Proximity Connector for Two-Dimensional Electromagnetic Wave Communication

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In this paper we engage in a challenging issue in sensor networks, how to physically connect a lot of sensing elements to the room-size network. Last year, we proposed a new physical layer of communication named “Two-Dimensional Communication (TDC).” TDC is a communication in which electromagnetic wave is localized in a two dimensional medium and any element connected to the medium can communicate with each other without individual wires. Power supply through the sheet by microwave is also available, since the electromagnetic energy is restricted within a two dimensional medium. Therefore, we can easily realize sensor network arranged in two dimensions without any efforts for wiring. No battery is required for each sensor element. In this paper, we show one configuration of a signal and power transmission connector that works anywhere on the TDC sheet without presice positioning. Moreover, it works as a proximity connector requiring no electrical contacts to the TDC sheet. If the surfaces of desks, floors, clothes, or vehecles have TDC layers, the sensors simply put on the surfaces can work and connect with networks.

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

1. Introduction

Recently, “sensor network” has become a more important field with a background 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 [2], synchronization of nodes [3], node localization [4], communication protocols [5] and practical usages [6] mainly based on wireless communication.

In this paper we engage in another challenging issue in sensor networks, how to physically connect a lot of sensing elements to the room-size network on the surfaces of desks, floors, clothes, or vehicles. Last year, we proposed “Two-Dimensional Communication (TDC)” as a new physical layer of communication [1]. Fig. 1 shows the schematic illustration of the communication sheet. The sheet is composed of three layers. A dielectric layer is sandwiched by two conductive layers. We showed that there is a propagation mode of electromagnetic wave in the dielectric layer for a sheet thinner than the wave length. When the sensor nodes are attached on the TDC sheet, communication is achieved by the electromagnetic wave without any individual wiring between each sensor node. Since arbitrary frequencies are available within the TDC sheet for communication, one can use not only conventional communication protocols such as IEEE 802.11a/b/g, Bluetooth and etc. but also newly developed ones without the radio law constraints. In our previous study, we used 2.4 GHz electromagnetic wave and achieved 11 Mbps data transmission using IEEE 802.11b protocol.

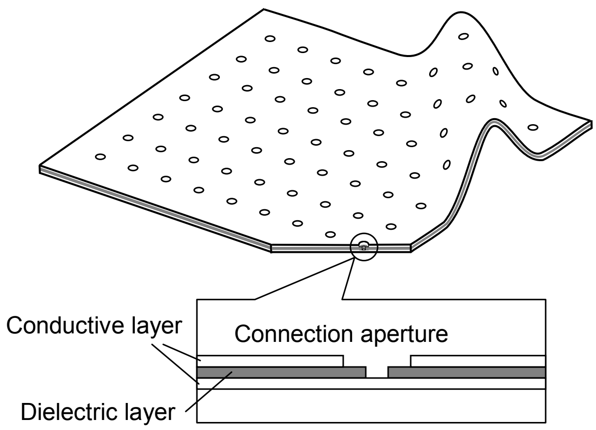

Figure 1 Schematic illustration of TDC sheet. [1]

One of the remarkable aspects in TDC is that an electrical power is also supplied through the sheet by microwave. This is due to the fact that signal energy is restricted within a two dimensional medium. Ideally, power decreasing rate is inversely proportional to the first power of the distance from the source, while in the usual wireless communication, it is inversely proportional to the second power. In addition, since the signal energy does not leak to an atmosphere, we can use high power microwave without harmful effects to a human body. The TDC sheet can be fabricated by various conductive materials such as conductive films, foils, and fabrics. A stretchable and foldaway communication medium is achieved. They can be buried into floors, walls, desks or curtains at low costs.

In our prototype proposed last year, the alternate electric field was applied only through the connection apertures on the TDC sheet (Fig. 1). This property limited flexibilities of sensor nodes arrangement. It is preferable that the connector can be used everywhere on the TDC sheet. Another disadvantage in our prototype was that direct connection between the connector and the conduc-

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tive layer was required for communication and power supply. Proximity connection that requires no electrical/mechanical contact is preferable for stability and easiness of connection.

