Proceedings of the 2003 IEEE
International Conference on Robotics & Automation
Taipei, Taiwan, September 14-19, 2003

Two-Dimensional Signal Transmission Technology for Robotics

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Abstract

The forms of communication available now are categorized into the one or three dimensional. One dimensional communication includes metal wires and optical fibers in which the electro-magnetic field is confined in one dimensional medium. Wireless communication based on RF or optical connection emits electro-magnetic field in 3-D space. Now what if we have “two-dimensional communication” in which signals travels from one point to another point freely in elastic two-dimensional space using electromagnetic field confined in 2-D space? In this paper, we describe such a new technology of 2-D communication brings new paradigm to robotics. The methodologies of machine-design, system-integration, sensing, and computing will be drastically changed. We show architecture of the 2-D signal transmission based on relaying packets between communication chips on a thin sheet, the physical structure of the 2-D signal transmission, the protocols of the signal relay, and the results of the basic experiments.

Keywords; two-dimensional communication, diffusive signal transmission, packet communication, sensor network, robot skin, micromachine, ubiquitous, distributed computing

1. Introduction

The forms of communication available now are categorized into one or three dimensional devices. One dimensional communication includes metal wires and optical fibers in which the electro-magnetic field is confined in one dimensional medium. One dimensional communication causes a problem when a large number of elements are to be connected with each other. The wiring comes to need a major effort in system design including circuit design, connecting distributed sensors and actuators, powering micromachines, and distributed computation.

Wireless communication based on RF or optical connection can be classified into three-dimensional communication, as the electromagnetic field is released in three-dimensional space. Wireless communication had been considered to be a hope to solve the wiring problem [1,2,3,4,5]. The problem of it is that the electromagnetic field propagates beyond the target, which makes energy transmission difficult, and degrades the communication capacity when multiple elements communicate simultaneously.

Now what if we obtain a “two-dimensional communication” device in which signals from one point to another point travel freely in flexible two-dimensional space? In this paper, we show a method to realize such a 2-D signal transmission device. We describe how it changes the robotics in machine design, system integration, sensing, actuating and computing.

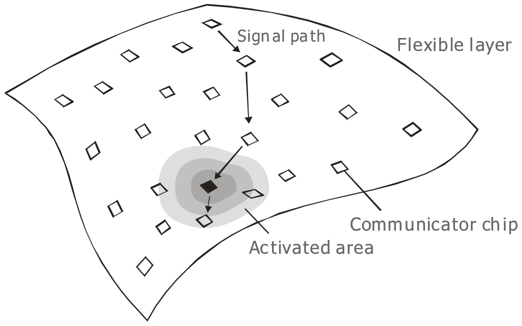
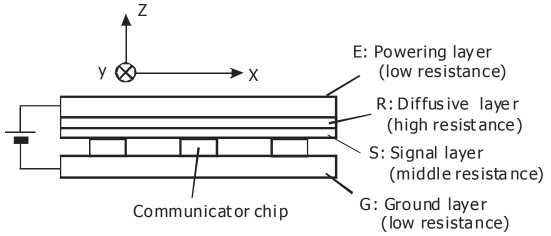


Fig. 1: Schematic diagram of two-dimensional signal transmission. Signals are transmitted in an isotropic 2-D space.

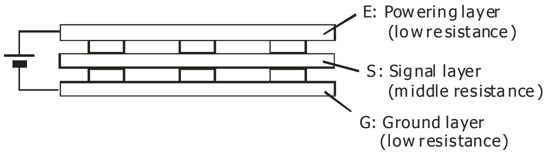
2. Diffusive signal transmission in 2-D layer

The two-dimensional communication we call here is the one in which signals are transmitted in two-dimensionally isotropic structure using electromagnetic field confined in 2-D space.

