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A Novel Approach to Powerline Communication via Conductive Fabric

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ABSTRACT

This paper presents a novel approach to communication systems by integrating conductive fabric with powerline communication. The proposed system leverages frequency-shift keying (FSK) using direct digital synthesis (DDS) for modulation and digital signal processing (DSP) for demodulation at the physical (PHY) layer, and a frame structure at the medium access control (MAC) layer for the conductive fabric channel with multiple nodes. The primary innovation lies in the practical application of conductive fabric as a dynamic communication medium, showcasing its modulation adaptability and robust data exchange along with the power supply. The frame format, in the PHY and MAC layers, serves to efficiently transmit reliable data between multiple nodes over the fabric. The implementation validates the nodes and system design, showing its signal and communication robustness and its potential for diverse applications such as the chatting program example and beyond the realm of wearable devices. The paper shifts the spotlight towards conductive fabric communication, emphasizing its relevance and significance as an adaptable and promising medium for future communication systems.

Key Words : wearable devices, conductive fabric, signal processing, physical layer, powerline communication

Ⅰ. Introduction

In the relentless pursuit of innovative mediums to enhance connectivity, the evolution of communication systems has taken a transformative turn towards wearables devices[1-3] . The burgeoning field of wearable devices with flexible and adaptable bodies, has captured significant interest, particularly in applications seamlessly integrated into clothing or accessories[4-9]. Beyond the promise of augmenting human capabilities and contributing to advancements in physical rehabilitation[10-12], the crux of this evolution hinges on the need for a communication system that not only facilitates interaction with the environment but also responds seamlessly to user input[6-9].

Amidst the extensive research on wireless body area networks (WBANs) for wearable sensors[10,13], including the development of the IEEE 802.15.6 international standard[14], our focus diverges towards an innovative avenue. Rather than relying on traditional wireless channels with their susceptibility to interference and the need for individual power sources for each node, we turn our attention to the transformative capabilities of power line communication[15,16]. This technology, leveraging the

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existing electrical power grid, emerges as a compelling solution for wearable robotics[3]. By transmitting both communication signals and power through conductive yarns or fabrics, the complexities of intricate wiring are mitigated, enhancing the system's flexibility and mobility.

1.1 Related Works

Within the expansive domain of wearable communication systems, notable works have contributed valuable insights[4,17,18]. Conductive fabric garment was investigated to determine a resistance model approximation between different location a the conductive fabric shirt[4]. Power line communications (PLC) was adapted to establish the power level and frequency response of a communication signal through the conductive garment[4,19,20]. A wearable body sensor network was described and implemented with conductive yarns in a mesh topology[17]. Each node is a four port router that handles data between inter node communications. Due to the multiple connections, network scalability will be hard to mitigate for wearable applications. A power and data transfer network on a square mesh double-layer conductive fabric utilizing the InterIntegrated Circuit (I2C) protocol have been proposed, showcasing the efficacy of conductive fabric in facilitating communication[18,21]. The network requires an external power supply and signal generators to operate. Authors assume that the impedance is almost independent of the frequency and design a set of filters according to fixed frequencies for every node.

1.2 Contributions

This article marks a pivotal step in this trajectory, concentrating on the design and implementation of a network that facilitates communication among multiple nodes in conductive fabric layers. Design and implement a communication network based on a two layers conductive fabric and PLC systems. A node design must take in consideration the channel medium and signal adaptability. Robust data transmission and reception between nodes, as well as managing device access in a network, are critical to achieving this. Together, these layers ensure the seamless transmission and reception of communication signals within the network, accommodating the diverse needs of multiple interconnected nodes such as a chatting example program[22-25].

Beyond the confines of wearables, this communication paradigm opens up a spectrum of applications. From healthcare to smart textiles and industrial environments, the versatility of conductive fabric communication heralds a new era in wearable technologies. This article delve into the intricacies of our proposed and implement a network architecture, we unravel not only a technical advancement but a transformative shift towards wearable devices powered by the seamless integration of conductive fabrics as a communication medium.

Ⅱ. System Model

The communication channel is made of two conductive layers that are isolated by a non-conductive layer in between them and each node is plugged in the network via two node connectors as shown in Fig. 1.

