Your Heart on Your Sleeve

Advances in textile-based electronics are weaving computers right into the clothes we wear

Hoi-Jun Yoo

Wearable health care is part of the more general category of wearable computers or wearable electronics. Wearable electronics and wearable computers appeared in the mid-1990s, when the computer was regarded as the ultimate equipment for information processing and before laptop computers, tablet computers, and smartphones. At that time, people tried to find what kind of portable form factors would be good for the computer as an information device for daily living. *Wearable computers* refers to miniature electronic devices that are worn under, with, or on top of clothing [1]. With the help of human-computer interaction (HCI) technology, which previously made use of the "windows" concept, as Web browsers do, by means of a graphic user interface (GUI), wearable electronics have tried to use other modalities for HCI beyond the display and keyboard. In many respects, the current smartphone has already achieved the computing power the early wearable computers aimed at. But in addition to the smartphone's strong computing power, more human body–compatible, wearable IO devices and sensors are necessary so that users can experience the full benefits of mobile computing, which the smartphone and tablet PC have begun to open up. In many applications, the user's skin, hands, voice, eyes, and arms, as well as the user's motion or attention, are actively exploited in appropriate engagement with the physical environment. Of course, this area shares many basic technologies with the mobile computing, ambient intelligence, and ubiquitous-computing research communities, including those that handle power management and heat dissipation, software architectures, and wireless and personal-area networks.

Most wearable computers still take an awkward form that is dictated by the materials and processes traditionally used in electronic fabrication, even though the ideal wearable computers would be as convenient, durable, and comfortable as clothing. The packaging of electronics uses hard plastic boxes, and alternatives are difficult to imagine. As a result, most wearable computing equipment is not truly wearable except in the sense that it fits into a pocket or straps onto the body. What is needed for the wearable computer is a way to integrate technology directly into textiles and clothing. The application areas of the wearable computer are also increasing, so that wearable computers and electronics have been developed for many possible applications, such as behavioral modeling, health care

Digital Object Identifier 10.1109/MSSC.2012.2232781
Date of publication: 4 February 2013

FIGURE 1: History of wearable computers. (a) Pocket-based computers, (b) clothing-based computers, (c) e-textile, and (d) planar technology.

monitoring systems, service management, mobile phones, smartphones, electronic textiles, fashion design, and many others. Today, "wearable computing" is a topic of active research, with areas of study including user interface design, augmented reality, and pattern recognition. The use of wearables for health care applications or to compensate for disabilities as well as to provide support to elderly people is increasing steadily.

As outlined above, wearable electronics need a specific substrate and package—textiles and clothes—and have many applications, such as health care and entertainment. In addition, they require not only specific I/O systems and means of interconnection but also custom ICs for optimal performance in the wearable environment. In this article, we give an overview of these items and discuss the associated technological trends. In the first section, the history of wearable electronics is summarized, with special emphasis on I/O systems and substrate and packaging issues. Interconnections for wearable devices are introduced in the second section; they can be split into wireline and wireless approaches, as well as permanent versus detachable connections. In the third section, wearable health care systems on a chip (SoCs) and systems on textiles (SoTs) are explained in connection with their appropriate applications. Since wearable health care applications are a good match with wearable technologies, most of the dedicated chips have been developed for health care monitoring, diagnosis, and treatment. A final section presents a number of conclusions regarding wearable electronics.

A Brief History of Wearable Computers

The concept of the wearable computer emerged in 1961, when mathematician Edward O. Thorp and Claude Shannon built the world's first such device, a concealed, cigarette pack–sized analog computer designed to predict the behavior of roulette wheels for blackjack [2]. But compared with mainstream computer research, study of wearable computers remained merely a part of hobby electronics until the mid-1990s. The wearable computer then became popular even in mainstream computing circles, as the Media Lab at MIT demonstrated a small, head-mounted camera and a special input device that operated much like a keyboard [1][1]. Even though the aim of the technology is to build electronic garments and textiles that exhibit "integrity"—that is, garments that look, feel, wash, and wear as well as ordinary clothing—the early wearable computers were constructed by just assembling computing boards and batteries in a backpack or a small bag or were simply "pocket-based" computers. The weight and hardness of those devices made the wearers uncomfortable and compare poorly with the ease of use of current smartphones and tablet PCs (see Figure 1).

More garmentlike "clothing-based" computers appeared when conducting yarns were introduced. Conducting yarn intertwines gold, copper, or stainless steel threads with other fabric fibers to give electrical conductance to the yarn. It can be used to weave a fabric or to stitch electrical interconnections between embroidered electronic boards on the clothes. Optical fiber was even used to weave a jacket—the wearable motherboard [3]. Off-the-shelf commercial chips were soldered onto a flexible circuit board and sewn on the clothes [4]. And touch sensors were developed, with the conducting yarns and fabric functioning as new fabric input devices. LEDs, along with such devices, are sewn onto the clothing and interconnected by means of the conducting yarns so it is possible to turn on the LEDs with the fabric capacitive sensors [5]. Some commercial devices have been sold as "wearable computers" for warehouse maintenance and military applications.

As this conducting yarn technology matured, the concept of "e-textiles" was introduced. A digital sewing machine is used to embroider circuit patterns, component connection pads, or sensing surfaces on the cloth; numerically controlled CAD programs make the work fast and precise. Electrical conductors can be formed anywhere on clothes using conductive threads, and electrical connections can thus be made. The electronic components are preassembled on flexible substrates, and the flexible film is embedded on the fabric by soldering, bonding, stapling, or stitching. Based on this e-textile technology, complete MP3 handling functions were integrated on a commercial outdoor jacket with a fabric capacitive touch sensor as the input device [6]. Developments in portable electronics and mobile computing also brought many possible applications to these wearable electronics, and this trend has been accelerating as tablet PCs and smartphones have become mainstream technologies.

Recently, planar fashionable circuit board (P-FCB) technology [7] has opened up the new field of "planar technology" for wearable computers. The process draws complicated electrical circuits directly onto the textile using the well-known screen-printing technology. Bare semiconductor chips can also be bonded directly to the P-FCB, enabling the assembly of a complicated system right on the textile—these are known as SoTs, as previously mentioned. The planar resistors, inductors, and capacitors can be fabricated on the textile using P-FCB technology. With the help of P-FCB techniques, all these electronic components can easily be incorporated into complete systems.

Wearable Body-Area Networks

A wearable computer is composed of distributed sensing and computation, thin interconnects, and small packages with fully integrated circuitry; the wearable components destined for placement in fabric circuitry to complete a computer do not demand high connection densities. Using appropriate networks, however, they can be connected together using wireline or wireless technology to function as a complete system on the body. A permanent connection or a temporary (detachable) connection can be created. A wireline network can be constructed using the conducting yarns sewn into or attached to the clothes as the communication medium. The basic network architecture is placed on the clothes as the communication platform—the so-called "wearable motherboard"—and the system components are placed at convenient locations on the clothes to assemble a wearable computer. Of course, many network configurations used in long-distance communication network can be utilized in wearable platforms, such as mesh and star networks with packet communication.

Permanent connections can be made by sewing, knitting, and weaving or through secure bonding and soldering. The conductive yarn is easy to sew, knit, and weave, but the bonding and soldering require special care because the metallic fibers in the conducting yarn are thin and brittle. Another challenge is creating a temporary connection between wearable devices. The buttons, gripper snaps, and Velcro used in conventional clothes can also be adapted to make removable connections on clothes [8]. In addition to the wireline communication technology that is useful for single garments, more versatile wireless technology has recently been introduced to enable communication between different garments, i.e., between underwear and outwear. For example, near-field communication using inductive coupling has been reported for transfer of biological signals measured on underwear to mobile devices kept in the wearer's pocket [9] (see Figure 2).

