A Method of Increasing Data Rate for Human Body Communication System for Body Area Network Applications

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Human body communications (HBC), which have been standardized in IEEE 802.15.6 standard for wireless body area networks (WBAN), provides a maximum data rate of 1.3125 Mbps through frequency selective digital transmission (FSDT). This paper reviews FSDT and proposes a modified FSDT (MFSDT). By exploiting the efficient modification of the FSDT's transmitter structure, MFSDT achieves a maximum data rate of 3.9375 Mbps, and the decoding complexity of MFSDT increases linearly with an increase in the data rate. In addition, FSDT and MFSDT performance are investigated with respect to the effects of the transmit filter provided to meet transmit spectral mask requirements, and a human body channel modeled as a finite impulse response filter.

Keywords-human body communication; frequency selective digital transmission; body area network

I. INTRODUCTION

Human body communication (HBC) is a wireless communication method used to connect devices through the human body as a transmission medium [1]-[3]. This method can be used to create a wireless network among on-body devices or between an on-body device and a reachable device; for example, this method can be used to establish communication among medical equipment attached to the human body or between a smart phone and a PC. Simple touch can transfer data such as video files, image files, and document files using HBC, as shown in Figure 1 [4]. Hence, this method is applicable to the so-called touch and play (TAP) applications [2] whose intuitive services enable convenient use of appliances, especially for the elderly and young children. Recently, HBC has been standardized in IEEE 802.15.6 standard for wireless body area networks (WBAN) [4]. The proposed scheme for the HBC transmitter is frequency selective digital transmission (FSDT), where the data transmitted in digital form can be spread over the selected frequency domain using Walsh codes. FSDT supports a maximum data rate of 1.3125 Mbps [4]. In this paper, a modified FSDT (MFSDT) method is proposed, which provides a maximum data rate of 3.9375 Mbps. The current FSDT transmits Walsh codes for data transmission using one frequency selective spreader (FS-spreader) [3], [4]. MFSDT, on the other hand, consists of three FS-spreaders in parallel and this structure allows a combination of three Walsh codes into one transmitted code to increase the data rate to three times that of FSDT.

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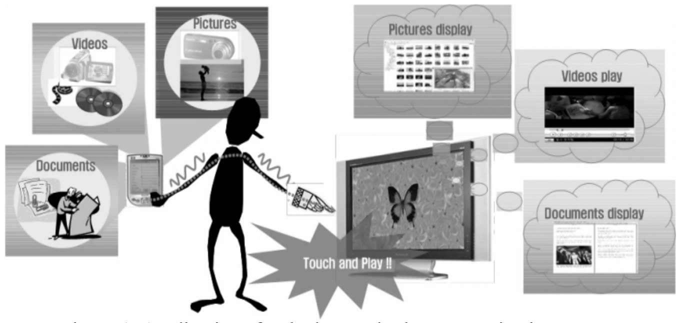

Figure 1. Applications for the human body communication system

This paper is organized as follows. In Section II, according to the channel modeling for body surface to body surface CM3 [5], the impulse response of a human body channel is investigated. In Sections III and IV, the transmitter structure, the power spectral density (PSD) of the transmitted signal, and the transmit filter provided to meet transmit spectral mask requirements for FSDT and MFSDT are described, respectively. In Section V, the performance of the band limited signal transmitted through a transmit filter is evaluated in the human body channel. Finally, conclusions are given in Section VI.

II. CHANNEL MODEL FOR HUMAN BODY COMMUNICATION

Consider the linear discrete-time channel whose output y_k is

$$y_k = \sum_{i=0}^{M-1} h_i x_{k-i} + n_k \tag{1}$$

where x_k is a binary input of $\{1, 0\}$, n_k is white Gaussian noise with power spectral density σ^2, and h_i is the human body channel impulse response of a casual system with M multipath terms.