In this paper, we show one configuration of the signal/power transmission connector that works anywhere on the TDC sheet and requires no electrical contact to the TDC sheet. If the surfaces of desks, floors, clothes, or vehicles have TDC layers, the sensors simply put on the surface can work and connect with networks. In Section 2 we show the design of our connector and TDC sheet. Simulation analyses and experimental results by prototypes of the connector are described in Section 3 and Section 4. Finally we conclude the paper in Section 5.

The idea of communication using two dimensional medium was originally proposed by us [7] and some other groups [8, 9] at the early 2000s. In the researches [8] and [9], however, high speed communication through the medium was out of consideration. In addition, mechanical and electrical connections of elements to the conductive layers were necessary.

2. Proximity Connection for Power Supply

2.1 TDC Sheet with Periodic Lattice Structure

In order to realize positioning-free connection between the TDC sheet and the connector, we modified configurations of both of the sheet and the connector. Figure 2 shows a new TDC sheet for the positioning-free connection. One side of the conductive layer of the sheet is periodic lattice structure. In this configuration, the electromagnetic energy propagating within the dielectric layer leaks to the atmosphere through the lattice. In a following discussion, we show that the leaked wave forms evanescent wave that does not propagate into the atmosphere for the lattice period much smaller than the electromagnetic wavelength. It is important for security of information and for effect on human health.

When we define x-axis and z-axis as shown in Fig. 3, the electromagnetic wave at frequency ω for $z > 0$ is written as a product of a fundamental component with wave length λ_d and modulation components that relate to the lattice period $d \ll \lambda_d$ as

$$E(x,z) = A\exp\left(\mathrm{j}\frac{2\pi}{\lambda_d}x\right)\left(\sum_{n=-\infty}^{\infty} B_n(z)\exp\left(\mathrm{j}\frac{2\pi n}{d}x\right)\right) \tag{1}$$

where E is an electric field component upon the TDC sheet. Here, A is constant and $B_n(z)$ represents behaviors of the electric fields in z direction.

Substituting the electric fields $E(x, z)$ to the wave equation, $B_n(z)$ is calculated as follows

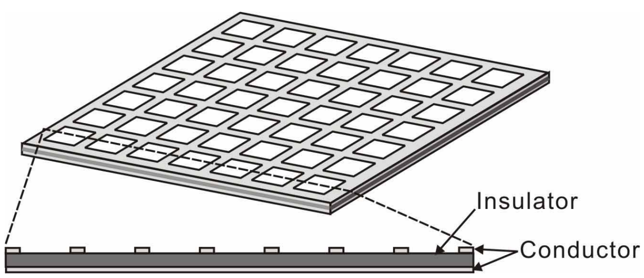

Figure 2 Periodic lattice structure of the TDC sheet.

$$B_n(z) = C_n\exp\left(-2\pi\sqrt{\left(\frac{1}{\lambda_d}+\frac{n}{d}\right)^2-\left(\frac{1}{\lambda}\right)^2}\,z\right) \tag{2}$$

where λ is the wave length of the carrier signal in atmosphere and C_n is a constant. Since the wavelength in the dielectric layer is smaller than that of the atmosphere, the following inequality is always satisfied.

$$\left(\frac{1}{\lambda_d}+\frac{n}{d}\right)^2-\left(\frac{1}{\lambda}\right)^2 > 0 \tag{3}$$

This inequality indicates that the electromagnetic energy exponentially decreases in z-direction (evanescent wave) producing no propagation modes leaving the sheet.

