Software-Defined Ultrasonic Communication System with OFDM for Secure Video Monitoring

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ABSTRACT Ultrasonic communication is a desirable method for information transfer through solid channels such as metallic bars, plates, or pipes by overcoming the physical barriers that prevent conventional wired or radiofrequency transmission. In this paper, we investigate the architecture of a reconfigurable software-defined ultrasonic communication (SDUC) platform that can make use of the complete channel bandwidth for real-time video transmission through a highly reverberant solid channel. Reverberations in solid channels are complex and generated by surface wave, lamb wave, longitudinal wave, shear wave, reflection, refraction, dispersion, mode conversion, and scattering phenomena. To explore the multipath and fading effects on bitrate, experimental studies were performed using an aluminum rectangular bar (ARB) of 25, 40, and 50 cm channel length. We investigated the feasibility of utilizing orthogonal frequency-division multiplexing (OFDM) combined with quadrature amplitude modulations (QAM) for peak bitrate performance. Design strategies and guidelines have been established for the best solutions to combat intersymbol interference caused by the severe reverberation inherent to ultrasonic solid channels. A practical solution for video transmission, adhering to the Digital Video Broadcasting Terrestrial (DVB-T) standard, is also examined for video streaming transmission of 240p, 480p, and 720p resolutions at 20 frames per second across an ARB channel. For experimental studies and performance evaluation, we designed a high-performance reconfigurable system-on-chip (SoC) SDUC platform for video transmission and bit error rate (BER) assessment. Through experimental studies for ultrasonic channel analysis, we achieved a peak video transmission rate of 1074 kbps with 3.3×10⁻⁴ BER despite reverberation, the multipath effect, and signal fading within the ARB channel.

INDEX TERMS Communication channels, Ultrasonic transducers, OFDM, Software radio, Multipath channels, Digital video broadcasting

I. INTRODUCTION

Ultrasonic communication is a viable method for transmitting information through solid communication channels, such as metal pipes, rectangular bars, or plates [1][2][4]. This method overcomes the physical barrier that prevents conventional wired or wireless communication. For example, nuclear facilities are partitioned into different blocks for isolation and safety purposes. Each block is hermetically sealed by a thick reinforced concrete wall with an existing in-place metal infrastructure, such as pipes. Consequently, ultrasound is a promising technique for communication by utilizing embedded metal structures.

Also, pipelines and chemical containers have metal structures that can be used as channels for ultrasonic communications. An 800-bps communication system [5] using multitone frequency-shift keying (FSK) was designed using steel corner posts from shipping containers as the communication channel. In our earlier work [2] [3], only a 2-Kbps bitrate with a bit error rate (BER) of 1×10⁻³ was achieved for image transmission using amplitude shift keying (ASK) due to the signal complexity within the solid channel.
Most advancements in ultrasonic communication are made for underwater applications [6]. The underwater acoustic communication technology is relatively mature, and acoustic communication platforms are utilized by submarines or ships [7]. There is a large interest in maximizing the data rate and bandwidth efficiency in underwater communication [8]. Ultrasonic waves are known to have propagation characteristics through not only solid or liquid materials but also biological tissues. An intrabody ultrasonic communication network system mimicked by a tissue phantom achieved a 28.12 Mbps data rate using orthogonal frequency-division multiplexing (OFDM) [9].

Ultrasonic communications through solid channels such as bars, plates, and pipes suffer from reverberation, dispersion, and attenuation [10] [11] [12]. Reverberations in such solid channels are generated by surface wave, lamb wave, longitudinal wave, shear wave reflection, refraction, dispersion, mode conversion, and scattering phenomena [13]. Time-reversal and pulse-shaping techniques can be applied to reduce the impact of reverberations [14] [15].

