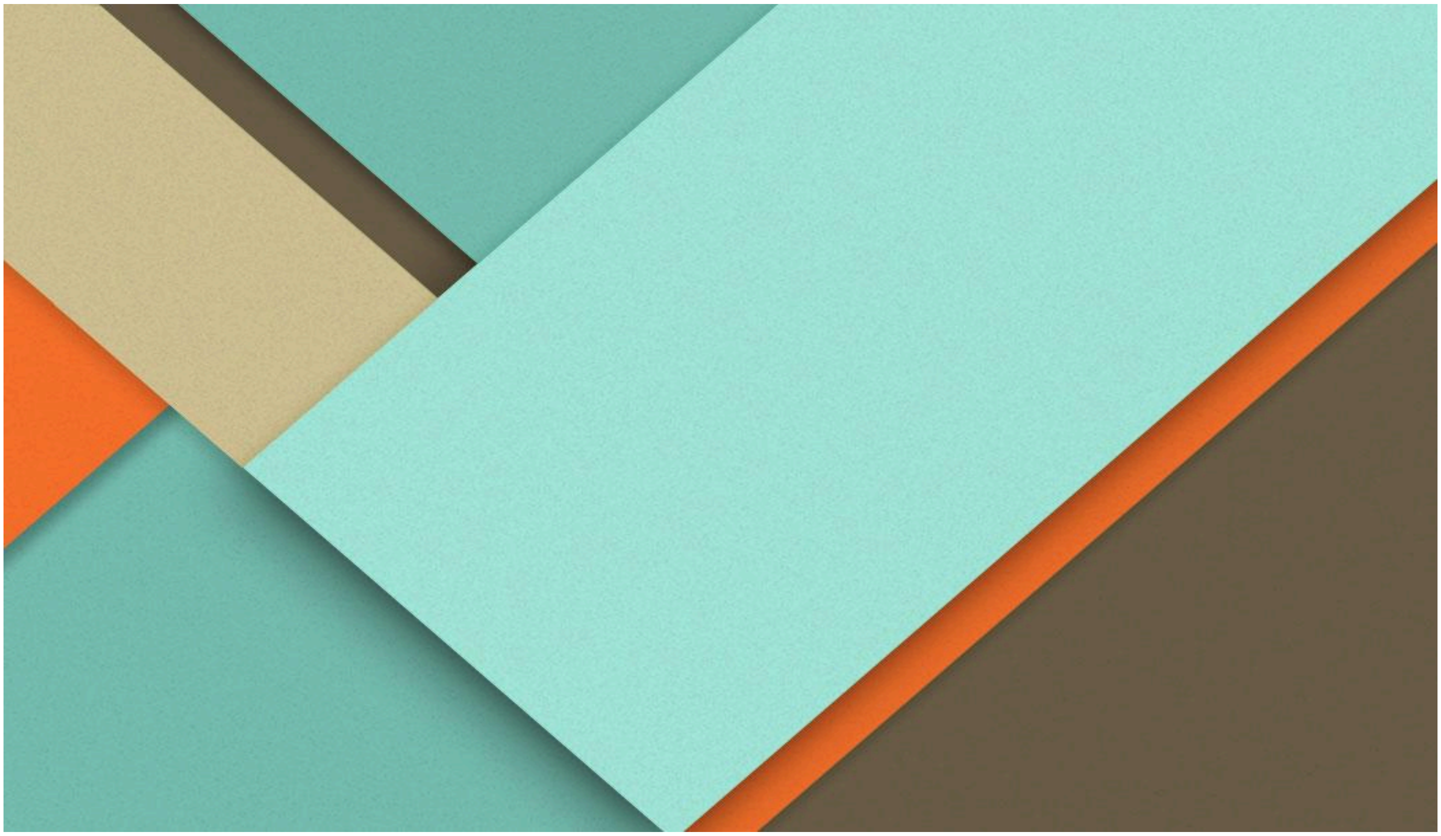

FMCW-IM

Phase II

Communication Systems

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Introduction

Wireless communication technologies are continuously evolving to meet the escalating demands for higher data rates, enhanced spectral efficiency, and multifunctional capabilities. This evolution intersects with two crucial areas of research: index modulation and the integration of radar functionalities into communication systems. This juncture holds significant promise for revolutionizing wireless communication by enabling efficient data transmission while concurrently enhancing sensing capabilities.