Consider a conductive fabric network (CFN) with multiple battery-less nodes. Every node and a power supply are connected to the conductive layers of the CFN as shown in Fig. 2.

There is one type of node in the network that can

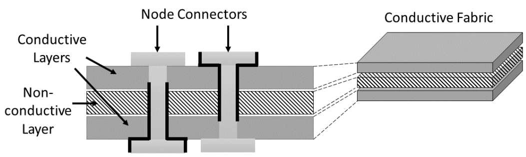

Fig. 1. Cross-sectional view of the node connectors and the conductive fabric

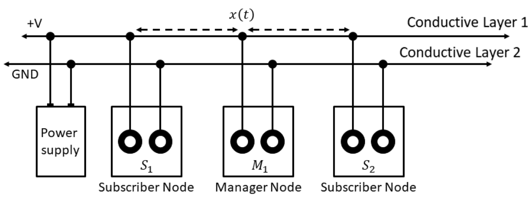

Fig. 2. System model scheme

be configured into a manager node M or a subscriber node S. The nodes are able to transmit or receive data through the conductive layers while simultaneously receiving energy from the power supply that is connected in the CFN. Any node can transmit a modulated signal $x(t)$ according to the data and the other nodes on the CFN get the data by demodulating the received signal through the shared conductive layer[4,19,20].

Ⅲ. Physical Layer Design

The physical (PHY) layer is a fundamental component of the communication system, playing a crucial role in transmitting and receiving data over the medium. A conductive fabric channel has an imperative characteristic of being a high noise channel[3,4]. Due to this, analog modulations, such as amplitude modulation (AM) or frequency modulation (FM), were not an attractive approach for communication on this medium. Amplitude shift keying (ASK) may be one approach to consider within digital modulation[4,18]. However in previous schemes that use ASK, a noiseless channel was considered[4] or multiple equalizer circuits were design for given frequencies[18]. However, in various applications, such as wearable technology, smart textiles, and medical monitoring systems, actuators and sensors may cause random peak voltage pulses within the network or require different carrier frequencies to avoid interfere with ASK modulation. Thus in this section, we delve into the technical aspects of the physical layer design, particularly focusing on the utilization of Frequency-Shift Keying (FSK) modulation and demodulation techniques in conductive fabrics that can adapt the carrier frequencies and tackle the high noise medium while having a low complexity design.

3.1 Conductive Fabric

One important aspect for FSK implementation is the carrier frequency selection. The two layers of conductive fabric communication channel have a frequency response according to the material and the dimensions[4].

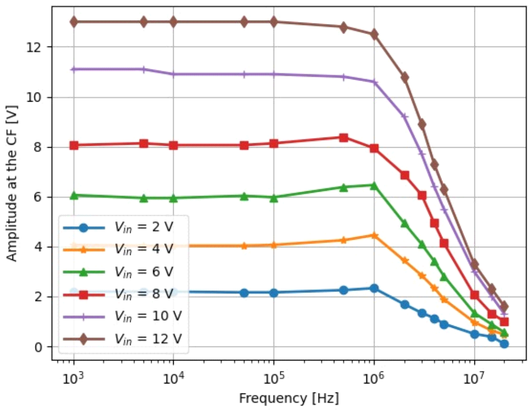

Fig. 3. Magnitude response of the conductive fabric

Fig. 3 shows the magnitude response when a sine signal input with amplitude V_{in} and time t as $x(t) = \frac{V_{in}}{2} sin(2\pi ft)$ goes through the conductive fabric channel of dimension 32 × 20 cm without any load.

From Fig. 3, the magnitude response of a sine signal remains constant for lower frequencies but it greatly decreases after frequencies higher than 1 MHz for every input level. The observed frequency response is due to the capacitance dominance of the communication medium as a lowpass filter by decreasing the impedance for high frequencies. It indicates that narrowband signals should be employed for modulation in the system.

3.2 Modulation

FSK modulation is a widely used technique in PLC for transmitting data over electrical power lines[4,26,27]. In FSK modulation, digital data is encoded by shifting the frequency of a carrier signal between multiple frequencies. By using different frequencies for each bit, FSK modulation enables a robust communication, even in the presence of interference and high noise channel.