When the lattice period d is sufficiently smaller than the wave length λ_d (i.e. $\lambda_d >> d$), $B_n(z)$ are approximated as

$$B_n(z) = \begin{cases} C_0\exp\left(-2\pi\sqrt{\left(\frac{1}{\lambda_d}\right)^2-\left(\frac{1}{\lambda}\right)^2}\,z\right) & (n=0) \\ C_n\exp\left(-\frac{2\pi n}{d}z\right) & (n>0) \end{cases} \tag{4}$$

Therefore, $E(x, z)$ is rewritten as follows.

$$E(x,z) = AC_0\exp\left(\mathrm{j}\frac{2\pi}{\lambda_d}x\right)\exp\left(-2\pi\sqrt{\frac{1}{\lambda_d^2}-\frac{1}{\lambda^2}}\,z\right) + A\sum_{n\neq 1} C_n\exp\left(\mathrm{j}\frac{2\pi \mathrm{n}}{\mathrm{d}}x\right)\exp\left(-\frac{2\pi n}{d}z\right) \tag{5}$$

The first term relates to the fundamental electromagnetic wave within the TDC sheet (i.e. carrier wave). On the other hand, the second term relates to the interval of the lattice. Since the wave length λ_d is sufficiently larger than the lattice interval, the second term rapidly decreases in z direction with the attenuation length smaller than $d/2\pi$. That means high power electromagnetic energy is trapped around the sheet whose leakage height mainly depends on the lattice period. We can control the leakage by changing the period.

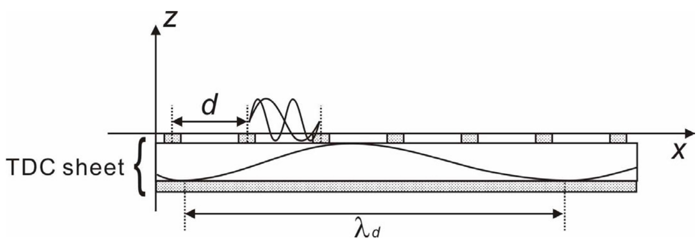

Figure 3 Two wave components in the TDC sheet. One is related to the fundamental electromagnetic wave within the dielectric layer (signal carrier). The other is modulation components that relates to the period of the lattice d.

2.2 Proximity Connector

So as to receive the leaked electromagnetic energy efficiently we also propose a proximity connector shown in Figure 4. The connector is used by putting it on the sheet without electrical contact.

The principle of the proximity connector is qualitatively explained in Fig. 5. When we put the connector on the surface of the TDC sheet, the micro wave impressed from the coaxial cable follows the winding path shown by the arrow of the broken line. Then reflections occur at three points in the connector due to the significant 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 composed of a sum of the reflected signals at each point. When connector radius *r* is chosen so that the phase of the reflected signals from 2 and 3 counteract the phase of the reflection at 1, total reflected power can be lessened. In an ideal case, the input signal transmits into the sheet without reflection back to the coaxial cable.

A preferable feature of the proximity connector is that the distance between the connector and the TDC sheet are not a main parameter to determine the reflection if the distance is smaller than the efficient range of the leakage. Consequently, we can put insulator layer including air between the connector and the sheet surface. An electrical contact is not required.

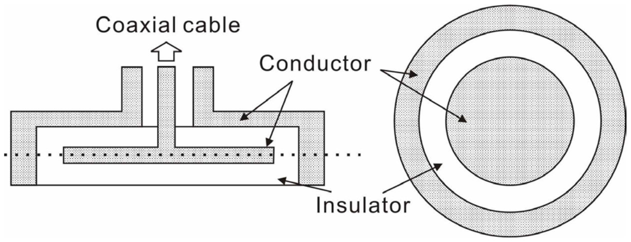

Figure 4 Schematic illustration of the proximity connector. The left figure illustrates the side view of the connector. The right figure shows the top view (cross section on the broken line).

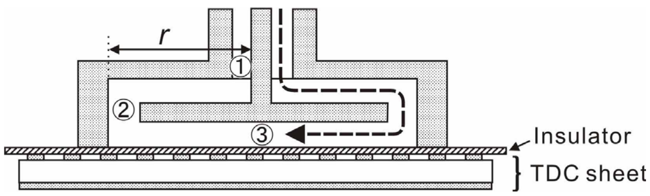

Figure 5 Principle of the proximity connector.

3. Simulation Analyses

3.1 Simulation Model

We confirmed the above discussions by simulation analyses. Figure 6 shows the models of a TDC sheet and a proximity connector. The size of the connector was determined so that it can work at 2.4 GHz. Based on pilot simulation results, we decided the size *r* is 17.5 mm.