Importance of Index Modulation

Traditional modulation techniques such as Amplitude Shift Keying (ASK), Frequency Shift Keying (FSK), and Phase Shift Keying (PSK) have served as cornerstones in wireless communication systems. However, these techniques exhibit limitations in spectral efficiency and data rate scalability. Index modulation introduces a paradigm shift by leveraging additional parameters beyond those utilized in conventional modulation schemes. By exploiting parameters such as antenna indices or waveform characteristics like bandwidth and initial frequency, index modulation enables the concurrent transmission of multiple bits per symbol interval. This advancement promises substantial enhancements in spectral efficiency and data rate capacity compared to traditional methods.

Significance of Radar-Communication Integration

Radar systems have traditionally been deployed for object detection, tracking, and localization through the transmission and reception of radio waves. Concurrently, wireless communication systems facilitate data exchange between devices over the air. Integrating radar functionalities into communication systems presents compelling synergies. This integration optimizes hardware utilization by capitalizing on resource sharing between radar sensing and communication functions, mitigating complexity and reducing costs. Moreover, leveraging common signal processing techniques for both radar and communication tasks enhances computational efficiency. The concurrent execution of radar sensing and data transmission introduces new avenues for applications such as cognitive radio networks, where environmental sensing data inform adaptive communication strategies.

System Model

Chirp Generation

The system is initiated by generating a series of base-band complex chirps to serve as the carrier waveforms for data transmission. Each chirp is characterized by the mathematical expression:

$$x(t) = exp\,(j2\pi(\frac{1}{2}\alpha t^2 + \beta t + \gamma)),\ \ 0 \le t \le T$$

where α, β, and γ denote the chirp parameters, and T represents the duration of each chirp.

Information Encoding

Information bits are encoded via the modulation of two pivotal parameters: bandwidth and initial frequency. Bandwidth modulation permits the instantaneous frequency to vary from $-B_l/2$ to $B_l/2$ (a), while initial frequency modulation spans this range from f_m - B/2 to f_m + B/2 (b). This approach enables the simultaneous transmission of multiple bits per chirp, enhancing spectral efficiency.

$$\{ B_{min} + l\frac{B_{max} - B_{min}}{L},\ l = 0, 1, ..., L - 1 \rightarrow \text{number of encoded bits} = log_2(L) \}\ \text{(a)}$$

$$\{ f_{min} + m\frac{f_{max} - f_{min}}{M},\ m = 0, 1, ..., M - 1 \rightarrow \text{number of encoded bits} = log_2(M) \}\ \text{(b)}$$

System Parameters

- Carrier frequency (f_c): $62.64\ GHz$.
- Sampling frequency (f_s): 2×10^9 samples/sec.
- Chirp duration (T_c): $15.2\ \mu s$.
- Guard Time: $0.1\ \mu s$. (introduced at the end of each chirp to 1. Mitigate inter-symbol interference, 2. Enhance signal separation, and 3. Improve Doppler Compensation)
- Encoded bits in bandwidth: 7 bits. (from 400 to 800 MHz)
- Encoded bits in varying initial frequency: 6 bits. (from -100 to 100 MHz)

Transmission Scheme

The chirp sequence is transmitted through an Additive White Gaussian Noise (AWGN) channel, with varying signal-to-noise ratios (SNR) to assess system performance across diverse noise conditions.

Reception Scheme

To recover the embedded information in each chirp, it is crucial to determine the initial frequency and bandwidth of the chirp. One of the approaches, as proposed in the source paper by Temiz et al, involves utilizing a maximum likelihood (ML) estimator on a codebook comprising all feasible chirps in the frequency domain. This approach entails calculating the minimum distance between the Fourier transform of the received chirp and the Fourier transform of the chirps in the codebook. However, this method is highly intricate and time-consuming as it requires both a Fourier transform and an iteration over the entire codebook. An alternative is to use the ML estimator directly on the received chirps and the codebook in the time domain. While this method takes less time than the former, it is more vulnerable to channel noise, and as the signal-to-noise ratio (SNR) increases, the likelihood of a mismatch also increases.