A structure of two-dimensional signal transmission proposed here is shown in **Fig. 1** and **Fig. 2**. Multiple LSI chips are distributed between flexible conductive layers of rubber or cloth. The chip can be a sensor or a connector to another functional device with a communication interface. The signal reaches a finite distance physically, and the packet is transmitted to an arbitrary point by being relayed (hopping) among the communicators as **Fig. 1** shows. Every element connected to the layers can communicate with each other without individual wires. The layer can be realized with elastic material allowing extension because the material of the 2D layer does not have to be conductive as much as a usual wire. A signal is transmitted from a chip to another neighboring chip by diffusive coupling. **Fig. 2** describes the cross-section of the communication layers. First we explain the principle of low-frequency signal transmission based on the structure type I in **Fig. 2** (a).



(a) Type I



(b) Type II

Fig. 2: Cross section of the 2-D signal transmission device. Each chip contacts with two layers in type I and three layers in type II.

[Diffusion mode I]

Suppose the lateral resistance of G and E layers is negligible. The sheet resistance of R layer in **Fig. 2** (a) is sufficiently larger than that of S layer. When the thickness of S layer is negligible, the alternative component of voltage distribution $V(x,y)$ on S layer satisfies the following diffusion equation

$$C\frac{\partial}{\partial t}V+\frac{1}{\eta d}V=\left(j\omega C+\frac{1}{\eta d}\right)V=\frac{1}{\rho}\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right)V \tag{1}$$

where C [F/m^2], η [Ω m], d [m], ρ[Ω], and ω [rad/s] are respectively capacitance between S layer and G-and-E layers, volume resistivity of R layer, the thickness of R layer, sheet resistivity of S layer, and angular frequency of the signal. The $V/\eta d$ implies the current density from the S layer to E layer through R layer.

At a low frequency where $j\omega C << 1/\eta d$, one dimensional solution $V(x)$ of Eq. (1) is written as

$$V=V_0\exp\left(\pm\frac{x}{D_{\mathrm{dif}}}\right)\exp(j\omega t) \tag{2}$$

where

$$D_{\mathrm{dif}}=\sqrt{\frac{\eta d}{\rho}}\quad . \tag{3}$$

As this equation shows, electrical potential changes occurring at a point on S layer does not go beyond the diffusion length D_{dif}. Then a signal sent from a chip is detected only by chips inside a circle with the radius D_{dif}. This is illustrated in **Fig. 3**.

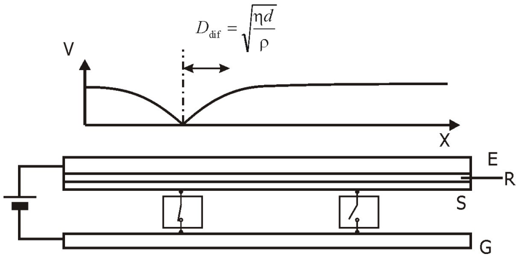


Fig. 3: Illustration of diffusive signal transmission in type I. A signal sent from a chip is detected only by chips inside the D_{dif} circle.

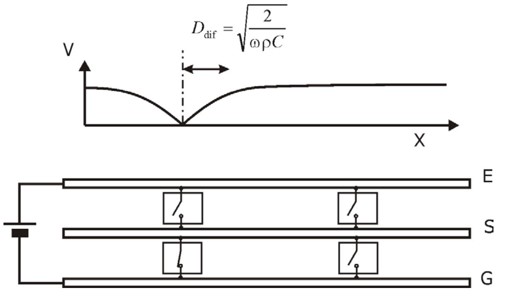


Fig. 4: Illustration of diffusive signal transmission in type II.

[Diffusion mode II]

A structure shown in **Fig. 2** (b) reduces power consumption. In this case the solution of Eq. (1) is written as

$$V=V_0\exp\left(\pm\frac{1+j}{\sqrt{2}}\sqrt{\omega\rho C}\,x\right)\exp(j\omega t)\quad\cdot \tag{4}$$

Then

$$D_{\mathrm{dif}}=\sqrt{\frac{2}{\omega\rho C}} \tag{5}$$

gives the diffusion length. When ω = 10^7 [rad/s], ρ = 500 [Ω], $C = 4\times10^{-8}$ [F/m^2], the diffusion length D_{dif} is given as 10 [cm].