To exhibit the multipath and fading effects due to reverberation, we resorted to simulating pulse wave propagation in an aluminum rectangular bar (ARB). Furthermore, we investigated the feasibility of using OFDM to realize intersymbol interference (ISI) mitigation [16]. OFDM is a bandwidth-efficient communication technique with high data rates that can transmit modulated symbols into orthogonal subcarriers. Separate narrowband subcarriers at different frequencies can reduce interference and crosstalk. In addition, a pilot symbol is inserted into OFDM symbols to assist channel estimation, and a cyclic prefix is appended as the guard interval to mitigate ISI. The payload modulation methods applied are QPSK, 16-QAM, and 64-QAM. The results are compared for several distances between the transmitter and the receiver to estimate the optimal ultrasonic communication bitrate.

In this study, we focus on ultrasonic guided wave propagation along ARB channels for video transmission. Video transmission is a promising approach that can deliver diverse types of information [17]. For experiments and performance evaluation, a software-defined ultrasonic communication (SDUC) video monitoring system is developed. The system consists of a Raspberry Pi single-board computer (SBC) for the user interface and a Red Pitaya, a reconfigurable and high-performance system-on-chip (SoC) platform [18][19], for transmitting/receiving video streams.

The proposed SDUC video monitoring system can deliver real-time video streaming to remote clients. The H.264 standard is used to compress the video stream and reduce the transmission delay while retaining video quality [20]. The video stream is modulated, interleaved, and mapped according to the Digital Video Broadcasting Terrestrial (DVB-T) standard [21], a TV broadcasting standard based on OFDM. This is a practical approach for signal recovery in the presence of ISI and multipath effects. The DVB-T protocol is supported by the GNU Radio software toolkit. We present both analytical and experimental results of the OFDM video transmission protocol for the 2K and 8K modes. The proposed video monitoring system offers fast data processing for real-time video transmission above 1 Mbps and a 3.3 × 10^-4 BER through the ARB channel.

Due to the limited transmission distance of ultrasonic waves, the receiver must connect to conventional communication channels, such as Ethernet or Wi-Fi, to interface with and transmit the video stream to a remote client. To create robust and secure communication, we developed a comprehensive and distributed end-to-end cryptosystem to secure the video stream transmission link. A chaotic encryption method utilizing 2D and 1D iteration models confuses and diffuses the video stream [22]. A 128-bit Advanced Encryption Standard (AES) Cipher Block Chaining (CBC) is proposed to encrypt the video stream [23]. The encrypted video file is uploaded to a content delivery network (CDN). Only the client is granted access to the server and has the chaotic and AES keys that can decrypt the received video from the mobile device or web remotely. Chaotic map encryption provides high randomness at a lower key length and computation time compared to the AES Encryption Algorithm. This is beneficial for computationally constrained embedded systems. Our platform switches to AES Encryption when transmitting the video stream to the CDN Server since more computational resources are available. The end-to-end cryptosystem assures secure data transfer and provides system-level data protection for video monitoring.

The paper is organized as follows. In Section II, we present the model of an ultrasonic wave propagating in a plate channel. Section III describes the encrypted video streaming architecture, including the video codec encoder, the end-to-end cryptosystem, and the DVB-T standard channel encoder and decoder based on OFDM. In Section IV, a laboratory benchmark ultrasonic video monitoring system configuration is demonstrated. Section V presents experimental studies for low BER communication through solid channels using different modulation schemes and channel lengths. Video streaming test results are presented in Section VI. Section VII summarizes and concludes the contributions of this paper.

II. ULTRASONIC WAVE PROPAGATION IN ARB CHANNEL

The geometry of the ultrasonic communication channel impacts the severity of reverberation and multipath effect and consequently the bitrate performance [4] [24]. We performed a finite element analysis (FEA) with Abaqus/Explicit software to simulate ultrasonic wave propagation in the ARB channel. The ARB size is 100×10×2 cm. Multiple longitudinal and shear waves are produced due to mode conversion [25] at the boundary of the ARB. As can be seen in Fig. 1, a pseudo-color map of the displacement distribution depicts the amplitude of
the ultrasonic wave patterns. Fig. 1a–e shows the transmitted wave patterns at 21, 48, 97, 143, and 189 µs corresponding to distances of 12, 27, 55, 82, and 99 cm. As shown in these figures, ultrasonic waves collide with the boundary of the ARB, causing mode conversions, reverberation, and wave spreading. Consequently, the ultrasonic wave energy disperses along the length of the ARB (compare Fig. 1a–e) with lower intensity.