In order to realize positioning-free connection, it is preferable that a lattice interval of the sheet is smaller than the diameter of the connector. In that case, the lattice structure is seen uniform independent on the location of the connector. However, as the interval becomes smaller the leakage height also becomes smaller, which makes the connectable height from the sheet surface short. We empirically decided the size of the interval *d* is 5 mm and the line width of the lattice is 0.6 mm.

The model was constructed by a simulation software MW-STUDIO (AET Japan Inc.) The TDC sheet was made of the two copper layers which sandwiched the glass epoxy substrate. The thickness of the copper layers (as the conductive layers in Fig. 2) were 35 μm each, and the resistivity was 0 Ω. The thickness of the glass epoxy layer (as the dielectric layer whose relative permittivity $\varepsilon_r = 4.9$) was 1.6 mm. The interval of the lattice was 5 mm and the line width of the lattice is 0.6 mm. Though the total size of the sheet was modeled as 55 mm x 55 mm, a boundary condition at the sides of the sheet was determined that the all electric energies passed through to the outside. Therefore the infinitely spreading TDC sheet was modeled. In the proximity connector, a relative permittivity of the insulator is 10.5. The width of the outer conductive ring is 5 mm. The total diameter of the connector is 45 mm in the simulation. Using these models, following two simulations were conducted.

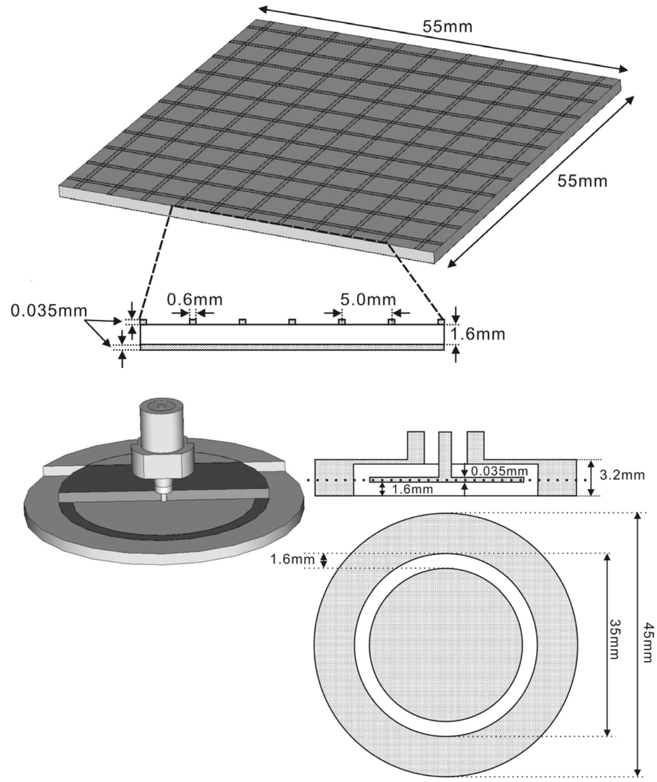

Figure 6 Simulation models of the TDC sheet and the proximity connctor.

3.2 Effective Range of the Leakage

We confirmed whether the leakage from the surface of the TDC sheet decreased exponentially or not. In the simulation, a plane wave was impressed from one side of the sheet. The impressed energy passed through the sheet. As is mentioned above, the other three sides were no-reflection boundaries. No standing waves occurred in the simulation.

Figure 7 shows the cross section of the TDC sheet. The gray scale variation indicates the energy density of the electric field. The white squares shows the lattice. It is clear that the signal power exist within the sheet and near the surface.

Figure 8 shows the energy density along the arrowed broken line shown in Fig. 7. The horizontal axis indicates the distance from the sheet surface and the vertical axis shows the the energy density of the electric field. Each axis is logarithmic. The graph indicates that the electromagnetic energy decreases exponentially. At 2mm height from the surface, the energy density is about 1/1000 of the energy density at the surface. We also confirmed that the effective range of the leakage changed as the lattice period varied.

