Two Dimensional Communication Technology for Networked Sensing System

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Abstract

In this paper we propose a new field of communication technology "Two Dimensional Communication (TDC)." TDC is a communication in which electromagnetic energy is localized in a two dimensional medium and any element connected to the medium can communicate each other without individual wires. Using this method, we can easily allocate a lot of sensors on the two dimensional sheet, and gather data from each node with high throughput. First we show an electromagnetic traveling-wave mode for TDC exists between a couple of conductive layers. Next we present how to realize TDC sheet and show its feasibility for the networked sensing system.

Keywords: *Two Dimensional Communication, Networked Sensing, Wearable Computing, Wireless.*

1. Introduction

Today, we can use minute sensors inexpensively by a technical development in MEMS and other device technologies. There is no doubt that distributing many sensors and gathering their data using network is a new focus of sensing system. A lot of researches about sensor networks are mainly engaged in realizing optimal sensors for networks [1], synchronization [2], node localization [3], communication protocols [4] and practical usages [5].

Another important challenge in networked sensing is how to physically connect a large number of sensor elements to the network. Researchers already have noticed that collecting sensor elements can create new functions of sensing system. However the idea of equipping ten thousands of small sensors on a floor or an elastic cloth has been considered impractical in the available wiring technology and wireless connections. What we propose in this paper is to break through the challenge above, paving the way for a new communication for networked sensing.

The communication technologies, we can use now, are categorized into one-dimensional or three-dimensional communication. One dimensional communication means that signal energy is localized in one dimensional wires, cables or optical fibers. On the other hand, three dimensional communication is wireless communication realized by radio. In some cases, light or sound waves are also available.

When we connect a lot of elements by one dimensional communication, a large number of wires are required and it makes the system complex. Inflexibility or fragility of wires also becomes critical issues for the wearable computer or robot skin where softness is especially required. In contrast, when we use wireless communication, complexity of wiring can be avoided, meanwhile, the problem arises that the signal energy also reaches undesired area. Therefore it is difficult to obtain a large communication capacity and to assure the secure communication. Moreover, even though the communication is wireless, wires or batteries are actually necessary for power supply. These problems can be critical issues for distributing a lot of elements to form a sensor network.

To solve these problems, we propose a new form of communication named two dimensional communication (TDC). TDC here means a communication in which electromagnetic energy is localized in a two dimensional medium, but it has no individual wires. And any element connected with the medium can communicate with any other elements on the sheet.

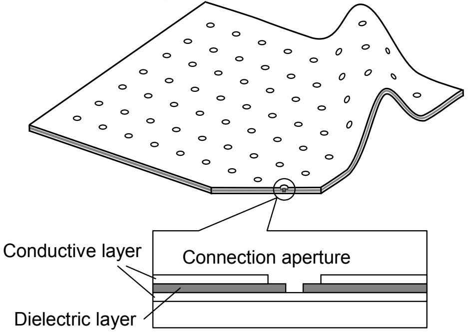


Figure 1 Schematic illustration of a two-dimensional communication sheet.

In a previous paper, we have proposed one configuration of TDC sheet [6]. In that paper, we implanted

INSS2005 June 27-28, 2005, San Diego, California USA, pp. 168-173

many communication LSI chips in a TDC sheet and realized communication by multi-hopping transmission. The signals were transmitted only to the neighboring chips and the designated chip sent the signals to the next neighbors.

In this paper we show another configuration of TDC sheet that needs no communication chips in the sheet. Schematic illustration is shown in Figure 1. The communication is realized by micro waves traveling in the sheet. The features or the new form of TDC are summarized as follows.

1) TDC sheets can be fabricated with various materials including conductive rubber, paint, fabrics, and paper with conductive foil,. Stretchable materials are available. They can be buried into floors, walls or desks.
2) A TDC sheet does not leak the electromagnetic radiation outside of the sheet. This is useful to construct a secure communication environment and also useful to use in a space where we are particularly sensitive to the effect of electromagnetic radiation, such as in a hospital.
3) A TDC sheet provides no-reflection area which allows a communication space free from the multi-path problem. This brings high throughput signal transmission among the elements.
4) High efficiency of electrical power transmission is achieved since the signal is restricted within the sheet. Electrical power is also transmitted by microwave.

