SUMMARY We have proposed a human-area networking technology that uses the surface of the human body as a data transmission path and uses an AC electric field signal below the resonant frequency of the human body. This technology aims to achieve a “touch and connect” intuitive form of communication by using the electric field signal that propagates along the surface of the human body, while suppressing both the electric field radiating from the human body and mutual interference. To suppress the radiation field, the frequency of the AC signal that excites the transmitter electrode must be lowered, and the sensitivity of the receiver must be raised while reducing transmission power to its minimally required level. We describe how we are developing AC electric field communication technologies to promote the further evolution of a human-area network in support of ubiquitous services, focusing on three main characteristics, enabling transceiver technique, application-scenario modeling, and communications quality evaluation. Special attention is paid to the relationship between electromagnetic compatibility evaluation and regulations for extremely low-power radio stations based on Japan’s Radio Law.

key words: AC electric field, intra-body communication, human-equivalent phantom model, communication quality

1. Introduction

Communication technologies using the AC electric field around a human body are promising for new ubiquitous services in areas like security systems, intelligent tutoring systems (ITSs), medical information systems, production/work management systems, and payment/settlement systems. This technique of using the human body as a signal transmission path has many advantages over conventional radio frequency (RF) approaches such as Bluetooth and Zigbee radios. Since its operation is based on near-field coupling, most of the signal from the transmitter is confined to the body without interference from external RF devices. The initial prototypes of the transceiver using the human-centric communication paradigm have been reported [1]–[5].

The human-body near-field communications system discussed in this paper enables data communications via an AC field that is formed using the surface of the human body as a transmission path. In this system, a transmitter attached to the body generates an AC signal modulated according to the data in question, and this AC signal modulates the electric field near the human body, thereby propagating an AC electric-field signal along the surface of the human body. The weak potential-difference signal induced by this AC field is then picked up by the electrode of a receiver, which demodulates the signal and recovers the data.

As described in classical electromagnetism textbooks, application of an AC current to an electric dipole antenna generates three electric-field components according to the distance \( r \) from the antenna: a quasi-electrostatic field inversely proportional to the cube of distance \( r \), an induction field inversely proportional to the square of distance \( r \), and a radiation field inversely proportional to distance \( r \). Human-body near-field communications aims to achieve a “touch and connect” intuitive form of communications by using the quasi-electrostatic component that propagates along the surface of the human body while suppressing both the induction and radiation field components radiating from the body. To suppress the radiation field, the frequency of the AC signal that excites the transmitter electrode must be lowered, and the sensitivity of the receiver must be raised while reducing transmission power to its minimally required level.

Thomas G. Zimmerman proposed the first quasi-electrostatic-field communications technology using a 0.1–1.0 MHz AC electric field and demonstrated the feasibility of communications in quasi-electrostatic-field mode using a 330 kHz prototype system [1]. At that time, Dr. Zimmerman was affiliated with IBM and was trying to use quasi-electrostatic-field communications technology for communications between multiple wearable computers. However, he stopped his development of this technology and turned his attention to short-range wireless communications technologies like Wi-Fi and Bluetooth [6]. Although a low frequency band from 0.1 to 1.0 MHz was used to suppress the radiation field in this prototype, it can be surmised that stable communications could not be achieved without transmitting signals at high transmission power since noise from the environment is significant at frequencies under 1 MHz. At the same time, high transmission power makes for intense radiation and induction fields, which can present problems in terms of the effects on the human body and compliance with Japan’s Radio Law.

By selecting the 5–10 MHz frequency band and developing receiver circuit technology that removes ham noise and other types of environmental noise, we developed human-body near-field communications technology for human-area networking that operates at the minimum transmission power required for achieving the communications quality demanded of communication services. Figure 1 shows a quasi-electrostatic-field model and a lump-constant equivalent circuit when an electric field transmit-
and SHINAGAWA: AC ELECTRIC FIELD COMMUNICATION FOR HUMAN-AREA NETWORKING

235

Fig. 1 Quasi-electrostatic-field model and lump-constant equivalent circuit.

Fig. 2 Typical applications of AC-field communications.

Fig. 3 Graph of space propagation distance versus transmission rate for various wireless technologies.

We begin by describing three important characteristics and applications of human-body near-field communications in Sect. 2. We then describe receiver/transmitter circuit technologies needed for stable communications in Sect. 3, and application-scenario modeling and communications quality evaluation in Sect. 4. Finally, in Sect. 5, we describe the relationship between electro-magnetic compatibility (EMC) evaluation and standards for weak transmitters and touch upon future development policies.