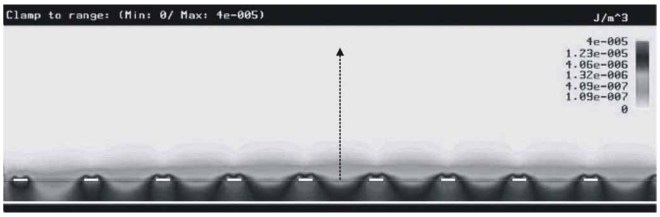

Figure 7 A simulation result of the electric field energy density seen from the side of the sheet. The white squares indicate the line of the lattice structure.

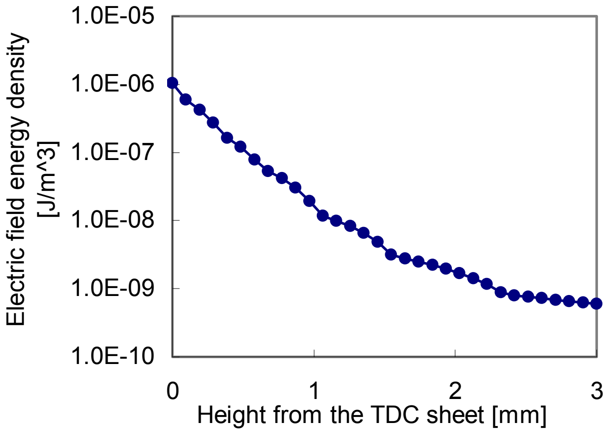

Figure 8 Energy density along the arrowed broken line shown in Fig. 7.

3.3 Proximity Connection

The behaviour of the proximity connector was simulated. The proximity connector model was put on the surface of the TDC sheet. Then 2.4 GHz microwave was impressed from the top of the connector.

Figure 9 shows the electric field in the connctor and the proximal TDC sheet. The arrows indicate the electric field at a certain moment. It is shown that a resonance occurs in the connector. The center of the connector becomes anti-node. We confirmed that the TDC sheet was excited by the connector. The impressed energy propagated concentrically in the sheet as shown in Fig. 10. When we used another frequencies, the connector marked worse performance of excitation.

We also simulated that the connector was excited by microwave propagating in the sheet. It is confirmed that the connector could impress the signal to the sheet, and receive the signal from the sheet.

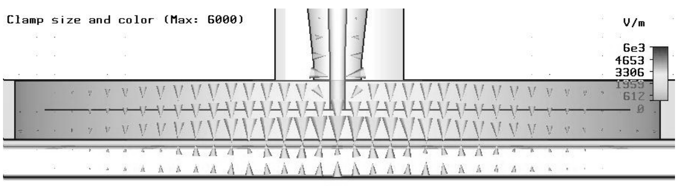

Figure 9. Side view of the electric field in the connctor and the proximal TDC sheet

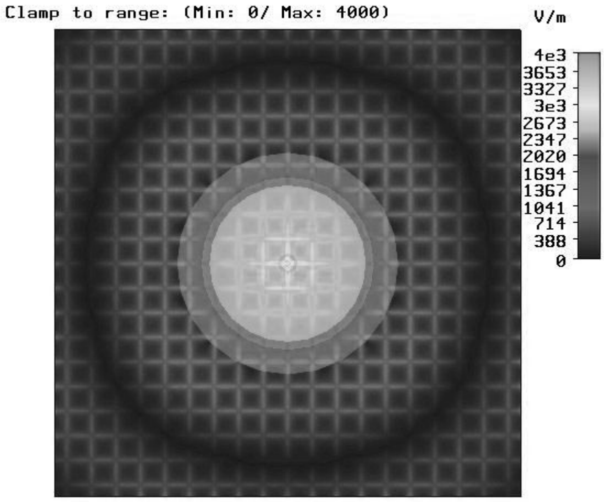

Figure 10. Top veiw of the TDC sheet. The electric field spreads in the TDC sheet concentrically.

