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Application of Wi-Fi Devices for Signal Processing to Send and Receive Data

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Abstract

This paper examines the implementation of Wi-Fi devices in signal-processing methods to transmit and receive data reliably in complex wireless networks. It describes radio signal mechanisms at the physical layer for transmitting digital information and decoding it at the other end, accounting for noise, interference, and multipath fading. Such technologies as Orthogonal Frequency Division Multiplexing (OFDM), Multiple-Input Multiple-Output (MIMO), and Channel State Information (CSI) are examined to demonstrate how contemporary Wi-Fi systems become very fast and powerful. It also discusses how these signal-processing techniques support uses like Wi-Fi sensing, security surveillance, and health tracking.

Keywords: Wi-Fi, signal processing, OFDM, MIMO, CSI, physical layer, multipath fading, Wi-Fi sensing, wireless security, health monitoring

1. Introduction

Wi-Fi is a wireless technology through which gadgets such as laptops, smartphones, and routers communicate through radio waves. Wi-Fi networks are electromagnetic networks rather than physical cables that transfer electrical impulses; the data is received by a receiver. These radio waves are sent in a very noisy environment with the reflections of walls and other objects, as well as other wireless devices. Such impairments require more than just transmission and reception to establish effective communication; this requires more sophisticated signal processing devices at both ends of the connection.

With a Wi-Fi transmitter, the sender encodes binary data, which is then converted into a radio channel, which undergoes modulation and occupies a radio frequency channel. This signal spreads to the receiver, having been corrupted by multipath fading, attenuation, and noise. To get back the data sent the receiver needs to estimate how the channel has distorted the signal and adjust those distortions. It entails modulation, channel estimation, filtering, and decoding, which are applied to the physical (PHY) layer of Wi-Fi devices (Paul & Ogunfunmi, 2008; Harkat et al., 2022).

Modern Wi-Fi is efficient and robust due to three major technologies, namely Orthogonal Frequency Division Multiplexing (OFDM), Multiple-Input Multiple-Output (MIMO), and

Channel State Information (CSI). OFDM splits the bandwidth into a large number of narrow subcarriers to be less sensitive to multipath distortion, MIMO employs multiple antennas to capitalize on spatial diversity and transmit many data streams, and CSI measures the wireless channel effects on the signal in great detail. A combination of these methods enables Wi-Fi systems to adjust to the dynamic radio conditions and ensure high data throughput.

2. Wi-Fi Transmission and Reception

The Wi-Fi communication starts with digital data, which can be a webpage or video, which is a stream of bits. These bits have to be encoded into a radio channel transmission waveform. This is converted in the Wi-Fi physical layer that carries out channel coding, modulation, and generation of waveforms (Paul & Ogunfunmi, 2008).

Error-correcting codes are performed at the transmitter, at which point the receiver is able to detect and correct bit errors due to noise and interference. The coded bits are then mapped onto the modulation symbols, like QPSK or QAM, which are various values of amplitude and phase. They are the symbols allocated to the subcarriers of the OFDM, and an inverse Fourier transform is employed to create a time domain signal. This is translated to an analog radio signal and broadcast with the antenna.

The signal sent by the transmissions flows through the wireless medium through which it experiences attenuation, noise, and multipath distortion. When in an interior setting, the signal is reflected at the walls, furniture, and individuals, and thus, the receiver will receive several delayed copies of the signal. These overlapping copies introduce frequency-selective fading, i.e., certain areas of the spectrum are weaker as compared to others (Harkat et al., 2022).

The antenna at the receiver picks up a distorted signal. The receiver initially matches the transmitting signal and trims the cyclic prefix that was appended during the transmission of the OFDM signal. The preamble in the packet contains known training symbols, which are then used to estimate the channel. This estimate enables the recipient to balance all the subcarriers, which redresses the effects of fading and distortion. With equalization, the subcarriers are demodulated again into digital symbols and decoded to obtain the original bitstream.

With this transmit-receive channel process, it can be seen that Wi-Fi relies on the constant monitoring and correction of the radio signal through signal processing and not by direct broadcast.