In the context of conductive fabrics, FSK modulation can be employed to transmit data signals over the fabric itself, turning it into a communication medium, allowing for the seamless integration of electronic components and sensors into clothing or other fabric-based products. For the purpose of preventing power loss at the received signal in our system implementation, we must choose the carrier frequencies f_C lower than 1 MHz by following the conductive fabric magnitude response of the channel in Fig. 3, as $x(t) = sin(2\pi f_c t)$. Furthermore, a sine waveform can be generated and adapted with a direct digital synthesis (DDS) module.

3.3 Demodulation

FSK modulation involves shifting between different frequencies that represent digital symbols, and when these signals in the time domain are received, they are affected by path loss, noises, and interference. To tackle this, we employ digital demodulation by using a digital signal processing (DSP) approach. By sampling the received signal and applying the discrete Fourier transform (DFT), the signal can be transformed from the time domain into the frequency domain, decomposing it into its constituent frequency components. This transformation simplifies the identification and extraction of the frequency values corresponding to the FSKmodulated symbols. The DFT thus provides a powerful tool for FSK demodulation in wearable device communication systems, contributing to the robustness, adaptability, and reliability of the communication process.

Let us consider an N-points DFT and the sampled points x_n^o from n = 0, 1, ..., N − 1. First, to remove any bias, the mean is subtracted from the sampled points as

$$x_k = x_n^o - \frac{1}{N}\sum_{i=0}^{N-1} x_i^o, \quad (1)$$

where x_n are the unbiased sampled points of the received signal. Then, the DFT can be written as follow

$$X_k = \sum_{n=0}^{N-1} x_n e^{-\frac{i2\pi}{N}kn}, \quad (2)$$

where X_k are the sampled data representation in the frequency domain for k = 0, 1, ..., N − 1. The analog-to-digital converter (ADC) sampling time is t_S and in order to process the data, we perform the N-points DFT. Thus the DFT frequency step is $\frac{1}{Nt_S}$, which allow to select frequencies around the steps $\left\{\frac{1}{Nt_S}, \frac{2}{Nt_S}, \dots, \frac{N/2}{Nt_S}\right\}$ to maximize symbol detection.

3.4 PHY Layer Frame Format

On the other hand, a PHY layer frame format is designed to make the communication system functional among multiple nodes. The PHY layer is responsible for activate or deactivate the node transceiver, and for the data transmission and reception. Each frame consists of a header, a payload, and a frame check sequence (FCS) as shown in the Fig. 4. The desired application determines which PHY layer to use[10]. The header starts with a wake-up sequence for frame detection and time synchronization, and a register information if necessary. The payload contains the data from subsequent layers, and the FCS is to verify if there is an error within the frame.

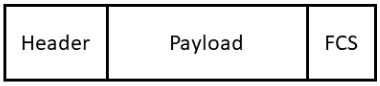

Fig. 4. PHY layer frame format

Ⅳ. MAC Layer Design

The medium access control (MAC) layer, on top of the PHY layer, plays a critical role in permitting an organized channel access among multiple nodes in the system[2]. In this section, we present the design and implementation of the MAC layer, showcasing a frame structure that enables efficient data transmission between the manager node and multiple subscriber nodes in the system over the conductive fabric channel.

4.1 MAC Layer Frame Format

The MAC layer in our system adopts a frame format, which serves as the foundation for reliable communication over the conductive fabric. The manager node takes the entire time resource and allocates frames for channel access coordination. For implementation, the MAC frame of the CFN is divided into four main parts, source node ID, destination node ID, payload, and FCS as shown in Fig. 5.

Nodes in a network are distinguished from one another by a node ID, which is an unique bit sequence assigned to each subscriber and manager node prior to any communication taking place. The node from which the data is transferred is identified by the source node ID, and the node that receives the data is identified by the destination node ID. With the use of the node identifier, messages can be precisely addressed and routed, facilitating effective communication between the manager node and subscriber nodes. Then, depending on the application, the payload is essential for transmitting control information and meaningful data between the nodes, such as sensor data, actuator commands, node frame status, and others. In addition, a FCS is applied in the MAC frame to verify errors that may occur during the communication.

The MAC frame structure is designed to exploit the characteristics of the CFN as a communication system and prove the feasibility of efficient wearable device communication basis. Note that the MAC frame corresponds to the payload inside the PHY frame. Fig. 5 shows the frame structure of the implemented CFN.

