Two-Dimensional Signal Transmission for Networked Sensing

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Abstract

We propose a new signal transmission method named "Two-Dimensional Signal Transmission (2DST)" for connecting a large number of devices, using microwave propagation localized in a thin two-dimensional sheet. In this method, we can use a wide range of materials for the communication sheet, and realize flexible connection among many devices by high-speed signal transmission. In this paper, first we analyze two dimensional propagation of electromagnetic wave in a thin layer. We show there exists a traveling mode between two conductive layers. We examine the signal transmission experimentally and confirm communication through conductive clothes based on IEEE 802.11b.

Keywords: Two-Dimensional Signal Transmission, Networked Sensing, Microwave, Wireless

1. Introduction

Today, the advancement in device technology has made huge sensor networks possible, and there are a lot of researches that uses many distributed sensors. The Intelligent Space [1] and The Robotic Room [2] are focusing on recognition of human or robot behaviors and support people by the actuators set in the space. These approaches are expected to have a broad range of applications in home, hospital and factory. Now, one research issue in networked sensing is how to connect these many devices physically.

Conventionally, we have two categories of communication to connect these devices; one-dimensional signal transmission (1DST) and three-dimensional signal transmission (3DST). 1DST means connecting devices by wires or optical fiber cables, and 3DST means connection by radio, light, or sometimes sound waves. When we use huge number of devices, 1DST requires many wires that lack flexibility. On the other hand, 3DST does not require wiring, but it is inefficient in energy and the leaks of unnecessary electromagnetic radiation wreaks the negative effect on surrounding equipments or the risk of interception of radio transmission. In addition, it does require wire connections for power transmission. Walls and impediments in the space that reflect the wave cause the multi-path problem, which results in signal distortion and limits communication capacity. These issues become more harmful as the scale of the sensor network increase.

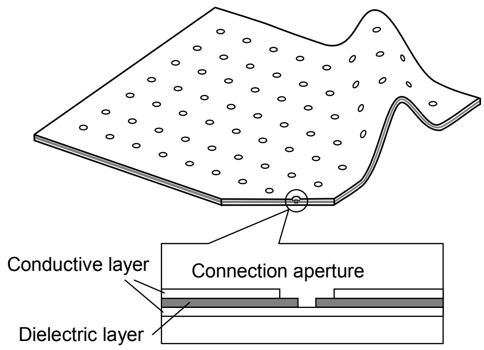


Fig.1: Schematic illustration of the 2DST sheet. The sheet consists of three layers. Two conductive layers are set to sandwich a dielectric layer.

To solve these issues, we have aimed to develop a new method of signal transmission that combines merits of 1DST and 3DST, which can connect a large number of devices flexibly without unnecessary electromagnetic radiation. In a previous paper [3], we proposed "Two-Dimensional Communication" as the solution. In this paper, we propose a new type of two-dimensional signal transmission in which signals are conveyed by microwave propagation localized within a two-dimensional signal transmission (2DST) sheet (Fig. 1).

A 2DST sheet can be made of flexible materials such as fabric, which suggests that 2DST sheets can actualize flexible and wearable sensor networks on clothes. A communication device generates high-frequency (more than 1 GHz) current in these conductive layers, and then microwaves are emitted and propagate concentrically.

An optical fiber cable can realize a large throughput, and wireless LAN enables connection among multiple devices with the highest freedom of device locations. 2DST has an intermediate property between 1DST and 3DST; it enables flexible connection and high-speed signal transmission simultaneously. The merits are summarized as follows.

(A) Wireless flexible connection

If 2DST sheets are implemented on the table, wall, floor or ceiling, we can connect many devices just attaching them on the 2DST sheets. In addition, applying voltage between two conductive layers, we can transmit the power to the devices without wiring.

(B) Realizing a soft communication sheet

Conventionally, it is difficult to wire between many devices on a soft material with keeping softness. On the other hand, the 2DST sheet can be made of soft materials such as rubber and fabric. Therefore, it will be possible to construct sensor networks on fabric and cover any shape by the sheet; it is expected to be applied to wearable computer and robot skin.