The potential applications range from communication infrastructures in buildings and vehicles to wearable computing and artificial skins of robots.

2. Principles

2.1. Propagation mode of TDC

In this section, we show an electromagnetic traveling-mode for TDC between a couple of conductive layers. Figure 1 shows the configuration of a communication sheet. The sheet consists of three layers. Two conductive layers are set to sandwich a dielectric layer. An electromagnetic wave signal propagates within the dielectric layer by impressing alternate current along the conductive layers. In order to impress the current along the two conductive layers, the sheet has connection apertures as shown in the figure. The sheets are composed of infinite conductive and dielectric layers.

For the theoretical analysis, we modeled the TDC sheet as shown in Figure 2 and assumed the following conditions.

1) A feeding point is a circular hole with its radius of r_0 and we impress the alternative current to the upper and lower layers symmetrically.
2) Permeability of both the conductive layers and the dielectric layer is equal to μ. The conductivity σ of the conductive layers is sufficiently large.
3) Thickness of the dielectric layer d is smaller than electromagnetic wave length. Consequently magnetic field in the dielectric layer is approximately uniform along z axis.

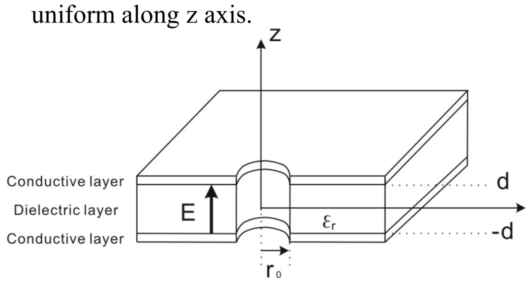


Figure 2 Coordination system for analysis of the microwave in the two dimensional communication layer.

Under these conditions, the following omnidirectional traveling-mode induced in the layer structure satisfies Maxwell's Equations where $B(r,z)$ and $I(r)$ are the z-axis-symmetric magnetic field in the layers and skin current in the conductive layer, respectively.

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

Here $H_1^{(2)}$ is the Hankel function of the second kind.

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

The wave number k in the dielectric layer is given with angular frequency ω and 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 p where

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

This model reveals that there exists electromagnetic traveling wave between the two conductive layers. When the resistivity $1/\sigma$ is as low as metal resistivity $10^{-6}\Omega\cdot\mathrm{cm}$, the attenuate distance for d = 1 mm and ε_r = 2×10^{-11} F/m is about 25 m when we impress the current at 10 GHz.

2.2. Trapping electromagnetic wave

One remarkable parameter is the skin depth in which the current lies (given by eq.(5)). When we use the copper or other well-conductive materials as the conductive layers, the skin depth is about 1.3 μm at 2.4 GHz that is the frequency of wireless LAN standard IEEE802.11b. Therefore the electromagnetic wave is trapped within the TDC sheet when the conductive layer is thicker than the skin depth.

Even though the conductive layer is thinner than the skin depth, the propagating waves are trapped around the sheet when the dielectric constant of the dielectric layer is higher than that of the environment. Since the wave velocity in the layers is smaller than that of environment, the leaked electromagnetic field forms an evanescent wave around the sheet.

The side of the sheet is another possible area of the leakage. However, when we put an absorber (argued in the following sections), signals do not leave out.

Next we examine the leakage from the connection apertures. In order to lessen the leakage from the holes, we propose a structure of the hole configuration as shown in Figure 3. The fringe around the hole acts as a circular wave guide to prevent electromagnetic radiation from the hole. It is well known that the microwave does not travel in a circular wave guide when

$$\lambda > \frac{2\pi r}{1.84} \quad (r\text{: fringe radius}). \tag{6}$$

This advantage is useful to realize secure communication system. It is also useful to use in a place where the electromagnetic wave is particularly harmful like in a hospital.

