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Low Energy Wearable Body-Sensor-Network

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***Abstract*—Wearable body sensor network (WBSN) is realized with wireless and wireline techniques. Body channel communication (BCC), which uses the human body as a signal transmission medium, can reduce energy consumption of a wireless on-body transceiver to less than 0.5nJ/b. The 3 pulse-based transceivers for BCC are reviewed in this paper, and their interference issues are discussed. To enhance BCC robustness, an adaptive frequency hopping scheme is applied. Fabric Area Network (FAN) is introduced with a low energy inductive coupling transceiver and a fault-tolerant switch to realize intra- and inter-layer WBSN at once. Unique wearable environment issues and the adaptation technique to overcome those issues are discussed.**

I. INTRODUCTION

Recent advances in the semiconductor technology and circuit innovations significantly reduced size and power consumption of various physiological sensors, enabling those devices carried by a patient. For continuous and ambulatory healthcare, the body sensor network (BSN) which provides connectivity among the wearable sensors is drawing great interests.

There are wireless and wireline approaches to implement BSN. Due to convenience of use, the wireless communication is preferred in initial BSN prototypes and Zigbee or UWB transceivers are integrated in the wearable devices [1, 2]. However, the recent investigations found that the WPAN techniques using several GHz band is not suitable for BSN because of the large path loss affected by the body shadowing effect [3]. Moreover, the energy consumption of the WPAN radios is >10nJ/b, which is unacceptable to on-body sensors powered by a small battery.

Several groups have studied wearable BSN using conductive fabric wires [4, 5]. Since the communication channels are parts of the woven fabric, they are conveniently worn by a patient and not tangled each other. Thanks to high signal-to-noise ratio (SNR) and data rate of the wireline communication, its energy consumption is less than 100pJ/b. However, the communication reliability is not satisfactory as the fabrics made with conductive yarns are prone to tearing and wearing out. The interconnections formed only on a single layer also limit the network flexibility.

This paper introduces two novel techniques that overcome difficulties of the previous wireless and wireline BSNs. One is the body channel communication (BCC) [6-9] and the other is the multi-layered, fault-tolerant fabric area network (FAN) [10]. BCC may be an alternative solution of the wireless BSN. This technique uses the human body as the communication channel. Signal transmission in BCC is done by forming electrical coupling between transceivers through the conductive human skin, and hence the signal attenuation can be much lowered compared with RF communication. One constraint of the BCC is that the transceivers need to be attached to skin using electrodes. However, this is not a problem in most BSN applications at all. The FAN proposed in this paper uses inductive coupling link for the convenient and reliable communication between the networks realized on the separate clothes. To achieve fault-tolerance, the hybrid routing scheme is developed in the intra-layer network switch. Section II and III describe the design and implementation of the transceivers for BCC and FAN in detail. In section IV, this paper is concluded by proposing a hybrid BSN which combines the pros of BCC and FAN techniques.

II. BODY CHANNEL COMMUNICATION

A. Communication Principle

Fig. 1 shows the near-field coupling model of BCC [11]. The electrodes of the BCC TX and RX are attached to human skin to make a signal path. The signal emitted from the BCC TX propagates the body channel and goes into the BCC RX. The capacitive coupling between the ground planes of the BCC transceivers makes signal return path. Since impedance of the return path gets smaller when frequency increases, using a high frequency band for signal transmission is advantageous in terms of SNR. However, at beyond 200MHz the signal loss through the body coupled to environment is dominant. Therefore, 10 – 200MHz band proves to be proper for BCC.

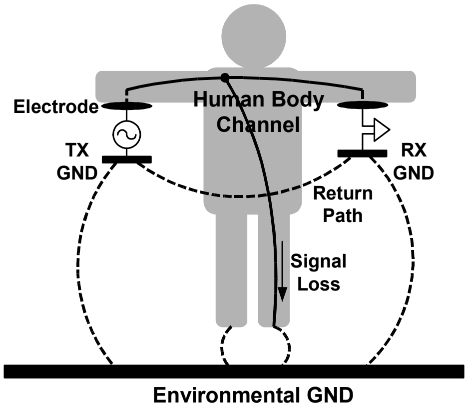
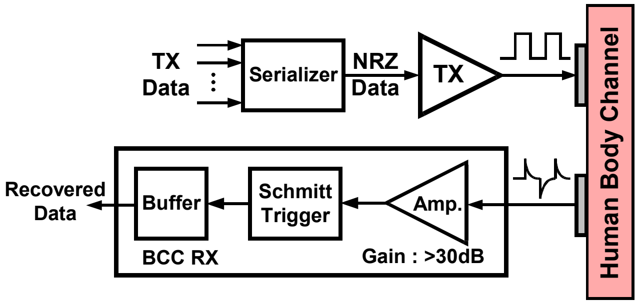