![Figure 1](image1)

**FIGURE 1.** Computer simulation of a 2.5-MHz ultrasonic wave propagating in the ARB channel. Ultrasonic wavefronts are visualized with a pseudo-color map of the displacement distribution at 21, 48, 97, 143, and 189 µs.

Fig. 2 shows experimental pulse wave responses in the ARB channel for different channel lengths. Two 2.5-MHz PZT transducers with 60° oblique angle wedges are used as the transmitter and receiver. The transmitted pulse shown in Fig. 2a is 1 µs. The received pulse wave response is spread and faded due to the ultrasonic beam spreading in the wedges, longitudinal and shear wave mode conversion within the bar, and the propagating wave on the surface of the bar. The severity of the multipath effect and signal fading is governed not only by the size of the bar but also by the location of the transmitter and the receiver on the ARB channel. The received waveform is the superposition of all propagating wave modes. Consequently, Fig. 2b–d displays the superposition of several scattered wave-packets associated with different traveling paths in the received signal. Furthermore, the wave dispersion and fading effect become more pronounced as the channel length increases.

**III. ENCRYPTED VIDEO STREAMING ARCHITECTURE**

In this section, we present the major components of our encrypted video streaming architecture. Fig. 3 displays the experimental setup of the SDUC system for video transmission. After acquiring the video stream from the webcam, the video codec encoder is used to compress the video data. The stream bits are encrypted using the chaotic encryption method [26] [27]. Then the DVB-T standard is applied to code, interleave, and map the stream data to QPSK, 16-QAM, and 64-QAM modulation, followed by error correction codes and the shuffling of the bit positions in the blocks. The symbols are modulated using the OFDM. The modulated video stream data is transmitted by the PZT transmitter through the ARB channel.

![Figure 2](image2)

**FIGURE 2.** Pulse wave response test for multipath effect exhibition of different channel lengths. (a) Transmitted pulse, (b) Received signal at 25 cm channel length, (c) Received signal at 40 cm channel length, and (d) Received signal at 50 cm channel length.

The received stream is demodulated at the receiver side using a DVB-T decoder. The DVB-T decoder is used to retrieve the signal back to the original video stream. Thus, the OFDM demodulation, demapping the constellation, deinterleaving, and decoding are performed consecutively. In addition, the recovered video stream is encrypted with AES encryption [28][29] and uploaded to the CDN server [30]. The CDN grants permission to the remote user to access the video stream. Chaotic encryption is implemented on the transmitter side of the ARB channel, AES encryption is implemented on...
the receiver side of the ARB channel, and the CDN server constructs the end-to-end cryptosystem to secure the video stream data. On the side of the remote client, the user is required to have two private keys and a public key to decrypt the video streaming. The video codec decoder follows the inverse steps of the encoder to recover the data from the compressed data. Note that all the encoding/decoding processes are lossless.

The DVB-T standard is a practical method to broadcast transmission of digital terrestrial television [21]. The benefit of channel encoding is signal recovery, avoiding the multipath effect of solid channels for ultrasonic communication and noise. As shown in Fig. 3, the DVB-T information processing sequence contains a forward error correction (FEC) encoder and an OFDM modulator by which the information is coded, interleaved, and mapped to the QPSK, 16-QAM, or 64-QAM constellations. The symbols are transmitted at different frequency subcarriers using the inverse fast Fourier transform (IFFT) method. The number of IFFT points is also referred to as the number of subcarriers. The 2K mode has a total of 2048 subcarriers, out of which only 1705 are used; the 8K mode has a total of 8192 subcarriers, out of which only 6817 are used. The remaining subcarriers are reserved for reference pilot signals. Various sets of pilots are applied depending on the transmission parameters. There are three types of pilot signals: scatter pilots, continual pilots, and transmission parameter signal (TPS) pilots. Note that 45 continual pilots, 131 scatter pilots, and 17 TPS pilots are used in the 2K mode and that 177 continual pilots, 524 scatter pilots, and 68 TPS pilots are used in the 8K mode. The position of the pilots is indexed based on the DVB-T standard [21].