Recently, the IEEE 802.15.6 working group has provided a standard for wireless body area networks (BANs) for possible use in wearable devices [10]. The standard tries to cover wide application areas, but the initial target applications are in wearable health care and mobile entertainment. The new standard provides a reliable network in which many devices on the body can form a complete system or collect data from distributed devices and transfer them to the wearable system hub. The standard supports three physical methods: the ultrawide-band (UWB), narrow-band (NB), and human body communication (HBC) methods. Among them, HBC, which uses the human body itself as the communication medium based on the near-field coupling mechanism (see Figure 3), has advantages over UWB and NB in energy efficiency because it provides low path loss without the body-shadowing effect found in low-frequency bands below 150 MHz.

HBC uses a rather low-frequency spectrum, 21 MHz $\pm$ 5.25 MHz, and its required data rates are 164 Kb/s, 328 Kb/s, 656 Kb/s, and 1.3125 Mb/s. Body channel communication (BCC), which was studied ealier and provides the theoretical background, enables the HBC [11]. The human body itself can serve as a low-loss channel with a bandwidth of from approximately 1–100 MHz, and physical and theoretical analyses of this channel's characteristics have already been performed [12], [13]. Even with its relatively low frequency, it needs only small electrodes, rather than a large antenna, to be attractive as a communication method for wearable electronics. A modulated biosignal is launched from the transmitter into the human body through a metallic electrode in contact with

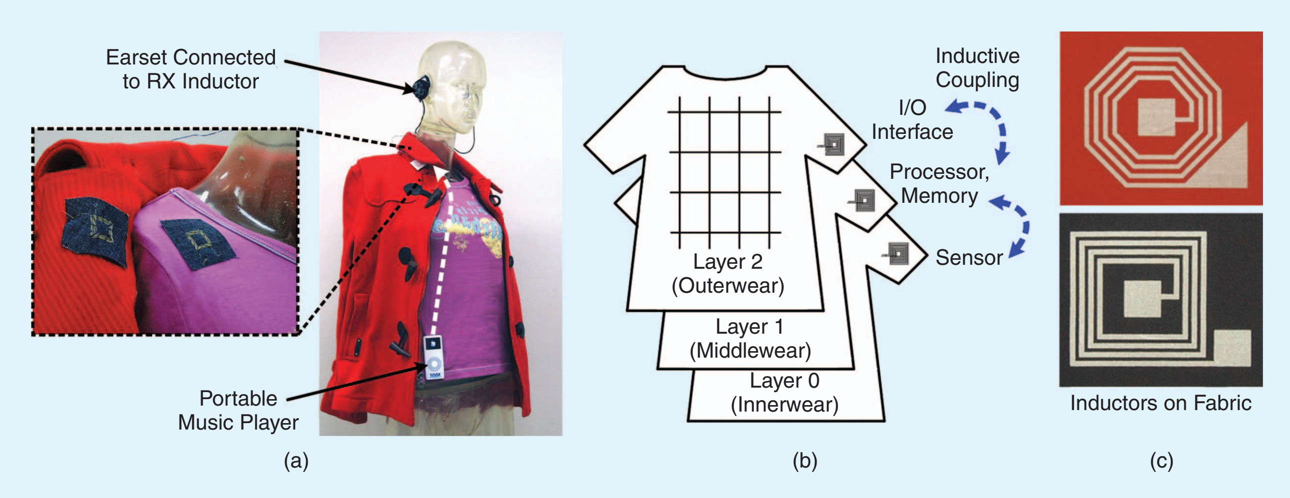

FIGURE 2: Wireless communication among different items of clothing. (a) MP3 system with wireless communication between different garments, (b) an interlayer communication structure, and (c) inductors on fabric.

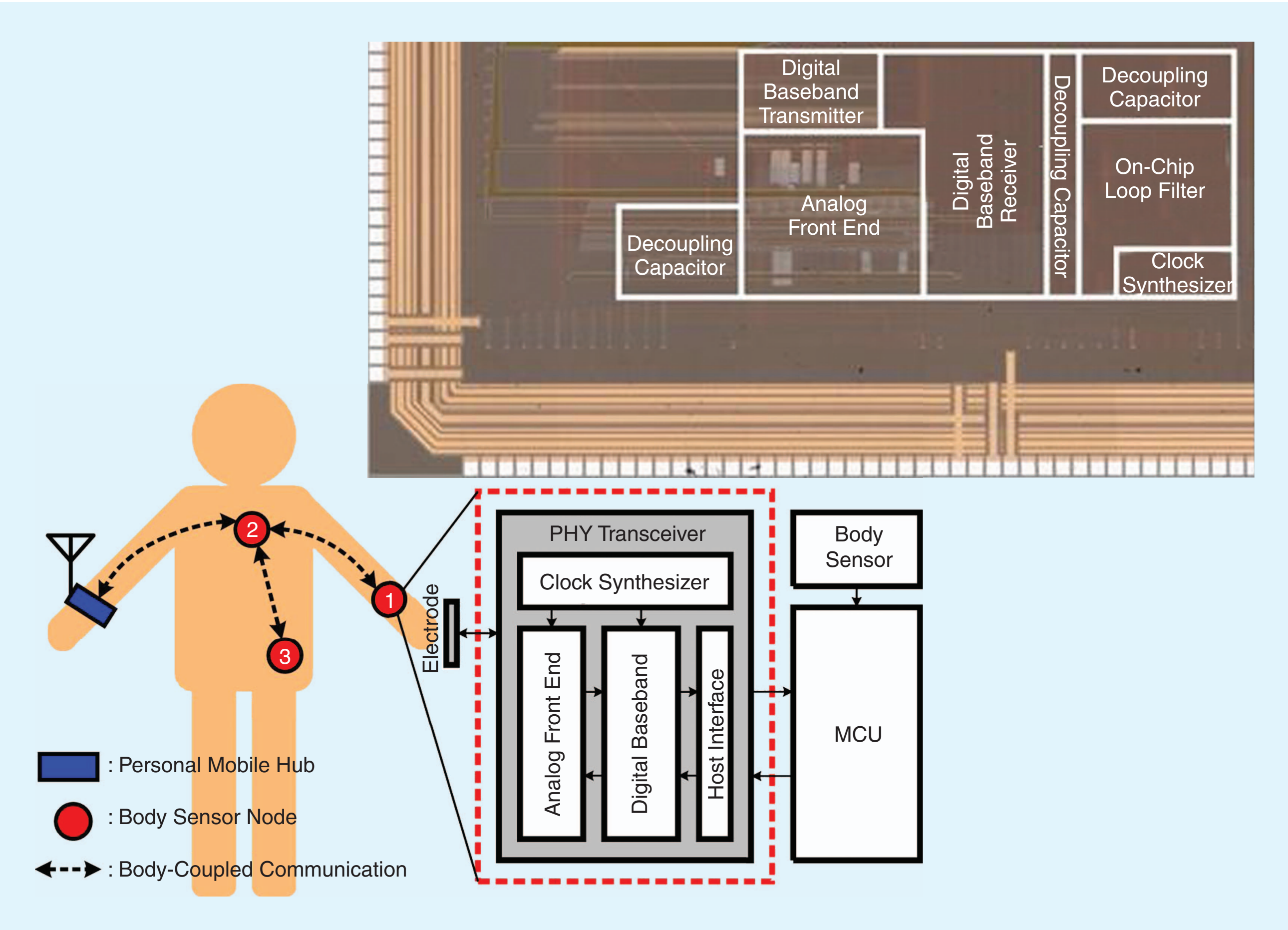

FIGURE 3: HBC.

the skin. The signal crawls on the surface of the skin toward the receiver electrode, and then it is amplified and demodulated into the original biosignal. Such a system can support multichannel operation with CDMA coded for privacy protection. In addition, data rates of more than 10 Mb/s can be achieved for multimedia data transmission among devices located on the skin and outside but close to body.

