Multi-channel FM transmission of vibrotactile signals on 2-D communication textile

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Abstract: This paper proposes a frequency-division multiplexed vibrotactile signal transfer system on conductive textiles for implementing wearable tactile suits. For multiplexing, many carrier frequencies are in one-to-one correspondence with many receivers. Each carrier signal is frequency-modulated with analog vibrotactile waveforms, and each receiver demodulates it and drives its built-in actuator. The analog waveform transmission achieves multi-channel real-time vibrotactile actuation, which is suitable for applications such as virtual reality (VR) games. A commercially available frequency modulation (FM) radio receiver chip achieves high sensitivity and superior channel selectivity. Carrier frequencies can be located in a 32 MHz bandwidth, from 76 MHz to 108 MHz, every 200 kHz, and 160 channels of vibrotactile waveforms can be transmitted simultaneously.

Keywords: Two-dimensional communication, wearable system, haptics, virtual reality

Classification: Wireless communication technologies

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1 Introduction

With the widespread virtual reality technologies, tactile sensing/actuating has attracted much interest. We can find some research works investigating wearable tactile suits in the literature [1, 2]. Many vibrotactile actuators distributed over the whole body require many cables for power supply and control signal transfer.

Conductive-textile-based power and data transfer methods have been proposed to eliminate one-to-one wirings [3, 4, 5, 6]. Those research works include synchronous serial data transfer [6, 7] and asynchronous transfer [5]. They are all digital communication schemes, and no analog communication on conductive textile has been reported to the best of the author’s knowledge.

The main contribution of this paper is to demonstrate the feasibility of simultaneous transmission of many vibrotactile waveforms to antenna-less receivers over conductive textiles. The previous works developed the analog front-end specialized for over-textile communication, while the digital interface was integrated into a commercially off-the-shelf (COTS) microcontroller chip. The high-frequency analog circuit was composed of some discrete and integrated components. Implementing a sophisticated signal processing circuit that achieves high spectral efficiency under the restriction of circuit footprint was impractical. Contrarily, in the system presented in this paper, a COTS single-chip FM receiver completes the high-frequency signal processing, thus enabling spectrally efficient multiplexing with a small circuit.

The proposed method can achieve real-time vibrotactile waveform transmission without digital data buffering or signal compression/expansion.
receivers implemented with a COTS one-chip FM receiver IC achieve a small footprint, high sensitivity, and high reliability. The superior channel selectivity of the receiver chip enables dense carrier location with a 200 kHz interval. Using a receiver IC compatible with worldwide broadcast FM radio frequencies from 76 MHz to 108 MHz, 160 channels of independent vibrotactile signals can be transferred simultaneously.

2 Vibrotactile signal transfer over textile transmission line

VR applications require higher tactile sensation fidelity than cell phone vibration alerts. An eccentric rotating mass (ERM) vibration motor, commonly used in mobile devices, vibrates at a fixed frequency when a constant voltage is applied. It is cost-effective for notifying phone calls, but other actuators such as voice coil actuators (VCAs) are more suitable for applications requiring higher fidelity of tactile sensation.

In a previously reported inter-IC for wearables (I²We)-based wearable tactile suit [8], the VCA-loaded receivers play back vibrotactile waveforms preset in the flash memory. The controller transmits only short digital frames specifying the waveform to be played back, instead of the analog waveforms. This approach reduces the data transferred over the textile, but the tactile representation is limited to only the combinations of the preset waveforms.

The analog signal transfer system presented in this paper, shown in Fig. 1, supports transferring arbitrary waveforms to drive such actuators in real-time. The system enables real-time generation and display of arbitrary vibrotactile stimuli without being limited to preset waveforms. The frequency range of vibrotactile signals is up to about 1 kHz [9]. The audio signal bandwidth of FM receiver IC, 15 kHz [10], is sufficient for the vibrotactile signal transfer.

![Fig. 1: Experiment system of the proposed FM vibrotactile signal transfer and prototyped RX module closeup. RX module is 20 mm in diameter. The FM radio receiver IC completes the signal processing from RF to vibrotactile waveform. The RX module is composed of the FM RX IC, microcontroller (MCU) to configure the IC, and a class-D amplifier to drive the VCA.](image-url)
3 Multi-carrier FM signal transfer

In the proposed FM transmission system, a one-chip FM radio receiver IC completes the entire signal processing from the radio frequency (RF) input to the vibrotactile waveform output. The special-purpose IC optimized for FM receiver yields the advantages of high sensitivity, high immunity to fading, and high channel selectivity with a small footprint. The selectivity between two adjacent channels with a 200 kHz interval is 50 dB [10]. The remarkably high selectivity enables many signal multiplexing with high carrier density.