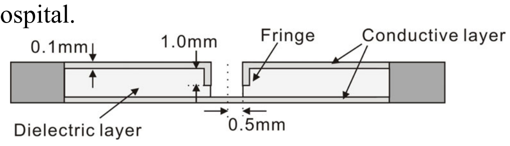


Figure 3 Crosssection of modified connection aperture.

2.3. Sending electrical power

In the case of wireless communication, electrical power propagates three-dimensionally also in unnecessary directions. Therefore, it is hard to supply an electrical power to the communication node by microwave. Each node must have a power line or its own battery.

However, in TDC, electrical power is localized within the sheet which makes the power transmission easy. In this section, we calculate the theoretical limit of power transmission by TDC sheet.

At first, we model the TDC sheet as shown in Figure 4. From a detailed theoretical analysis, the radiation impedance of the communication sheet is given as a serial connection of an inductive reactance jX and a resistance R (a) when $r_0 << \lambda$. The equivalent circuit at the reception node is given as (b).

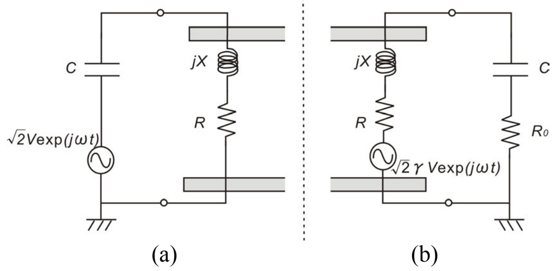


Figure 4 An equivalent electrical circuit of the TDC sheet. (a) is the circuit seen from the impression node toward the communication layer, and (b) is seen from the reception node toward the receiver circuit.

In order to supply the electrical power most effectively from the impression node, we should put capacitance for impedance matching so that $jX = 1/j\omega C$. In this situation, applied electrical power P_s by a voltage source $\sqrt{2}V\exp(j\omega t)$ is given as

$$P_s = \frac{V^2}{R} \tag{7}$$

To maximize the electrical power extracted from the TDC sheet, we have to receive the signal by the capacitance C and resistance $R_0 = R$ as shown in the figure (b).

The equivalent voltage source to a transmitter at a distance r is written as $\gamma V\exp(j\omega t)$ where

$$\gamma = \mathrm{Re}\left[\frac{jkH_0^{(2)}(kr)}{\omega\varepsilon\mu H_1^{(2)}(kr)}\right]|H_1^{(2)}(kr)| \tag{8}$$

Then the maximum received power is given as

$$P_r = \frac{V_a^{\,2}}{R_0} = \frac{\left(\frac{1}{2}\gamma V_o\right)^2}{R_0} = \frac{\left(\gamma V_o\right)^2}{4R_0} \tag{9}$$

The power efficiency

$$T = \frac{P_r}{P_s} = \frac{\gamma^2}{4} \tag{10}$$

is approximated as follows when the distance r is sufficiently larger than the electromagnetic wave length λ.

$$T \approx \frac{c_r}{2\pi\omega r} = \frac{\lambda}{4\pi^2 r} \tag{11}$$

The plots of T are shown in Figure 5. The horizontal axis indicates normalized distance from the source kr

($=2\pi r/\lambda$). When the normalized distance kr is 6, the actual distance is 10 cm for 2.4 GHz micro wave.

The energy absorption by the receiver is schematically understood as Figure 6 shows. An impressed energy Q uniformly propagates in the sheet and electromagnetic energy passing through within an effective width

$$w = \frac{T}{t} = \frac{\lambda}{2\pi} \qquad (12)$$

around the reception node is absorbed. For example, when we use 2.4 GHz signal and relative permittivity of the dielectric layer is 4.8, the effective width w is about 9 mm.