3. OFDM in Wi-Fi

Orthogonal Frequency Division Multiplexing (OFDM) is the modulation scheme of new generations of Wi-Fi standards like IEEE 802.11a, 802.11n, and others. OFDM breaks down the spectrum available into a large number of subcarriers, which are spread closely and carry a share of the data. These subcarriers are mathematically orthogonal; thus, they can overlap in frequency and not interfere with each other (Harkat et al., 2022).

The foremost strength of the OFDM is that it is resistant to distortion by multipaths. Inter-symbol interference in single-carrier systems is due to delayed signal copies that reduce the performance of the system. In the OFDM, many narrowband subcarriers are used to transmit each symbol, thus the symbol period is long relative to normal multipath delays. After each OFDM symbol, a cyclic prefix is inserted to avoid the interference of the main signal by echoes.

A Fourier transform is used at the receiver to split the signal received into subcarriers. Independent equalization of each subcarrier can then be done based on the channel estimate. It is now possible to compensate for frequency-selective fading, in which various regions of the spectrum are subjected to varying attenuation.

Hernandez and Bulut (2022) state that fine-grained frequency-domain information about the wireless channel is also available under OFDM and can be used to channel estimate and higher-layer processing. This is the reason why Wi-Fi communication and Wi-Fi-based sensing rely on the basic principles of OFDM.

4. MIMO in Wi-Fi

Wi-Fi modern systems include a variety of features that are based on Multiple-Input Multiple-Output (MIMO). MIMO applies multiple transmit and receive antennas in place of one antenna in order to enhance data throughput and link reliability. Standards derived under the IEEE 802.11n up to IEEE 802.11ng are capable of supporting MIMO space multiplexing, space-time block coding, and beamforming (Paul & Ogunfunmi, 2008).

In spatial multiplexing, the data streams of various antennas are sent at the same frequency band but via different antennas. Due to the fact that propagation of each of the streams takes place across slightly different wireless channels, the receiver is able to isolate the streams by channel estimation and signal processing. This multiplies the data rate without the need to add more bandwidth.

MIMO also uses beamforming, whereby the transmitter tunes the phase and amplitude of signals in its antennas so that they can constructively add at the receiver. This enhances signal strength and eliminates interference. Space-time block coding offers diversity relaying redundant information over two or more antennas, and this is beneficial in fading conditions.

Harkat et al. (2022) note that MIMO-OFDM systems need to estimate and equalize channels correctly to decipher and decode several spatial streams. This also shows that the Wi-Fi devices are actually real-time signal processors, which constantly examine the wireless channel to maximize performance.

5. Channel State Information (CSI)

Channel State Information (CSI) is the description of the radio channel propagation of a wireless signal between a transmitter and a receiver. CSI in Wi-Fi networks with MIMO and OFDM is described as a complex-valued matrix that describes the attenuation and phase shift of each subcarrier in every pair of transmit and receive antennas (Ma, Zhou, & Wang, 2019). CSI, as opposed to coarse metrics like Received Signal Strength Indicator (RSSI), reflects finer-grained frequency-domain and spatial channel response.

Every CSI value comprises both an amplitude component and a phase component. The amplitude is the amount that has been attenuated by the channel, and the phase is the delay and the path length due to multiple path propagation. When CSI is viewed across subcarriers, frequency-specific fading is apparent, with some frequencies deep-fading (frequent) and others strong (Ma et al., 2019). Since Wi-Fi applies the OFDM, CSI is calculated per subcarrier, so one can model the channels fine-granularly.

CSI is vital to a stable Wi-Fi communication because it allows the receiver to rectify the distortion of the channel, and allows advanced techniques, such as beamforming and spatial multiplexing. According to Gringoli et al. (2019), when a frame preamble is received, the CSI is estimated to equalize the remaining data symbols. CSIS feedback to the transmitter can also be sent to adjust its transmission strategy, such as the choice of beamforming weights or the choice of MIMO mode.