According to the channel modeling for body surface to body surface CM3 [5], the human body channel impulse response of $h(t)$ can be written as

$$h(t) = h_R(t) \cdot C_h \tag{2}$$

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TABLE I. CONSTANT VALUES OF A, t_r, t_0, x_c, AND w

Time range (μs)	A	t_r	t_0	x_c	w
$0 \leq t < 0.025$	0.00032	0.00000	0.00621	-0.00097	0.00735
$0.025 \leq t < 0.058$	0.00003	0.02500	0.01684	-0.01225	0.00944
$0.058 \leq t$	0.00002	0.05800	0.05610	0.00100	0.01109

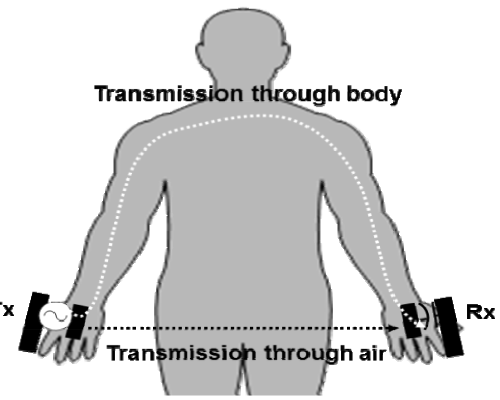

Figure 2. Channel model for HBC

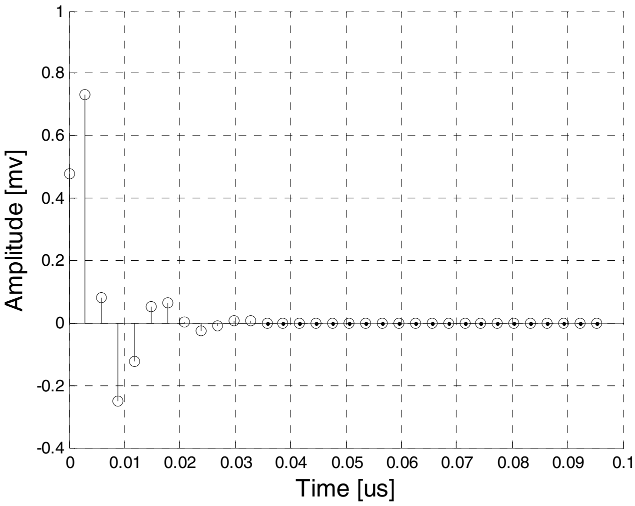

Figure 3. Impulse response for the channel model shown in Figure 2

where $h_R(t)$ is the reference impulse response, and C_h is a coefficient related to the sizes of the ground planes and the distances between the transmitter (Tx) and the receiver (Rx). $h_R(t)$ is represented as

$$h_R(t) = A_v \cdot A \cdot exp(-(t - t_r)/t_0) \cdot sin(\pi(t - t_r - x_c)/w) \quad (3)$$

where A_v is a coefficient that represents the fluctuation of signal loss and has a Gaussian distribution as follows:

$$A_v \sim N(1, 0.16^2) \quad (4)$$

and A, t_r, t_0, x_c, and w are constant values listed in Table I. In addition, C_h in (2) is

$$C_h = (0.0422G_T - 0.184) \cdot (0.0078G_R - 0.782) \cdot \left(\frac{120.49}{d_{body} + d_{body}(d_{air}/d_{body})^5}\right)^2 \quad (5)$$

where G_T and G_R are the ground plane sizes at the Tx and the Rx and d_{air} and d_{body} are the distances between the Tx and the Rx through the air and the body, respectively. Each value is limited for validity of the channel model as follows:

$$10cm^2 \leq G_T, G_R \leq 270cm^2$$
$$10cm \leq d_{air}, d_{body} \leq 200cm \quad (6)$$

The human body channel depends on both the distance between the Tx and the Rx and the ground plane sizes of both the Tx and the Rx. From (5), it can be inferred that the path loss increases as G_T and G_R decrease, and d_{air} and d_{body} increase.