Figure 4 shows transceiver circuits for the BCC [14]. The contact impedance between the electrode and the human body varies dynamically, and up to 30 dB of overall signal path loss variation can be observed

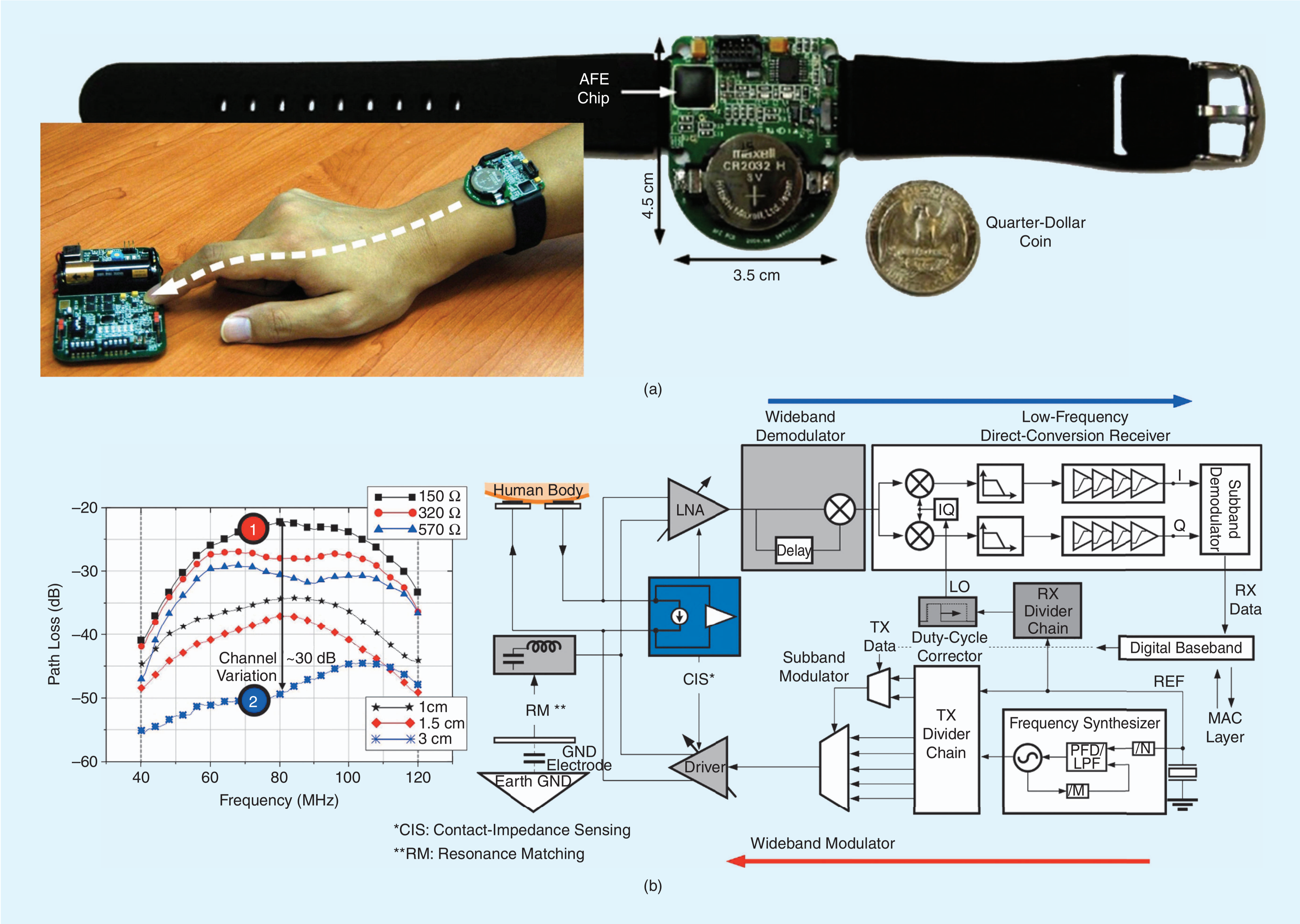

FIGURE 4: A BCC transceiver. (a) Wrist-type BCC test board and (b) BCC transceiver architecture with contact-impedance sensing.

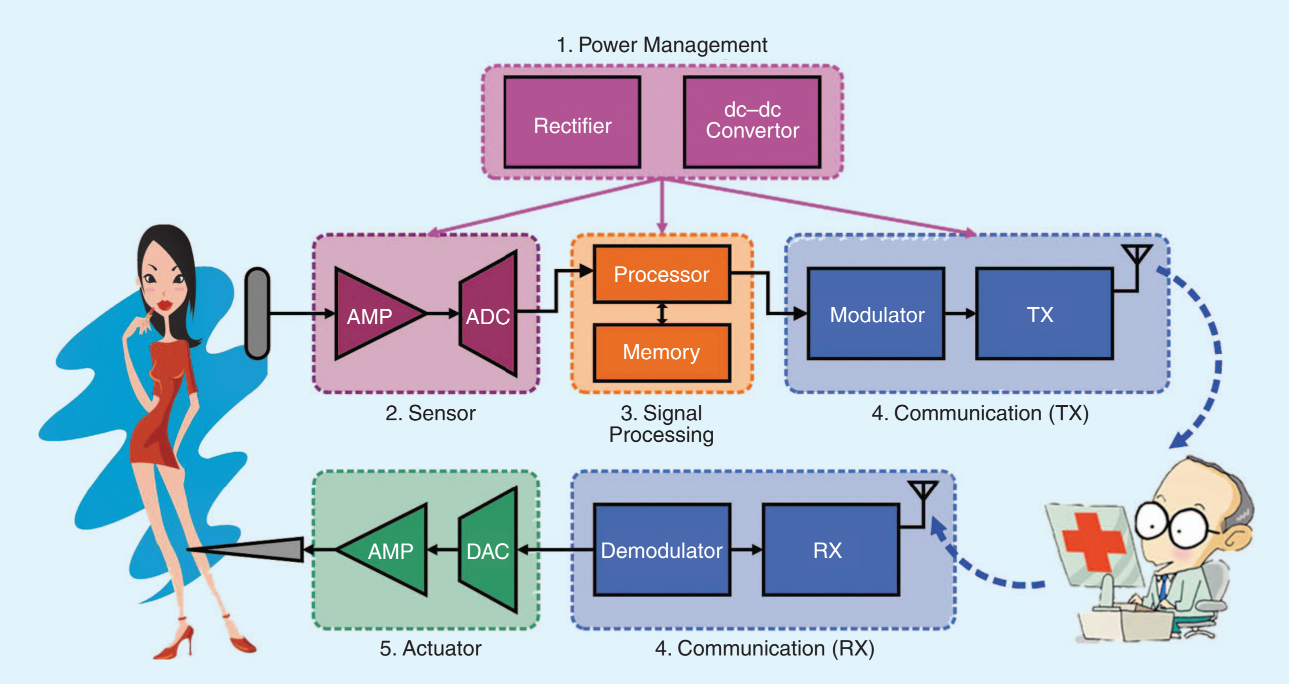

FIGURE 5: Block diagram for a wearable health-care system.

when the electrode is in contact with or apart from the body. Therefore, a contact impedance–monitoring circuit detects the impedance variation and automatically determines the operation mode of the receiver for better power efficiency. Owing to this technology, the optimal power consumption can be reduced to 1/10 of the worst-case power consumption, or 0.2 mW. The transceiver achieves 0.24 nJ/b at a data rate of 10 MB/s, which is adequate for most applications in the wearable computer and electronics area.