[Two dimensional point current source]

The two-dimensional solution with cylindrical symmetry is given as follows. When an electrode with the radius r_0 (See **Fig. 5**) located at the origin has a potential $V_0\exp(j\omega t)$, the potential at a distance r from the origin is written as

$$V(r)=V_0\frac{J_0\left((1-j)\frac{r}{D_{\mathrm{dif}}}\right)-jN_0\left((1-j)\frac{r}{D_{\mathrm{dif}}}\right)}{J_0\left((1-j)\frac{r_0}{D_{\mathrm{dif}}}\right)-jN_0\left((1-j)\frac{r_0}{D_{\mathrm{dif}}}\right)}\exp(j\omega t) \tag{6}$$

using Bessel functions in diffusion mode II. **Fig. 5** (b) shows a function $|H_0(x\text{-}jx)| = |J_0(x\text{-}jx) - jN_0(x\text{-}jx)|$ to evaluate the equation. For diffusive mode I, we can obtain $V(r)$ by substituting D_{dif} for

$$D_{\mathrm{dif}}=\frac{1+j}{\sqrt{\rho/(\eta d)+j\omega\rho C}}\,\cdot \tag{7}$$

When r, $r_0 << |D_{\mathrm{dif}}|$, the $V(r)$ is approximately written as

$$V(r) \approx V_0 \log r / \log r_0 . \tag{8}$$

If $r >> D_{\mathrm{dif}}$, the $V(r)$ decreases exponentially as the one dimensional case. Therefore, the diffusion length in the two-dimensional case is comparable to that in the one-dimensional case.

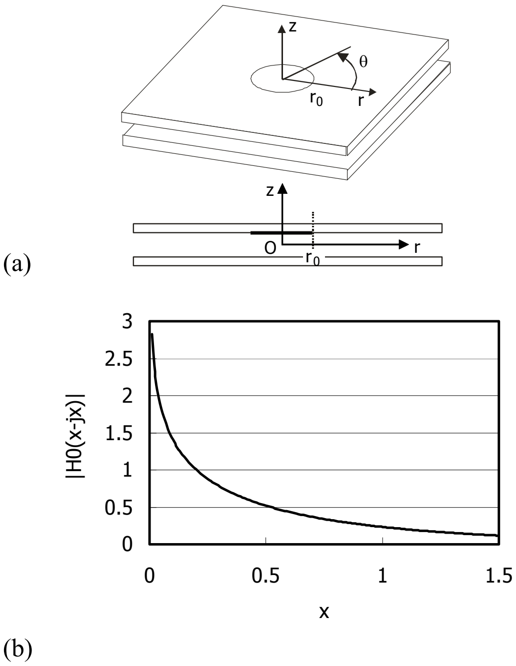


Fig. 5: (a): Definitions of r_0 and r. (b): Plots of a function $|H_0(x\text{-}jx)| = |J_0(x\text{-}jx) - jN_0(x\text{-}jx)|$ to evaluate Eq. (6).

[Electromagnetic wave radiation in the gap space]

When the switch in **Fig. 4** operates at a very high frequency so that the electromagnetic wavelength is smaller than the diffusion length, the gap between S and G (E) layer becomes a waveguide that allows TEM mode [6] to occur in which the electric field is perpendicular to the layer and magnetic field circles around the radiation point. The electromagnetic energy is localized in the gap between the two conductive layers. The current runs around the surface with the skin depth $\sqrt{2/\omega\mu\sigma}$ where μ and σ are the permeability and the conductivity of the conductive layers ($=1/\eta$), respectively. The magnetic field $\mathbf{B} = (0, B(r,z,t), 0)$ in the cylindrical coordinate is given as