Source Node ID	Destination Node ID	Payload	FCS

Fig. 5. MAC layer frame format

4.2 State Diagram

Each node has an internal data processing according to a received signal or an external system command, which allows the communication in the system. This can be represented for the manager and the subscriber node in state diagrams.

The manager node has four main states as shown in Fig. 6. As soon as the node is powered on, it will enter the standby state. In the standby state, when the node receives a command from the system, the state goes into the frame generation state. The command from the system depends to the application, for instance it can be a signal from a sensor. The node transmits a frame and it waits for the acknowledgement (ACK) frame. If the ACK is not received, the state goes back to frame generation. The node goes to the standby state if it received the ACK or if it does not receive the ACK within a time window.

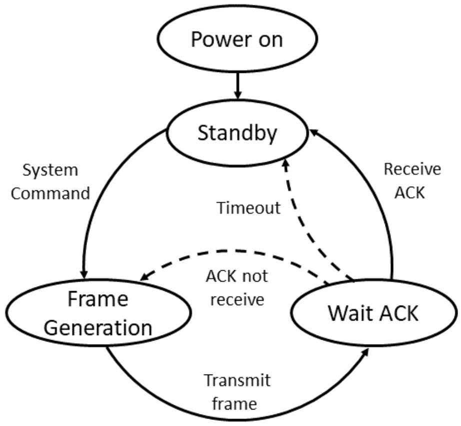

Fig. 6. State diagram of the manager node

The subscriber node has four main states, as shown in Fig. 7. The node goes into standby as soon as it is powered on. The node in the standby state enters the frame analysis state upon receiving a frame. The state returns to the standby state if the received ID does not match its own node ID or if there is an error in the received signal; otherwise, it moves on to the command analysis stage. The node transmits an ACK and goes back to the standby phase after analyzing and executing the incoming

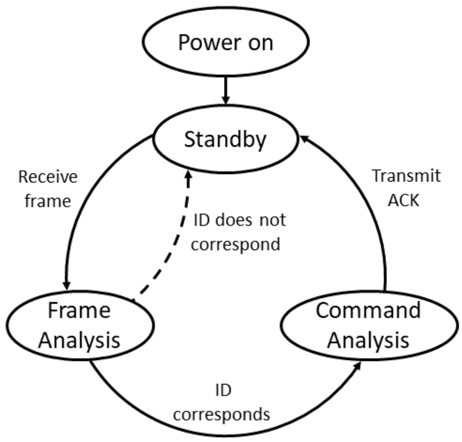

Fig. 7. State diagram of a subscriber node

command. In this scenario, the command execution activates a digital signal, which can be adapted according to the application, for instance to activate an actuator.

Ⅴ. Experimental Setup and Results

We first construct a node that can function as a manager node or a subscriber node, generate a modulated signal, use digital demodulation to receive the data, and then implement a communication system in order to test the CFN.

As shown in Fig. 8, each node has a voltage regulator that runs off the conductive fabric power supply voltage, eliminating the need for batteries. Each node has an analog front end to enable the communication path through the conductive layers, a modulation and a demodulation modules to transmit or receive the desired signal respectively, and a microcontroller unit (MCU) to generate the data for transmission and to process the received signal.

A prototype of the node circuit is designed as in the block diagram shown in Fig. 8. The final design of the node circuit can be seen in Fig. 9. For the analog front end the ADA4807 rail-to-rail high speed performance amplifier with a 180 MHz bandwidth was selected. The FSK modulation was performed by the AD9838 low power DDS device capable of producing high performance sine outputs. And the ultra-low-power 32-bit MCU STM32L151C8 was used for demodulation with its dedicated ADC and for data processing. The node has a square shape of 35 × 35 mm. External communication modules, such as USB, were use in order to calibrate and test each node in the network before and during operation by following the PHY and MAC layer guidelines. Notice that the carrier frequencies are not fixed[18] can be adjusted according to the conductive fabric medium or modulation.

(a) (b)

Fig. 9. Node circuit (a) Top view (b) Bottom view

For performance evaluation, we consider a CFN with one manager node, two subscriber nodes and one power supply as shown in Fig. 10. An oscilloscope is used to observed the signals at different locations of the CFN while the power supply energizes the conductive fabric with 5 V.