There are pre-established training symbols in Wi-Fi packet preambles to compute CSI. Halperin et al. (2011) add that the IEEE 802.11n receiver uses known long training symbols (LTFs) to ascertain the channel frequency response. The model below provides the received signal on each subcarrier:

$$y = Hx + n,$$

where,

x is the transmitted symbol, y is the received symbol, H is the CSI matrix, and n is noise. Using the received y and the known x, the receiver decides the estimation of H per subcarrier and antenna pair. This CSI is then used by the equalizer to undo channel distortion and is then demodulated.

6. The Signal Processing at the Receiver

The Wi-Fi receiver uses a set of signal processing to reconstruct the message sent by a mangled and noisy radio signal. Noise and interference mitigation is the first phase, during which filtering, timing, and frequency alignment are used to eliminate out-of-band noise and synchronize the receiver with the timing and frequency of the transmitter (Hernandez & Bulut, 2022).

The estimation of the channels is then done through CSI. The packet preamble includes training symbols that the receiver uses to calculate the frequency response of the wireless channel of each OFDM subcarrier. Equalization is applied to this channel estimate to correct attenuation of amplitude and phase distortion to ensure that the received signal is more similar to the one sent (Yang et al., 2022).

Upon equalization, demodulation is done by the receiver to recover the complex OFDM symbols in the form of digital symbol values. These codes are decoded by means of error correcting decoders like convolutional decoders, LDPC decoders, etc., to reconstruct the original bitstream. This last step removes remnant errors due to noise, fading, or interference (Hernandez & Bulut, 2022).

More recent work has been done on receiver processing with deep learning. As demonstrated by Wang et al. (2023), convolutional neural networks are capable of training the mapping between received signals, which are noisy, and sent signals, which reduces bit-error rate in noisy impulsive receiver settings. It proves that recent Wi-Fi receivers are moving towards a combination of more traditional signal processing and data-driven algorithms.

7. Current uses of Wi-Fi Signal Processing

In addition to data communication, Wi-Fi signal processing also allows numerous sensing and monitoring applications. Since CSI measures finer details of signal propagation, it can be employed to monitor environmental changes without the need to install more sensors.

Wi-Fi sensing may sense human presence, gestures, and patterns of activities to control the appliances without the devices in smart homes (Ma et al., 2019; Yang et al., 2022). In security and motion detection, the variation of the amplitude and phase of the CSI signal detects motion, and the Wi-Fi system can detect intrusions even through the walls.

CSI variations have been applied in health monitoring in order to monitor respiration rate, falls, and human activity. Ma et al. (2019) demonstrate that the patterns of breathing and motion are present in the CSI time series, allowing non-contact monitoring of the vitals. Hernandez and Bulut (2022) also show that these signal processing pipelines can execute on low-priced embedded Wi-Fi gadgets.

These applications are based on the same OFDM, MIMO, and CSI technologies that facilitate data transmission, which underscores the dual nature of Wi-Fi as a communication and sensing platform.

8. Difficulties and Future Enhancement

The noise, interference, and hardware limitations are some of the problems that hinder Wi-Fi signal processing. Saturated wireless space brings about the problem of co-channel interferences whereas the low-cost hardware reduces sampling rate and computing capabilities (Hernandez & Bulut, 2022). Multi-path fading and noise of impulse further decrease reliability.

A potentially successful direction is the processing of AI. Wang et al. (2023) show that deep learning is more effective in a high noise environment than traditional receivers, meaning that the next generation of Wi-Fi systems will combine traditional signal processing with neural networks to be stronger and more efficient.

9. Conclusion

The Wi-Fi is not simply a radio connection, but a more sophisticated signal-processing system. OFDM divides the spectrum into subcarriers, which are easily manageable; MIMO leverages the diversity in space, and CSI provides more channel knowledge. Combined, these technologies enable Wi-Fi devices to be flexible to changing environments, to be used in providing high-speed communications, and to be used in sensing applications. With the further development of signal processing and AI, Wi-Fi will be one of the underlying technologies in connectivity and smart spaces.

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