$$B(r,z,t) = B_0 H_1^{(2)}(kr)\exp(j\omega t) \tag{9}$$

in the gap where

$$\mathrm{Re}[k] \sim \omega/c \quad (c\text{: light velocity}), \tag{10}$$

$$\mathrm{Im}[k] \sim \frac{1}{d}\sqrt{\frac{\varepsilon_0\omega}{8\sigma}} \quad \text{(attenuation constant)}, \tag{11}$$

and

$$H_1^{(2)}(z) \equiv J_1(z) - jN_1(z). \tag{12}$$

The signal transmission by electromagnetic wave realizes short-delay and large-throughput communication. In the following sections, however, we discuss only diffusive signal transmission.

3. Two-dimensional signal transmission by distributed LSI chips

The proposed system transmits signals by relaying packets among neighboring communication chips. Comparing with other imaginable methods in which electromagnetic field travels in a long range passively in the 2-D medium, we notice the following advantages in relaying packets (hopping).

1) The excited domain on a signal path forms a one-dimensional chain. Then required energy for signal transmission is not wasted in unrelated area.
2) Multiple pairs of chips can communicate simultaneously without interference because the excited domains are localized into a one-dimensional chain.
3) If some area of the device damaged, a new path can be produced dynamically.
4) It is free from multi-path and reflection problems.

Next we summarize the relationship between the density of the chip distribution and the specification of communication.

Throughput and delay

Until a packet reaches a place as far as L, the packet is relayed

$$N \approx L / D_{\mathrm{dif}} \tag{13}$$

times. As Eq. (5) shows, the diffusion length D_{dif} is proportional to $1/\sqrt{\omega}$ at a high frequency in type II. Therefore if we keep the chip spacing comparable to the diffusion length, signal delay of K bit packet is given as

$$T_D \approx KT_0 N \approx KL\sqrt{\frac{\rho C}{\omega}}, \tag{14}$$

where T_0 is the period for one bit supposed to be comparable to $1/\omega$. Then the signal delay decreases as the signal frequency is heighten though it results in increase of the number of chips and relaying.

On the other hand, the throughput is simply determined by the signal frequency, and is proportional to the signal frequency.

Energy consumption

Suppose the minimal change of electro-magnetic energy density detectable by a communication chip in the 2-D medium, is written as e [J/m^2]. Then the energy consumed for one-bit transmission by N relaying is given as

$$esN \approx eD_{\mathrm{dif}}{}^2 \frac{L}{D_{\mathrm{dif}}} = eL\sqrt{\frac{1}{\rho C\omega}} \tag{15}$$

where s indicates the diffusion area comparable to $D_{\mathrm{dif}}{}^2$. Then the energy consumption in the communication layer decreases as the signal frequency increases. For example, the energy consumed in the communication layer is given as 1 [nJ/m/bit] when $D_{\mathrm{dif}} = 10$ [cm], $d = 1$ [mm], and the voltage amplitude in signals is 1 [V].

On the other hand, the total power consumption inside communication chips increases as the chip number and operation frequency increase. The tradeoff is a factor to determine the optimal chip density and signal frequency. In our first design of 10 MHz operation, the energy consumed by one chip is estimated at 1 mW. When we locate the chips with a density 10^4 [1/m^2], the total power consumption inside the chips amounts to 10 [W/m^2]. This total power consumption can be reduced with the technique of gated clock. In table 1, we summarize specification of the communication chip in type II that we are developing.

Table 1: Specification of the projected communication chip (Type II)

Signal throughput between neighboring chips	10 Mbps
Power consumption in signal layer	1 nJ/m/bit
Chip operation	10 MHz
Chip size	3 mm square
Power consumption in the chip	1 mW/chip
Diffusion length	10 cm

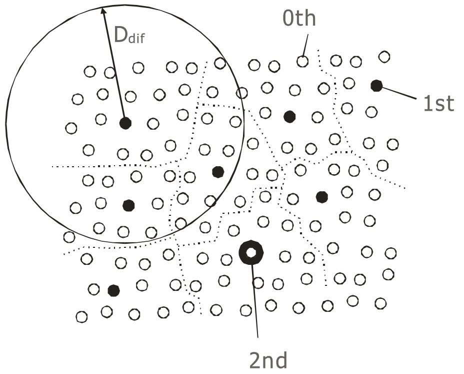


Fig. 6: Distribution of communication chips. The figure shows a system with a single 2nd-order chip.