2. Important Characteristics and Applications

When a transmitter is capacitively coupled to the human body and generates an AC field of a lower frequency than the resonant frequency of the body (approx. 70–100 MHz), in the range of 5–10 MHz, the signal propagates over the surface of the body. The body does not act as an antenna, and the signal is not radiated into the surroundings, but propagates over the surface and escapes to earth ground. The body can be considered essentially conductive, so the direction of the induced field is mostly perpendicular to the body, and it has been shown through bio-electromagnetic simulation that almost none of the field penetrates the body. Clothing, shoe soles, and flooring can be considered as capacitive and transparent to the AC signal.

Below, we provide an example of applying this phenomenon for an office entry/exit control system, as shown in Fig. 2. Employees attach a card to their body/clothes, which transmits an ID signal from their body to a receiver built into the doorknob. Without having to take out their ID card, and by simply touching the doorknob, authentication is performed and the door is unlocked. Train ticket gates are another example. A receiver is embedded in the ticket gate, or in the floor directly beneath it. Fares are then processed and the gate opens by simply touching part of the gate or by stepping on the floor, and without having to take out a card, as with current contactless solutions. With the receiver in the floor, the AC signal passes through shoes and flooring, forming a communications path from transmitter to receiver. Using this principle, there is no interference even at very close quarters, which is in contrast to other wireless technology, and communication can be started and stopped through natural human actions. Figure 3 is a graph of space propagation distance versus transmission rate for various wireless technologies. It compares conventional short-range wireless specifications and AC-field communication with a carrier frequency of 5–10 MHz. Compared with an 802.11 series wireless LAN, Bluetooth, ZigBee, or UWB, which transmits signals in all directions through space over a distance of ten meters or more, AC-field communication is limited to the reach of the hands and feet, or in other words, the human area. AC-field communication is comparable in space communication distance to contactless IC cards. Therefore, the location of the user can be precisely speci-
fied. Unlike contactless IC cards, it has higher transmission speed. In addition, using the surface of the body as a transmission medium improves the convenience of contactless IC card systems, such as a ticket gate or electronic money systems.

We call this new communications technology, which uses the surface of the body as a communications channel, RedTacton. Since it allows communication and various actions (“Act on”) through natural movements like touching, we combined the words “Touch” and “Act-on,” making “Tacton.” We then added the word Red to give a sense of warm communication to arrive at the final name, RedTacton [8]. RedTacton was introduced at the 2nd World Summit on the Information Society (WSIS 2005), held in Tunis in November, 2005 as an advanced information and communication technology from Japan. Various dynamic exhibits, such as the hand-shake business-card exchange were shown to very positive response [9].

Three major characteristics of RedTacton are shown in Fig. 4. The first is communication by simple touch. Natural actions like touching, grasping, sitting, walking, stepping-on or kicking can unlock a key, start a device, or retrieve information. The second is that communication distance is limited to the “human area” within the reach of the hands and feet compared with an 802.11 series wireless LANs, Bluetooth, ZigBee, or UWB which transmits signals in all directions through space over a distance of ten meters or more. The physical relationship between users and things can be specified very precisely. The third is that the transmission medium is not fixed. Any material with a highly conductive surface is a good transmission medium, and various materials, such as dielectrics can be used. In addition to these characteristics, RedTacton gives an intuitive sense of the connection to the network, linking the user’s own actions with starting and stopping communication. This makes the technology a universal data-transmission interface, with potential for entirely new applications areas and expanding the boundaries of ICT [7], [10].

Preventing leakage of confidential information, including customer data, has become a critical issue for business, and there is an urgent need for creating secure office spaces. Conversely, as security levels increase, employees are required to go through authentication procedures more frequently, leading to decreases in productivity. RedTacton can resolve this type of problem and create secure office spaces with no sense of inconvenience of the authentication processes. Figure 5 shows a prototype test bed for such a system. Users place an ID transmitter card in their shirt pocket or hang it from a strap around their neck. When the user enters an area, a receiver in the floor detects their ID through the floor and activates navigation lights in the floor. A personal post box notifies the user if there is mail and automatically unlocks with a touch. Doors are opened automatically by simply standing in front of them if an authorized ID is detected.

These types of systems normally have the shortcom-
ing that when the door is opened, persons without an ID can enter, so-called “tailgating.” With this new technology, a suspicious person entering without an ID transmitter can be detected. By embedding transmitters and receivers alternately in the floor, a person’s body can become a transmission path simply by walking on the floor. Transmitters and receivers would normally be concealed beneath the carpet, so intruders would not know their location and, unless they could fly, could not avoid detection. This sort of function is not possible using near-field wireless technologies such as Bluetooth or ZigBee, or contactless IC cards.