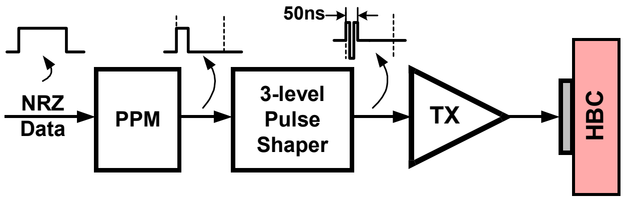
Figure 1. Near-field coupling model of BCC

B. Pulse-Based BCC Transceivers

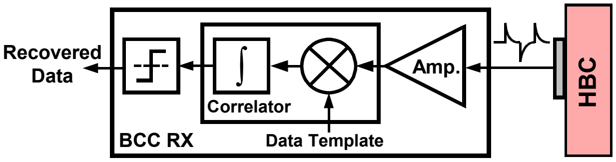
The initial BCC transceivers transmitted the digital signal directly to human body as shown in Fig. 2 (a) [6]. Then, the signal arrives at RX in the form of wide-band pulse due to the capacitive return path. The RX simply amplifies the pulse signal by more than 30dB and recovers original data with a schmitt trigger. Fig. 2 (b) shows the improved TX structure where a TX bit is represented by the position of a 3-level, 50ns pulse signal within the bit period [7]. Using this pulse-position modulation, the frequency band of NRZ data can be shifted to 10-70MHz band showing less path loss through human body. Recently, the RX structure is also complemented with a correlation circuit to average noise power out and integrate the desired signal (Fig. 2 (c)) [8]. These transceivers successfully achieved the low-energy BCC with less than 0.5nJ/b, and the sensitivity of <200µW is also satisfactory to cover less than 2m body area. However, the transceivers like the pulse-based UWB are easily attacked by external interferences.



(a) Direct digital transceiver



(b) 3-level wide-band pulse transmitter



(c) Correlating receiver

Figure 2. Pulse-based BCC transceiver

C. Body Antenna Effect and Adaptive Frequency Hopping

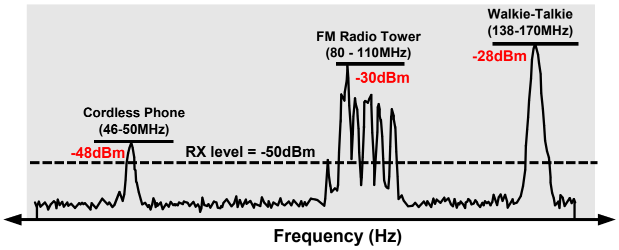


Figure 3. Interferences due to the body antenna effect

Main cause of the interferences in BCC is the human body itself [9]. It is well known that the body under electromagnetic fields resonates with the frequency (40-400MHz) determined by the wavelength equal to twice of the human height [12]. Owing to this body resonance, the human body functions as the receiving antenna and couples many wireless signals to a BCC RX. Fig. 3 shows the strength of the interferences measured at various circumstances. When we consider that the typical BCC RX signal is around -50dBm, the worst case signal-to-interference ratio (SIR) is -30dBm that the pulse-based BCC transceivers cannot handle without BER degradation. To solve the interference issue, an adaptive frequency hopping (AFH) scheme is applied to BCC [9]. As shown in Fig. 4, the BCC band is divided into multiple channels. During the communication, the transceiver continuously monitors BER of the channel that it currently uses. After sufficient data transact, channel assessment is performed and only clean channels which show the BER less than a threshold are selected for communication. To enhance robustness further, the number of channels within BCC band is scalable according to interference condition. Table I compares the performance of a recent BCC transceiver with WPAN radios. Thanks to the AFH, the interference rejection is 10dB higher than recent UWB transceivers. And since the BCC signal is confined to body area less than 2m, it does not interfere with the other BSNs. The energy efficiency of the BCC transceiver is at least 7 times better than other works. In summary, the BCC can successfully meet the requirements for wearable BSN such as low energy, robustness and low interference.