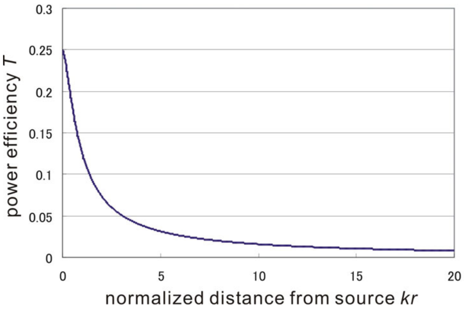


Figure 5 Efficiency of the power transmission.

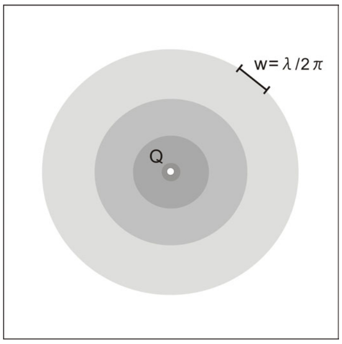


Figure 6 Illustration of effective energy-absorption width w.

2.4. Avoiding boundary reflection

In the case of three-dimensional communication (wireless communication), a multi-path problem is inevitable. Signals are reflected on the walls, floors, and tables and so on, consequently, the signals interfere with each other. That limits the communication capacity. In TDC, we can easily avoid the problem. Since the reflection only occurs on the side of the communication sheet, we can attenuate the signal power by putting appropriate absorbers along the side of the sheet. It is also helpful to lessen the leakage from the side.

Appropriate absorber is determined as the same manner of an impedance matching in one-dimensional cable. The difference from the one dimensional case is that the absorber is set uniformly along the side of the sheet as shown in Figure 7. When we put resistive materials, the appropriate resistivity is given as follows.

$$\rho = \frac{2}{\omega\varepsilon_0\varepsilon_r} \qquad [\Omega\cdot\mathrm{m}] \qquad (13)$$

The width of the absorber a should be larger than the attenuation distance

$$a = \sqrt{\frac{2}{\omega\mu\sigma}} \qquad [\mathrm{m}] \qquad (14)$$

When we impress the current at 2.4 GHz, the electric resistivity ρ is 3.12 $\Omega\cdot\mathrm{m}$ and the attenuation distance is 18 mm, if the relative permittivity is 4.8.

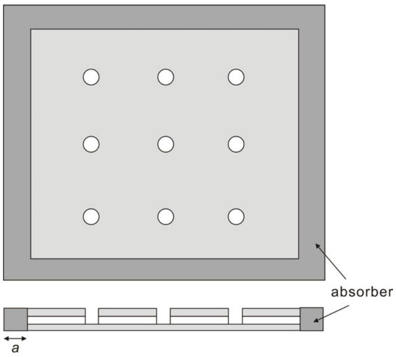


Figure 7 TDC sheet with resistive absorber along the side of it.

3. Simulation analysis

To confirm the above discussions, we carried out simulation analysis using Finite Element Method with ANSYS.

3.1. Leakage from a single aperture

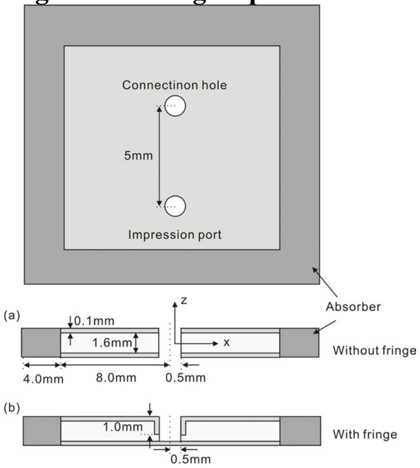
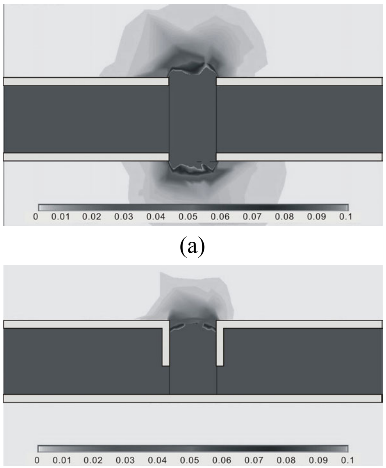


Figure 8 FEM model with a single connection hole (aperture) and an impression port without a fringe (a) and with a fringe (b).