Wearable Health Care SoCs

Since wearable systems have specific substrates (textiles), I/O devices, and network environments, dedicated, custom chips must be designed with their target applications in mind. For example, textiles are good for heat protection—keeping the human body warm—and therefore are not good for heat dissipation, which most computer systems need. And textiles are good insulators, easily inducing rather high static charges that can damage CMOS ICs. Most component packages are optimized for joining to printed circuit boards. Instead, wearable components must be optimized to interface with textile circuitry, and this new environment brings new challenges for the IC designer. Wearable health care systems are usually composed of a power management unit, a sensor analog front end (AFE), a digital signal processor, a communication block, and an actuator (see Figure 5). All of these blocks should be optimized for the textile environment. I would like to address these issues using published chips as examples.

The first example we will discuss is a self-configured, wearable body sensor network (BSN) system with high-efficiency, wirelessly powered sensors that can continuously monitor a patient's electrocardiogram (ECG) [15] (see Figure 6). This system has eliminated the large form factors and the battery power limitations of previous wearable, chronic disease–monitoring systems. The adhesive bandage–type sensor patch is composed of the sensor chip, a P-FCB inductor, and a pair of dry P-FCB electrodes. The sensor chip harvests its power from the surrounding health-monitoring band using an adaptive threshold rectifier (ATR). With an ATR, the V_{TH} drop of the diode-connected transistor is minimized to improve the rectification efficiency, and this ATR improves rectification efficiency by up to 54.9% at the high-frequency band. The health-monitoring chest band with the integrated P-FCB inductor array is worn over the chest, and the network controller automatically locates the sensor position, configures the sensor type, wirelessly provides power to the configured sensors, and transacts data with only the selected sensors while dissipating 5.2 mW using a single 1.8-V supply.

The second system is a low-power, highly sensitive, wearable SoC for cardiac patients that performs thoracic impedance variance (TIV) and ECG monitoring, implemented as a poulticelike plaster sensor [16] (see Figure 7). The 15 cm by 15 cm patch fabricated using P-FCB consists of four layers. Layer 1 is a 25-electrode array for reconfigurable TIV and ECG sensing; layer 2 is a fabric inductor for system start-up; layer 3 is a thin, flexible battery; and layer 4 is a fabric circuit board onto which the SoC is directly wire-bonded. A user puts the patch on the chest to

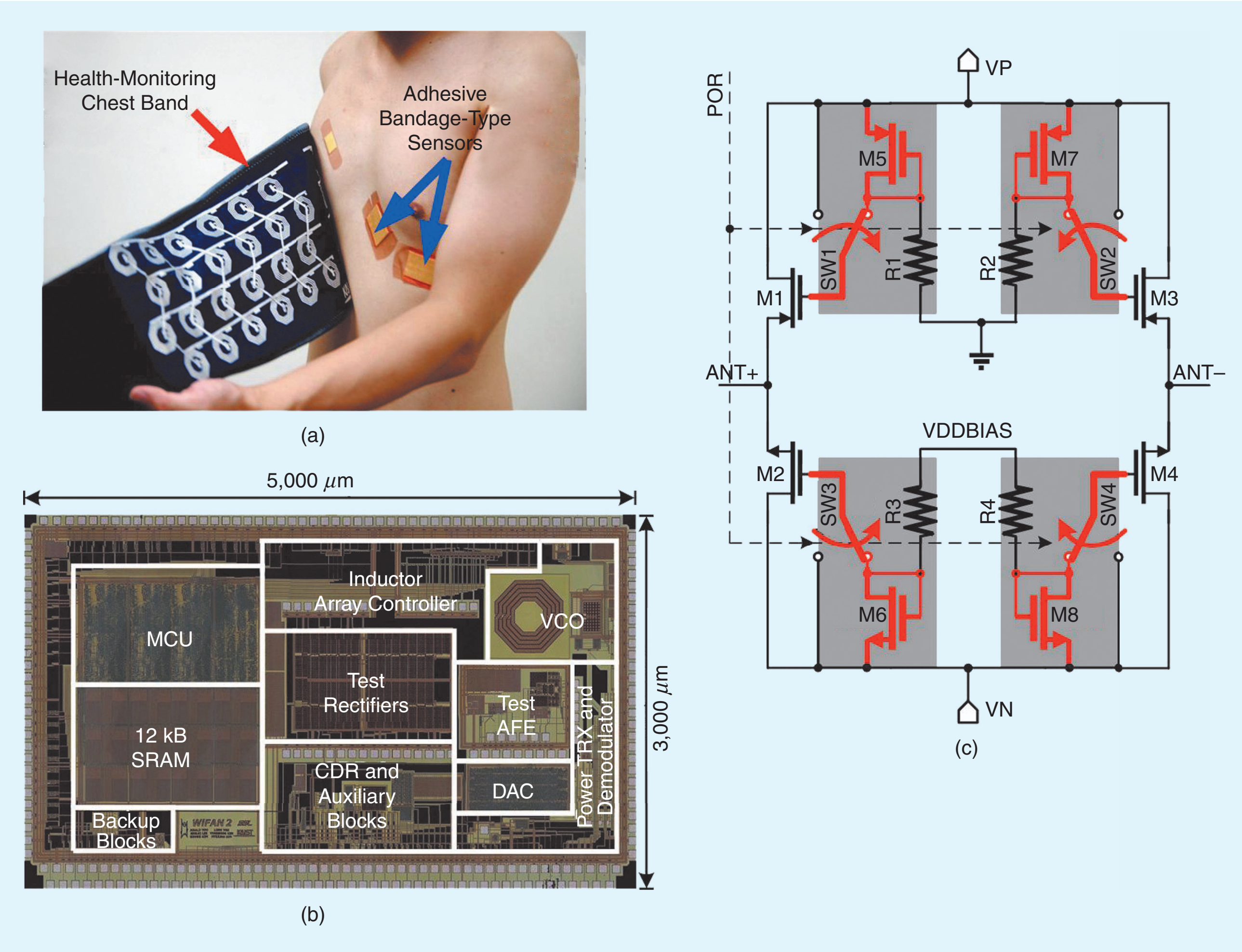

FIGURE 6: Self-configured wearable BSN system. (a) Adhesive bandage sensors with network controller, (b) chip photograph, and (c) circuits of an adaptive threshold rectifier.

monitor the TIV and ECG signals, and he or she can start and stop the system by using an inductively coupled power switch that includes an ID verification function. BCC is used to upload recorded data to a central base station when on-chip storage is full and download system commands when a new configuration is required. With the help of a high-quality, balanced sinusoidal current source and low-noise, reconfigurable readout electronics, 0.1-Ω TIV detection is possible with a sensitivity of 3.17 V/Ω and an SNR of 40 dB. A cm-range, 13.56-MHz fabric inductor coupling is used to start and stop the SoC remotely. Moreover, a 5% duty-cycled BCC is exploited for 0.2 nJ/b, 1-Mb/s energy-efficient external data communication. The proposed SoC dissipates a peak power of 3.9 mW when operating in body channel receiver mode and consumes 2.4 mW when operating in TIV and ECG detection mode.