In the previously reported I²We systems, two carriers were modulated by two pulse sequences of I²C data and clock. Simple resonant bandpass filters were composed of discrete chip inductors and capacitors to distinguish the two carriers with a small footprint. Due to the broad passband characteristics of the filters with relatively low-quality-factor components, two carriers must be chosen to have a significant interval [6]. Therefore, adding another I²C bus on the same textile transmission line by frequency-division multiplexing (FDM), i.e., using additional carriers, requires occupying an order of magnitude broader frequency range. Thus, increasing the communication channel capacity by FDM was impractical.

Using the FM carrier frequencies as many as the RX modules, the system can uniquely assign one carrier frequency to one RX module. Based on this scheme, each RX can be simply tuned to a fixed carrier frequency, and no dynamic frequency exchange among many RXs is required. When the transmitter sends the modulated signal with one of the carrier frequencies, the corresponding RX immediately receives the signal, without any overhead process such as listen-before-talk or addressing. This is one of unique features of the proposed scheme compared with the serial-communication-based I²We.

4 Prototype evaluation

Two-channel vibrotactile signal transfer using two carriers with the 200 kHz interval was evaluated in the system shown in Fig. 1. The schematic diagram of the system is shown in Fig. 2(a). The configuration of the FM receiver ICs including tuning frequency and output volume are preliminarily programmed into each on-board microcontroller (MCU) of the RX modules. The waveforms of the two baseband vibrotactile signals and two demodulated currents flowing through the RX VCAs are shown in the Fig. 2(b). The waveforms were obtained with the FM carrier frequencies $f_1 = 80.0$ MHz and $f_2 = 80.2$ MHz, and carrier magnitudes $V_1 = V_2 = -40$ dBV, where the magnitudes are represented in open circuit voltage. The spectrogram of the FM signals actually generated under the configuration is shown in Fig. 2(c).

The result shows that the two RXs almost accurately demodulate the original vibrotactile waveforms. By looking closer, there exists crosstalk between the two current waveforms. When RX1 current reaches the peak, RX2 current fluctuates, and vice versa. This crosstalk is due to the DC power supply voltage fluctuation at each RX. All RXs share the same power supply voltage applied to the textile transmission line; therefore, when one of
the RXs instantly draws a significant current for actuator operation, the DC voltage on the textile drops, and all the RXs experience the supply voltage drop. To clarify this effect, when RX1 is removed from the system and the two carrier strengths are kept equal, i.e., $V_1 = V_2 = -40$ dBV, no crosstalk appears on the RX2 current waveform as shown in Fig. 3. Therefore, the crosstalk seen in Fig. 2(b) is independent of the interfering adjacent channel carrier at the same signal level. This is a problem with the DC voltage regulating, but not with the mechanism of FM transmission. It can be resolved by implementing an on-board voltage regulator on each RX module.

The RX2 current waveforms with increased interfering adjacent channel strength are also shown in Fig. 3. The result shows that the interference to RX2 load current waveform is almost rejected for the interference wave up to about 50 dB greater than the desired wave.

Thus, interference-free demodulation under a wide range of interfering carrier strength has been confirmed. Therefore, the proposed multi-channel FM transmission system enables transferring a large number of vibrotactile waveforms simultaneously using densely located carriers. In practical textile two-dimensional communication systems, standing waves are generated in the textile because the edges are not terminated with matched load. Therefore, the carrier strength varies depending on the receiver position. Even with such a spatial fading, the wide-range interfering carrier rejection capability will provide robust and stable demodulation performance.

5 Conclusion and Prospects

We have presented a multi-channel vibrotactile actuator control system using frequency modulation for real-time analog waveform transfer instead of digital signal transfer. Using an FM radio receiver IC, up to 160-channel vibrotactile waveforms can be transferred simultaneously. In the experiment, the signal transmitter was built with benchtop signal generators. Future work will be to integrate the multi-channel FM transmitter into a small, battery-driven circuit module.

Another critical issue of battery-driven wireless wearable system is the battery life. The measured quiescent power consumption of the RX module was approximately 150 mW, which is slightly higher than the 110 mW power consumption of the I2We RX. Additionally, stronger and more power-consuming actuators will be suitable in applications requiring higher fidelity and a wider dynamic range of tactile sensation. Reducing power consumption for longer battery life will be one of the critical issues in future work.

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Fig. 2: Experiment system (a) and measured waveforms (b). Baseband signals for FM modulator and demodulated current flowing through VCAs in RX1 and RX2 are shown in (b). Two actuators are independently controlled. With these baseband signals, FM-modulated RF signals are generated as shown in a spectrogram (c). The spectrogram was obtained by connecting a spectrum analyzer at point A shown in (a).
Fig. 3: Crosstalk between RX1 and RX2 caused by the power supply voltage fluctuation due to RX1/RX2 load currents disappears when RX1 is removed from the textile transmission line. Interference of the adjacent 80.0 MHz channel to the desired 80.2 MHz channel, observed on the RX2 load current waveform, is almost negligible for the interference wave of up to about 50 dB greater than the desired wave.