Figure 2 depicts a human body channel model considered in this paper. The Tx can be a mobile device such as a smart phone and the Rx can be a mobile device such as a tablet PC. The distances between the Tx and the Rx through the air and the body (i.e., between the fingertips of each hand) are assumed to be approximately $60cm$ and $150cm$, respectively. Hence, d_{air}, d_{body}, G_T, and G_R are given as $60cm$, $150cm$, $80cm^2$, and $230cm^2$, respectively. Figure 3 shows the channel impulse response; this response is generated by substituting the parameter values into (2), where A_v is assumed to be the mean value of 1 and the sampling rate is 336 MHz.

III. FREQUENCY SELECTIVE DIGITAL TRANSMISSION

The example of FSDT transmitter implementation for a data rate of 1.3125 Mbps using a 42 MHz operating clock is shown in Figure 4 [3], [4]. The baseband signal DIN passes through a serial to parallel converter ($S2P$) to form a 4-bit parallel signal. Then, the 4-bit signal is converted to the corresponding 128-chip Walsh code from the FS-spreader to yield the $DOUT$ signal. On the other side, the received signal can be decided as a binary signal (0 or 1) using a comparator and clock and data recovery (CDR) in the analog front end (AFE). The receiver calculates the Hamming distance between the decision bit stream from the AFE and all of the 16 Walsh codes shown in Figure 5; it selects the code that has a minimum distance value as a transmitted $DOUT$. Then, the transmitted DIN of b_0 to b_3 are obtained by a backward process of $S2P$.

Each Walsh code has its own fundamental frequency that depends on the operating clock frequency. The lowest index Walsh code without toggling has the lowest frequency, and the highest index Walsh code where toggling between 0 and 1 is repeated has the highest frequency. If the operating clock frequency is 42 MHz, a maximum fundamental frequency of 21 MHz will be obtained. In order to mitigate interference to other devices and systems, and to meet the regulatory policies

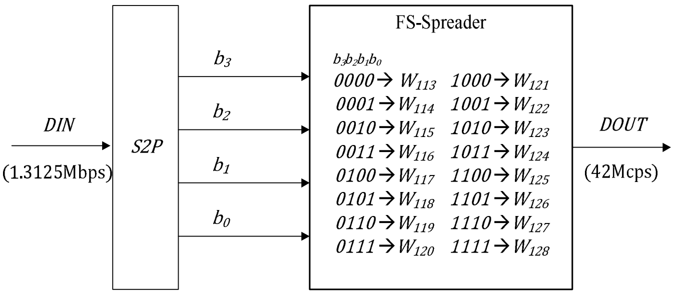

Figure 4. FSDT transmitter implementation for a maximum data rate of 1.3125 Mbps

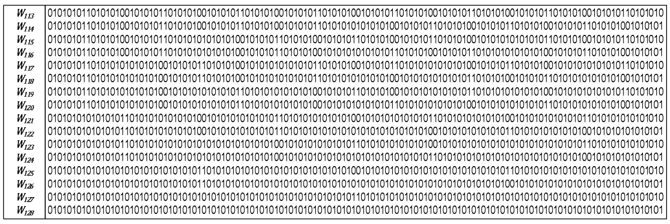

Figure 5. Walsh code set for the FS-spreader of FSDT

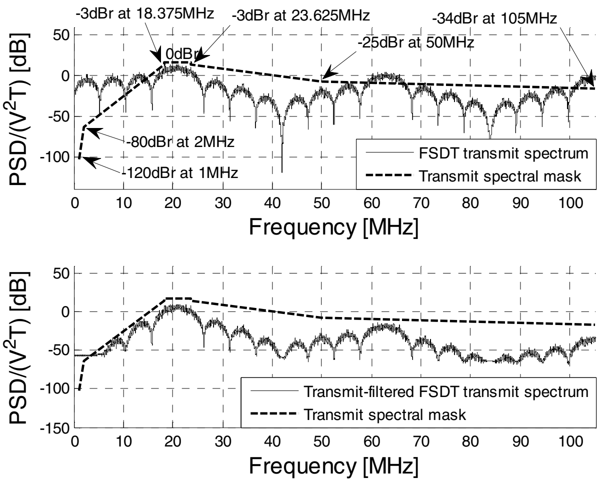

Figure 6. PSD of the FSDT transmitted signal and the transmit-filtered FSDT transmitted signal where T is the sampling rate of 336 MHz and V is the binary 1 voltage level

