

Sensor Networking Using Two-Dimensional Electromagnetic Wave

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In this paper, we propose a new technology for sensor networks named “Two Dimensional Communication (TDC).” TDC is communication in which electromagnetic wave propagates within a two dimensional medium and communication is realized between the nodes which are connected to the TDC sheet. In TDC, a large number of communication nodes can connect with each other with no individual wires, while TDC has advantages over wireless communication; (1) it is free from harmful electromagnetic wave radiation, (2) the waste of the energy for signal transmission is smaller, and (3) electrical power is also provided by electromagnetic wave in the sheet. These advantages are useful to construct sensor network. In this paper, we show how to construct a TDC sheet and fundamental experimental results for evaluating the TDC sheet performance.

Keywords : sensor network, two-dimensional communication, wireless, wearable computing

1. Introduction

Recently, “sensor network” becomes a more important field because of technical development in fabricating minute sensors by MEMS. Distributing a lot of sensors and gathering their data from each of them will open an epoch of sensing systems. A lot of researches on sensor networks have already been reported related to optimal sensors for networks [1], synchronization of nodes [2], node localization [3], communication protocols [4] and practical usages [5] mainly based on wireless communication.

In this paper we engage in another challenging issue in sensor networks. The challenge is how to physically connect a lot of sensing elements to the network. Researchers already have noticed that collecting the data from each sensor element 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 present wiring technology and wireless connections. We propose a new way of communication named “Two-Dimensional Communication” to break through the problem.

The communication technologies available today are categorized into two types by their physical forms. One is “one-dimensional communication” in which the signal energy is localized in one dimensional media such as cables, or optical fibers. A serious problem in the one dimensional communication is that the number of required wires expands when the elements increase. Even when we manage to connect the elements with conventional wiring technology, we frequently confront a problem that the physical flexibility of the device is impaired because of the inflexibility or fragility of the wires. Flexibility is an important factor for realizing wearable computers or robot skins.

The other type of the conventional communication is “three-dimensional communication” by wireless radio communication. In some cases, light or sound waves are the alternatives. Recently, wireless communication becomes popular in such as mobile phone, wireless LAN, Bluetooth and so on. One of the

problems in using it for sensor networks is that the allowed bandwidth is narrow. As a result, the number of connectable nodes and the throughput are limited. Another problem is that the signal energy propagates to undesired area. This issue causes wastes of energy and interferences of communication. Since intense electromagnetic wave is harmful to people, wireless power supply to the sensor nodes is difficult, which results in that the communication elements require wires or batteries for power supply. These problems in both one and three dimensional communications are often critical for sensor networks.

In this paper, we propose a new way of communication named “Two Dimensional Communication (TDC)” as a solution for these problems. The TDC means that the signal energy is localized in a two dimensional sheet. The communication is realized between the nodes on the TDC sheet without individual wires.

The features of TDC are summarized as follows.

- 1) TDC sheet can be fabricated by various conductive materials such as conductive films, foils, and fabrics. Therefore stretchable and foldaway communication sheet is realized. They can be buried into floors, walls, desks or curtains at low costs.
- 2) The waste of energy for communication is small compared with the case of 3D communication since the electromagnetic energy is confined in the TDC sheet.
- 3) Electrical power is also transmitted to the sensor nodes by microwaves safely since the wave does not reach people being outside of the sheet. Efficiency of the electrical power transmission is practically acceptable in many cases.
- 4) A TDC sheet does not leak the electromagnetic radiation outside of the sheet. This is useful to construct secure communication environment. It is also available where the electromagnetic radiation is harmful such as in a hospital.
- 5) Wide frequency band is available. In the TDC sheet, we can use wide band of electromagnetic wave since the communication in it is free from Radio Law.
- 6) A TDC sheet provides a no-reflection communication space free from the multi-path problem. This brings high throughput signal transmission among the nodes.

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In section 2, we show one configuration of a TDC sheet and the principle of signal transmission. Then we show theoretical and simulation analyses of TDC sheet in section 3 that have already described in [6] partly. In section 4, a prototype system of a TDC sheet is presented and new experimental results are reported.