(C) No leak of electromagnetic radiation

The microwave propagates only in the communication sheet because the conductive layers prevent it from getting out. Therefore, 2DST can be used in the space where is very sensitive to effect of the electromagnetic radiation, such as in hospital. In addition, it provides secure communication. No leak means no risk of radio interception. Since the emitting area of microwave is restricted in the two-dimensional layers, the amount of energy for signal transmission is lower than 3DST case.

(D) Higher signal transmission speed than three-dimensional transmission

Wave reflection is one of the most serious issues on wireless network. It causes signal distortion and disturbs high-speed transmission. In a 10 m square room, for example, the dispersion of wave-arrival times extends to about 10 ns and it is hard to improve transmission speed over 100 Mbps (=1bit/10ns).

In 2DST, we found that it can be prevented by inserting wave absorber at the edge of the sheet. Therefore the multi-path problem is avoidable and the higher-limit of transmission speed is expected to be easily raised.

2. Principles

2.1. Electromagnetic traveling-mode

In this section, first we show an electromagnetic traveling mode for 2DST between two conductive layers. Fig.1 shows the configuration of a communication sheet. An electromagnetic wave propagates within the dielectric layer by impressing alternate current along the conductive layers. In order to impress the current along the two conductive layers, consider hypothetical apertures with the radius r_0 in the infinite conductive layers as shown in Fig.2. High-frequency currents are symmetrically applied through the hole.

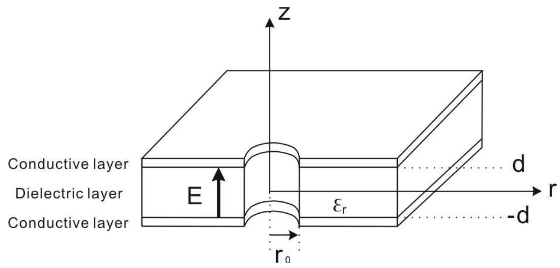


Fig.2: Coordination system for analysis of the microwave in the 2DST layers.

Under this condition, the electromagnetic traveling mode is given below where $B(r,z)$ is magnetic field in the layers and $I(r)$ is current in the conductive layer.

$$\begin{pmatrix} B(r,z)[z>d] \\ B(r,z)[z<d] \\ I(r)/2\pi r \end{pmatrix} = B_0 H_1^{(2)}(rk) \begin{pmatrix} \exp\{\lambda(z-d)\} \\ 1 \\ 1/\mu \end{pmatrix} \exp(j\omega t) \tag{1}$$

Here $H_1^{(2)}$ is the Hankel function as

$$H_1^{(2)}(x) \equiv J_1(x) - jN_1(x) \tag{2}$$

The wave number k in the dielectric layer is given with angular frequency ω and the light speed in the dielectric layer c_r as

$$\mathrm{Re}[k] \sim \frac{\omega}{c_r} \qquad (c_r = c/\sqrt{\varepsilon_r}) \tag{3}$$

The imaginary part of k means the reciprocal of attenuation distance of the electromagnetic wave along the sheet surface. Using the conductivity σ of the conductive layers, it is written as

$$\mathrm{Im}[k] \sim \frac{1}{d}\sqrt{\frac{\varepsilon_r \omega}{8\sigma}} \tag{4}$$

The impressed current only lies near the surface of the conductive layers. Its depth (skin depth) is given as a reciprocal of the real part of λ where

$$\mathrm{Re}[\lambda] \sim -\sqrt{\frac{\mu\sigma\omega}{2}} \tag{5}$$

According to this analysis, there exists an electromagnetic traveling-wave mode between the two conductive layers. When the resistivity is as low as metal resistivity, the attenuate distance for d = 1 mm and ε_r = 2e10 F/m is about 25 m when the current is at 10 GHz, which proves that 2DST have large transmission range enaugh to available for sensor networks in a room or inside a building.

