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Ubiquitous Networking Based on Two Dimensional Signal Transmission Technology

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In this paper, we introduce the latest results of our two-dimensional communication project. The communication elements that touch the surface of a Two-Dimensional Signal Transmission (2DST) sheet establish the connection being supplied with the power by the 2DST sheet. The system allows free location of the element, and proximity (non-contact) connection is realized stably. The structure of 2DST sheet is simple and fabricated with various materials at low cost. Since the elements communicate with electromagnetic waves confined in two-dimensional medium, they are free from the interference from the devices apart from the sheet. The technology also enables us to integrate sensors in stretchable materials.

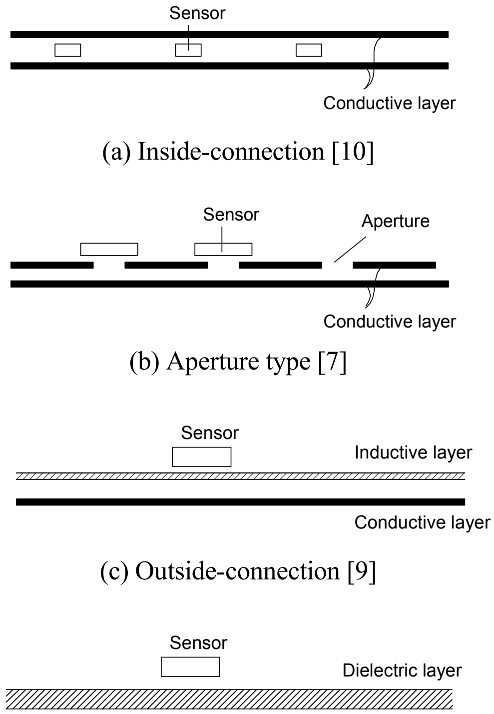
1. Introduction

A promising strategy for assisting human to interact with computers is to embed sensors in the environment to sense the human intensions. The intensions come out in voices, eye-gazes, and body motions. The myoelectric signals and other nerve potentials appearing on the skin also reveal them. It is desired that such signals are detected without annoying devices.

For embedding a large number of sensors in rooms and clothes, we are proposing two-dimensional signal transmission (2DST [6]-[10]) as an alternative other than the traditional wiring and wireless communication. This paper introduces the latest results of our 2DST project. In the proposed system, the sensor node that touches the surface of a 2DST sheet establishes the connection. The nodes communicate using microwave which propagates in two-dimensional sheet. The system allows free location of the node, and proximity (non-contact) connection is realized stably.

The first merit of 2DST is that the communication is free from the interference [1] from unexpected signals outside of the room. The sensors belonging to a 2DST sheet is also harmless to the sensors apart from the sheet. The second important merit is that sensor nodes can receive the power for operation from the sheet that enables wide band communication without batteries. The third merit is that the required energy for signal transmission is smaller than usual radio. In addition, it is easy to avoid the multi-path problem by termination at the sheet edge.

The sheet structure is simple, and the simplicity enables us to form the 2DST structure on the surfaces of various materials of walls, desks, floors, and even clothing. The drawback of 2DST compared with usual radio connection is that we have to prepare special surfaces for signal transmission. However, when we produce desks with the 2DST structure, the additional cost is low and becomes negligible in mass production.



(a) Inside-connection [10]

(b) Aperture type [7]

(c) Outside-connection [9]

(d) Connection by simple dielectric layer

Fig. 1. Cross-sections of possible types of 2DST

The idea of communication using two dimensional medium was originally proposed by Lifton et al. [3], Laerhoven et al. [4] and us [2] at the early 2000s. In research [3], however, the 2D plane was used for DC power supply and radio was used for the communication. Also in research [4], high speed communication through the medium was out of consideration, since a pair of parallel large conductors makes a huge condenser. In addition, mechanical and electrical contacts of elements to the conductive layers were necessary in the preceding researches. Networked surfaces [5] proposed by Scott et al. was also based on a concept similar to two-dimensional communication. But their device was not a continuous medium and required a complex structure of surface with multiple electrodes combined by wires.

