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Node Localization in the "Two-Dimensional Communication" Networks Based on Electric Field Pattern Measurement

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Abstract: In this paper, we propose a method for node localization in the "Two-Dimensional Communication" Networks. Our group has developed the novel communication technology named "Two-Dimensional Communication (2DC)". On the 2DC sheet, sensor nodes can communicate with each other and acquire electricity without any direct electrical contact. The localization function on the 2DC sheet makes it easy to install and maintain sensor nodes in a large network. In addition, it enables us to design various location-aware applications of ubiquitous computing and human-interface. We show the fundamental principle and current results of our project.

Keywords: Node Localization, Two-Dimensional Communication, Sensor Networks, Ubiquitous Computing

Fig. 1 The demonstration of both signal transmission and power supply through the Two-Dimensional Communication sheet. The right PC displays the movie data sent from the left one. The LEDs and the small fans receive electricity from the power source shown in the upper–left of the picture via the 2DC sheet.

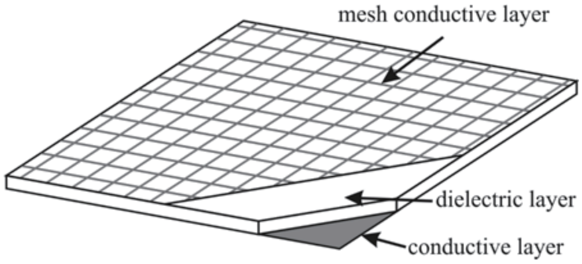


Fig. 2 The structure of the 2DC sheet. Two conductive layers sandwich a dielectric layer. The upward-facing side of the conductive layer has a meshed structure.

1. INTRODUCTION

Our group has developed "Two-Dimensional Communication" for sensor networks [1] (Fig. 1). Sensor nodes placed on the Two-Dimensional Communication (2DC) sheet can communicate with each other and receive electricity anywhere on the sheet without any direct electrical contacts to it. Signals and electricity are transmitted with microwaves propagating in the 2DC sheet two-dimensionally. Currently, 54 Mbps communication and 10 W powering are achieved. Two-Dimensional Communication provides wireless and batteryless ubiquitous environment.

In this paper, we propose a method for the node localization in the "Two-Dimensional Communication" networks. One general problem in sensor networks is node localization. It is difficult to specify the positions of large numbers of nodes in installing them in the facility. Even for relatively small numbers of nodes, if they are placed at arbitrary positions or their positions are time-varying, some positioning mechanism is required to relate each node to its position.

In addition, the localization function on the 2DC sheet is important for ubiquitous computing or human-computer interface. It is possible to provide the location-specific functions to various network devices like laptops, PDAs, or mobile phones placed on the 2DC sheet. We can also use the location information of these devices as user interfaces.

The concept using two dimensional surface for communication, powering, and localization has been proposed by Scott et al. [2], Kishino et al. [3], or Kurakake et al. [5]. In research [2], communication, powering, and positioning functions are achieved on Networked Surface which is implemented by combining small conductive pads two-dimensionally. Objects on the surface can communicate or receive electricity through direct electrical conduction between the pads. The positions of the pads which touch the objects correspond to the objects' locations. Research [3] focuses on the positioning function in Pin&Play system proposed by Laerhoven et al. [4]. Pin&Play provides communication and powering using a pair of large conductor and a small pin. The vision-based method is used to detect the position of the pin. Kurakake et al. proposed Magic Surfaces in [5]. They connect small modules for communication and localization two-dimensionally. The communication and localization are realized by using small coils embedded in the modules, which generate and sense the magnetic field. In addition, positioning systems on two dimensional surfaces are also developed in the field of Human-Computer Interfaces. For example, Microsoft Surface [6] uses a camera placed at the backside of the display to detect the positions and orientations of various devices on it. Data Tiles proposed by Rekimoto et al. [7] use RFID tags embedded in the surface to detect the positions of tiles on the surface.