The technology can also be used to divide areas into zones with different security levels, without requiring physical partitions. For example, the system could be configured to allow only authorized personnel into a zone for storing important documents. A security lamp would illuminate if an unauthorized person simply steps into the secure zone. A secure printing system could also created. Documents printed on remote printers would be spoiled to the printer, but not printed until the owner arrived and physically touched the printer. Still further, a PC could connect to the Internet, printers, or a presentation projector, by simply placing it on the tabletop without requiring any cable connections. A key point is that, in contrast to a wireless LAN, multiple PCs can be used without any interference between them. By simply wearing a card-style terminal as described above, and with no further actions, a totally secure office space can be achieved.

With ever increasing concern for safety, security, and health in our aging society, this technology is promising for new applications in areas like security systems, ITSs, medical information systems, production/work management systems, and payment/settlement systems, as shown in Fig. 6. Some examples of promising applications are in ticket gates with RedTacton, embedded in mobile phones, to enable empty-handed payment.

3. Enabling Technologies

Figure 7 shows a model of the electric-field distribution around a human body when electric field transmitter and receivers are attached to the body. The person stands on earth ground, and the transmitter and receiver also have signal and ground terminals. An AC field can be transmitted to the body’s surface as long as there is a capacitive connection, so the terminal is isolated with an insulating layer, and no DC current flows into the body. The body is quite a good conductor, so the AC electric field forms perpendicular to the bodily surface. Communication is achieved at the receiver by detecting this AC electrical field before it escapes to earth ground. Part of the AC electric field induced on the body returns to the ground electrode of the transmitter and a significant part escapes directly to earth ground. Furthermore, the field distribution changes continuously with the person’s movements. Thus, the receiver must detect a signal that is quite faint and unstable. This presents a problem in improving the quality of transmission and making the technology practical.

As shown in Fig. 8, we first describe an equivalent circuit model, which simplifies the basic approaches to this problem. On the transmitter side, we need to address how to efficiently induce an AC electric field signal to the body surface. Both the human body and the transmitter are floating with respect to earth ground, and they are capacitively coupled. This capacitance tends to attenuate the AC signal induced by the transmitter. The capacitance of the connection also changes continuously with bodily movement. Figure 9 is a schematic and circuit model of signal transmission to the body. There are two parasitic capacitances that affect signal attenuation. One is the capacitance, Cb, between the body and the earth ground; and the other is the capacitance between the circuit ground and the earth ground, Cg. Vs is the output voltage of the transmitter, and Vb is the voltage between the body and the earth ground, and Rs is the output resistance of the transmitter, which is usually small. Therefore, the ratio of Vb to Vs is a function of Cg and Cb. If the transceiver is in a hand or a pocket, the circuit ground is far from the earth ground. Therefore, Cg is much smaller than Cb, which causes the induced signals to be attenuated.

Our new transceiver provides a series resonance among the parasitic capacitances to boost the amplitude of Vb. Figure 10 shows a schematic and circuit model of electrical-signal transmission using our new transceiver. We put a reactance, Xr, between the electrode and the output of the transmitter to produce a series resonance between Cb and Cg. When the conditions for series resonance are satisfied, the ratio of Vb to Vs reaches its largest value. For an ap-
appropriate selection of $X_r$, $f_s$, and $R_s$, the series resonance boosts $V_b$. In an actual situation, the parasitic capacitances are not constant. Therefore, we provided a way of regulating the reactance, $X_r$, in accordance with the changes in those capacitances. This technique enables us to implement the transceiver in a standard CMOS LSI and to achieve stable communications under a variety of conditions.

Figure 11 shows a circuit model of the receiver side. As shown in Fig. 11(a), the human body acts as the signal line, but the ground line is floating electrically. Therefore, the balance between the impedance for the signal line, $Z_s$, and that for the ground line, $Z_g$, with respect to the earth ground is poor. This causes the single-ended amplifier to be easily affected by common-mode noise. It is important to suppress common-mode noise, such as ham noise, in order to detect the weak signal arriving at the receiver terminal. Thus, we developed a technology, through careful design, to maintain an equivalent differential structure on the receiver side from the receiver terminal to the input of the first stage low-noise amplifier, and from the ground terminal to the amp ground (See Fig. 11(b)).

This improves the balance between the impedances for the signal and ground lines, and reliably eliminates common-mode noise at the first stage, improving the signal-to-noise ratio and allowing the weak signal to be amplified. These basic technologies allow stable communication to be
A prototype portable card transmitter and a receiver that can be built into environments, such as doors and floors, are shown in Fig. 12. The prototype uses a 5-MHz carrier frequency with binary phase shift keying (BPSK) modulation, and achieves a transmission rate of 200 kbps. In examples such as entry control or transport ticket gates, as described earlier, the transmitter can be worn in a jacket breast or trouser pocket, transmitting ID information, and achieve communication with packet error of less than $10^{-3}$. This transmitter can also function for approximately one year using a single CR 3032 button-type lithium-ion battery.