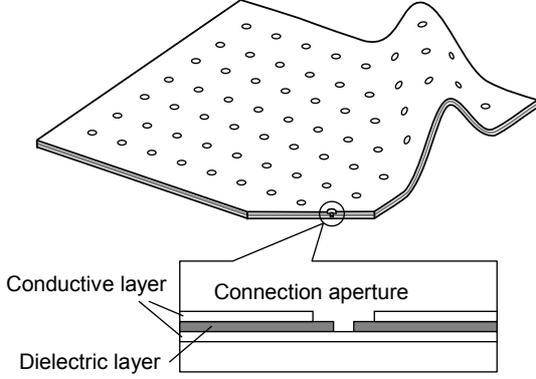


Figure 1 Schematic illustration of TDC sheet.

2. Electromagnetic Wave in TDC Sheet

In our former paper [7], we have proposed one configuration of a kind of TDC sheet. In the paper, we put many LSI chips for multi-hopping signal transmission. The signals reached only to the neighboring chips and the designated chip sent the signals to the next neighbor. In this paper, we show another realization of TDC sheet.

Figure 1 shows the schematic illustration of the TDC sheet. The sheet consists of three layers. Two conductive layers are set to sandwich a dielectric layer. The sheet has connection apertures for inputting and receiving signals. When an alternate current along the conductive layers are impressed, there exists a propagation mode of the electromagnetic wave signal within the dielectric layer, which enables communication. In the following analyses, we theoretically derive the propagation mode of the TDC sheet.

We model the TDC sheet as shown in Figure 2 and assume the following conditions.

- 1) The sheet extends infinitely.
- 2) The feeding point is a circular hole with a radius of r_0 and we impress the alternate current to the upper and lower conductive layers symmetrically.
- 3) The permeability of both the conductive layers and the dielectric layer is equal to μ . The conductivity σ of the conductive layers is sufficiently large.
- 4) The thickness of the dielectric layer $2d$ is smaller than electromagnetic wave length. Consequently magnetic field in the dielectric layer is approximately uniform along z axis.

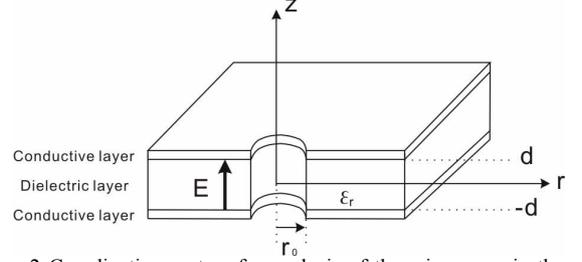


Figure 2 Coordination system for analysis of the microwave in the two dimensional communication layer.

Under these conditions, the following omnidirectional traveling-mode 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.

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

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

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

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

$$\text{Re}[k] \sim \frac{\omega}{c_r} \quad (c_r = c/\sqrt{\epsilon_r}) \quad (3)$$

The imaginary part of k is equal to 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

$$\text{Im}[k] \sim \frac{1}{d} \sqrt{\frac{\epsilon_r \omega}{8\sigma}} \quad (4)$$

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

$$\text{Re}[p] \sim -\sqrt{\frac{\mu\sigma\omega}{2}} \quad (5)$$

When the resistivity $1/\sigma$ is as low as metal resistivity $10^{-6} \Omega \cdot \text{cm}$, the attenuate distance for $d = 1 \text{ mm}$ and $\epsilon_r = 2 \times 10^{-11} \text{ F/m}$ is about 27 m when we impress the current at 10 GHz.

3. Theoretical Examinations on TDC

3.1 Trapping Electromagnetic Energy One of the advantages of the TDC sheet is that the sheet does not leak the electromagnetic energy to the environment. However, you may think it might be incorrect since the sheet has the connection apertures on the surface of it. Quantitative evaluation of the leakage from the aperture is an important issue.

First, we have to notice that the leaked electromagnetic wave forms evanescent wave when we array the connection apertures periodically with their intervals smaller than the wave length of the signal in the case that the wavelength in the TDC sheet is smaller than that of the air. That means the energy of the signal decreases exponentially with the distance from the surface of the sheet with no radiation to the far field.