4. Experimental Result

4.1 Prototype

We fabricated prototypes of the TDC sheet and the proximity connctor (Fig. 11). The TDC sheet was 180 mm x 180 mm. The size of the prototype connector was larger than the simulation model to obtain the best experimental result. The outer diameter of the connector was 60 mm and the *r* was 20 mm. As an insulator between the sheet and the connector, we put a paper whose thickness was 0.1 mm. Using these prototypes, we conducted following two experiments.

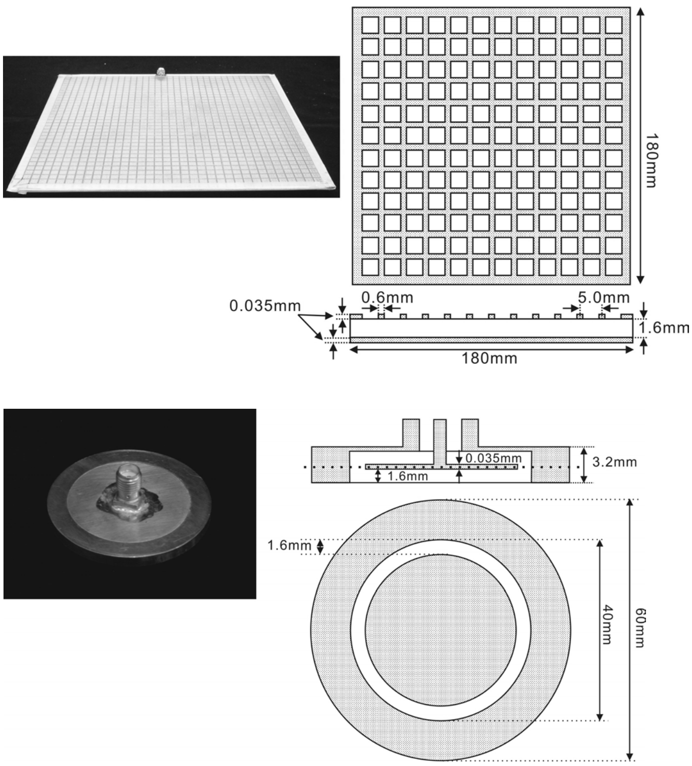

Figure 11. Prototypes of the TDC sheet and the proximity connector.

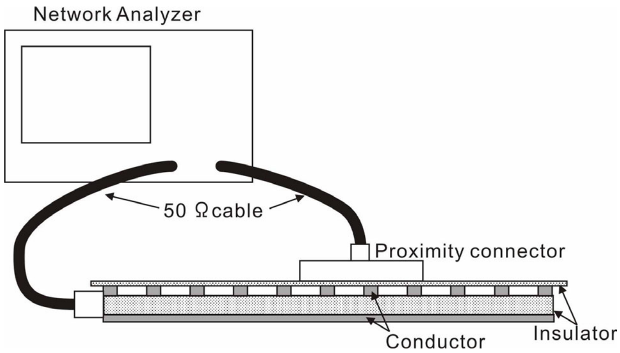

Figure 12. Experimental settings for confirming the dependence on the carrier frequency.

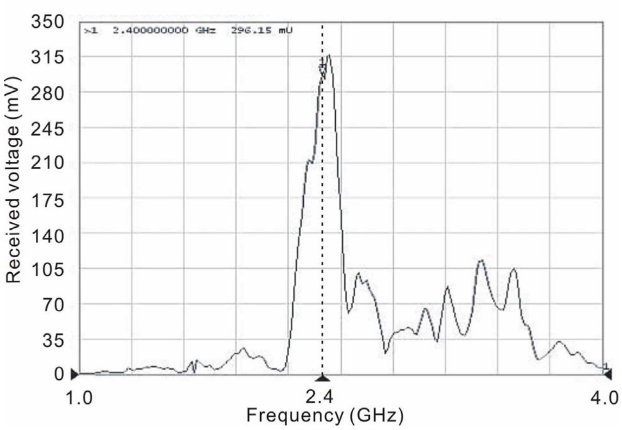

Figure 13. Dependence on the carrier frequency. The connector shows the best performance at the designed frequency (2.4GHz).