4. Modeling and Communications Quality Evaluation

To evaluate the quality of communication using the human body as a medium, we used a phantom model with the same electrical properties as the human body and built models equivalent to practical scenarios. Figure 13 shows an example of a railway ticket gate scenario. A transmitter is attached to the person and a receiver is embedded in the floor when the passenger wearing shoes steps on the floor. The human-equivalent phantom model used was a cylinder of about 80 cm in circumference and approximately hips-to-chest in height. The lower surface of the cylindrical phantom model was attached to the receiving plate electrode (approx. 40 cm square) through flooring material, and the transmitter was placed on the top surface. Signal loss along the transmission path could be adjusted by placing insulating spacers of various thicknesses between the transmitter and the top surface of the phantom. A digital signal generator was connected to the transmitter, and a data logger recording the decoded digital signal was connected to the receiver, enabling us to measure the error rate of the transmission path. Both a human body and the phantom model can be considered as conductors for 5–10 MHz signals, so the evaluation system can be expressed as a lumped-constant network. The simplest equivalent circuit model is shown in Fig. 13. En-
loop antenna was then placed 3 m from the person wearing the transmitter, and precision measurements of the field strength were taken in the position that yielded the highest strength, as noted above. According to Japan’s Radio Law, the permissible electric field strength for an extremely low-power radio station without license must be lower than 500 $\mu$V/m at a distance of 3 m from the station below frequencies of 322 MHz [11].

The results of measuring over a frequency sweep from 1 MHz to 1 GHz are shown in Fig. 16. We confirmed that both horizontal and vertical polarizations were beneath the permitted field strength for very-weak transmitters by an order of magnitude. The human-body communication device (using carrier frequency of 5 MHz and output amplitude of 1 V) was clearly shown to be within protection guidelines against nonionizing radiation, for both current induced in the body and Specific Absorption Rate (SAR: the energy absorbed by a unit of material in unit time). This was done through a bio-electromagnetic simulation analysis conducted by Prof. Taki’s group at the Tokyo Metropolitan University using a finite-difference time-domain method at 5 MHz and 1-V amplitude [12]. The simulation also showed that almost no electric field penetrates the human body. The induced current density was computed to be $2.8 \times 10^{-2}$ A/m$^2$, which is small relative to the limiting value of 10 A/m$^2$. The computed result for SAR was $9.9 \times 10^{-7}$ W/kg, also small relative to the upper limit of 2 W/kg. This value is about six orders of magnitude lower than the SAR value for a mobile telephone (0.1–1 W/kg).

We also conducted experiments with the transmitter attached in various positions on a human-body phantom model with an embedded pacemaker to ensure that no ill effects resulted, as recommended by Goldstein [6]. We were able to confirm that there was absolutely no effect on several different types of pacemaker models in use in Japan. As described above, RedTacton transmitters satisfy the requirements for extremely low-power radio stations in accordance with Japan’s Radio Law, and comply with radio-emission protective guidelines.

5.2 Future Developments and Design Challenges for RF-LSI

As concerns over safety, security, and health grow in our aging society, this is a promising technology for new applications in areas like security systems, ITSs, medical information systems, production/work management systems, and payment/settlement systems (See Fig. 17). A next-generation settlement/payment system could replace the current contactless IC card wireless interface with RedTacton embedded in mobile phones to enable empty-handed payment. The miniaturization of the transceiver module using this technology is spurring the further expansion of RedTacton applications. The first prototype module had a volume as large as 20 cc, excluding coin-type batteries and electrodes. The latest module now being developed has a volume of only 0.1 cc. Miniaturization enables RedTacton
technology to be embedded in a variety of common devices, such as mobile phones, wristwatches, and key holders. The key point in constructing a small, low-cost module is making a programmable CMOS LSI that has the robust wireless functions necessary for wide-area use in various situations.