The second important property is that a single hole in the TDC

sheet structure can radiate little electromagnetic energy.

Figure 3 shows the 3D Finite Element Method (FEM) model for simulation analysis. We assumed the signal frequency at 2.4 GHz. The absorber which is composed of resistive materials is located at the side of the sheet to reduce the reflection.

The result shows that the amplitude at the center of the aperture 1.0 mm distant from the surface is attenuated to be -56 dB of the amplitude at the midpoint of the sheet.

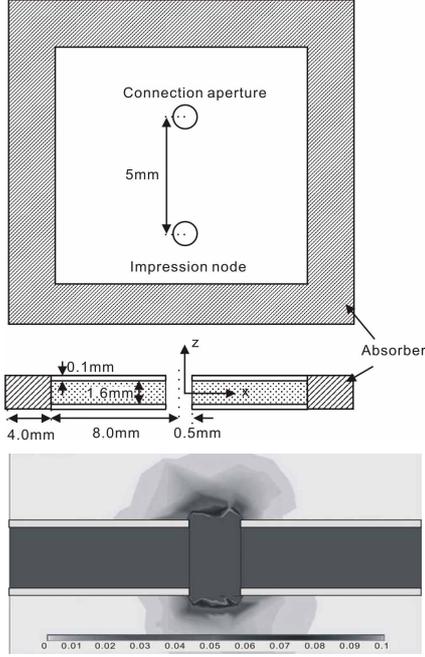


Figure 3 Cross sectional illustration of the FEM result. Amplitude of electric field near the connection aperture on the TDC sheet. Given amplitude of the impression point is 1.

Even when the leakage is still critical issue, there is another solution. The solution is putting the fringe structure at the connection aperture as shown in Figure 4. The fringe works like a circular wave guide. It is well known that the microwave does not travel in a circular wave guide when the wave length λ satisfies the following inequality

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

Our FEM analysis supported this theory. Figure 4 shows the result with fringe. The amplitude at the center of the aperture 1.0 mm distant from the surface is attenuated to be -70 dB of the amplitude at the midpoint of the sheet.

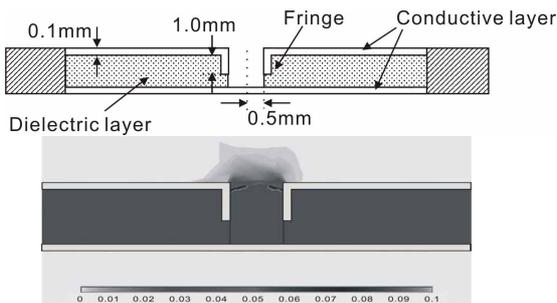


Figure 4 FEM analysis on a connection aperture with a fringe.

3.2 Electrical Power Transmission In the case of ordinary wireless communication, electrical power of the signal propagates three-dimensionally. That means the energy density decreases inversely proportional to the second power of the distance from the source (impression node), which makes it hard to supply an electrical power to the communication node by microwave.

However, in the TDC system, the energy is localized within a two dimensional medium. As a result, the energy density decreases inversely proportional to the first order of the distance from the impression node. This advantage enables us to send electrical power more easily. In this section, we calculate the theoretical limit of power transmission by TDC sheet. Another important factor we should not miss is that we are allowed to send intense electromagnetic waves in the TDC sheet, since people are not exposed to the radiation.

At first, we consider the radiation impedance seen from the impression node. This also can be calculated based on the Maxwell's equations as

$$Z = \frac{d\mu\omega}{\pi} P(kr_0), \quad (7)$$

where r_0 is the radius of the connection aperture. Figure 5 shows the real and imaginary part of the $P(kr_0)$ as the function of non-dimensional parameter kr_0 . The size of the aperture affects the radiation impedance. We find that the real part converges to $\pi/2$ around $kr_0 = 0$ and that the reactance is inductive for small kr_0 .

