

An Efficient Wireless Power Transmission System Using Phase Control of Input Electrode Array for Two-dimensional Communication

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Abstract— The two-dimensional (2D) communication is a novel physical form of communication that utilizes the surface as a communication medium to provide data communication and contactless power transmission services to the devices. In the previous works, we have developed 2D communication system (2DCS) that allow the devices to simultaneously perform both data and power transmission wherever it is placed on the 2D sheet. From the viewpoint of the power transmission efficiency, it is not desirable that the microwave spreads over the place where the device doesn't put. Instead of spreading the electromagnetic wave thoroughly in the thin 2D sheet, we concentrate it only on the place where the device is put, by adjusting the phase of the multiple input signals. To largely strengthen the efficiency of power supply in the 2D communication, in this paper, we build up an efficient power transmission system by using phase control of input electrode array to converge the electromagnetic wave on a specific area in the 2D sheet, and evaluate its performance by both computer simulation and realistic measurement of the output power over the developed 2DCS.

Keywords— two-dimensional communication, phase control, power transmission,

I. INTRODUCTION

The ubiquitous communications are fast growing area in recent years, and many innovative researches and developments in this area have brought the idea and concept to real applications beneficial to our daily life. The two-dimensional communication technology has a huge potential as an epoch-making technology for realizing the ubiquitous home networks, because the novelty of 2DCSs combine the best features of both technologies of wired and wireless networking. 2DCS allows a 2D sheet as a communication medium to provide room-size communications and other services to device. The devices may include sensors, laptops, PDAs, mobile phones, home appliances, and other types of device habitually placed on the sheet. This new form of 2D communication medium is not just able to establish a communication connection between two devices, but it also can provide other services including high-speed transmission, power supply provision, high security, high accurate

estimation of the device's location, and efficient spatial reuse, etc.

In the previous works, we have developed 2DCSs that allow the device to simultaneously perform both data and power transmission by spreading the electromagnetic wave thoroughly in the 2D sheet. In the previous system, one electrode transmits signal into the 2D sheet, and the microwave spreads over 2D sheet. From the viewpoint of the power transmission efficiency, it is not desirable that the microwave spreads over the place where the device doesn't put. If the microwave can be concentrated only on the place of the device put, and not be spread to other places, the efficiency of power supply can be largely strengthened.

In this paper, we thus propose an efficient power supply system to converge the electromagnetic wave to a specific area in the 2D communication sheet. To make the electromagnetic wave converge on a specific area in the 2D sheet, we need to adjust the signal phases of inputs. Through changing the phase of every input signal, the optimal phase value for every input signal can be obtained to maximize the output power. We also evaluate the system performance by both computer simulation and realistic measurement of the output power over the developed 2DCS.

The rest of this paper is organized as follow. Section II briefly reviews the related works and Section III overviews the 2DCS. Section IV describes the proposed efficient power supply system in the 2D communication and numerical simulations. The experiment settings, scenarios, results are described in Section V. The last section concludes the paper.

II. RELATED WORK

A dearth of research has been published in relation to a surface as medium for power and networking. The core idea was first inspired by Scott et al. in October 1998 at the Laboratory for Communications Engineering, Cambridge University. Scott et al. [1] named their idea as "Networked Surface." The Network Surface is composed of cleverly placed tiles. Objects can be connected to the surface through circular pads designed to map with connection points onto the tiles. The drawback of the Networked Surface is the complexity: the network has to manage a large number of tiles

in the surface, which leads to complex negotiation in between tile's connection points and objects.

Lifton and Paradiso have proposed Pushpin Computing system [2]. They use a surface with pushpins and layered conductive sheets, where direct contact to the conductive layers in the board is used to obtain power. Networking is established locally via infrared and capacitive coupling, with neighboring pushpins in a closed (about 10 cm) range. The pins are required to be close to each other, and the network routing needs to be completely handled in a distributed fashion, which increases the complexity a great deal for use as a network in home environments. To envisage high-speed networking capabilities,

Laerhoven et al. [3] proposes that the conductive layer can be used as a bus network for pins. Instead of using pin-shaped connectors, Sekitani et al. [4] have successfully manufactured a large-area power transmission sheet by using printing technologies. The position of electronic objects on the sheet can be contactlessly sensed by electromagnetic coupling using an organic transistor active matrix. Power is selectively fed to the objects by an electromagnetic field using a plastic MEMS-switching matrix. The major disadvantage of this system is the issue of capacitive coupling. This is because it is difficult for people to put together the receiver on the exact position on top of the transmitter.