The next example is a wearable mental health measurement system incorporating the nonlinear analysis of physiological rhythm, including heart-rate variability (HRV) and electroencephalography (EEG) signals, for high accuracy [17] (see Figure 8). This system is implemented in a 31-g headband that measures scalp signals and performs nonlinear chaotic analysis to measure stress levels. In this system, an independent component analysis (ICA) accelerator is adopted to extract the original EEG source from measured scalp signals. The four-channel, 10-b signals acquired by the sensor front end are mixed with other signals inside the brain and body. The ICA enhances HRV signal extraction, removes noise, and achieves noise-free EEG signals. As a result of ICA, each signal is divided into four independent components according to their non-Gaussian characteristics. Compared with the extracted HRV from the ECG signal, the HRV extracted from the independent component has only a 1.84% root mean square difference (PRD) while the HRV from scalp signals has a PRD that is four times greater.

A lightweight BAN using three-layer, coin-sized fabric patches has been developed for sleep-monitoring systems [18] (see Figure 9). It consists of a network controller (NC) patch, 14 ExG sensor node (SN) patches (φ = 20 mm, T = 2 mm), and a wearable band of conductive-yarn with

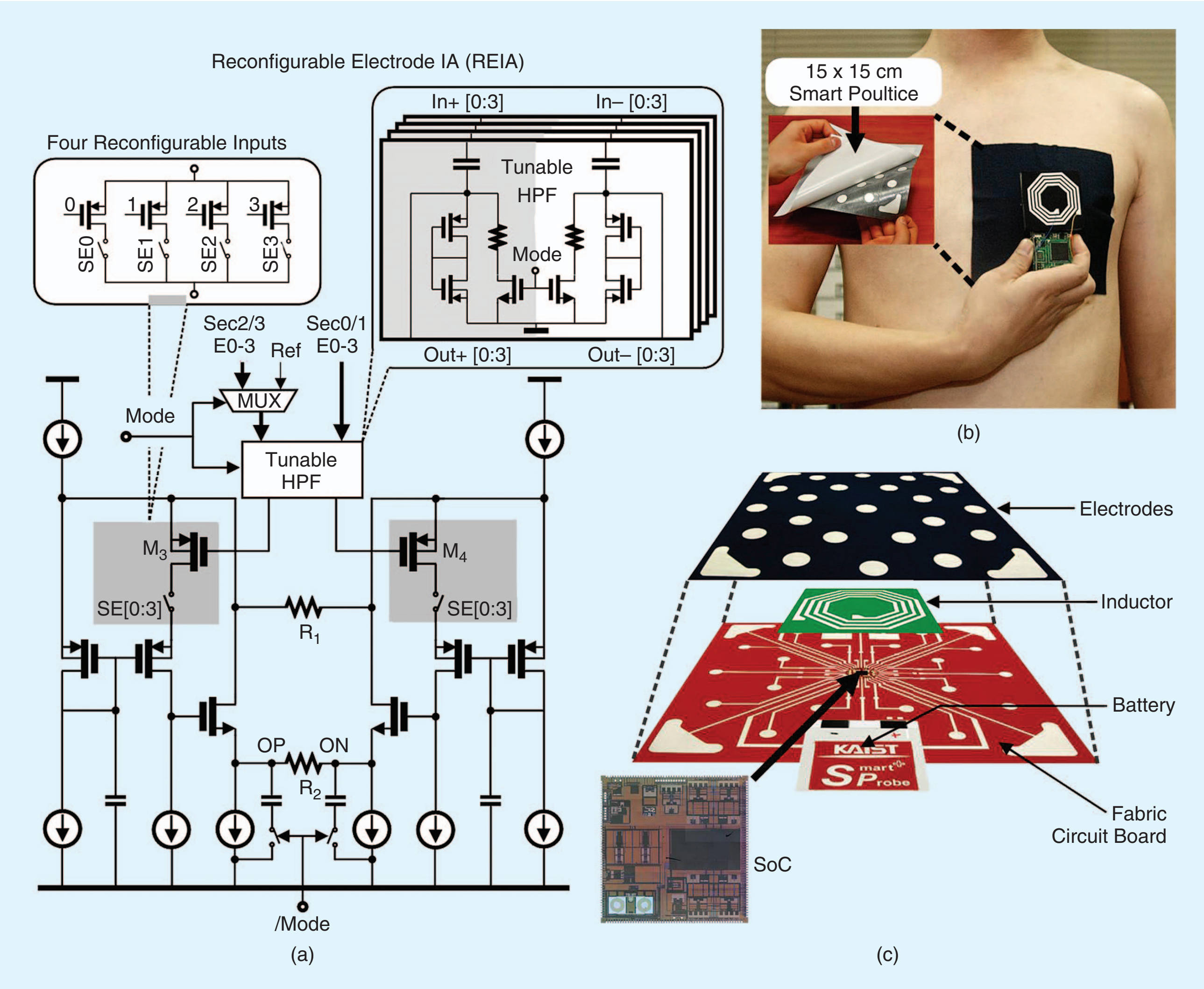

FIGURE 7: TIV and ECG monitoring system. (a) Circuits of reconfigurable electrode IA (REIA), (b) a poultice-like plaster sensor for ECG/TIV monitoring, and (c) a four-layer structure of the sensor.

five sublines (P, D, C, G, and R representing power, data, clock, ground, and reference). The NC patch and the SN patch have three P-FCB layers, and total thicknesses are fewere than 5 mm and 2 mm, respectively (layer 1 is an electrode; layer 2 is a power plane; and layer 3 consists of electronics). A continuous data transmission (CDT) protocol is proposed for low power and real-time scalability by in-order data transmission using the wearable band with several sensors. Based on this protocol, a linked list–based network manager (LLM), an adaptive dual-mode controller (ADMC) in the network controller IC, and a low-swing data transmitter (D-TX) with its own back-end circuits are introduced. The LLM and ADMC can adaptively change the network configuration according to the dynamic network variances in real time, and the D-TX can become a low-energy data transmitter (0.33 pJ/b) with a data rate of 20 Mb/s for the wearable band interface. These two low-power ICs, which are implemented in a 0.18-μm CMOS process and operate with a 1.5-V supply, consume 75 μW and 25 μW, respectively.