However, a simpler method can be employed that relies on the fact that the initial frequency and the bandwidth of the chirp encapsulate the relevant information, which is readily accessible from the Short-Time Fourier Transform (STFT) of the chirp. The STFT is a potent tool in signal analysis, providing a means to observe how the frequency content of a signal evolves over time. The spectrogram, which visualizes the results of the STFT, displays the amplitudes at each frequency at any given time. Given that the frequency of the signals in this scheme changes linearly over time, the spectrogram of each chirp reveals a line of maximum amplitude, starting at $f_{start} = f_m - \frac{B_l}{2}$ and ending at $f_{end} = f_m + \frac{B_l}{2}$, which denotes the instantaneous frequency of the chirp.

Utilizing these characteristics, the center frequency and the bandwidth of any chirp can be determined from its STFT. This approach eliminates the need for a codebook and an iteration over said codebook, thereby reducing time compared to other methods. However, the run-time of this method is contingent on the necessary precision of the STFT. If the bandwidth and the initial frequencies are not sufficiently distinguishable after channel noise, a more precise STFT will be required, which may increase the run-time of the receiver.

Nevertheless, in large systems with high bit rates, this method proves to be much more efficient, regardless of the precision. However, it is crucial to note that using the STFT of the signals requires the characteristics of the chirp frequency, i.e. α and β, to be discernible after distortion due to channel noise and STFT. This might consequently reduce the bit rate of the FMCW scheme. Considering the significant difference in run-time, complexity, and memory usage that STFT offers, this might be an acceptable trade-off. Future research should focus on optimizing the precision and efficiency of the STFT to maximize the bit rate and overall performance of the proposed FMCW bit embedding scheme. Figure 1 shows the STFT of two transmitted chirps, the chirps received through an AWGN channel, and the chirps constructed from information decoded by the receiver.

One-Bit Transfer

Up-Chirp/Down-Chirp

The "up-chirp" has a rising frequency, while the "down-chirp" has a falling frequency. Here is the mathematical expression of up-chirp and down-chirp ($\alpha > 0$):

$$x_{up}(t) = exp\,(j2\pi(\gamma + \beta t + \frac{1}{2}\alpha t^2)),\ \ 0 \le t \le T$$

$$x_{down}(t) = exp\,(j2\pi(\gamma + \beta t - \frac{1}{2}\alpha t^2)),\ \ 0 \le t \le T$$

This feature can be used to represent binary numbers; for instance, an up-chirp can be used to indicate '1' and a down-chirp can indicate '0'. So in order to transmit a bit sequence, we can send a sequence of chirps corresponding to the bits. Additionally, in the receiver, a binary ‘1’ can be detected if an up-chirp is received, and a binary ‘0’ can be detected if a down-chirp is received.
It is noticeable that distinguishing an up-chirp from a down-chirp requires much less precision. As a result, the receiver structure can be much simpler, and good noise immunity can be achieved.

On-off keying

On-off keying (OOK) is a simple form of amplitude-shift keying (ASK) modulation, where the transmission of digital data is achieved by varying the amplitude of a carrier signal. In OOK, the presence of a carrier wave represents a binary '1', while the absence of the carrier represents a binary '0'.
In a receiver, OOK is much simpler because distinguishing the presence or absence of a signal is much easier than distinguishing whether it's an up-chirp or a down-chirp. However, on the other hand, it can have a negative impact on the receiver's operation if a sequence of binary '0's is transmitted. It also can't be used for dual purposes since we turn the transmitted signal on and off.

Transfer

To transfer a single bit, On-Off Keying (OOK) can be employed to determine the direction of frequency modulation, whether positive or negative. For example, to represent a binary '1', a positive slope is selected to convey an up-chirp, whereas for binary '0', a negative slope is chosen to transfer a down-chirp.

Figure 1- STFT of two consecutive chirps before transmission, before receiver, and after receiver