2. Non-contact connection to 2DST sheet

We can suppose at least four types of 2DST as shown in Fig. 1 In the first form of figure (a), the sensors are sandwiched by two conductive layers. In this structure the electromagnetic wave can be strictly confined within the sheet. TEM mode with the electric field vertical to the surface conveys the signals in this case. A method to make the proximity connector on the sensor chip much smaller than the wavelength using resonance is described in [10]. The second type as shown in Fig. 1 (b) allows the sensor chips to be attached on the sheet after the sheet production. Electro-magnetic waves are sent/received through apertures on the sheet. The structure is effective in the case that the sensor location is decided in advance. Fig. 1 (c) realizes free location of the sensors on the sheet. The sensor can even move on the surface keeping the connection. In the following sections, the electromagnetic field and the proximity connection of Fig. 1 (c) [9] are described.

2.1. Electromagnetic wave around 2DST sheet

Under the coordinate system shown in Fig. 2, the z component of electric field above the surface ($z > 0$) is written as

$$E_z = \frac{k_2^{\ 2}}{k_1} V \exp(-k_1 z)\exp(-jkx)\exp(j\omega t) \qquad (1)$$

$$\left(\begin{array}{l} k_1^2 = (\mu\varepsilon - \mu_0\varepsilon_0)\omega^2 - \dfrac{j\sigma\varepsilon\omega}{h} \\ k_2^2 = \dfrac{j\sigma\varepsilon\omega}{h} \\ k^2 = \mu\varepsilon\omega^2 - \dfrac{j\sigma\varepsilon\omega}{h} \end{array} \right)$$

for the wave traveling toward $+x$, where μ and ε denote respectively the magnetic permeability and dielectric constant of the sheet, and μ_0 and ε_0 are those of the atmosphere. The parameter V is the voltage between the top layer, S, and the bottom layer, B, at $x = t = 0$. The equation is an approximation based on the assumption $|k_1 h| << 1$ and $|k_2 h| << 1$, where h is the dielectric layer thickness. The parameter σ is the sheet impedance of the top layer defined as

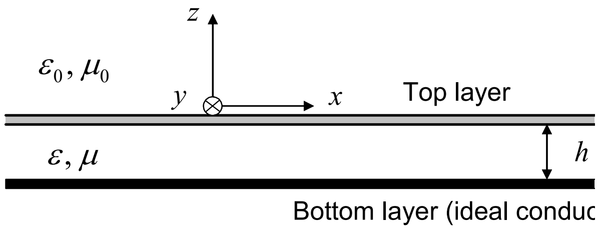


Fig. 2. Coordinate system and sheet parameters.

$$\sigma \equiv R + jX \equiv \frac{E_x}{i_x} \qquad [\Omega] \qquad (2)$$

where E_x is the electric field along the x axis at the top layer and i_x is the current density [A/m] along x axis. We assume that the bottom layer is an ideal conductor and that the top layer is sufficiently thin. If the top layer is ideal continuous conductor, σ is equal to 0, which results in $E_x = 0$. We call a top layer whose sheet impedance is inductive as $X > 0$ an "inductive layer." An inductive layer can be realized by a mesh of well conductive material with the period shorter than the wavelength. When S is a mesh whose period is smaller than the wavelength, E_x and i_x denote their averages in the period.

Based on the equation (1), we can calculate leakage ratio r that is defined as the ratio of the electromagnetic energy flow J_1 running along $+x$ direction outside of the sheet to the energy flow J_2 inside the sheet. The calculation result is

$$r \equiv \frac{J_1}{J_2} = \frac{\pi\varepsilon_0}{\varepsilon} \frac{\gamma^2}{\sqrt{1+\gamma}^3} h \sqrt{\frac{1}{\lambda^2} - \frac{1}{\lambda_0^2}} \qquad (3)$$

where λ_0 and λ are respectively equal to the electromagnetic wave length in the air and the one in a medium with ε and μ. Dimensionless parameter γ is defined as

$$\gamma \equiv X \frac{\varepsilon}{h(\varepsilon\mu - \varepsilon_0\mu_0)\omega}, \qquad (4)$$

which is a normalized sheet inductance that determines the electromagnetic leakage and the connection property. When $\varepsilon/\varepsilon_0 = 1.4$, $\mu = \mu_0$, $h = 1$ mm, and $\gamma = 1.0$, r is as small as 0.4 % at 2.4 GHz. Electromagnetic wave can be sent/absorbed to/from the 2DST sheet by placing a conductive plate near S, while the electro-magnetic energy outside of the sheet remains small without the proximate conductive plate.