Channel estimation and equalization are achieved by inserting pilot signals (pilot subcarriers transmit with a known data sequence) surrounded by the information subcarriers. The subcarriers are indexed by \( k \in \{k_{\text{min}}, k_{\text{max}}\} \), where \( k_{\text{max}}=1704 \) in the 2K mode and \( k_{\text{max}}=6816 \) in the 8K mode. Note that only 1512 (2K mode) and 6048 (8K Mode) of the subcarriers are used for information symbols. The remaining subcarriers are reserved for pilot signals. The subcarriers are indexed by \( k \in \{k_{\text{min}}, k_{\text{max}}\} \), where \( k_{\text{max}}=1704 \) in the 2K mode and \( k_{\text{max}}=6816 \) in the 8K mode.

FIGURE 3. Secure SDUC system architecture for remote video monitoring.

FIGURE 4. A frame structure of the DVB-T OFDM pilot subcarriers.

The IFFT/FFT size of the 2K mode is 2048 symbols, and that of the 8K mode is 8192 symbols. For the 2K mode, there are 342 null subcarriers, and for the 8K mode, 1374 null subcarriers are placed along the edges of the signal spectra as guard bands. Null guard bands are desirable to combat the spectrum spreading of OFDM signals. Furthermore, a null subcarrier in the middle of the spectrum suppresses the DC component in the OFDM signal. Fig. 5 illustrates the distribution of the OFDM subcarriers for the 2K mode. After the IFFT is performed on the OFDM subcarriers, the cyclic prefix is added to the OFDM waveform in the time domain,
whose value is the repetition of the end of each OFDM waveform. The cyclic prefix converts and accounts for the cyclic characteristic of the IFFT for obtaining the time-domain signal. A cyclic prefix of sufficient length in the time domain provides a guard interval to mitigate the multipath effect. As a result, one OFDM symbol consists of an OFDM waveform and a cyclic prefix.

![FIGURE 5. OFDM subcarriers (channel bandwidth) and OFDM waveforms (blue represents the in-phase signal, and red represents the quadrature signal).](image)

The transmitting time of video frames determines the video stream symbol rate. The I/Q symbol rate of the Red Pitaya platform is configurable, and six settings are available: 20k, 50k, 100k, 250k, 500k, and 1250k symbols per second (SPS). The efficiency of the symbol rate can be calculated as the number of video symbol subcarriers within one OFDM frame over one OFDM symbol length. For 2K-mode video transmission, only 1512 OFDM subcarriers are information symbols, so the efficiency of the symbol rate is 65.625%. Similarly, for 8K-mode transmission, only 6048 OFDM subcarriers are allocated for information symbols, resulting in a 71.59% symbol rate efficiency.

### IV. SDUC SYSTEM CONFIGURATION FOR REMOTE VIDEO MONITORING

In this section, the prototype and configurations of a secure video transmission/reception system are examined. The dedicated hardware and software parts of the video monitoring system are developed on a Zynq-based field-programmable gate array (FPGA) platform known as Red Pitaya [31]. Zynq system-on-chip (SoC) FPGA devices integrate dual ARM processors and FPGA architectures into a single device. Consequently, they provide higher integration, lower power, a smaller board size, and higher-bandwidth communication between the processor and the FPGA. This platform incorporates the GNU Radio software to create an SDUC system. The SDUC system is an adaptive and reconfigurable ultrasonic communication system with the capability to interface with Raspberry Pi (a single-board computer) for the development of a video transmission protocol. Both the Raspberry Pi computer and the Red Pitaya platform are low-cost, low-form factor, and power-efficient modules.