It also presents that we can prevent the electromagnetic radiation from leaking out of the layer by keeping the thickness of the conductive layer more than 10μm, thus the microwave is really localized between the two conductive layers and hardly leaks out of the communication sheet.

2.2. Signal distortion in 2DST

One of the most remarkable advantages of 2DST over 3DST is avoidance of the multi-pass problem that causes signal distortion and loss of the communication capacity. Our next interest is the inevitable signal distortion in 2DST.

Under the coordination system in Fig. 2, the inter-layer voltage $V(r)$ at the distance r from the signal source for input current $I(r_o)$ at the connection aperture is given as

$$\begin{aligned} V(r) &\approx \frac{d\mu\omega}{\pi}\frac{-1}{jkr_0}\frac{H_0^{(2)}(kr)}{H_1^{(2)}(kr_o)}I(r_o) \\ &= -\frac{\mu c d}{j\pi r_0}\frac{H_0^{(2)}(r\omega/c)}{H_1^{(2)}(r_o\omega/c)}I(r_o) \\ &\equiv H(\omega, r_o, r)I(r_o) \end{aligned} \tag{6}$$

When $x = r_0\omega/c << 1$, $H_1^{(2)}$ is approximately written as

$$H_1^{(2)}(kr_o) = \frac{x}{2} + j\frac{2}{\pi x} \tag{7}$$

and when $x = r\,\omega/c >> 1$, $H_0^{(2)}$ is approximated as

$$H_0^{(2)}(x_o) = \sqrt{\frac{2}{\pi x}}\exp(-j(x - \pi/4)) \tag{8}$$

therefore, when $r_0\omega/c << 1 << r\,\omega/c$, $V(r,\omega)$ is given as

$$V(r,\omega) \approx \mu d\sqrt{\frac{c\omega}{2\pi r}}\exp(-j(r\omega/c - \pi/4)I(r_0,\omega) \tag{9}$$

Eq.(9) shows that the radius of the connection aperture r_0 is not effective to the function between I and V. Fig.3 shows an example of signal transmission. This figure shows that the shape of the signal is distorted, but the localization property of the signal from input to output is kept well. It means that the throughput in 2DST can be easily heightened to a comparable value to the signal frequency.

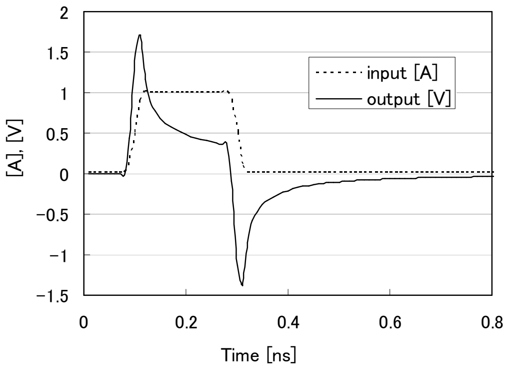


Fig.3: Distortion of the detected signal voltage $V(t)$ for an input signal current $I(t)$, where d = 1 mm, and r = 1 m.

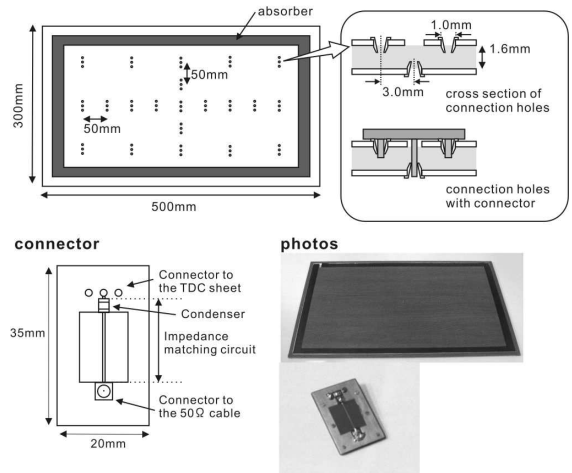


Fig.4: Prototype of 2DST sheet. The conductive layers are made of cupper and the dielectric layer is made of glass epoxy. Radio absorber is attached at the edge of this sheet. An impedance-matching-unit is mounted on the connector.