We examined the electromagnetic radiation from a single hole. The 3D model of a TDC sheet is shown in Figure 8. We assumed the signal frequency at 2.4 GHz for simulation. In order to confirm the effect of the fringe around the connection aperture, we simulated electromagnetic field under the two conditions. One has a simple aperture and the other has an aperture with a fringe.

Figure 9 shows the result of the FEM analysis. With fringe, the amplitude at the center of the aperture 1.0 mm distant from the surface is attenuated to be -70 dB of midpoint of the connection aperture, while it is -56 dB without fringe.



(a)

(b)

Figure 9 Cross sectional illustrate of electric field nearby the TDC sheet. Given amplitude of the impression point is 1.

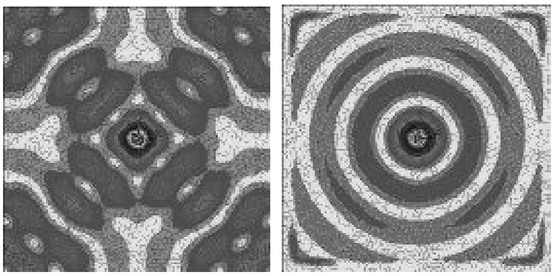
3.2. Effects of absorber

Next, we confirmed the effect of the absorber along the side of the sheet. In this simulation the sheet has no connection apertures. Figure 10 shows the top view of the electric fields in the TDC sheet. Figure (a) for the case without the absorber reveals standing waves by the boundary reflection. In contrast, Figure 10 (b) shows the electric fields for the case with a 20 mm width absorber whose resistivity ρ is 3.12 $\Omega \cdot \mathrm{m}$. It is obvious that the reflection does not occur with an appropriate absorber which provides a communication space free from the multi-path problem.

4. Prototype

4.1. Measurement of power transmission

Based on the theories, we fabricated a prototype TDC sheet as shown in Figure 11. There are small holes to impress/receive the alternative current. The black band around the edge is a resistive rubber as an absorber.



(a) (b)

Figure 10 Top view of the electric field distributions in the TDC sheet without an absorber (a) and with an absorber (b).

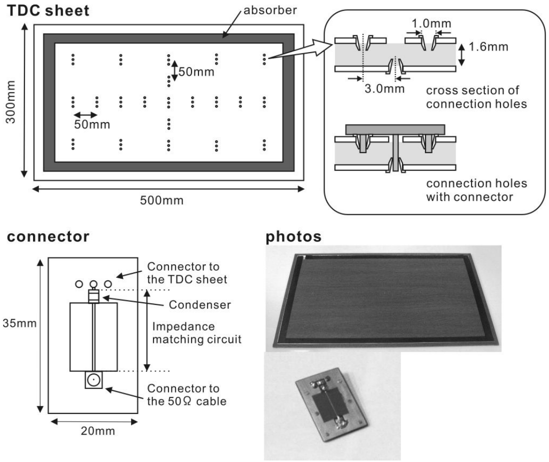


Figure 11 Prototype of TDC sheet and the impedance matching unit in the connector

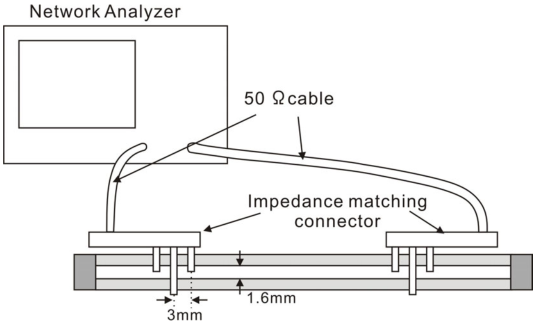


Figure 12 Schematic illustration of evaluation system for power transmission measurement.