The manager node modulates and transmits the FSK signals, which are received and demodulated by the subscriber nodes. For demonstration, each frame consists of 4 bits and the bit time is set to t_b = 50 μs. To reduce complexity we use binary FSK with carrier frequencies f_0 and f_1 corresponding to the bit 0 and the bit 1 respectively, and the generated signals are sine waveform. The digital demodulation sets the DFT size as N = 8 and the required sampled points x_n^0 to perform DFT is

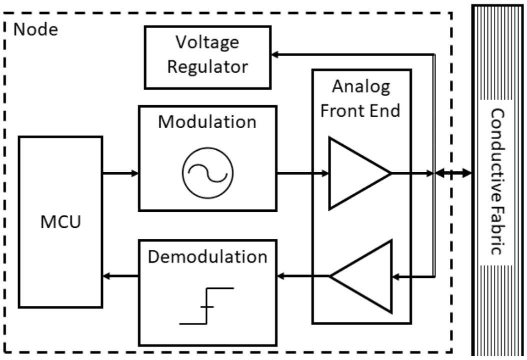

Fig. 8. Node block diagram

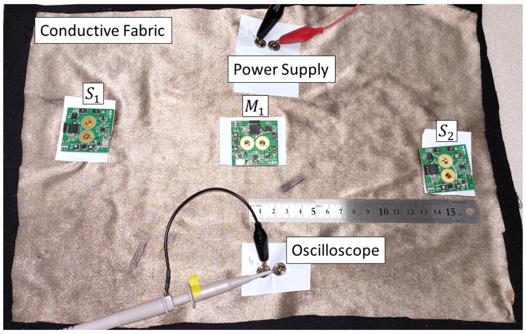

Fig. 10. System Implementation

selected from the ADC samples. The ADC sampling time by design is t_S = 1 μs and the ADC buffer size is set to $N \times tb$ = 200. Then the sample frequency step is $\frac{1}{Nt_S}$ = 125 kHz and the carrier frequencies are set to f_0 = 125 kHz and f_1 = 250 kHz which are lower than 1 MHz as indicates Fig. 3.

Fig. 11 shows the modulated signal at different locations of the CFN. The green line at the top represents the generated signal before amplification in the node, the yellow line in the middle is the signal after the amplifier, and the purple signal is the signal at the conductive fiber 15 cm separated from the origin of the signal. Clearly, the binary FSK modulation can be generated by the node prototype and it can be used in the communication medium according to the demonstration parameters. There is a loss of energy between the yellow and purple lines due to the channel path loss, the power supply and the analog front end filters. The frame shown in Fig. 11 represents the bits 1001 in an FSK modulated signal with f_0 and f_1.

Fig. 12 displays the modulated signal in the time domain and in the frequency domain. The purple line at the top represents the modulated signal at the conductive fabric, and the pink line at the bottom represents the fast Fourier transform (FFT) of the signal from the oscilloscope. The FFT of the signal shows the two carrier frequencies, f_0 = 125 kHz and f_1 = 250 kHz with higher spectral power than the other frequencies, allowing direct use of DFT in both frequencies with the node design.

Fig. 13 shows when the node detects a four bits modulated signal and starts the ADC sampling and