To tackle the mismatching problem on the connector, Minamizawa et al. [5] introduces a simple 2DCS whereby a proximity connector touches the surface freely without restraint for both power supply and data transmission. In the previous works [6]-[7], the 2DCS has achieved the power supply of tens of mW wherever the devices is put on the 2D communication sheet, by spreading the electromagnetic wave thoroughly in it. To raise the transmission power to several watts, the efficiency of power supply for the 2DCS needs to be largely improved. Meanwhile, the leakage problem of electromagnetic wave should also be considered for the 2DCS.

III. 2D COMMUNICATION SYSTEM

The 2DCS consists of two components: a sheet and a connector. Figure 1 illustrates the basic structure of the 2D sheet, which composes of four layers: solid conductive (S-) layer, dielectric (D-) layer, mesh conductive (M-) layer and protection (P-) layer. The conductive fabric is usually copper or aluminum, whereas the dielectric material is polystyrene. The purpose of P-layer in Fig. 1 is to protect human directly in contact with the M-layer. With this layered composition, an electromagnetic wave can be confined within the 2D sheet depending on the relative permittivity of D-layer and the mesh size of M-layer. The inter-stripe distance and the stripe width of M-layer are 7 mm and 1 mm for a 2.4 GHz electromagnetic wave. However, the electromagnetic wave still can seep out from the surface of 2D sheet. We call this phenomenon as 'evanescent wave'. The evanescent wave is formed when the electromagnetic wave inside the 2D sheet is reflected off the surface. The energy flow of evanescent wave is parallel to the input direction of the electromagnetic wave. Meanwhile, the connector is an antenna that an electromagnetic wave is

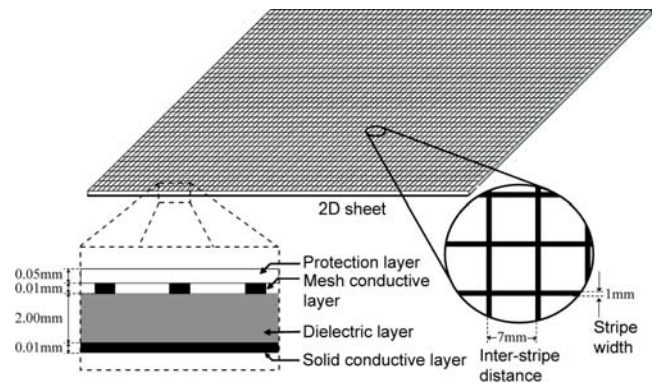


Figure 1. 2D sheet construction.

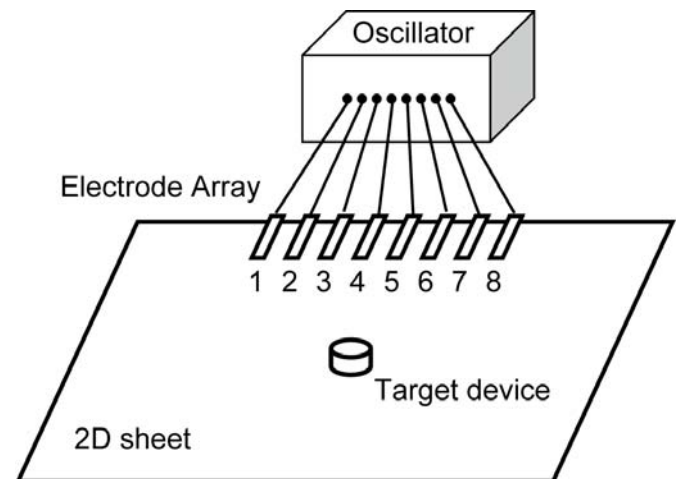


Figure 2. The outline chart of the proposed power supply system

extracted from or inserted into the 2D sheet. Since the connector is one type of antenna, the design of the connector is not described in this paper.