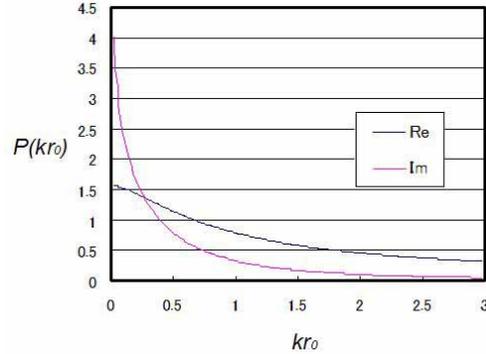


Figure 5 Real part and imaginary part of the function $P(kr_0)$

As a result, the TDC sheet can be modeled as shown in Figure 6. The radiation impedance of the communication sheet is given as a serial connection of an inductive reactance jX and a resistance R when $r_0 \ll \lambda$ as shown in Figure 6 (a).

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

$$P_s = \frac{V^2}{R} \quad (8)$$

Similarly, the equivalent circuit at the reception node is given as Figure 6 (b). To maximize the electrical power extracted from the TDC sheet, we have to receive the signal with the capacitance C and resistance $R_0 = R$ as shown in the figure (b).

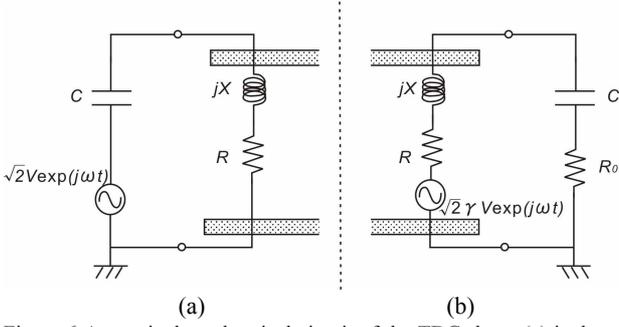


Figure 6 An equivalent electrical circuit of the TDC sheet. (a) is the equivalent circuit seen from the impression node toward the communication layer, and (b) is seen from the reception node toward the receiver circuit.

The equivalent voltage source to the TDC sheet at a distance r from the impression node is written as $\mathcal{N} \exp(j\alpha r)$ where

$$\gamma = \text{Re} \left[\frac{jkH_0^{(2)}(kr)}{\omega\epsilon\mu H_1^{(2)}(kr)} \right] |H_1^{(2)}(kr)| \quad (9)$$

Then the maximum received power is given as

$$P_r = \frac{V_a^2}{R_0} = \frac{(\frac{1}{2}\gamma V_o)^2}{R_0} = \frac{(\gamma V_o)^2}{4R_0} \quad (10)$$

Finally, the power efficiency is written as

$$T = \frac{P_r}{P_s} = \frac{\gamma^2}{4} \quad (11)$$

The plots of T are shown in Figure 7. The horizontal axis indicates normalized distance from the source kr ($=2\pi r/\lambda$). When the normalized distance kr is 2π , the actual distance is 12.5 cm for 2.4 GHz micro wave in a medium of $\epsilon_r = 1$.

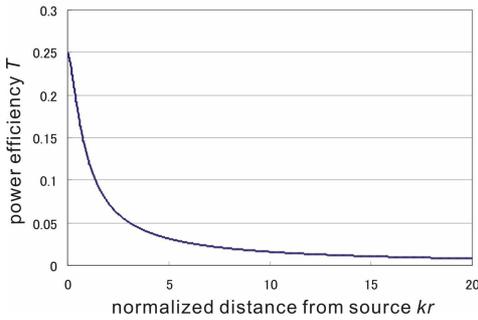


Figure 7 Efficiency of the power transmission.

When the distance r is sufficiently larger than the electromagnetic wave length λ , the power efficiency is approximated as follows.

$$T \approx \frac{c_r}{2\pi\omega r} = \frac{\lambda}{4\pi^2 r} \quad (12)$$

This equation reveals that the received power decreases in inverse proportion to the first power of the distance from the impression node.

The energy absorption by the receiver is schematically understood as Figure 8 shows. An impressed energy uniformly propagates in the sheet and electromagnetic energy passing through the

line segment of the effective width

$$w = \frac{T}{t} = \frac{\lambda}{4\pi^2 r} \bigg/ \frac{1}{2\pi r} = \frac{\lambda}{2\pi} \quad (13)$$

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.