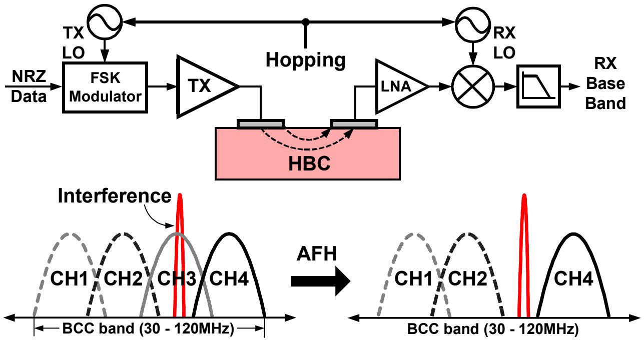


Figure 4. AFH for interference avoidance

Table I. BCC Performance comparison

Parameters	B. W. Cook '06 ref. [15]	W. Kluge '06 ref. [16]	F.S. Lee '07 ref. [2]	BCC ref. [10]
Data Rate BER Scalability	500kb/s Fixed BER	250kb/s Fixed BER	16Mbps-10kbps Fixed BER	10Mbps-60kbps Scalable BER
SIR @ 10^{-3} BER	NA	NA	-15dB	-28dB
Network Coverage	20m	15m	10m	2m
Path Loss/Distance on a Body	50 - 70 dB/dec	50 - 70 dB/dec	50 - 70 dB/dec	25 dB/dec
Energy/bit	3nJ/b	130nJ/b	2.5nJ/b	0.37nJ/b

III. FABRIC AREA NETWORK

If a BSN is integrated into everyday clothing, application of BSN is expanded even more at ease. To realize this concept, Fabric Area Network (FAN) is introduced [10].

There are two types of communications to form a FAN: the first is the within-a-layer communication (intra-layer), and the other is the between-layers communication (inter-layer) [10]. As shown in Fig. 5, the intra-layer network provides connection between sensors around the body, whereas the inter-layer network, which takes advantage of layered environment of clothing, provides a channel between the layers of intra-layer networks.

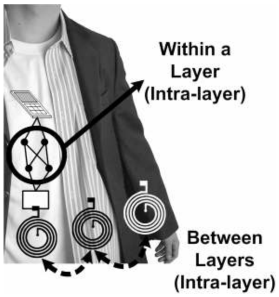


Fig. 5. Proposed fabric area network concept.

FAN has 4 unique network situations that a designer must consider: First, since clothing is a multi-layered environment (such as underwear, inner wear, and outer wear), appropriate inter-layer channel to connect between the layers is necessary. Second, 2-D network is formed in 3-D clothes, and its shape changes with respect to time and space (dynamic variation); therefore, proper compensation is required. Third, weaving is electrically too irregular (static variation). Lastly, clothing is easily damaged or worn-out, so the network must be tolerant to faults.

To form an intra-layer FAN, conductive yarn is widely used [4, 5, 10]. The conductive yarn composed of seven 10μm copper warp threads is adopted to connect devices [4].

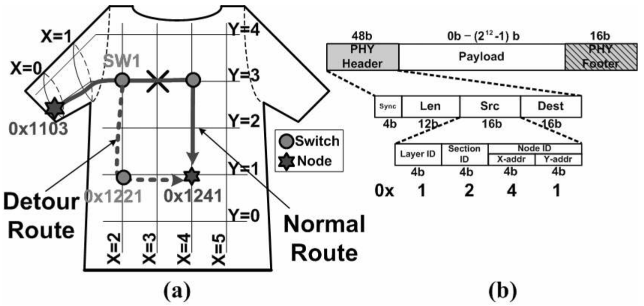


Fig. 6. Intra-layer network: (a) architecture, and (b) packet structure.

A. *Fault-tolerant network for intra-layer communication*

A rectangular coordinate-based network is deployed for intra-layer FAN (Fig. 6 (a)), and a switch can be placed at a cross section; also, a sensor can be combined with a switch. The packet supports multiple communication layers and each layer can be partitioned into sections. A unique 16b address is assigned to each node to identify the current node position: a layer ID, a section ID, and a node ID (Fig. 6 (b)). Cut-through routing is employed, and right after a switch parses the incoming packet header to find the destination address, it routes the packet to an appropriate link; it is done by comparing x addresses first, and then y addresses, without using routing tables [10].

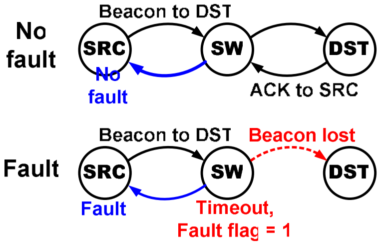


Fig. 7. Intra-layer fault search process.

To obtain fault tolerance, hybrid routing scheme is introduced. That is, the routing is done in two phases: first, fault search, and second, normal data packet routing. Prior to the data packet transmission, as shown in Fig. 6 (a), a beacon packet is transmitted from the source node (0x1103) to the destination node (0x1241), and if the destination successfully receives the beacon packet, it replies with an acknowledgment packet; therefore, no acknowledgment after a certain time implies there are one or more faults existing within the path between source and destination (Fig. 7). In this case, the switch (SW1) within a path automatically re-routes the path, with routing into y direction first, followed by x direction (Fig. 6(a)). After the path is set up, the intra-layer network functions just as circuit switch network, until next fault-search phase.