IV. AN EFFICIENT POWER SUPPLY SYSTEM FOR 2D COMMUNICATION

It is known that in the three-dimensional (3D) space, the electromagnetic wave can be settled to a specific area by arranging the transmission electrode array at equal intervals. Based on the same principle, in the 2D sheet, the electromagnetic wave can also be converged to a specific area by adjusting the phases of two or more input signals. If it is true, the efficiency of power supply for the 2DCS can be largely improved, by converging the electromagnetic wave to the place where the device is put on the top of the 2D sheet. To confirm that, we build up a 2DCS that concentrates the power on a specific position by controlling the phase of every input signal. Meanwhile, in order to achieve a relatively big output power to activate the devices, it is needed to raise the input power. However, when the input power is increased, the leakage of the electromagnetic wave from the 2D sheet becomes a serious problem [7], and especially the peak value of electromagnetic wave is severely limited. To alleviate this

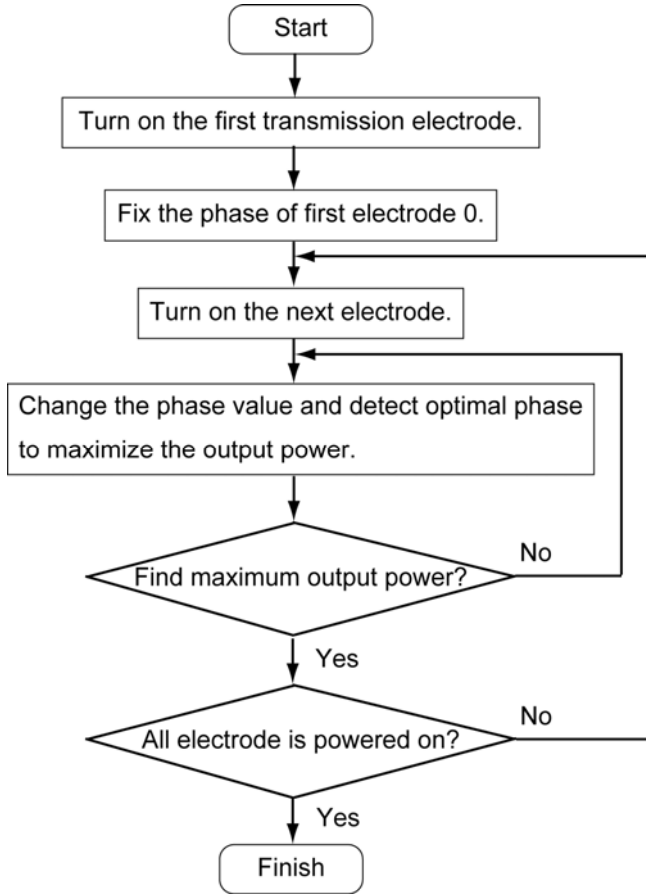


Figure 3. The flow chart to obtain the optimal input phase.

problem, we here increase the number of input signal to decay the magnitude of every input.

Figure 2 shows the outline chart of the proposed phase control system. To make the electromagnetic wave converge on a specific area in the 2D sheet, the output power is measured with multiple input signals. Through changing the phase of every input signal, the optimal phase value for every input signal can be obtained to maximize the output power. The procedure finding the optimal phase value for every input signal is described in Fig. 3. Since the electrodes located around the center may largely affect the output power, their phases should be first decided. We here start the adjustment from the 4th electrode by turning it on, and fix its phase to 0. We then turn on the next electrode (5th), and change its phase to find the optimal value that maximizes the output power. In the similar way, we turn on the input electrode in order to “6-3-2-7-8-1”, and find the optimal phases of the input signals one by one. Therefore, the maximum output power can be finally obtained when the last electrode is turned on and its optimal phase value is found.