The theoretical attenuation distance (the dis-

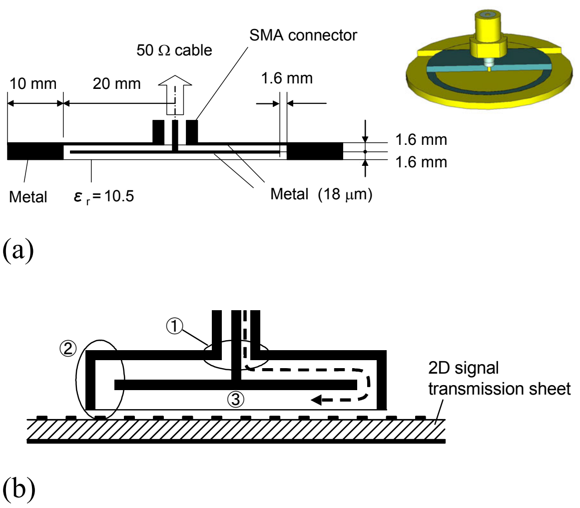


Fig. 3. An example of proximity connector design. The detail of the axisymmetric connector (a) and an illustration of the principle [9].

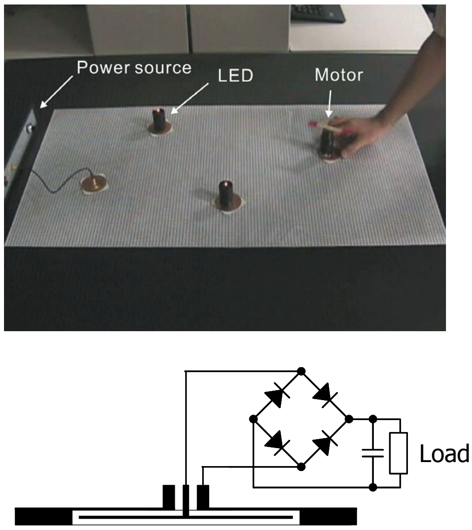


Fig. 4. Photo: view of power transmission experiment. The sheet size is 50×95 cm^2. Lower diagram: the power receiving circuit.

tance for $1/e$ attenuation) in the 2DST sheet is given as follows.

$$\zeta = \frac{1}{-\mathrm{Im}[k]} \approx \frac{1}{\frac{\omega}{2c}\tan\theta + \frac{\varepsilon_{re} c}{2h} R} \tag{6}$$

where $|\mathrm{Re}[k]| >> |\mathrm{Im}[k]|$. For example, ζ is as large as 17 m at 2.4 GHz for the sheet thickness h = 1 mm, the relative permittivity of the dielectric layer 1.1, the sheet resistance of the mesh layer R = $5\times10^{-2}\,\Omega$ at the signal frequency.

2.2. Proximity connection

An example of proximity connector is shown in Fig. 3. The design concept is qualitatively explained in Fig. 3 (b). When we put the connector on the surface of the 2DST sheet, the micro wave impressed from the coaxial cable follows the winding axisymmetric path shown by the arrow of the broken line. Then reflections occur at three parts in the connector due to the discontinuous change of the impedances. Those positions are illustrated as ①, ② and ③ in the figure. As a result, reflected signal back to the coaxial cable is the mixture of the reflected signals at each point. By choosing connector radius so that the reflected signals from ② and ③ counteract the reflection at ①, we can reduce the reflected power. In an ideal case, the input signal is fed in the sheet without reflection back to the cable.

For the inner connection shown in Fig. 1 (a), we have developed a proximity connector much smaller than the electromagnetic wave length. The details are described in [10]. Fig. 5 shows an application of Fig. 1 (a) to a stretchable robot skin. In 2DST, each node works without electrical contact to the sheet. The proximity connection allows displacement of the sensor chip in 2DST sheet (knitted fabrics in this case), which endows the functional sheet with toughness keeping the elasticity.

