Fast half-duplex communication on e-textile based wearable networks

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Abstract: Two-dimensional communication (2DC) textile is a technical combination of e-textile and two-dimensional signal transmission (2DST) technology. 2DC textile-based wearable system has several benefits, whereas designing a transmission scheme that ensures both power and high data rate transfer among numerous distributed devices on the textile is still challenging work. This paper proposes a charge/communication switching approach based on a baseband transmission system without modulation/demodulation of carriers. Successful power and more than 1 Mbps, half-duplex data transfer between one master and ten slaves was achieved. We also explain the trade-off relationship between the charging power, data rate, and device number by applying this approach.

Keywords: e-textile, wearable system, baseband transmission

Classification: Transmission Systems and Transmission Equipment for Communications

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1 Introduction

Using of e-textile bridges the gap between our daily life clothes and electronics. E-textile based wearable applications sprung up and enriched our lives in various fields such as health monitoring, sports training, and fashion design. One conventional way of using e-textile is to pattern circuits with conductive threads or conductive screen printing ink on textile, in a similar manner as conventional printed circuit boards (PCBs) array copper patterns [1]. There are two main concerns of such usage: a fetal breakdown would be caused by fraying or wrinkling the textile [2]; the electronic components are often non-detachable, which causes the lack of customizable design.

The above two concerns can be dispelled by employing two-dimensional signal transmission (2DST) technology to e-textile. A particular implementation of this technology is a double-sided conductive textile, as shown in Fig. 1. Two conductive layers are isolated from each other, working as a single planar bus for both power and data transfer shared by all devices mounted on the textile [3]. This kind of two-dimensional communication (2DC) textile has the following benefits: it is robust to textile wrinkling and partial breakage of conductive mesh; the number and position of distributed devices on the textiles are customizable; also, it partly retains the flexibility of the original base textile not to hinder the user’s body movement. Despite the benefits gained from 2DC textiles, designing a transmission scheme that ensures both power and high data rate transfer among numerous distributed batteryless devices on the textile is still challenging work.

In this paper, we propose a charge/communication switching approach based on a baseband transmission system. This approach enabled both power and more than 1 Mbps half-duplex data transfer between one master and ten slaves mounted on the 2DC textile. We also explain the trade-off relationship between the charging power,
data rate, and device number by applying this approach.

In previous work, a comparable charge/communication switching approach with a less than 10 kbps designed transmission scheme has been proposed by Akita et al. [4]. A simultaneous power/data transfer approach by applying frequency-division-multiplexing (FDM) was verified by Noda et al., and about 100 kbps two-wire serial communication on the textile has been proved. However, the data rate is limited depends on carriers used for modulation/demodulation [3]. To increasing
data rate, Noda et al. presented a baseband transmission system without modulation/demodulation carriers based on another serial transmission protocol: universal asynchronous receiver/transmitter (UART). Up to about 1 Mbaud, simplex data transfer between two devices has been tested [5]. In this paper, we further develop a charge/communication switching approach based on the same baseband transmission system. The charge/communication switching approach eliminates large RF-decoupling inductors required in dc power supply paths for simultaneous power/data transfer approach [5]. The power inductor hinders increasing data rate to more than 1 Mbaud, due to its self-resonant frequency. This paper presents experiment results of faster communication with 5 Mbaud.

In section 2, the design detail of our approach will be presented. The feasibility experiment of our approach will be shown in section 3. The paper will be concluded in section 4.

2 Our proposal

Our approach alternately enables power and data transfer, as shown in Fig. 2. There are switch pairs only in the master for controlling the entire system switching fast between the charging phase and the communication phase. Thus, there is no need for synchronization between master and slaves. When switches are at points A and B, the system is in the communication state. When switches turn to points P and G, power charging starts. There are capacitors in every slave for storing energy. The dc voltage applied to P is higher than the operating voltage of slaves, because the voltage drops on conductive textile and at diodes in each slave.

Our approach is based on the baseband transmission scheme, which means there are no carriers required for modulation/demodulation. This scheme is utilized for increasing the data rate, as introduced in section 1. We choose UART for data transfer because it only requires one signal line when in simplex transmission. To enable half-duplex transmission among multiple devices, we combine the UART equipped microcontroller (MCU) with a transceiver (XCVR) MAX3362 (Maxim Integrated) for RS-485, as shown in Fig. 2(a). The master and slaves can select their roles as a transmitter or a receiver by controlling the transceiver’s TX enable (TX_EN) and RX enable (RX_EN) pins. In the transmitter mode, differential UART signals are output from the transceiver’s ports A and B. In the receiver mode, the ports A and B without termination resistors has a 96 kΩ input impedance. Also, we choose high-performance MCU EFM8LB1 (72MHz, Silicon Labs Inc.), which can operate more than 5 Mbaud UART signal transfer to ensure a high data rate. The "data rate" is defined as \( v = n/(T_{ch} + T_{com}) \), where \( n \) bits are sent in time span \( T_{com} \), and \( T_{ch} \) represents time span for charging, as shown in Fig. 2(b).
Fig. 2. Our proposed charge/communication switching approach. A system consisting of a master and slaves (a) works in the manner of fast switching between the charging and communication phases (b), where the equivalent circuit diagram for each phase can be represented by (c).