Last, a compact electroacupuncture (EA) system has been proposed for multimodal feedback EA treatment as one type of wearable health care application [19] (see Figure 10). The proposed system is composed of a needle, a compact EA patch, and an interconnecting conductive thread. The compact EA patch is 3 cm in diameter and is fabricated with P-FCB; it consists of three layers. An electrode layer includes surface electrodes for the closed-current loop, differential electrodes for multimodal sensing, and a BCC electrode for external communication. A power layer provides reliable power to the system. Finally, a circuit layer is made up of a P-FCB on which the adaptive stimulator IC is directly wire-bonded and to which a coin battery is attached. The adaptive stimulator IC can form a closed-current loop for even a single needle and measure the electromyography (EMG) signal and skin temperature

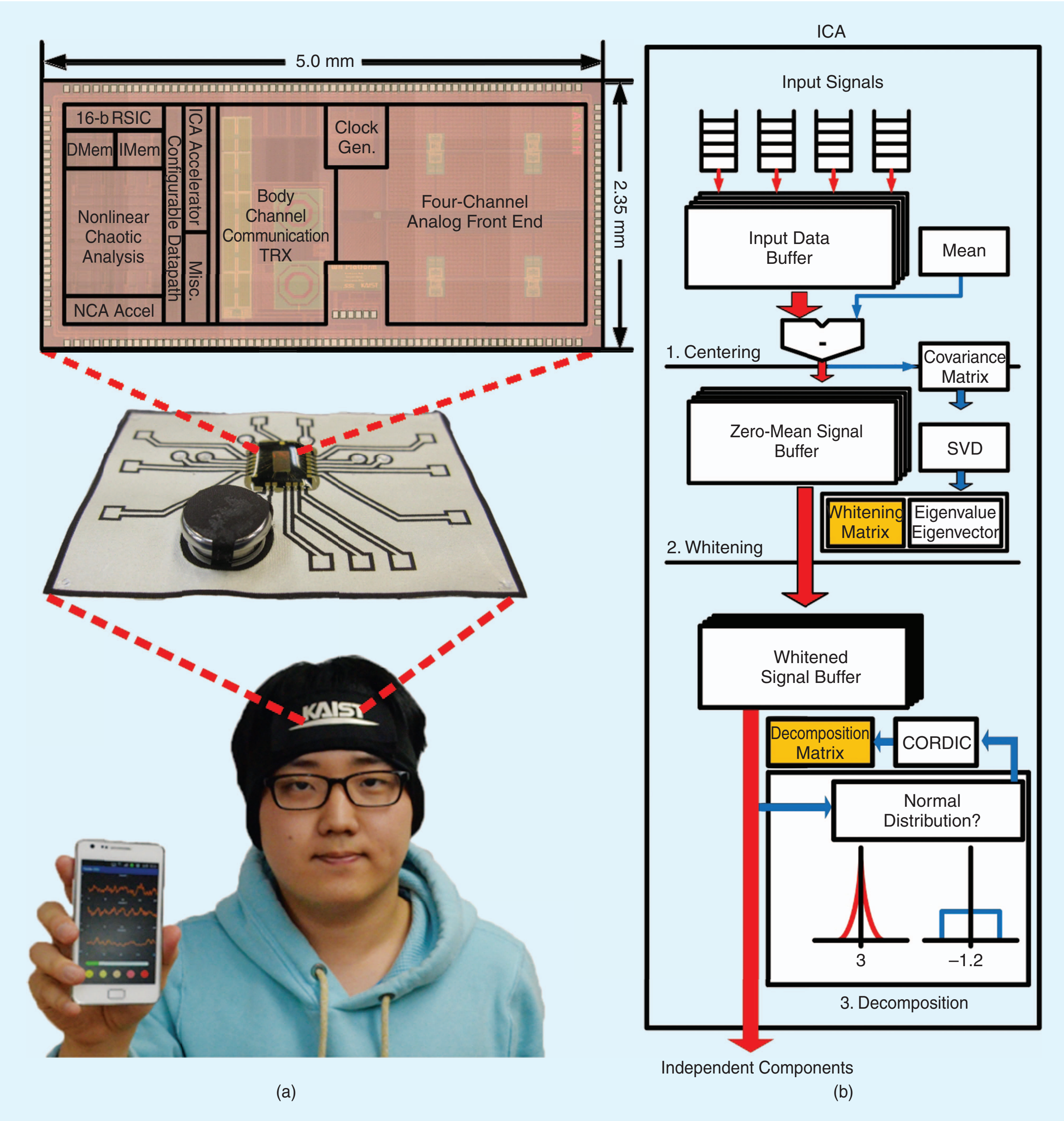

FIGURE 8: Wearable mental health measurement system. (a) A system and chip photograph and (b) operation of the ICA.

to analyze the stimulation status as well as supply programmable stimulation current (from 40 μA to 1 mA) in five different modes. The large time constant (LTC) sample and hold (S/H) current-matching technique achieves high-precision charge balancing (< 10 nA) for the patient's safety. The measured data can be wirelessly transmitted to the external EA analyzer through the BCC transceiver for low power consumption. The external EA analyzer can show the patient's status, such as muscle fatigue and changes in the skin temperature, and based on these analyses the practitioner can adaptively change the stimulation parameters to achieve optimal treatment value. This stimulator chip consumes 6.8 mW at 1.2 V and supports 32 different current levels.

Conclusions

The smartphone and tablet PC are about to realize the dream of the wearable computer, and the remaining issues concern the required technology for the ultimate seamless interface with the human body. That is, the hardware platform for the wearable computer and wearable health care is almost settled—the smartphone and tablet PC—and what

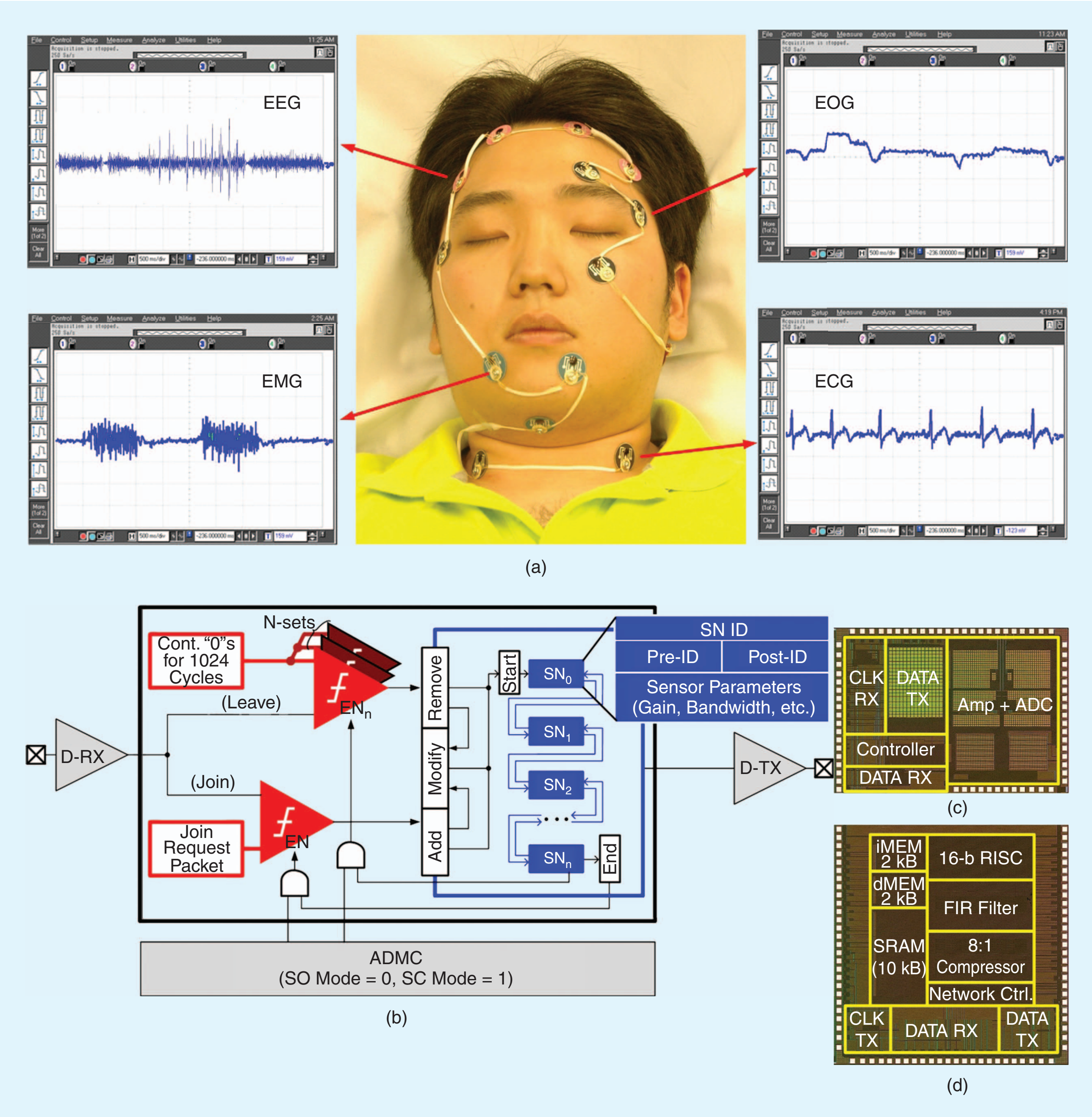

FIGURE 9: Wearable sleep-monitoring system. (a) System photo and measured biosignal waveforms, (b) linked list manager (LLM) in the network controller IC, (c) sensor node IC, and (d) network controller IC.