2.3. Microwave power transmission

Since the 2DST sheet confines the electromagnetic energy inside the sheet, intense microwave is allowed to be radiated into the sheet. Microwave power transmission is a robust way since a local short-circuiting between the conductive layers causes only local break-down within the wavelength radius. That property makes it realistic to embed 2DST sheets on the desks, floors and walls. (In DC or low frequency AC power supply, only one point short-circuiting is fatal.) We experimentally confirmed 100 mW energy absorption by one node from 10 W power source through 50×95 cm^2 sheet, based on type (c) in Fig. 1. A technological challenge in microwave power transmission is to heighten the efficiency.

3. Applications in universal communication

Two-dimensional communication provides an alternative other than wirings and wirelesses. The application ranges from traditional connection of LAN, RFID tag, and computer peripherals, to new ubiquitous connection that was impossible by wirings and wirelesses.

If we can embed the 2DST sheet on the surface of the room, 2DST provides more efficient signal

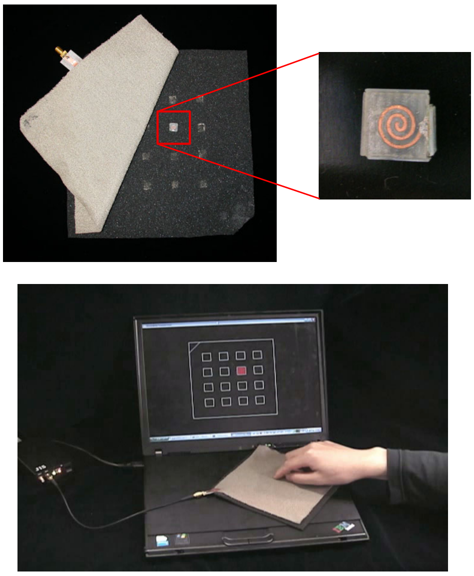


Fig. 5. Stretchable sensor skin using connection type (a) in Fig. 1 [10]. The outer radius of the spiral electrode (proximity connector) on the sensing chip is 4 mm for 2.4 GHz operation.

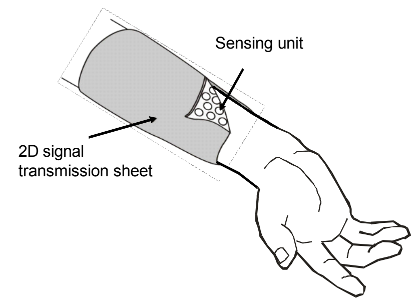


Fig. 6. Wristband device to measure myoelectric potential pattern [8].

transmission than usual radio. The communication is more secure against information leak. Intuitive access control by desk is also possible. We can read passive RFID tags (typically 2.4 GHz in the current technology) stably on a large area of sheet. The challenge resides in promoting the business to embed the 2DST sheet on the floors, walls, and desks.

Since sub-watt power can be sent to each node, a large number of sensors and computers with human interfaces can work. If passive RFID tags attached to the products put on a sheet have visual and audio interfaces like LEDs and buzzers, for example, we can easily find out what we want even if many kinds of products are put on the sheet disorderly. The room-size equipment of temperature sensors on the wall and pressure sensors on the floor is the primitive step of sensor embedding applications.

An important aspect of 2DST is that it enables us to construct high density sensor network on an elastic and stretchable materials. In the traditional technologies, the electronic components are integrated on a rigid plate. Although bendable films are available as the substrate, it is difficult to mount them on stretchable materials. In 2DST, each node works without electrical contact to the sheet. The proximity connection allows displacement of the sensor chip in 2DST sheet, which provides the functional sheet with toughness keeping the elasticity.

As an application of elastic sensor integration, a flexible device measuring myoelectric potential patterns has been proposed. EMG had been used in some special situations that rationalize wearing bulky devices. The device proposed in [8] enables EMG to be used for human interfaces in daily lives. A thin device that can be worn comfortably as shown in Fig. 6 tells the forces of fingers preceding the real motion, with the hand free [8]. Pressure sensors on a seat and acoustic devices on a curtain are also interesting examples realized by 2DST technology.

The current challenge in 2DST technology is to establish the standard of protocols that includes node location identification, powering, and multi-hop routing. Such standardized communication chips will further enhance the applications.

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