![FIGURE 6. SDUC system architecture for secure remote video monitoring.](image)

Fig. 6 displays the real-time ultrasonic video transmission and reception architecture through an ARB channel using the SDUC platform. The ultrasonic video transmitter is in a sealed environment and is fully isolated within a physical containment structure. The webcam is interfaced with the Raspberry Pi computer by a USB cable, and the data link between the Raspberry Pi computer and the Red Pitaya platform is realized through an Ethernet cable. Raspberry Pi computes encryption, compression, DVB-T formatting/packetization, and OFDM modulation of the video stream. Then, the Raspberry Pi computer transfers the packetized video streams to the Red Pitaya platform for ultrasonic transmission through an ARB channel using a PZT ultrasonic transducer. On the receiver side, the Red Pitaya platform acquisitions the OFDM data stream by a PZT ultrasonic transducer. The Red Pitaya platform transfers the acquired data to Raspberry Pi for video stream recovery. Then, the DVB-T decoder and OFDM demodulator are implemented in the Raspberry Pi computer. The wireless router accesses the Internet to deliver a secured video stream from the Raspberry Pi computer to the end-users through the CDN server. The prototype of the SDUC video streaming architecture shown in Fig. 6 is depicted in Fig. 7.

The Red Pitaya platform (a Zynq SoC-based system operating at a master clock frequency of 125 MHz) used in the system is equipped with a 14-bit analog-to-digital converter (ADC) operating at 125 mega samples per second and a 14-bit digital-to-analog converter (DAC) operating at 125 mega samples per second. On the transmitter and receiver sides, the digital up converters (DUCs) are implemented within the FPGA fabric to match the ADC and DAC sampling rate to the
I/Q symbol rate. Note that the symbol rate is governed by the SNR and decided by the user to obtain an acceptable BER.

Raspberry Pi is the host computer, generating the OFDM baseband video and processing the received baseband to recover the video data. The DVB-T transmitter/receiver protocol is implemented in GNU Radio software in the Raspberry Pi computer. The GNU Radio software is supported with a configurable communication library that allows customization of modulation/demodulation and signal processing algorithms. In addition, the encryption/decryption and the video codec encoder/decoder are computed in the Raspberry Pi computer using Python software tools. A pair of broadband ultrasonic transducers (with a center frequency of 2.5 MHz and a 3-dB bandwidth of 2.0–3.0 MHz) with 60° oblique angle wedges driven by the Red Pitaya platform are used as transmitters and receivers.

![SDUC video monitoring prototype assembled in the laboratory.](image)

**FIGURE 7.** SDUC video monitoring prototype assembled in the laboratory. (a) Ultrasonic video transmitter system in a sealed containment, and (b) Ultrasonic receiving system outside the sealed containment.

V. EXPERIMENTAL STUDIES OF VIDEO TRANSMISSION

In this section, we present test results and the feasibility of applying the DVB-T OFDM standard to ultrasonic communication for remote video monitoring. The SNR of the received signals is affected by two factors: the video stream data rate and the propagation distance. We examined the performance of different modulation schemes (i.e., QPSK, 16-QAM, and 64-QAM) and 2K-mode DVB-T and 8K-mode DVB-T for OFDM communication. Furthermore, we examined six symbol rate settings for efficient and reliable video transmission. Also, the impact of the channel transmission distance (for three different lengths: 25, 40, and 50 cm) using the ARB is studied. These efforts were directed to determining the optimal configuration in terms of bitrate and BER for video data transmission using ultrasound.

A. MULTIPATH EFFECT AND BER EVALUATION

We modeled an ultrasonic multipath channel model to study the BER and the overall performance of the ultrasonic communication system using the OFDM method. The multipath channel model is extracted by using the experimental pulse wave response of the ARB channel shown in Fig. 8a. Fig. 8b reveals the eight multipath wavelets in terms of delays and normalized amplitudes associated with the measured signal shown in Fig. 8a.