4. Algorithm of signal relay

The system is based on packet communication [7,8]. The signal path between an arbitrary point and another point is established dynamically. The condition that density of communicators is very high and the diffusion length is limited is similar to that of wireless sensor network [3-5]. However signal power reduction is less important than that in wireless sensor network and topology changes of signal paths happen less frequently than that in ad hoc network. Here we show the outline of a hierarchical architecture in which all chips have global IDs and connection between arbitrary two chips is assured. The proposed method satisfies the following conditions.

1) Since vast amount of chips are used, the produced chip should have a uniform or a small variation of design. The ID numbers of the chips are also desired to be assigned dynamically using random number generators.
2) The signal paths (selection of chips in relaying) are established for all the chips in sufficiently short time.
3) The signal paths are established without a priori knowledge of the chip positions.

Table 2: Composition of packet

1	ID of the next receiver of this packet.
2	Command (forward, path_search, echo_requirement, echo_back, id_assign)
3	Length of header
4	Length of data
5	ID of the destination
6	ID of the sender of this packet
7	ID of the signal origin
8	Series of the IDs of the *n*-th order chips to the destination
	⋮
	Series of the IDs of the 1st order chips to the next 2nd order chip or the destination
9	Data

In our system, we prepare from 0th to *n*th order communication chips. In **Fig. 6**, the white circles indicate 0th communicators. The 0th chips are the terminals (sensors or connectors to outer devices) of this system, and they can communicate only with the 1st-order "parent" chip that supervises the 0th chips. One 1st-order chip can have *M* 0th-order children within the diffusion area in which the signal reach directly from the 1st-order chip. The spacing of 1st order communicators is comparable to or smaller than the diffusion length D_{dif}. The 2nd order chip can also have *M* 1st-order children. In our system, the *M* is set at 256. A *n*th-order chip ($n > 0$) possesses the following functions to relay signals.

1) It knows all the IDs of the (n-1)th order children of itself. It also knows the relay path (a series of IDs of (*n*-1)th order chips) to every children chip of it. It also knows the next chip toward its parent.
2) The *n*th order chip has all functions and information that it should have if it was a 0, 1, $\cdots, n-2$, or (*n*-1)th order chip. Therefore a *n*-th order chip also has a table of *n*-2, *n*-3,$\cdots$,0 th order children as a *n*-1, *n*-2,$\cdots$,1st order parent. Then a *n*th-order chip has an ID table of *nM* chips as the maximum.

A packet is composed of the contents shown in Table 2. A *n*th-order chip that received a packet behaves as follows.

1) If the ID of item 1 in Table 2 does not coincide with the receiver's ID, the receiver ignores the packet.
2) If the destination is included in the children table, it creates a packet adding the path data of item 8 in Table 2 and sends it. The "path data" includes ID series from 1st order to (*n*-1)th order. The "ID series of *k*th order" ($0 < k < n$) is the series of the chip IDs of *k*th order to the next (*k*+1)th order chip (if it exists).

3) If the destination (the goal of the transmission) designated in the packet is not included in the table of the children, it creates the path data to the *n*th-order chip indicated by the path data of item 8, and it sends the packet to the next chip. If the next *n*th-order chip is not indicated in item 8, it transmits the packet toward its parent.

Based on this algorithm, each chip can send a packet to an arbitrary chip in total of M^n chips. (Notice that packets are always relayed by the 1st-order chips physically.) The commands for establishing IDs and signal paths are summarized in item 2 of Table 2.