4.2 Dependence on the Carrier Frequency

The prototype connector was designed so that the size *r* corresponds to 2.4 GHz microwave. We confirmed whther the connector worked appropriately at the designed frequency. Figure 12 shows the experimental settings. Microwaves ranging form 1 GHz to 4 GHz were impressed to the TDC sheet through the 50 Ω cable from the network analyzer. The impressed signals were received through the proximity connector that was put on the TDC sheet.

We fabricated several sizes of the proximity connectors for determining the apropriate size *r*. Based on our results, the size of the connector had to be larger than the size used in the simulation. As we mentioned before, the total diameter of the connector was 60 mm and the *r* was 40 mm for 2.4 GHz if the relative permittivity of the insulator was 10.5.

4.3 Effective Range of the Leakage

Using the prototype, we also confirmed how long the effective range of the leakage was. Figure 14 shows the experimental settings. The proximity connector was moved by 0.1 mm along *z*-axis. The received voltages were measured at each height.

Figure 15 shows the experimental results. The horizontal axis indicates the height from the surface of the TDC sheet. The vertical axis indicates the amplitude of the received signal for 1 V input. Up to 0.3 mm from the surface, strong connection is realized, while the signal power decreases exponentially when the distance becomes larger than 0.4 mm.

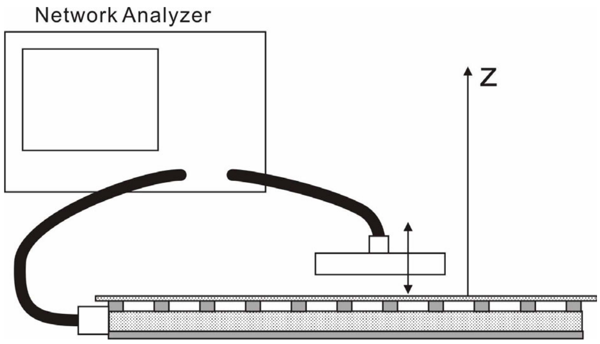

Figure 14. Experimental settings for measuring the leakage height.

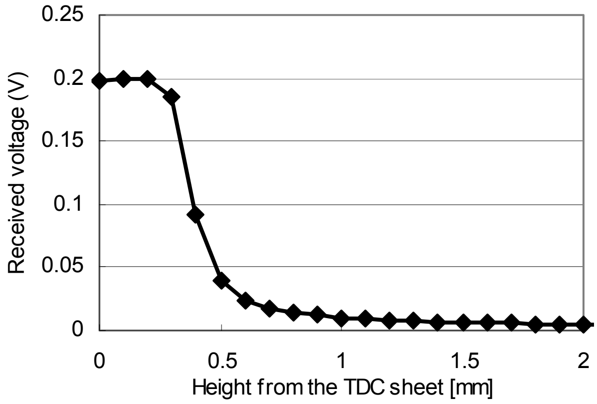

Figure 15. Experimental results of the leaked signal energy measurement.

The result indicates that we can put insulator under the connector if the height of the insulator is less than 0.4 mm. Slight dirt or dust is acceptable.

4.4 Signal Transmission

We confirmed that signal transmission between two PCs through the TDC sheet and a pair of proximity connectors could be achieved by IEEE 802.11b protocol. Moreover, 100 mW power supply to another connector on the sheet was accomplished simultaneously using the same frequency.

5. Conclusion

Last year, we proposed "Two-Dimensional Communication (TDC)" as a new physical layer of 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.

In this paper, we showed one configuration of the signal and power transmission connector that works anywhere on the TDC sheet. In addition, it works as a proximity connector requiring no electrical contacts to the TDC sheet. If the surfaces of desks, floors, clothes, or vehecles have the structure of TDC sheet, the sensors simply put on the surfaces can work and connect with networks. Based on simulation analyses and experiments of prototypes, we confirmed that both signal and power was successfully transmitted through the TDC sheet by 2.4 GHz microwave.

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