We explain trade-off relationships among the data rate, charging power, and slave number, by introducing a simple analysis model. We define symbols as follows: $P_s = V_s I_s$ is the power consumption of each slave except the diodes. $P_c = V_c I_c$ is the charging power supplied by the master in the charging phase. $P_o$ is the power dissipated by the conductive mesh resistance $R_{textile}$ and the diodes during the charging phase. $N$ is the slave number, and $C_{textile}$ is the capacitance held by the textile. Then, for stable system operation, the total charging energy $P_c T_{ch}$ must satisfy:

$$P_c T_{ch} \geq N P_s (T_{ch} + T_{com}) + P_o T_{ch},$$  \hspace{1cm} (1)

where $P_s$ is assumed to be constant in this model, regardless of the communication state.

Also, we can simply obtain
\[ P_c - P_o = V_s I_c, \]  
(2)

since all slaves (except diodes part) are assumed to have an equal voltage of \( V_s \), and the total current flowing to all slaves is \( I_c \) during the charging phase.

From Eq. (1) and (2), charging duty ratio \( r \equiv T_{ch}/(T_{ch} + T_{com}) \) must satisfy:

\[ r \geq \frac{N I_s}{I_c}. \]  
(3)

Using the constant UART baud rate, \( X \), we have

\[ n = \alpha X T_{com}, \]  
(4)

where \( \alpha \) (0 < \( \alpha \) < 1), assumed to be constant, represents that \( n \) is less than \( X T_{com} \) because of the mandatory start/stop bits and data processing time consumption each time a character is sent. Then the data rate \( v \) can be rewritten as

\[ v = \alpha X (1 - r). \]  
(5)

Substituting Eq. (3) into Eq. (5), and we finally obtain

\[ v \leq \alpha X \left( 1 - N \frac{I_s}{I_c} \right), \]  
(6)

where \( (N < I_c/I_s) \) is satisfied, and \( I_s \) is also assumed to be constant for the same reason as \( P_s \).

From Eq. (6) if we want to add more slaves in the system with the charging current or power constant, the attainable highest data rate will decrease. Moreover, we should take the relation \( (N < I_c/I_s) \) into consideration to ensure the proper functioning of the system.

3 Experimental results

In this section, we present an experiment to verify the feasibility of our approach, and also to show the trade-off relationship between the data rate and the slave number while the charging power remains basically unchanged. We measured the attainable highest data rate as we increased the slave number from 2 to 10.

Figure 3(a) shows the measurement environment. The 2DC textile used in this experiment is about 40 x 40 cm\(^2\) with a 600 pF capacitance \( C_{textile} \) and a 6 \( \Omega \) conductive mesh resistance \( R_{textile} \). The slaves with the structure shown in Fig. 2(b) were installed with a particular pattern on the textile. This pattern is for more easily observing the charging effect deviation when slaves have different relative distance with the master. The master was connected to the left side of the textile by metal clips, while it can also be fabricated to have a similar structure with the detachable slaves. All slaves were fully charged at first, and then the regular charging/communication working pattern started. The charging current \( I_c \) was about 220 mA, and the current consumption of each slave \( I_s \) was about 8 mA. The UART baud rate \( X \) was always programmed as 5 Mbaud, and the parameter \( \alpha \) was around 0.42 determined by the proportion of transmission time for 8 bits data in one-character transmission cycle under our experimental conditions. By using Eq. (6) we can approximately calculate the attainable highest data rate as shown in Fig. 3(b). In the communication phase,
The attainable highest data rate is measured as we increase the slave number from 2 to 10. (a) shows the measurement environment and a signal transmission example: the character ‘T’ (ASCII: 01010100) sent by a slave successfully received by the master.

The transmission was half-duplex. The master called slaves in sequence and got information back from each slave. The master specified a slave by sending a unique character recognized by that slave. And then the slave sent back a particular character to be judged by the master to confirm the transmission.

In the charging phase, the voltage on the textile was about 5 V dc, while it swung between 0 V and 3 V during the communication phase. The transition time between the two phases was less than 350 ns. As shown in Fig. 3(a), the waveform at the time of communication was not a standard square wave due to the time constant caused by the capacitance and resistance of the textile and other parasitic resistances/capacitances. Time constant $R_{\text{textile}}C_{\text{textile}} \approx 4$ ns is significantly smaller than the time constant of the actually observed waveform shown in Fig. 3(a). By minimizing parasitic resistances/capacitances in transceivers, the maximum data transmission frequency can reach 250 MHz.

The charging power in this experiment remained about the same. We adjusted the charging duty ratio $r$ to ensure successful transmission when more slaves added. The measurement results, as shown in Fig. 3(b) demonstrates the trade-off relationship between the slave number and the data rate. As the slave number increased, the attainable highest data rate decreased. The data rate $v$ reached up to about 1.5 Mbps.
when 10 slaves were attached to the textile. Moreover, the slaves that had the same relative distance with the master worked at the same voltage level. The further away from the master, the lower the working voltage was. The deviation of the voltage level was slight, within ±2.5%, in this experiment.

4 Conclusion

This paper proposed a charge/communication switching approach based on a base-band transmission scheme. By applying this approach, successful power and up to about 1.5 Mbps half-duplex data transfer among eleven devices mounted on a 2DC textile is demonstrated. Also, the trade-off relationship among the charging power, data rate, and slave number is clarified. Additionally, the slaves distributed patterns on the textile and the relative position to the master cause deviation in the charging effect. Nevertheless, the deviation is negligible, provided that all slaves obtain enough energy. This approach extends 2DC textile-based wearable applications. For example, dozen of sensors distributed on wear collecting information with more than 1 kHz sampling rate is possible.

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