A. Propagation Model in 2D Sheet for Numerical Simulation

In this section, we describe how the electromagnetic wave can be converged to a specific area in the 2D sheet. To approximate the electromagnetic waves within the 2D sheet

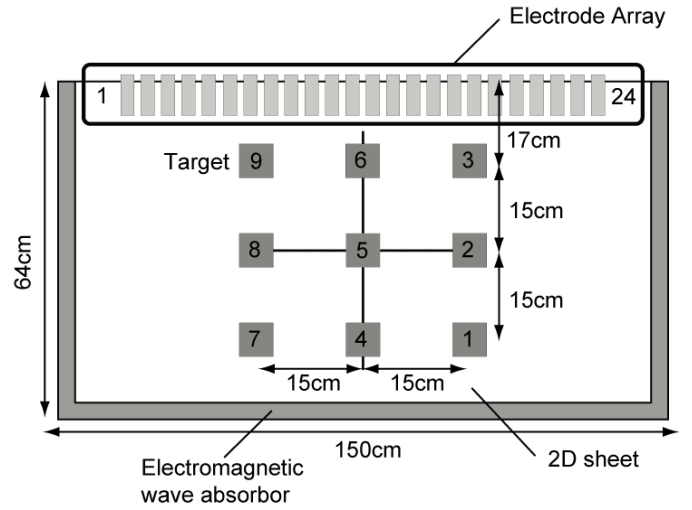


Figure 4. Focusing target on 2D sheet

by cylindrical waves, we use the Hankel functions of the first and second kind to express inward- and outward-propagating cylindrical wave solutions of the cylindrical wave equations. An outward-propagating cylindrical wave radiated from an electrode is described as the second kind of the Hankel function.

$$H_0^{(2)}(x) = J_0(x) - iY_0(x) \quad (1)$$

where $J_0(x)$ and $Y_0(x)$ are the first and second kind of Bessel functions. Converging waves are described as a combination of cylindrical waves from the input electrodes.

$$Z_{\text{total}} = \sum_n H_0^{(2)}\left(\frac{2\pi r_n}{\lambda}\right) e^{-i\theta} \quad (2)$$

where λ is the wave length, n is the index of electrode, θ_n is the phase shift of the wave from each electrode and r_n is the distance from each electrode.

The electric power P is proportional to the absolute value of square of Z_{total} .

$$P \propto |Z_{\text{total}}|^2 \quad (3)$$

V. EXPERIMENTAL PROCEDURES AND MEASUREMENT RESULTS

In this section, we actually develop a power supply system using phase control, in order to verify the feasibility of the proposed 2DCS. We investigate the performance of the developed 2DCS, focusing on nine different points as shown in Fig. 4, and adjust the phase of every input signal to converge the electromagnetic wave on them. To confirm whether the output power is concentrated on each point, we also measure the output power over the whole sheet.

A. Experimental Setup and Description

Figure 5 shows the experiment setup that mainly consists of input electrodes, a connector plate, three dimensional positioned and a power meter. An anti-reflection edged sheet