For establishing IDs of 1st-order chips, for example, a 2nd-order chip sends "echo_requirement" command to the 1st-order chips in the diffusion area as **Fig. 7** (a) shows. Next as **Fig. 7** (b) shows, the chips that received the echo_requirement command responds with "echo_back" after a certain waiting time following a random number. The 2nd-order chip gives an ID to the sender of the echo-back by "id-assign" command. Then as **Fig. 7** (c) shows, the 2nd-order chip sends "path_search" to the chip that obtained ID in the previous process. The chip that received the path-search creates echo-requirement, assigns the IDs around them, and tells the path from the 2nd-order parent. The newly assigned 1st-oder chip repeats this process until the 2nd-order chip obtains a certain number of 1st-order children.

Drawbacks of this method are that the packet has a relatively large overhead including path data, and that signals gather around high order chips. One practical solution is that we assign the x-y coordinate as the IDs to the first order chips in advance. Then the first order chips can decide the next receiver from the coordinate without second or higher order chips.

5. Prototype and basic experiment

Up to now, we have already designed the 0th and 1st order communication chips whose physical architecture is shown in **Fig. 8**. The floor plan shown in **Fig. 9** was obtained by Avant! (Synopsys) Apollo, based on CMOS 0.35 μm rule. All functions required for the 1st order chip with a 128 byte buffer were realized in a 3 mm by 2 mm area of digital circuit and 1.5 mm square area of input-output analogue circuits. The chip is fabricated by ROHM Ltd., Japan. The operation of the LSI of the 0th order chip was tested and the LSI was molded as **Fig. 10** shows.

Experimental results of diffusive attenuation of signals are shown in **Fig. 11**. A signal layer of sheet resistance 1 kΩ, distant from the ground layer by 0.2 mm was tested for 1, 5, and 10 MHz sinusoid. Detected voltage amplitudes at a distance *r* from the signal source are plotted in **Fig. 11**. The plots are the ratios of measured amplitude to the measured amplitude where *r* = 1 cm. Experimental results of attenuation coincided with the theory of Eq. (6).

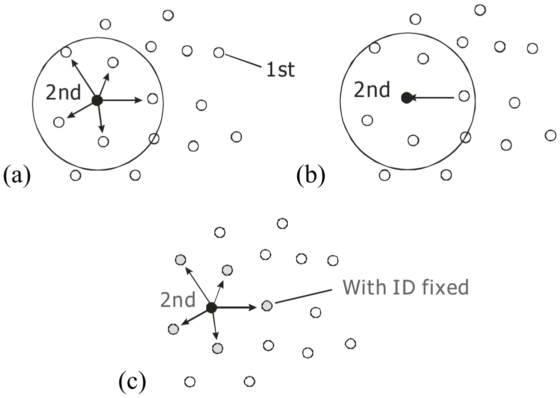


Fig. 7: Procedures of ID fixation. The 2nd-order parent sends "echo-requirement" first to neighboring 1st-order chips. Next the parent gives IDs to the neighbors based on the order of response. After fixing the IDs, the parents send "path-search" to the neighboring children to establish the IDs around them.

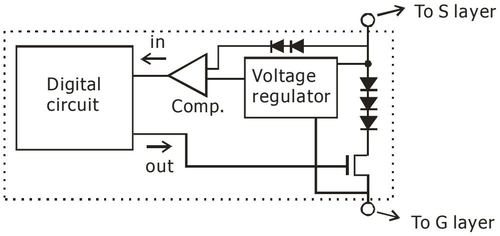


Fig. 8: The structure of the communication chip for Type I architecture.

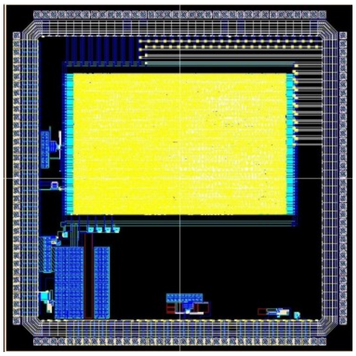


Fig. 9: The mask pattern we designed for a 1st-order communication chip. The chip size is 5 mm by 5mm with digital circuit of 3 mm by 2mm.