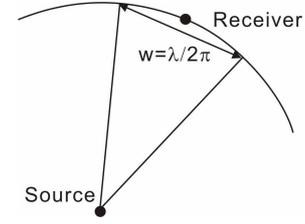


Figure 8 Illustration of effective energy-absorption width w .

4. Prototype System

4.1 Settings Figure 9 shows the prototype TDC system. There are small holes to impress/receive the alternating current. The black band around the edge is a resistive rubber as an absorber so that the sheet is seen as infinite. The connector contains an appropriate capacitance and a $\lambda/4$ impedance matcher by a microstrip line for impedance matching at 2.4 GHz.

The evaluation system is shown in Figure 10. A 50Ω cable from a network analyzer is connected to the TDC sheet through the connector. The received signal was measured through the same connector and cable by the network analyzer.

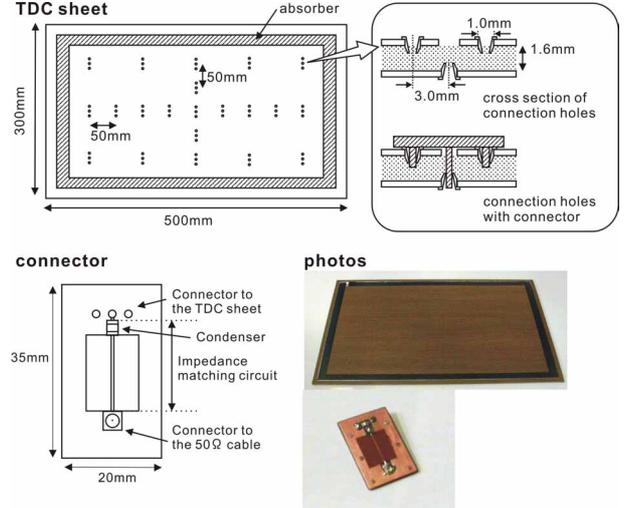


Figure 9 Prototype of TDC sheet and the impedance matching unit in the connector

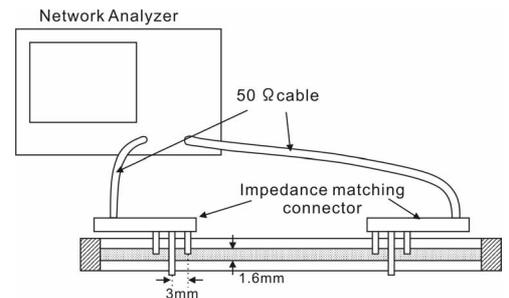


Figure 10 Schematic illustration of evaluation system for power transmission measurement.

Figure 11 shows the effect of the impedance matcher on the connector. Figure 11 (a) shows the reflection coefficient at the impression node. At 2.4 GHz, the impedance matching occurs. It is seen that 10 % of the supplied power was reflected in the prototype system. Figure 11 (b) shows the transmittance between two nodes 5 cm apart. The plot shows the detected amplitude [V] by the network analyzer for the 1 [V] input amplitude at each frequency. At 2.4 GHz, strong peak is seen. The peak value is a quarter of the theoretical value. It is considered that the energy loss occurred at the impedance matching connectors.

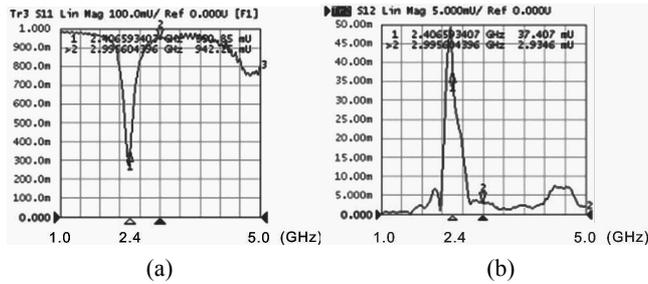


Figure 11 (a) The reflection coefficient at the impression node. (b) The transmittance between two nodes 5 cm apart. The plot shows the detected amplitude [V] at the network analyzer at each frequency for the 1 [V] input amplitude at each frequency.