Trends in RF-CMOS LSI technology are shifting from analog centric circuits to digitally assisted circuits. Compared to analog circuits, digital circuits are more stable and robust, and have the added feature of being programmable. To achieve the severely high performance required for RF-LSI in RedTacton terminals, we are investigating designs that would make the analog circuits of RF components compatible with the digital circuits of base band components. For a RedTacton transceiver it is important to ensure that the receiver has a high sensitivity as well as a wide dynamic range. For example, it is important to control signal gains so that a signal is not saturated even if a strong signal is received from a directly-contacted transceiver. Consequently, the key is gain control through use of a low noise amplifier in the first stage and use of a gain control amplifier in the

---

**Fig. 15** EMC evaluation near human body.

---

**Fig. 16** Compliance with Japan’s Radio Law and assessment of effects on human body.

---

**Fig. 17** Applications and future directions.
In regard to transmission, it is necessary to control the lower limit values of power that is transmitted, so as to maintain a stable communication, especially when the level of ambient noise is high. An important point also is gain control of the power amplifier. Since it is easy for the amplifier gains to be affected by changes in the LSI manufacturing process, it is important to control gains in accordance with the threshold value voltage (Vth) of transistor lots produced in trial production runs.

Furthermore, the voltage regulators that supply stable power supply voltage to the transmitter and the receiver are easily influence by changes in Vth. In addition, since the RedTacton terminals will be used in various environments, indoors and outdoors, it is necessary to control changes in wireless performance and reception signal saturation in real time, while monitoring the surrounding temperature and the ambient noise level. To overcome the problems mentioned above, we need to try a design using digital calibration and adaptive compensation, based on the concept of making the RF circuits and the base band digital circuits compatible.

6. Conclusions

We have developed a communications technology that uses the surface of the human body as a data transmission path. To suppress the radiation field, we selected the 5–10 MHz frequency band to avoid the intense environmental noise under 1 MHz and to suppress the radiation field from the human body and transmitter electrode. Two key technologies have been developed to provide stable communications. On the transmitter side, a reactance-matching circuit was implemented in the output stage of the transmitter to efficiently induce an AC electric field signal to the surface of the body. In addition, we developed the technology to maintain an equivalent differential structure on the receiver side to suppress common-mode noise. This reliably eliminates common-mode noise in the first stage, thereby improving the signal-to-noise ratio and enabling a weak signal to be amplified. As a result, we minimized the transmission power required for achieving the communications quality demanded of communication services. In actuality, the transmitters satisfy the requirements for extremely low-power radio stations in accordance with Japan’s Radio Law, and comply with radio-emission protective guidelines. Thus, we believe that this technology can be used as a universal interface for transmitting data in various application areas, such as security systems, ITSs, medical information systems, and production management systems, and that it offers a new approach that combines ICT technology with these fields.

Acknowledgments

We express our sincere thanks to R. Kawano, K. Ochiai, A. Furuya, N. Shibata, T. Mizota, T. Minotani, A. Sasaki, and T. Ishihara for their efforts to experimentally design and produce the transceiver and their helpful comments.

References


Yuichi Kado received M.S. and Ph.D. degrees in electronics from Tohoku University, Miyagi, Japan, in 1983 and 1998, respectively. In 1983 he joined the Electrical Communication Laboratories of Nippon Telegraph and Telephone Public Corporation (now NTT), Kanagawa, Japan, where he was engaged in research on SOI structure formation by hetero-epitaxial growth. From 1989 to 1998 he worked on the development of fully depleted CMOS/SIMOX LSIs and ultra-low-power CMOS circuits. From 1999 he was engaged in R&D on compact network appliances using ultralow-power CMOS circuit technologies for ubiquitous communications. Currently, he leads research and development projects on ultralow-power network appliances, sub-terahertz-wave wireless communication, and intra-body communication as director of Smart Devices Laboratory at NTT Microsystem Integration Laboratories. He has been the recipient of awards including the 1990 Young Engineers Award presented by the IEICE, the 2006 Top Innovation Award (NAB2006), the 2007 BIRTVAward, the 2009 Nikkei BP Technology Award, and the 2009 RadioWave Achievement Award presented by the ARIB. He is a member of IEEE.
Mitsuru Shinagawa received the B.S., M.S., and Ph.D. degrees in electronic engineering from Tohoku University, Sendai, Japan in 1983, 1985, and 2005, respectively. In 1985 he joined the Electrical Communication Laboratories, Nippon Telegraph and Telephone Corporation (NTT), Tokyo, Japan. He is currently a Senior Research Engineer, Supervisor in the department of Smart Devices Laboratory, NTT Microsystem Integration Laboratories, Kanagawa, Japan. His technical areas of interest include timing jitter analysis of high-speed sampling systems, electro-optic sensors, high-precision waveform measurement for ultra-fast electronics, electric field measurement of printed circuit boards, and communication technology for human area networks. He has received the Andrew R. Chi Prize Paper Award from IEEE Transactions on Instrumentation and Measurement in 1992 and the Okochi Memorial Award of Japan in 1997. He is a member of IEEE.