![Ultrasonic multipath channel model.](image)

**FIGURE 8.** Ultrasonic multipath channel model.

We used the experimental results shown in Fig. 8b to represent a realistic multipath effect associated with the ARB channel characteristics and ultrasonic transducers for transmission/reception. The QPSK, 16 QAM, and 64 QAM are used to modulate/demodulate the binary video information. Furthermore, 2K and 8K IFFT/FFT are examined in the OFDM simulation for BER evaluation. Fig. 9 compares the BER performance of different modulation schemes and the number of subcarriers applied in OFDM.
B. MODULATION METHODS AND DVT-B MODES

An experiment was conducted to evaluate the performance of ultrasonic communication using different modulation schemes under 2K and 8K operation modes. The distance between the transmitter and the receiver is set at 25 cm, and the symbol rate is 100 kSPS. The experimental constellation results using QPSK, 16-QAM, and 64-QAM based on 2K-mode OFDM are shown in Fig. 10. The Error Vector Magnitude (EVM) and BERs are used to quantify the constellation results [32]. Consequently, a higher-order QAM offers a higher bitrate but necessitates a lower EVM for an acceptable BER. The scenario of a lower-order modulation scheme, e.g., with QPSK, has more margin to failure and better BER performance. Similar observations can be made using 8K-mode OFDM (see Fig. 11). Compared with the 2K mode results, the constellation diagrams for QPSK, 16-QAM, and 64-QAM are more explicit for the 8K mode, and the scattering of the constellation points is more condensed with lower EVM. This observation indicates that 8K OFDM is the preferred mode for video transmission with a higher bitrate and a lower BER through the 25-cm-long ARB channel using the 2.5-MHz ultrasonic transducers.

C. BITRATE PERFORMANCE EVALUATION

Bitrate in ultrasonic communication defines the speed of digital transmission. An ultrasonic carrier with a high bitrate makes real-time remote video monitoring practical. However, a high bitrate requires more bandwidth and leads to a lower SNR and consequently a higher BER. Ultrasonic experiments using the Red Pitaya platform were performed to evaluate the highest possible transmission rate in an ARB channel. The symbol rate in the Red Pitaya platform can be adjusted to 20k, 50k, 100k, 250k, 500k, and 1250k SPS. The SNR is affected by the characteristic frequency of the ultrasonic transducer and the ARB channel.

Experimental studies in search of the optimal bitrate were conducted using an ARB channel length of 25 cm (distance between the transmitter and the receiver), 2.5-MHz ultrasonic transducers, and 8K-mode OFDM. Fig. 12 shows the QPSK constellation diagram at the different symbol rates. As the symbol rate increases, the received constellation symbols become more scattered, resulting in a higher BER. Figs. 12a–12f shows the constellations and EVMs for different symbol rates. As shown in Fig. 12f, the QPSK constellation for 1250k SPS is highly scattered with an unacceptable EVM value of 44.65%. On the other hand, the 500k SPS with an EVM value of 9.08% (see Fig. 12e) is the optimal symbol rate for the 8K mode using QPSK modulation.
To find the optimal (i.e., highest) bitrate for ultrasonic communication, we studied the combined impact of symbol rate and modulation order. Fig. 13 displays the 16-QAM (4th-order modulation) and 64-QAM (6th-order modulation) constellations at different symbol rates. The EVMs of 16-QAM for 250k SPS and 500k SPS are 7.04% and 17.68%, respectively. The EVMs of 64-QAM for 250k SPS and 500k SPS are 6.33% and 12.56%, respectively. When the symbol rate is 250k SPS, both 16-QAM and 64-QAM are viable according to the constellation diagrams (see Figs. 13a and 13c). In Figs. 13b and 13d, the symbol rate is 500k SPS, and both 16-QAM and 64-QAM failed to recover the video stream due to the high EVM.