remains is to define human body–friendly wearable systems that can be placed around the human body and the robust network connecting these systems to the host system, the smartphone or tablet PC.

The wearable computer has evolved from a "pocket-based computer" to a "clothing-based computer" that can be implemented as e-broidery and e-textile. Adoption of the conductive yarns with which to stitch circuit patterns and sensor spaces has contributed to this transition. Recently, printing technology (P-FCB technology) has enabled the system to be integrated directly on the clothes and textiles, bringing wearable electronics to real-life usage. Wearable health care is an especially useful development that is about to open society to ubiquitous health care. Conductive yarns can interconnect the distributed devices on clothes to integrate a wearable computer. And the new IEEE 802.15.6 standard is helping wearable health care to assemble a complete system by connecting many devices worn on the body and relaying their signals to a mobile hub such as a smartphone. BCC or HBC is already able to use the human

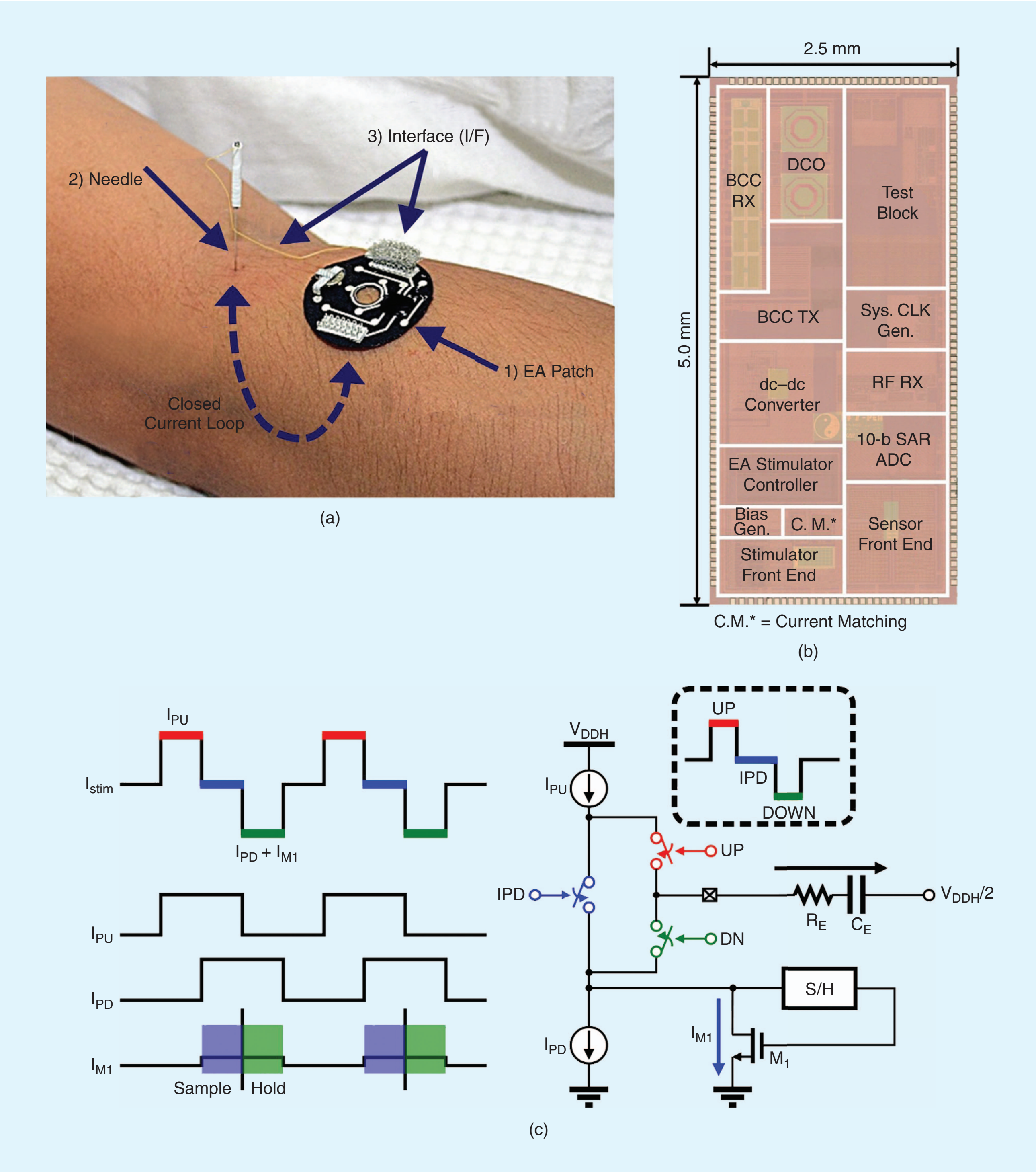

FIGURE 10: A smart EA system. (a) Smart EA system, (b) a chip photograph, and (c) circuits of S/H current matched stimulator (S/H CMS).

body as its communication medium to obtain a high level of energy efficiency in communication.

Some examples of the wearable health care systems have been introduced. Bandage-type "attachable systems" are exemplified by the wirelessly powered ECG monitor. Multilayered P-FCB plaster can measure TIV as well as ECG signals. These systems can communicate with external devices using BCC. A headband-type EEG monitor has been fabricated using P-FCB technology and can measure mental health parameters such as stress level and attention level. Multiple small patches can now be placed on the face to monitor the body's physiological signals during sleep. The stored signals can be retrieved upon waking and used to diagnose the wearer's sleep disorder. Wearable health care can implement a "smart"

Eastern medical device, the electric acupuncture system. The smart acupuncture device has a closed feedback loop to monitor the status of patient's muscle and modify the stimulation current according to the measured level of muscle fatigue.

As smartphones become more widespread and more people want to live healthy and happy lives, wearable electronics and wearable health care will play more important roles as intimate, smart interfaces with the human body. More-customized ICs will be required for wearable health care, and the role of circuit designers will be augmented accordingly.

References

[1] S. Mann, "Smart clothing: 'Wearable multimedia and personal imaging' to restore the balance between people and their intelligent environments," in *Proc. ACM Int. Conf. Multimedia*, Nov. 1996, pp. 163–174.

[2] E. O. Thorp, "The invention of the first wearable computer," in *Proc. 2nd Int. Symp. Wearable Computers (ISWC)*, Oct. 1998, pp. 4–8.