[4], the transmitted signal should be filtered to satisfy the transmit spectral mask. The upper and lower parts of Figure 6 show the PSD of the FSDT transmitted signal and the transmit-filtered FSDT transmitted signal, respectively. When FSDT uses upper index Walsh codes of $W_{113} - W_{128}$ as transmitted codes, the FSDT transmitted signals are mostly distributed at around 21 MHz in the frequency domain. The dotted-line represents the transmit spectral mask [6] whose center frequency is 21 MHz, and the 3dB bandwidth is between 18.375 MHz and 23.625 MHz. In addition, -120 dBr, -80 dBr, -25 dBr, and -34 dBr are achieved at 1 MHz, 2 MHz, 50 MHz, and 105 MHz, respectively. Filters can be implemented by a high-pass Butter worth filter of order 5 and low-pass Butter worth filter of order 2.

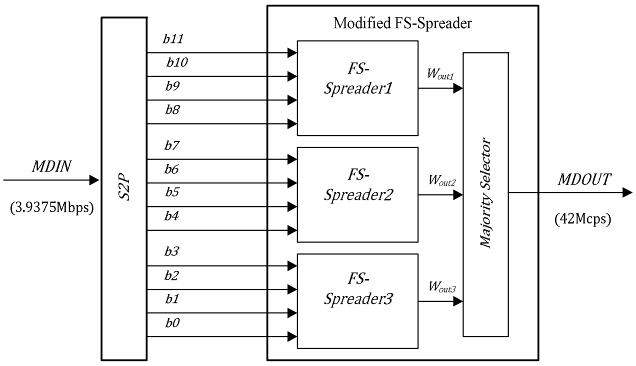

Figure 7. MFSDT transmitter implementation for a maximum data rate of 3.9375 Mbps

Figure 8. Three sub-Walsh code sets for the modified FS-spreader of MFSDT

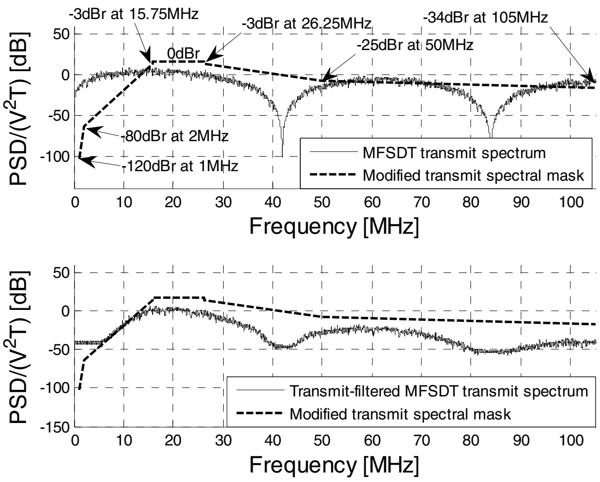

Figure 9. PSD of the MFSDT transmitted signal and the transmit-filtered MFSDT transmitted signal where T is the sampling rate of 336 MHz and V is the binary 1 voltage level

FSDT using direct digital baseband signaling can be implemented without a digital-to-analog converter (DAC), an analog-to-digital converter (ADC), and a radio frequency (RF) block. This ensures extremely low power consumption and small-size implementation.