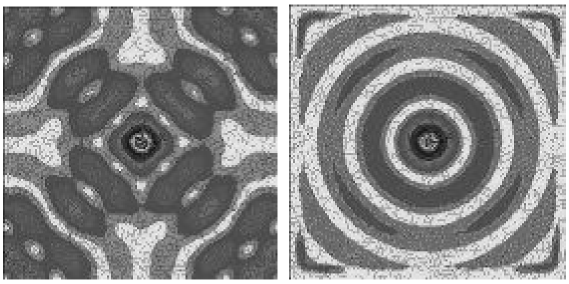
3. Prototype

3.1. Power transmission

We fabricated a prototype 2DST sheet (Fig.4). There exists small holes to connect the communication devices and the alternative current is impressed and received from the holes. The radio absorber obviates wave reflection and leak of the microwave (Fig.5).

We also experimented on energy transmission on the prototype communication sheet. Fig.6 shows that the transmission rate in the prototype was about 5% of the theoretical limit which the theoretical analysis tells. (The details of the calculation are omitted in this paper.) The propagation tendency agreed with the theory.

The reflection at the connector caused by the imperfect impedance matching decreased the signal transmission efficiency in this experiment.



(a) (b)

Fig.5. Simulation results. Top view of the electric field distributions in the 2DST sheet without an absorber (a) and with an absorber (b).

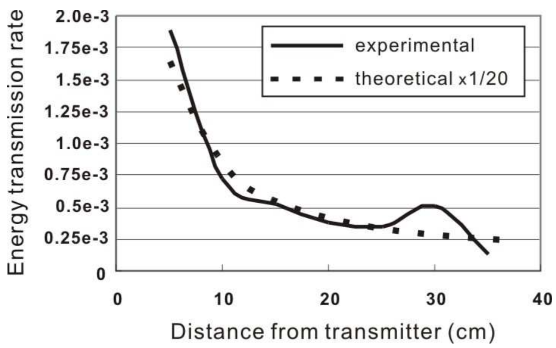


Fig.6. Signal transmission rate of the prototype measured by distance from the transmitter device. Note that the dot-line is 5% of the theoretical limit.

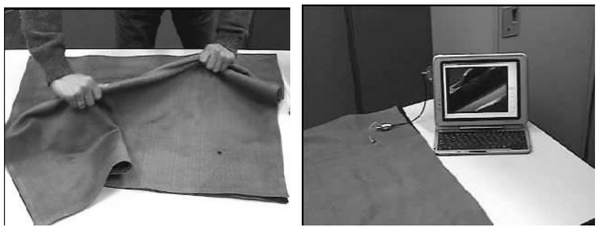
3.2. Feasibility of 2DST cloths

We fabricated a soft 2DST sheet with conductive fabric (Fig.8 (a)). We connected two PCs to the "2DST cloth" from wireless LAN port (Fig.8 (b)). The antennas of these wireless LAN ports were invalided and we confirmed that these PCs can communicate only through the 2DST cloth. Even when we stretched the cloth, the communication kept stable. When we took off the connecter from the PC, the communication was stopped immediately. This results present that this 2DST method could connect two communication devices.

4. Summary

In this paper, we proposed a new signal transmission method named "Two Dimensional Signal Transmission". We analyzed the behavior of microwave in the communication layer, and presented the following features in applying this method to in-room networked sensing.

1) We can connect multiple devices to a 2DST sheet easily by attaching the connectors to the communication layer.
2) A 2DST sheet can keep the microwave inside of the layers.
3) The 2DST method can provide higher-speed signal transmission than 3DST by avoiding the multi-path problem.



(a) (b)

Fig.8. (a) 2DST cloth made of stretchable conductive fabric. (b) PC to PC communication through the 2DST cloth using IEEE 802.11b.

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