With the help of the hybrid routing and the cut-through routing, unnecessary energy to search for faults and to find the destination address is removed. As a result, 70% power reduction over the torus topology with routing tables, is achieved [5].

B. *Inductive transceiver for inter-layer communication*

Inductive transceiver using woven inductor [10] provides a contactless inter-layer communication (Fig. 8). Low power consumption is achieved by adopting pulse-based inductive coupling, since it operates in much lower frequency (10 MHz)

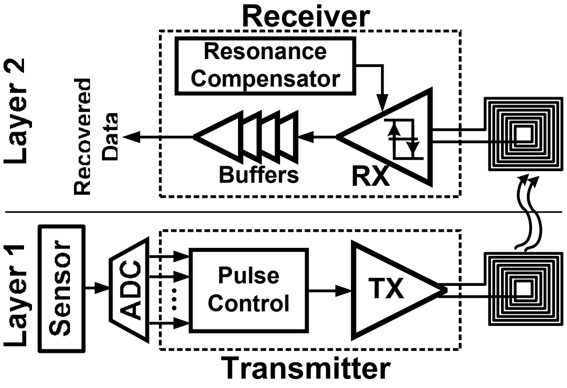


Fig. 8. Inter-layer network: the proposed inductive transceiver.

than the ZigBee or Bluetooth (800 MHz to 2.4GHz). Also, it is much more robust than RF: ZigBee or Bluetooth suffer from interference, since they share ISM bands with WLAN. The transceiver adopts a resonance compensator and a variable hysteresis Schmitt-Trigger for dynamic and static variance compensations [10]. The RX has an asynchronous variable hysteresis Schmitt-Trigger, where the logic threshold of the transceiver can be trimmed. The resonance compensator periodically calibrates the inductance variation, so an efficient coupling between the layers is maintained. The TX adopts bi-phase modulation (BPM) inductive transceiver [10] for better noise immunity against the conventional non-return-to-zero scheme. Table II shows the performance comparison of proposed FAN and previous works. Thanks to the resonance compensation and the variable threshold Schmitt-Trigger, the reception energy of the proposed FAN is the lowest. Small woven inductor size ensures pervasiveness, and the data rate is the highest with the fault-tolerant switch.

Table II. FAN performance comparison

Parameters	[4]	[5]	[15]	[16]	Proposed FAN [10]
Energy / bit	-	0.62nJ/b	-	56nJ/b	1.12pJ/b
Antenna Size (Diameter)	Bulky (> 15 cm)	-	-	Small	Small (< 2cm)
Wireless Interface	RFID	Bluetooth	RFID	Inductive	Inductive
Data Rate	125kbps	256kbps	-	100kbps	10Mbps
Chip Implementation	X	X	X	X	O
Inter-Layer Comm	O	X	X	O	O
Fault Tolerance	X	O	O	X	O

IV. HYBRID BODY SENSOR NETWORK

The BCC presented in this paper can solve the huge energy consumption and the interference issues of the wireless BSN on human body. However, its data rate and energy consumption are still inferior to the wireline approaches. The fault-tolerant FAN improves reliability and flexibility of a network realized on fabric efficiently, yet relocation of sensors in the wireline network is still much complicated. We can devise a hybrid BSN of Fig. 10 that combines BCC and FAN techniques together. All leaf nodes of the tree network communicate with their parent nodes woven into a cloth using BCC. Therefore, sensor nodes can be placed anywhere on skin, depending on what kind of vital signals we need to sense. Since the distance of BCC is less than 50cm, the sensitivity requirement for the BCC transceiver may be enough with only -40dBm and thus the energy consumption can be much reduced. For long range data communication with base station, the parent nodes use conductive yarns as the channel for high energy-efficiency. The locations of these nodes can be fixed to the particular points on the fabric to cover the whole body area communication regardless of the sensor location. This allows automated production of the wearable BSN platform. Through refinements of the network structure and communication protocols, this hybrid structure is expected to provide more energy-efficient and versatile solution to the wearable BSN.

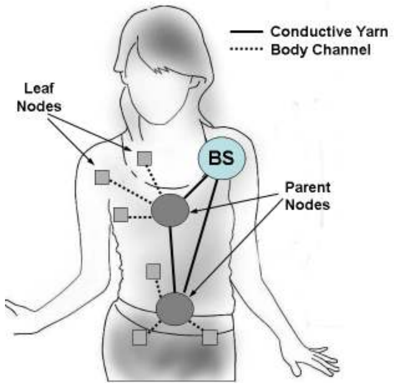


Figure 10. Hybrid body sensor network

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