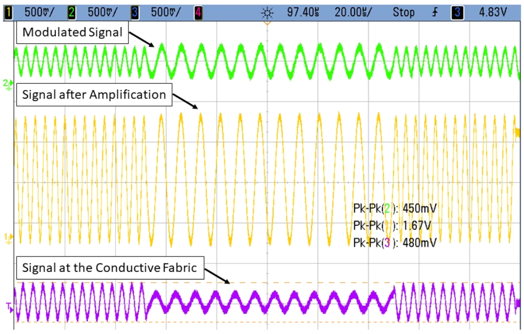

Fig. 11. Transmitted signal

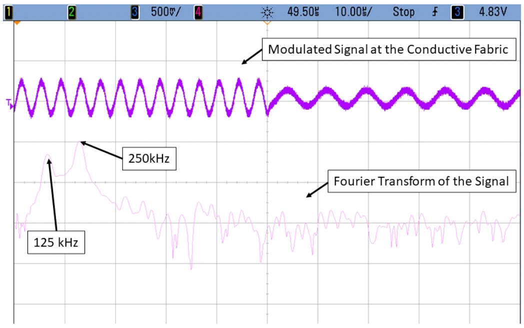

Fig. 12. DFT of the FSK signal at the CF

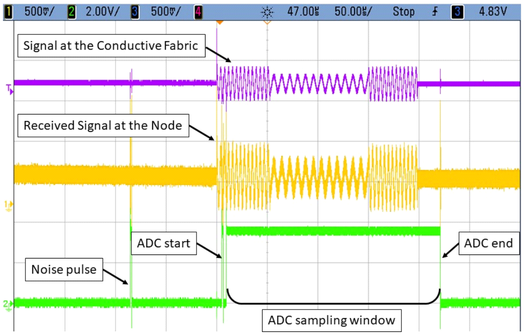

Fig. 13. Received signal

signal processing. The purple line is the modulated signal at the conductive fabric, the yellow line is the modulated signal at the receiver after the analog front end filter and amplification, and the green line is a digital output to indicate the signal processing status at the receiver node.

The first pulse of the green line indicates a random noise pulse in the system and the second pulse indicates the ADC starting time by doing a buffer reset before the data acquisition. Then, the square wave indicates the ADC sampling window of the received signal to be demodulated at the node by using DFT. The square wave and the received signal have a time offset due to the asynchronous communication nature. Because every node location at the CFN can be affected by a noise pulse, robust demodulation and frame structures are needed for communications.

For the final demonstration, a chatting communication between a manager node and a subscriber node was implemented. Further more, a chat program harnesses the innovative capabilities of the

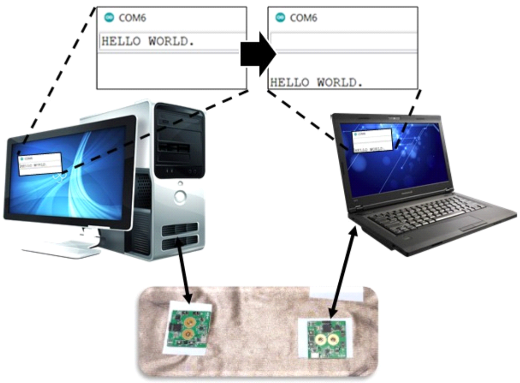

Fig. 14. Conductive fabric test program

CFN to enable seamless and reliable communications. The chat program allows users to input characters and messages through a serial port interface via a external driver of each node, and the conductive fabric acts as the communication channel between the two nodes as shown in Fig. 14. The PHY and MAC frame structures ensures reliable synchronization, precise addressing, and efficient data transfer. In the PHY layer frame, the header size was a 2 bits wake-up sequence and the payload size is the MAC layer frame. For the MAC layer frame, the source and destination node ID sizes were 2 bits each while the payload size was 8 bits due to the American character encoding standard (ASCII) character size. The FCS is given by the primitive polynomial $x^{16} + x^{12} + x^5 + 1$ for the PHY and MAC layer frames.

The implementation of the chat program not only demonstrates the practicality of conductive fabric communication between multiple nodes, but also underscores its potential for creating lightweight, flexible, and energy-efficient communication systems for various applications.

Ⅵ. Conclusions

The implementation of a conductive fabric communication network emerges as a testament to the transformative potential of integrating powerline communication with wearable devices. We have considered a CFN with multiple battery-less nodes and a single power supply, where a node modulates and transmits an FSK signal to multiple nodes that receive and demodulate the signal via DSP.

The conductive fabric frequency response was taken into consideration for the node design. The results show that the FSK modulation and demodulation are feasible in a two-layer conductive fabric channel by every node without an external signal generator module. The node location is not longer fixed in the conductive fabric and also the frequencies for modulation can be adapted to the communication medium or application followed by the digital demodulation. A frame format for chatting was implemented in the PHY and MAC layers in the CFN to test the communication channel between two nodes while a power supply simultaneously energize the nodes.

This work lays a foundation for future advancements in wearable technologies, fostering a new era of communication systems that seamlessly integrate with the dynamic and evolving nature of wearable devices.

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