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In Fig. 17a, 50k SPS can be achieved for the 8K mode using 16-QAM modulation with an EVM of 10.01% across a distance of 40 cm, while a symbol rate of 100k SPS with EVM of 22.49% fails to recover the video symbols. Similar experiments were conducted using a 50-cm-long ARB channel, with Fig. 18 displaying the QPSK constellation diagrams and frequency responses for several symbol rates. As expected, the 50-cm-long channel has the worst SNR compared with the 40-cm-long and 25-cm-long channels. For a 50-cm-long channel, 50k SPS (the highest symbol rate) and QPSK modulation with an EVM of 18.21% is the best solution for video transmission. Fig. 19 displays the 16-QAM constellation diagrams for 20k SPS and 50k SPS. According to the frequency responses and the constellation diagrams, 20k SPS is the only feasible symbol rate for 16-QAM with an EVM of 11.14% across a 50-cm-long ARB channel. In summary, the SNR of ultrasonic communication is inversely proportional to the ARB channel length. The optimal bitrates (i.e., best solution) for channel lengths of 40 and 50 cm are presented in Table I. Examining all the results for channel lengths of 40 and 50 cm, the best solution for a channel length of 40 cm is QPSK modulation and a symbol rate of 250k SPS. This arrangement allows a maximum bitrate of 358 kbps. The best solution for a channel length of 50 cm is QPSK modulation and a symbol rate of 50k SPS. This arrangement allows a maximum bitrate of 72 kbps.
VI. VIDEO TRANSMISSION TEST RESULTS AND ANALYSIS

We examined the functionality of the SDUC system by transmitting video streams with 20 frames per second (fps) and three video resolutions: 240p (320 x 240), 480p (640 x 480), and 720p (1280 x 720). The latency for the received video stream is a function of transmitted video resolutions. The optimal video transmission settings are chosen according to the data highlighted in blue in Table I. The video is encrypted before transmission. Fig. 20 shows a transmitted encrypted video frame with a 480p resolution using chaotic maps. The encrypted frame (Fig. 20b) is random with a uniform distribution (Fig. 20c) and not recognizable. Fig. 20 displays a correlation analysis of an encrypted frame. This figure reveals that chaotic encryption greatly reduces the correlation between neighboring pixels.

The 240p, 480p, and 720p encrypted video streams are transmitted through the ARB channel over a distance of 25 cm. The received and recovered video frames are shown in Figs. 21, 22, and 23, with resolutions of 320x240, 680x480, and 1280x720, respectively. The end-to-end BER, including the channel coding and encryption, is calculated by comparing the recovered video frames with the original frames. For example, as shown in Fig. 13c, the constellation with an EVM of 6.33% (for a 25-cm-long channel, 250k SPS, and 64-QAM) can realize a high-quality real-time video transmission (see Fig. 22) with a bitrate of 1 Mbps and BER of 3.3 x 10^-4. On the other hand, a higher transmission rate (e.g., see Fig. 13d showing a constellation diagram for a 25-cm-long channel, 500k SPS, and 64-QAM, with an EVM of 12.56%) is prone to an unacceptable BER of 4.8 x 10^-1, and consequently, fails to recover the video frame accurately (see Fig. 24).

![FIGURE 20. Ultrasonic transmission of a video frame. (a) Original video frame with a resolution of 640x480, (b) Encrypted video frame using a chaotic map, (c) Histogram analysis of an encrypted frame, and (d) Correlation analysis of adjacent pixels within the encrypted frame.](image)
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David Arnold received his B.S. degree in Electrical Engineering and M.S. in Computer Engineering from the Illinois Institute of Technology in May 2019. He is currently pursuing a Ph.D. degree in Computer Engineering with a focus on cybersecurity at the Illinois Institute of Technology. He is a Research Assistant at the Embedded Computing and Signal Processing (ECASP) Research Laboratory and is the head and founder of the Illinois Tech CyberHawks, a cybersecurity student organization. In Spring 2020, David was a recipient of the Department of Energy’s Office of Nuclear Energy’s Integrated University Program graduate fellowship. His current research interests include cybersecurity, Internet of Things, embedded computing, distributed systems, industrial control systems, and machine learning.
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