IV. MODIFIED FREQUENCY SELECTIVE DIGITAL TRANSMISSION

Figure 7 shows the proposed MFSDT transmitter structure. Compared to the FSDT transmitter structure, the output bit number from $S2P$ is increased to 12 bits and the modified FS-spreader is comprised of three FS-spreaders arranged in parallel. In addition, a Majority selector block is added. The MFSDT transmitter achieves a maximum data rate of 3.9375 Mbps, which is three times higher than the maximum FSDT data rate of 1.3125 Mbps. The 12 bits from $S2P$ are divided into three groups and enter FS-spreader1, FS-spreader2, and FS-spreader3. Figure 8 shows the three sub-Walsh code sets, which consist of $W_{81} - W_{96}$, $W_{97} - W_{112}$, and $W_{113} - W_{128}$ for FS-spreader1, FS-spreader2, and FS-spreader3, respectively. Each group of 4-bit signals from $S2P$ is mapped to the corresponding 128-chip Walsh code. W_{out1}, W_{out2}, and W_{out3} from the corresponding FS-spreader1, FS-spreader2, and FS-spreader3 are combined in the Majority selector as follows:

$$MDOUT = (W_{out1}\ and\ W_{out2})\ or\ (W_{out1}\ and\ W_{out3})\ or\ (W_{out2}\ and\ W_{out3}) \quad (7)$$

According to (7), the majority between a binary 0 or 1 among W_{out1}, W_{out2}, and W_{out3} is selected as $MDOUT$. For example, if $W_{out1} = 0$, $W_{out2} = 0$, and $W_{out3} = 1$, the majority is 0 and $MDOUT$ is 0. As a trade-off for the data rate increase using the Majority selector, the minimum Hamming distance of MFSDT transmitted code is reduced to half of the minimum Hamming distance of Walsh code used for FSDT.

As in the case of the FSDT receiver, the MFSDT receiver applies the same AFE structure, which performs the hard-decision of the received signal. The transmitted Walsh code from FS-spreader1 is detected by computing the Hamming distance between the decision bit stream and all 16 of the Walsh codes from the sub-Walsh code set for FS-spreader1, as shown in Figure 8. Assuming no errors occurred in the received signal, the Hamming distance value of the correct Walsh code is 32; however, the Hamming distance value of the rest of the 15 Walsh codes is 64. Thus, the Walsh code having a minimum distance value is selected as the transmitted Walsh code. By using sub-Walsh code sets for FS-spreader2 and FS-spreader3 instead of the sub-Walsh code set for FS- spreader1, we can find the transmitted Walsh codes from FS-spreader2 and FS-spreader3 in the same way. Then, the three Walsh codes are de-mapped to the three groups of b_0 to b_3, b_4 to b_7, and b_8 to b_{11}. The Hamming distance is calculated independently in each of the three transmitted Walsh codes so that the computing complexity for calculating the Hamming distance is increased only by a factor of 3 compared with that of FSDT.

The upper part of Figure 9 shows the PSD of the MFSDT transmitted signals and the modified transmit spectral mask is represented by the dotted-line. According to the data rate increase, the bandwidth of the MFSDT transmitted signal

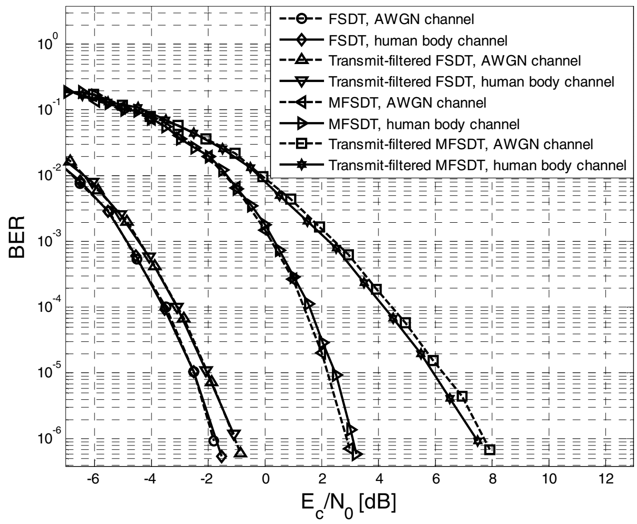

Figure 10. BER performance curves for FSDT and MFSDT with respect to the effects of transmit filter and the human body channel

increases compared to the bandwidth of the FSDT transmitted signal shown in Figure 6. The modified transmit spectral mask is the same as the FSDT transmit spectral mask except for the 3dB bandwidth which is increased by 5.25 MHz to 10.5 MHz, and it can be implemented by the same order as the FSDT transmit filter.