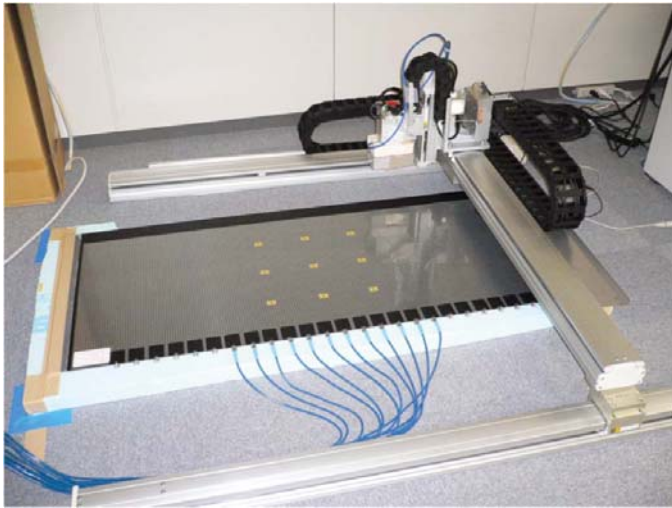


Figure 5. Experiment setup

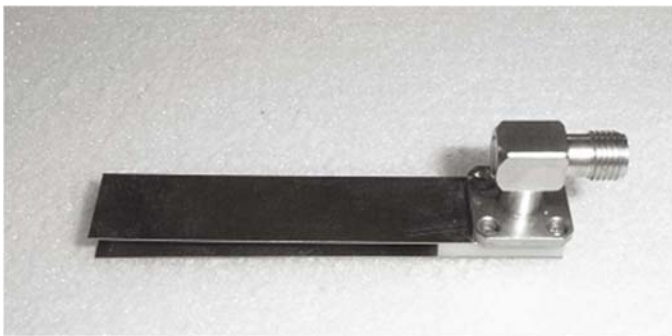


Figure 6. Transmission electrode

is used to diminish the effect of standing wave, which is a resultant of the reflected waves and the original wave. The size of the 2D sheet is 150 cm × 64 cm and measurement area is 50 cm × 45 cm.

An input signal is generated from the generator, which consists of 24 small generators. The small generator has a phase controllable switch that initiates the start of input signal in the phase range from -180 to 180 degree with the step of 1 degree. The input signal frequency that is set to 2.4 GHz is sent to a SMA connector via a coaxial cable. The SMA connector is directly clipped on the side of 2D sheet. 8 of 24 transmitting electrodes (from number 9 to 16) are used in this experiment (Fig. 4). The size of transmitting electrodes is 12 mm × 47 mm (Fig. 6). When transmitting electrode input the electromagnetic wave into 2D sheet, electromagnetic wave is reflected by the edge of 2D sheet. This causes standing wave in the 2D sheet. To converge the electromagnetic wave from the electrodes efficiently, the standing wave needs to be decreased. To decrease the standing wave, we attach a band-like attenuation mechanism on the edge of 2D sheet. Attenuation mechanism consists of electromagnetic wave absorber. Figure 7 shows cross-section view of the attenuation mechanism on the edge of 2D sheet. It is easy to implement the attenuation mechanism by simple structure.