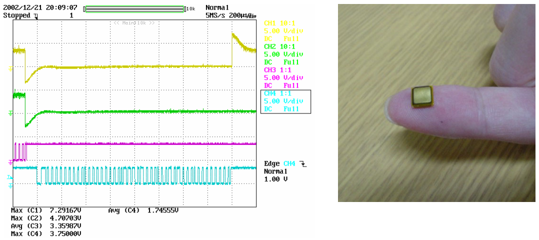


Fig. 10: The operation of the LSI of the 0th order chip of type I was tested (left) and the LSI chip was molded (right).

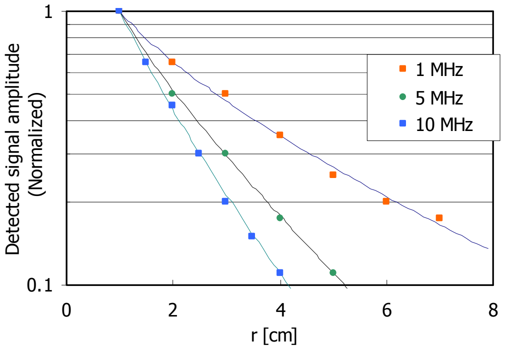


Fig. 11: Experimental results of diffusive signal attenuation for a signal layer with sheet resistance 1 kΩ distant from the ground layer by 0.2 mm. The ratios of measured voltage amplitudes to the measured amplitude where *r* = 1 cm are shown (r: distance from the voltage source).

6. Applications

A flexible 2-dimensional communication device in which signals can be transmitted with large throughput is useful in various aspects and scenes of robotics as follows.

1) Excluding complicated wires from robot system

If we cover a robot with this 2-D communication layer, elements of the robot such as computers, motors, and sensors can be connected to the device at arbitrary positions to communicate each other. In addition to the information exchange, they obtain energy by simply connecting the terminals to the E layer. The complicated wires combining those elements are removed.

2) A vast number of elements can be connected

A large number of elements including sensors, displays, and other functional parts can be connected and communicate at fast speed. An elastic tactile sensing device with more than 10^6 elements is realized.

3) Activating micromachines and small tags

Micromachines on the 2-D device can communicate each other and obtain energy through non-contact proximity connection between the 2-D device and micromachines using light or inductive coupling [9]. Objects with small communication interface chips without battery can communicate ubiquitously through a floor and a wall equipped with the 2-D device.

4) Wearable computing

Robot can wear a computing device formed into clothes. Signals with a frequency more than 1 MHz can be transmitted in the flexible clothes. The human can also wear it, and it can assist the communication between the human and the robot.

5) Wireless connection through a foot

Usual robots always have contact with floor by their feet. Then if they communicate through the feet with a floor equipped with the 2-D device, they can communicate with other robot as freely as the traditional wireless communication. The communication through the feet is free from the electromagnetic radiation. The communication capacity offered by the 2-D communication floor in which the signal path is a one-dimensional chain, will be far larger than that of 3-D communication sharing a single 3-D space for all communication elements.

6) Enabling a high-speed distributed computation

The elements connected to the communication layer can always communicate with each other if the elements follow the protocols of the 2-D communication. Computing element including memories, processors, and resistors in the processor can be connected through 2-D layers potentially. A flexible device can be a computer that also contains sensors, displays and other interfaces in it.

7. Summary

In this paper, we proposed a new concept of communication, “2-D” signal transmission. In a thin, flexible medium allowing extension, signals can travel with a large throughput. Basic concept and a method of realizing a device with 10 MHz-operation chips were described. A communication chip with 3 mm by 2 mm of digital circuit based on CMOS 0.35 μm rule was shown to be possible. Various applications of the device were described.

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