4.2 Evaluation of Power Transmission Efficiency We measured the efficiency of the power transmission through the sheet by changing the distance between the two nodes. Figure 12 shows the results of the measurement. The horizontal axis shows the distance from the source, and the vertical axis indicates the power efficiency. Note that the theoretical curve (shown with the solid line) shows 20 times smaller values than the actual theoretical values so that the plots fit the experimental results (shown with the diamonds). The efficiency of the power transmission of the prototype sheet was 5% of the theoretical limit. However, the tendency of the propagation is agreed with the theoretical curve.

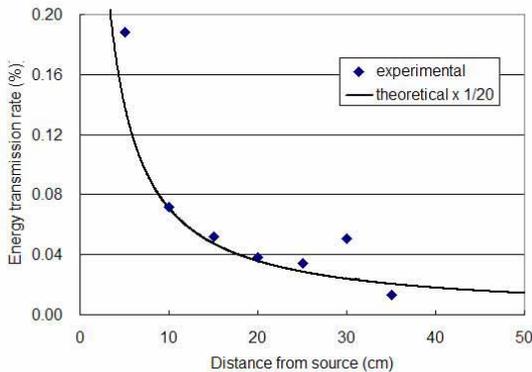


Figure 12 Experimental results of the power efficiency rate of the prototype TDC sheet with absorber.

4.3 Attenuation of the signal The former result illustrates the propagation tendency near the impression node. In this section, we examine the propagation distance in the TDC sheet. In a practical system, the dielectric loss and the low conductivity of the conductive layer can be factors for the signal attenuation.

We made two different types of TDC sheets. One system (Polyvinyl TDC Sheet) had a soft polyvinyl chloride layer with the relative permittivity 4.7 for the dielectric layer and the other one

(Paper TDC Sheet) had a paper layer with the relative permittivity 2.0. The size of Polyvinyl TDC Sheet was 3370mm x 430mm and the interval of the connection aperture was 300 mm. On the other hand, the size of Paper TDC sheet was 1550mm x 730mm and the connection aperture interval was 100 mm. The diameter of the connection aperture was 13 mm and the thickness of the dielectric layer was 0.5 mm in both the sheets (Figure 13). Conductive thin foils were glued onto the both surface as the conductive layer. There were no absorbers at the edge of the sheets.

We measured the received signal power through the sheets changing the distance between the two nodes. The evaluation system is shown in Figure 13. An extensional antenna port of the wireless LAN PC-card (IEEE 802.11.b protocol, 2.4 GHz) was used as an impression node and a reception node. The signal was fed to the connection aperture at the impression node. Then the signal was transmitted in the TDC sheet and it was received by another PC through the other apertures. The position of the impression node was fixed, while the distance from the source was changed.

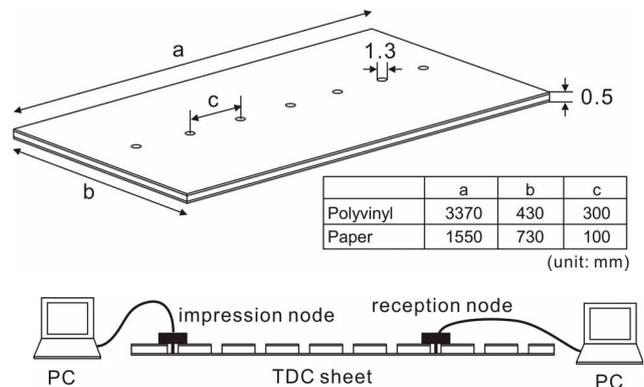


Figure 13 Settings for evaluating attenuation

Figure 14 shows the results of the measurements. The horizontal axis shows the distance from the source and the vertical axis indicates the received power. Here, the 0 dB is defined as the received power at 30 cm from the source. On Polyvinyl TDC Sheet, we find an obvious attenuation of -15dB/m in the sheet. On the other hand, in Paper TDC Sheet, it is hard to evaluate the attenuation from the acquired data.

The results suggest that we can realize several-meter-TDC using a wide range of materials including a sheet of paper, though we have to avoid some materials with large dielectric losses.