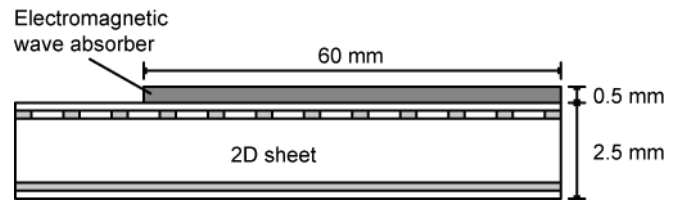


Figure 7. Attenuation mechanism

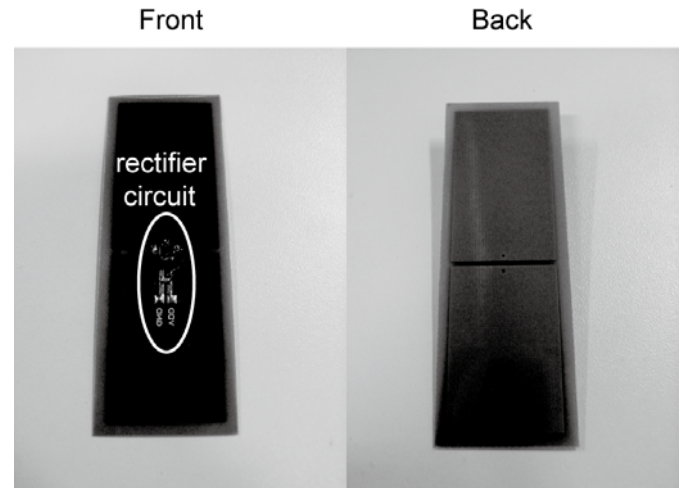


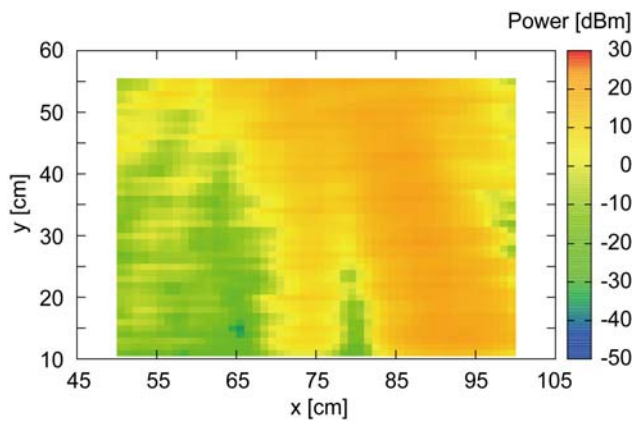
Figure 8. Receiving connector plate for power measurement.

The size of receiving connector is 25 mm × 70 mm (Fig. 8). The received power is converted to direct current by built-in rectifier circuit and its output is terminated with 70 ohm load resistance. We measured the voltage V between both side of the load resistance R and calculate the power P with the equation $P = V^2/R$.

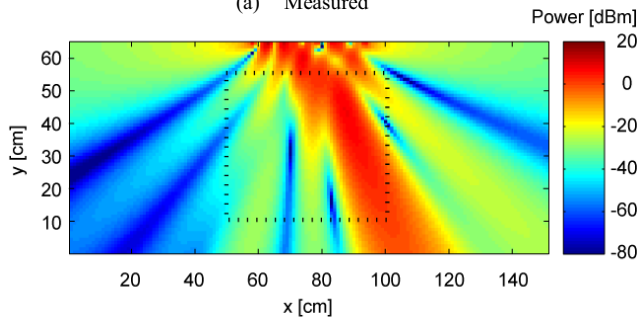
B. Measurement and Simulation Results

By using the optimal phase value for every input signal, we then measure the selected rectangular area of 2D sheet, to confirm whether the microwave in the 2D sheet concentrates on the target area. The receiving connector plate is moved with the measurement step of 10 mm for X-axis and Y-axis. Figures 9(a), 10(a) and 11(a) show the measured power distribution of the areas of the 2D sheet, by controlling the input phase value. For the measured area, we can clearly identify the power is condensed around the target area of the 2D sheet for nine targets. It is obviously identified the pattern of measured power contours for the selected area.

In this experiment, the total supplied power is 8W (1W × 8). The measured powers on target and maximum measured power in each case that electromagnetic wave converges on the target area are shown in Table I. Although the measured power becomes small far from the transmission electrode, large amount of power can be supplied to all targets. Near the electrode or more, the smaller the difference of electric power of maximum and target area is. Proposal scheme can supply two times or more electric power compared with the case of

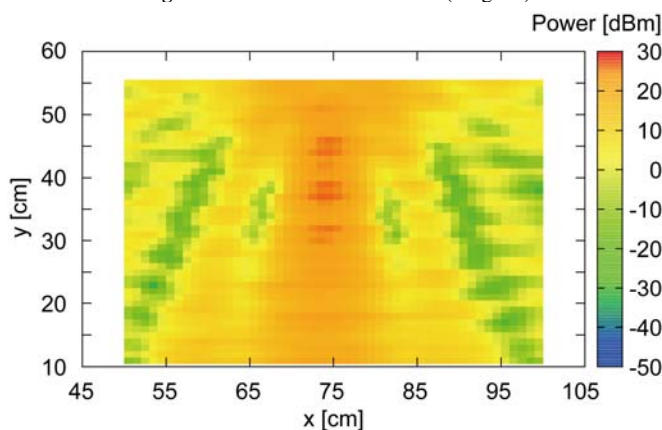


(a) Measured

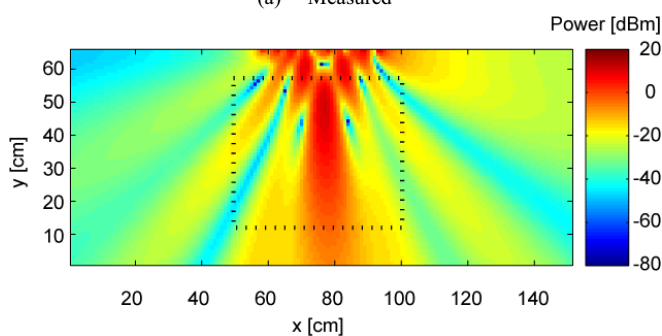


(b) Simulation

Figure 9. Power distribution in dB (Target 1).