V. PERFORMANCE EVALUATION

In this section, the performance simulation results are represented for FSDT and MFSDT with respect to the effects of the transmit filter and the human body channel, when the receiver is assumed to be perfectly time and frequency synchronized. As shown in Figures 6 and 9, filtering the observed signal results in the transmitted signal becoming band limited and repeated binary patterns of $'00'$ and $'11'$ in the transmitted signals induce ISI after transmit filtering. Hence, the performances are expected to be degraded by the effects of transmit filter. In the human body channel, the transmitted signals are passed through the impulse response of the human body channel, and white Gaussian noise is added. The impulse response of the human body channel shown in Figure 3 is modeled as an finite impulse response (FIR) filter whose sampling frequency of 336 MHz is eight times more oversampled than the transmitted chip frequency of 42MHz. The root mean square (RMS) delay spread τ_{rms} of the impulse response evaluated by (2) is approximately $3\ ns$, and it is obtained by computing the following equation:

$$\tau_{rms} \cong \sqrt{\frac{\sum_{i=0}^{M-1} t_i^2 |h(t_i)|^2}{\sum_{i=0}^{M-1} |h(t_i)|^2} - \left(\frac{\sum_{i=0}^{M-1} t_i |h(t_i)|^2}{\sum_{i=0}^{M-1} |h(t_i)|^2}\right)^2} \quad (8)$$

τ_{rms} indicates the maximum data rate D_{max} as follows:

$$D_{max} = \alpha(\tau_{rms})^{-1} \quad (9)$$

where $\alpha < 0.5$, in general [7]. If $\alpha > 0.5$, the transmitted signals can be corrupted by inter-symbol interference (ISI) in the channel. Since the chip rate of both FSDT and MFSDT corresponding to D_{max} is 42 MHz and α is computed as about 0.13, the human body channel is expected to incur negligible performance degradations.

Figure 10 shows BER versus the received energy per chip over the noise power spectral density (E_c/N_0) curves for FSDT and MFSDT. The required E_c/N_0 for achieving the BER of 10^{-6} in the human body channel is about -1.7 dB and 3.1 dB for FSDT and MFSDT, respectively. Enhancing the data rate by a factor of 3, MFSDT degrades the required E_c/N_0 by approximately 4.8 dB compared to FSDT.

At BER of 10^{-6}, the performance degradation in E_c/N_0 caused by the transmit filter is about 0.7 dB and 4.3 dB for FSDT and MFSDT, respectively. Since the number of the corresponding repeated binary patterns of $'00'$ and $'11'$ in the transmitted signal is increased in MFSDT where the three Walsh codes combine into one transmitted code by Majority selector, the MFSDT performance degradation is more severe than FSDT. There are no observable performance differences between the results in the human body channel and the AWGN channel where the human body channel is replaced by one tap impulse response of unity gain. Hence, the receiver does not need to assist with any diversity schemes such as an equalizer for the human body channel.

VI. CONCLUSIONS

TAP based HBC supports intuitive and context aware services. The system setup and pairing can be quick and simple. Moreover, it can ensure extremely low power consumption and small-size implementation since a DAC, an ADC, and a RF block are not needed. In this paper, FSDT is reviewed and MFSDT, which is an efficient method to improve the data rate for HBC, is proposed based on FSDT. Compared with FSDT with a maximum data rate of 1.3125 Mbps, MFSDT increases the data rate up to 3.9375 Mbps using the parallel structure of three FS-spreaders and the Majority selector while decoding complexity increases linearly with an increase in the data rate. The human body channel's ISI effect on the transmitted signal is negligible since the RMS delay spread of the human body channel impulse response is sufficiently smaller than the chip rate. Hence, FSDT and MFSDT are appropriate methods for data transmission in the human body channel. From the simulation results in the human body channel, the performance of the band limited signal transmitted through a transmit filter is evaluated.

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