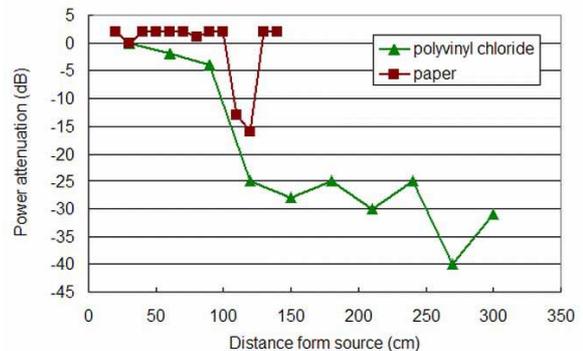


Figure 14 Experimental results of the signal attenuations of the prototype TDC sheets with two kinds of dielectric layers.

4.4 Communication between two PCs with TDC cloths We fabricated TDC cloths with stretchable conductive fabrics as shown in Figure 15 (a). Two PCs were connected to the TDC sheet through 50 Ω cables from extendable wireless LAN antenna ports (Figure 15 (b)). One of the two PCs is out of the picture. Communication between two PCs was realized using IEEE 802.11b protocol (2.4 GHz).

As the demonstration shown in figure (b), we realized stable communication through this stretchable communication sheet. We confirmed that the communication is realized with 11 Mbps which is limit of the protocol. Even when the sheet was stretched 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.

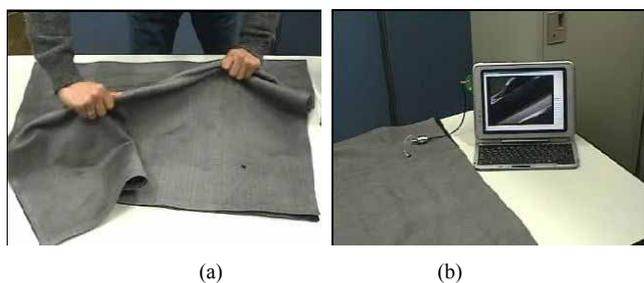


Figure 15 (a) TDC cloth made of stretchable conductive fabric. (b) PC to PC communication through the TDC cloth using IEEE 802.11b protocol.

5. Summary

In this paper we proposed a new technology for sensor networks named “Two Dimensional Communication.” In TDC, the signal energy is localized in a two dimensional sheet. A large number of communication nodes can connect with each other with no individual wires on the TDC sheet. TDC has advantages over wireless communication; 1) it is free from harmful electromagnetic wave radiation, 2) the waste of the energy for signal transmission is smaller, and 3) electrical power is also provided by electromagnetic wave in the sheet.

We confirmed these advantages by 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 results also showed that the several-meter-TDC sheet can be realized using a wide range of materials including paper.

We expect TDC is applied to various kinds of sensor networks. The possible applications will also cover the networks of non-sensor elements.

Sensor Networks in the Room: Putting the TDC sheet with pressure or temperature sensors on the floor for security and remote monitoring for an aged person. The sensors distributed in the room at low costs provide information for comfortableness.

Intelligent Desk: If we embed the TDC sheet into the desk surface, PC can communicate with peripheral devices on the desk without individual wiring. Power supply to the peripheral devices is also expected. For achieving this application, we are now developing proximity connection interface between the TDC sheet and the attached device. Connection without electrical contact is

possible with small power loss. Details will be soon presented in another occasion.

Tag Reading: Such a TDC sheet is effective device to read ID tags. A wide area of TDC sheet can read tags put on the sheet.

Robot Skin (Tactile Sensor Array): Since a TDC sheet can be realized with stretchable materials such as conductive fabrics, it is readily to cover a complex surface like a whole body of a robot with the TDC sheet. The sheet can be an artificial robot skin if we put tactile sensors on the sheet. The TDC sheet is also useful for communications among other sensors and actuators in the robot.

Substitution for Wire Harnesses: A huge number of wire harnesses are one of the problems in the automobile fabrication because of their complexity and heavy weight. A TDC sheet can be a substitution for conventional wire harnesses since the TDC sheet is applicable to the interior wall surface of the car.

Acknowledgement

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