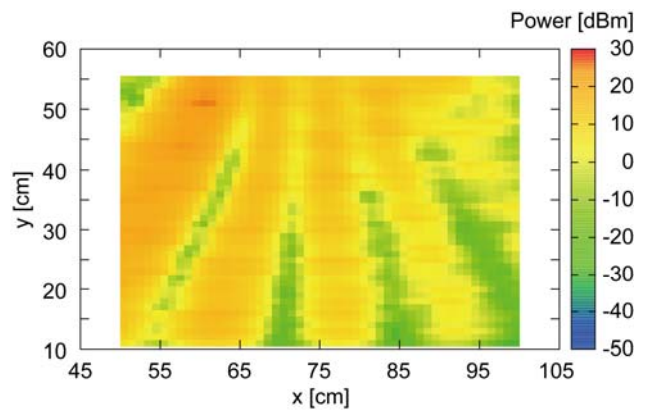


(a) Measured

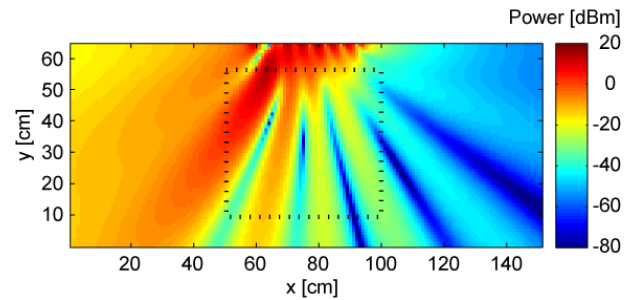


(b) Simulation

Figure 10. Power distribution in dBm (Target 5).



(a) Measured



(b) Simulation

Figure 11. Power distribution in dBm (Target 9).

coordinate phase. Especially, the proposal scheme can supply larger electric power than coordinate phase scheme even on the edge of the 2D sheet. Based on the measured power distribution, we can summarize that supplying power is concentrated on the target area of 2D sheet through using 8 input power points.

Proposal power transmission system consists of signal generator, coaxial cables, transmission electrodes, 2D sheet, and receiving module (proximity coupler and rectifier circuit). Consequently, product of transmitting efficiency of each component is equal to the system-wide transmitting efficiency. It is possible to supply larger amount of power to the device on the 2D sheet by improving transmitting efficiency of each component and connecting receiving modules in parallel, without larger amount of power input in transmission electrodes.

On the other hand, numerical simulations are performed on MATLAB. The parameters are shown in Table II. In these simulations, 8 electrodes are used. The phase sets are intended to make waves be converged at nine targets illustrated in Fig. 4 and identical to the sets used in the experiment. The simulation results for three of nine targets (1, 5 and 9) are shown in Figs. 9(b), 10(b) and 11(b). Input electrodes are placed on the top edge of each image, and dashed rectangle over each image indicates the experimental measurement area (500mm x 450 mm). These simulation results show that it is possible to converge to the target by phase control. The measurement results are same tendency as the simulation in all targets (Figs. 9(a), 10(a) and 11(a)). From these simulation

Table I. Measured power in the case of each target

Target (x, y)	Measured power				Ratio (Proposal /Coordinate)
	Proposal		Coordinate phase		
	(dBm)	(mW)	(dBm)	(mW)	
1(90, 17)	24.7	295.8	15.9	38.6	7.7
2(90, 32)	23.5	225.9	14.1	25.5	8.9
3(90, 47)	25.5	354.0	19.3	85.3	4.2
4(75, 17)	26.1	409.3	22.2	164.1	2.4
5(75, 32)	26.3	429.5	19.5	88.9	4.8
6(75, 47)	27.0	498.9	21.8	151.4	3.2
7(60, 17)	23.9	246.6	15.7	37.2	6.6
8(60, 32)	22.7	186.2	12.6	18.3	10.2
9(60, 47)	25.8	380.2	17.8	60.8	6.3