The evaluation system is shown in Figure 12. A 50 Ω cable from a network analyzer is connected to the TDC sheet through a λ/4 impedance matcher of a microstrip line. The received signal was measured through the same connector and cable by the network analyzer.

We measured the efficiency of the power transmission through the sheet by changing the distance between the two nodes. Figure 13 shows the results of the measurement. The horizontal axis shows the node distance, and the vertical axis indicates the efficiency.

Note that the break line plotted in the figure show 1/20 of the theoretical values so that the plots fit the experimental results shown with the solid line. The efficiency of the power transmission of the prototype sheet was 5% of the theoretical limit.

The reason for the low efficiency is that the impedance matching by the connector was not perfect. The tendency of the propagation agreed with the theoretical curve.

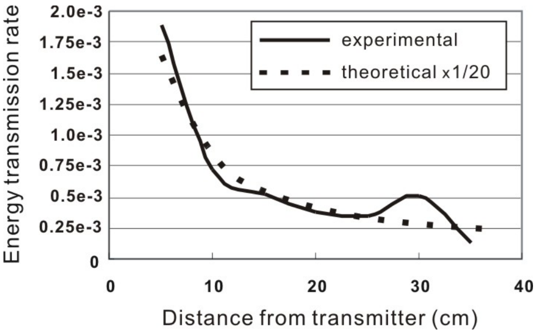
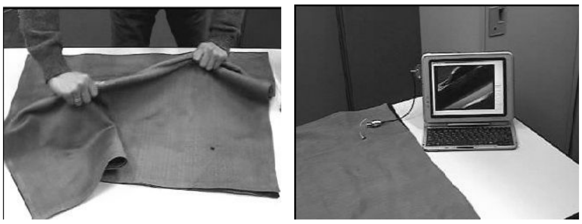


Figure 13 Efficiency curve of the prototype TDC sheet.

4.2. Communication between two PCs with TDC cloths

We fabricated TDC cloths with stretchable conductive fabrics as shown in Figure 14 (a). Two PCs were connected to the TDC sheet through 50 Ω cables from extendable wireless LAN antenna ports (Figure 14(b)). (One of the two PCs is out of the picture.) Communication between two PCs was realized by IEEE 802.11b protocol.

As the demonstration in figure (b) shows, we realized stable communication through this sheet. The throughput between two PCs was 11 Mbps which is the limit of the protocol. Even when we stretched the sheet like figure (a), the communication was stably kept. When we took the connector off from the sheet, the communication was stopped. The result proved that electromagnetic wave traveling in the TDC cloth could connect the two PCs.



(a) (b)

Figure 14 (a) TDC cloth made of stretchable conductive fabric. (b) PC to PC communication through the TDC cloth using IEEE 802.11b protocol.

5. Summary

In this paper we proposed a new communication form named “Two Dimensional Communication.” We showed an electromagnetic traveling-mode for TDC exists between a couple of conductive layers. TDC has the following features.

1) A TDC sheet traps signals around the sheet with small leakage of electromagnetic wave. TDC is useful to construct secure communication and to use in a space like a hospital where the electromagnetic wave is harmful.
2) Multi-path problem is avoidable since it is easy to reduce the reflection at the edge of a TDC sheet by attaching absorbers.
3) High efficiency of electrical power transmission is achieved since the signals are constrained within the sheet. It implies the possibility for electrical power supply by microwave.

We confirmed these advantages through simulation analysis and a prototype TDC sheet. The results indicate that high throughput communication can be realized by TDC sheet with no wires. The TDC sheet enables us to distribute many sensor elements and to gather data from each node at a high throughput.

Acknowledgements

We thank Yuichi Kasahara, a former student who conducted analysis on his graduation thesis to yield foundation of this research. Also our gratitude goes to Naoya Asamura, Cellcross Co., ltd. for his cooperation on fabricating the prototype and providing ideas on device structures and their applications.

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