[3] D. Marculescu, R. Marculescu, N. H. Zamora, P. Stanley-Marbell, P. K. Khosla, S. Park, S. Jayaraman, S. Jung, C. Lauterbach, W. Weber, T. Kirstein, D. Cottet, J. Grzyb, G. Troster, M. Jones, T. Martin, and Z. Nakad, "Electronic textiles: A platform for pervasive computing," *Proc. IEEE*, vol. 91, no. 12, pp. 1995–2018, Dec. 2003.

[4] T. Linz, C. Kallmayer, R. Aschenbrenner, and H. Reichl, "Embroidering electrical interconnects with conductive yarn for the integration of flexible electronic modules into fabric," in *Proc. IEEE Int. Symp. Wearable Computers (ISWC)*, Oct. 2005, pp. 86–98.

[5] E. R. Post, M. Orth, P. R. Russo, and N. Gershenfeld, "E-broidery: Design and fabrication of textile-based computing," *IBM Syst. J.*, vol. 39, no. 3–4, pp. 840–860, July 2000.

[6] W. Weber, R. Glaser, S. Jung, C. Lauterbach, G. Stromberg, and T. Sturm, "Electronics in textiles: The next stage in man–machine interaction," in *Proc. 2nd CREST Workshop Advanced Computing and Communicating Techniques Wearable Information Playing Interaction*, May 2003.

[7] H. Kim, Y. Kim, Y.-S. Kwon, and H.-J. Yoo, "A 1.12 mW continuous healthcare monitor chip integrated on a Planar Fashionable Circuit Board," in *IEEE Int. Solid-State Circuits Conf. (ISSCC) Dig. Tech. Papers*, Feb. 2008, pp. 150–151.

[8] P. P. Mercier and A. P. Chandrakasan, "A 110 μW 10 Mb/s eTextiles transceiver for body area networks with remote battery power," in *IEEE Int. Solid-State Circuits Conf. (ISSCC) Dig. Tech. Papers*, Feb. 2010, pp. 496–497.

[9] J. Yoo, S. Lee, and H.-J. Yoo, "A 1.12 pJ/b inductive transceiver with a fault-tolerant network switch for multi-layer wearable body area network applications," *IEEE J. Solid-State Circuits*, vol. 44, no. 11, pp. 2999–3010, Nov. 2009.

[10] *IEEE Standard for Local and Metropolitan Area Networks: Part 15.6 Wireless Body Area Networks*, IEEE Standard 802.15.6, Feb. 2012.

[11] S.-J. Song, N. Cho, and H.-J. Yoo, "A 0.2-mW 2-Mb/s digital transceiver based on wideband signaling for human body communications," *IEEE J. Solid-State Circuits*, vol. 42, no. 9, pp. 2021–2033, Sept. 2007.

[12] N. Cho, J. Yoo, S.-J. Song, J. Lee, S. Jeon, and H.-J. Yoo, "The human body characteristics as a signal transmission medium for intrabody communication," *IEEE Trans. Microwave Theory Tech.*, vol. 55, no. 5, pp. 1080–1086, May 2007.

[13] J. Bae, H. Cho, K. Song, H. Lee, and H.-J. Yoo, "The signal transmission mechanism on the surface of human body for body channel communication," *IEEE Trans. Microwave Theory Tech.*, vol. 60, no. 3, pp. 582–593, Mar. 2012.

[14] J. Bae, K. Song, H. Lee, H. Cho, and H.-J. Yoo, "A 0.24-nJ/b wireless body-area-network transceiver with scalable double-FSK modulation," *IEEE J. Solid-State Circuits*, vol. 47, no. 1, pp. 310–322, Jan. 2012.

[15] J. Yoo, L. Yan, S. Lee, Y. Kim, H. Kim, B. Kim, and H.-J. Yoo, "A 5.2 mW self-configured wearable body sensor network controller and a 12 μW 54.9% efficiency wirelessly powered sensor for continuous health monitoring system," *IEEE J. Solid-State Circuits*, vol. 45, no. 1, pp. 178–188, Jan. 2010.

[16] L. Yan, J. Bae, S. Lee, T. Roh, K. Song, and H.-J. Yoo, "A 3.9 mW 25-electrode reconfigured sensor for wearable cardiac monitoring system," *IEEE J. Solid-State Circuits*, vol. 46, no. 1, pp. 353–364, Jan. 2011.

[17] T. Roh, S. Hong, H. Cho, and H.-J. Yoo, "A 259.6 μW nonlinear HRV-EEG chaos processor with body channel communication interface for mental health monitoring," in *IEEE Int. Solid-State Circuits Conf. (ISSCC) Dig. Tech. Papers*, Feb. 2012, pp. 294–296.

[18] S. Lee, L. Yan, T. Roh, S. Hong, and H.-J. Yoo, "A 75 W real-time scalable body area network controller and a 25 W ExG sensor IC for compact sleep monitoring applications," *IEEE J. Solid-State Circuits*, vol. 47, no. 1, pp. 323–334, Jan. 2012.

[19] K. Song, H. Lee, S. Hong, H. Cho, and H.-J. Yoo, "A sub-10 nA DC-balanced adaptive stimulator IC with multimodal sensor for compact electro-acupuncture system," in *IEEE Int. Solid-State Circuits Conf. (ISSCC) Dig. Tech. Papers*, Feb. 2012, pp. 296–298.

About the Author

Hoi-Jun Yoo graduated from the Electronics Department of Seoul National University and received M.S. and Ph.D. degrees in electrical engineering from the Korea Advanced Institute of Science and Technology (KAIST). He was a pioneer in vertical-cavity surface-emitting lasers (VCSELs) at Bell Communications Research in Red Bank, New Jersey, and the manager of the DRAM design group at Hyundai Electronics. Currently, he is a full professor in the Department of Electrical Engineering at KAIST and the director of the System Design Innovation and Application Research Center (SDIA). From 2003 to 2005, he was a full-time adviser to the Korean Ministry of Information and Communication for SoCs and next-generation computing. His current research interests are bioinspired IC design, networks on a chip, multimedia SoC design, wearable health care systems, and high-speed and low-power memory.

He has published more than 250 papers and has written or edited five books: *DRAM Design* (1997, Hongneung); *High-Performance DRAM* (1999, Hongneung); *Low-Power NoC for High-Performance SoC Design* (2008, CRC); *Mobile 3D Graphics SoC* (2010, Wiley); and *Bio-Medical CMOS ICs* (coeditor with Chris Van Hoof; 2010, Springer).

He received the Korean National Medal in 2011, the Electronic Industrial Association of Korea Award in 1994, the Hynix Development Award in 1995, the Korea Semiconductor Industry Association Award in 2002, the Best Research of KAIST Award in 2007, the Design Award for 2001 from the Asia and South Pacific Design Automation Conference, Outstanding Design Awards for 2005, 2006, 2007, 2010, and 2011 from the Asian Solid-State Circuit Conference (A-SSCC), and the Korean Scientist of the Month Award for December 2010.

He is a member of the executive committees of the Symposium on VLSI and A-SSCC. He was the Technical Program Committee (TPC) chair for A-SSCC 2008 and a guest editor of *IEEE Journal of Solid-State Circuits* and *IEEE Transactions on Biomedical Circuits and Systems*. He was TPC chair of the International Symposium on Wearable Computers in 2010, an IEEE Fellow, an IEEE Distinguished Lecturer (2010–2011), and the Far East chair of ISSCC (2010–2011) and is currently chair of the ISSCC Technology Direction Subcommittee and an associate editor of *IEEE Transactions on Circuits and Systems II*.