Table II. Simulation conditions

2D sheet size	1500 mm x 640 mm							
Wave length	110 mm							
Number of electrodes	8							
Electrode interval	50 mm							
Target (x, y)	Phase in degree							
	CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8
1 (90, 17)	70	172	-62	0	62	-120	-125	-157
2 (90, 32)	-6	97	-115	0	124	-125	-59	-6
3 (90, 47)	-73	47	-159	0	127	-115	-165	-174
4 (75, 17)	-157	-75	-16	0	-7	-6	-51	-125
5 (75, 32)	158	-110	-10	0	1	-4	-59	-172
6 (75, 47)	88	-161	-47	0	-6	-48	-136	114
7 (60, 17)	93	82	70	0	-57	-98	115	-6
8 (60, 32)	76	64	65	0	-109	158	10	-113
9 (60, 47)	139	144	107	0	-147	85	-63	-174

and experimental results, it is possible to calculate the valid power distribution in 2D sheet through not solving the complex electromagnetic field computation but using relatively simple propagation model.

VI. CONCLUSIONS

In this paper, we developed an efficient contactless power transmission system by using phase control of input electrode array for 2D communication. The developed system aims at enhancing the efficiency of power supply in 2D communication by converging the electromagnetic wave on the place where the device is placed. In order to verify the feasibility of the proposed system, we perform numerical simulation on MTALAB and develop a power supply system using phase control. The results of both simulation and experiment revealed that the output power is well concentrated on three nine points of 2D sheet by adjusting the phases of every input signal. Since at the present stage we manually perform the phase control of input electrode array, a future work is required to automatically adjust the phase of all

input signals to converge the electromagnetic wave on the arbitrary position of the 2D sheet. Furthermore, position estimation with a high degree of accuracy using phase information is also future work.

REFERENCES

- [1] J. Scott, F. Hoffmann, M. Addlesee, G. Mappt, and A. Hopper, "Networked surfaces: A new concept in mobile networking," *ACM Mobile Network and Applications*, vol.7, no.5, pp.353–364, 2002.
- [2] J. Lifton and J. Paradiso, "Pushpin computing system overview: A platform for distributed, embedded, ubiquitous sensor networks," in *Proc. Pervasive Comp., Lecture Notes in Computer Science (LNCS)*, vol.2414, pp.139–151, 2002.
- [3] K.V. Laerhoven, N. Villar, A. Schmidt, and H.W. Gellersen, "Pin & play: The surface as network medium," *IEEE Commun. Mag.*, vol.41, no.4, pp.90–95, 2003.
- [4] T. Sekitani, M. Takamiya, Y. Noguchi, S. Nakano, Y. Kato, K. Hizu, H. Kawaguchi, T. Sakurai, and T. Someya, "A large-area flexible wireless power transmission sheet using printed plastic MEMS switches and organic field-effect transistors," in *Proc. IEEE Int. Electron Devices Meeting (IEDM) Conf.*, pp. 287–290, 2006.
- [5] K. Minamizawa, Y. Makino, and H. Shinoda, "Two-dimensional signal transmission for networked sensing," in *Proc. SICE Annual Conf.*, pp.3816–3819, 2005.
- [6] Hiroto Itai, Bing Zhang, and Hiroyuki Shinoda, "Method of simultaneous signal-power transmission using surface microwave," in *IEICE Technical Report on Ubiquitous and Sensor Networks (USN)*, vol.51, pp.115–118, 2007.
- [7] Azman Osman Lim, Hiroto Itai, Hiroyuki Shinoda, Bing Zhang, "Measurement of the Leakage of Electromagnetic Field Distribution over 2D Communication System," in *Proc. Global Symposium on Millimeter Waves (GSMM)*, 2009.