This paper begins with a description of our approach for localization and design goals. Section 3 describes the position information coding scheme on the 2DC sheet which realizes the design goals. In Section 4, we show the principle of the position information detection through the electric field measurement. We analyze the electromagnetic field above the 2DC sheet and determine the shape of the meshed conductive layer. Based on the analyses, we conducted a fundamental experiment to confirm the feasibility of the proposed method. The details are written in Section 5.

2. APPROACH

2.1 System overview

The basic idea of the proposed node localization method is inspired by a pen-positioning system by Anoto [8]. Anoto's digital pen identifies its own position on a special paper by capturing the fine pattern printed on it with an optical device. The printed pattern at each location is unique so that the pen can identify its location. On the other hand, in our framework, the location detector identifies its own position on the 2DC sheet by capturing the conductor pattern on it with an electric field sensor.

The 2DC sheet has three layers. Two conductive layer sandwich a dielectric layer (Fig. 2). Microwaves can propagate in the dielectric layer two-dimensionally. The top conductive layer has the meshed structure. When microwaves propagate in the dielectric layer, the meshed pattern generates the evanescent waves immediately above the top conductive layer. Sensor nodes placed on the 2DC sheet can communicate with each other and acquire electricity by coupling to the evanescent waves with special surface connectors. The two-dimensionally amplitude distributions of the evanescent waves depend on the meshed conductive pattern. If the local meshed pattern is unique to each location on the 2DC surface, the amplitude distributions of the evanescent waves also express the location information. Therefore, we can achieve the localization through the measurement of the electromagnetic field pattern above the 2DC sheet.

One of the features of our method is self localization. This means our method needs no external devices like cameras. With only an electric field sensor attached to a node and a small modification to the existing 2DC sheet, the nodes can easily obtain precise position to an accuracy of 1 mm. In addition, thin obstacles like a piece of paper can be placed between the 2DC sheet and the sensor nodes.

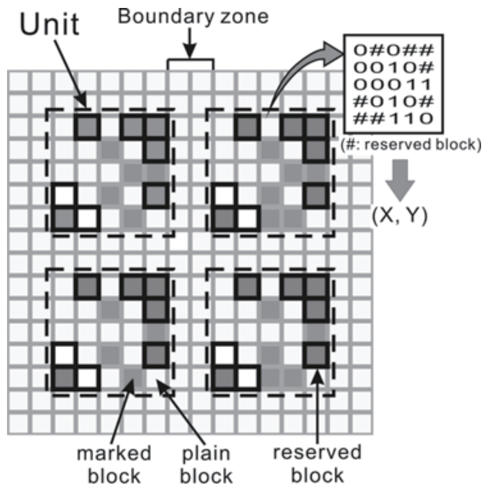


Fig. 3 The position encoding scheme on the 2DC sheet.

2.2 Design goals

Developing the localization method, we set the following design goals for the practical use in sensor networks or ubiquitous computing.

- Unique location identification on the 2DC sheet larger than 10 m square.
- Millimeter precision of position sensing.
- The size of the location detector is about 10 cm square or smaller.

In the following sections, we describe the detail of our method that achieves these goals.

3. POSITION INFORMATION ENCODING

As described in Section 2, we use the conductor pattern of the top conductive layer of the 2DC sheet as the location marker. In order to encode the position on the 2DC sheet, the pattern of the mesh is designed as follows.

The top conductive layer of the 2DC sheet has a meshed structure as shown in Fig. 2. In our position encoding scheme, one block of the grid represents one bit of information by changing its shape. We call the modified block a "marked block," and the non-modified block a "plain block." We make a "Unit" which is constructed with 5×5 blocks. One Unit represents its X-Y coordinate value on the 2DC sheet. There are 8 reserved blocks consisting of 6 marked blocks and 2 plain blocks in each Unit. The reserved blocks represent the boundary and the orientation of a Unit. The other 17 blocks correspond to the bit pattern of the binary X-Y coordinate value respectively. For separating neighbor Units, double width lines containing only plain blocks are used. We call this area a "Boundary zone." It is easy to detect and identify the Boundary zone because the reserved blocks prevent any Unit from having double-width-plain-block lines in the Unit.

We calculate how large area the proposed 2DC sheet can cover. A Unit has 17 bits information. Therefore we

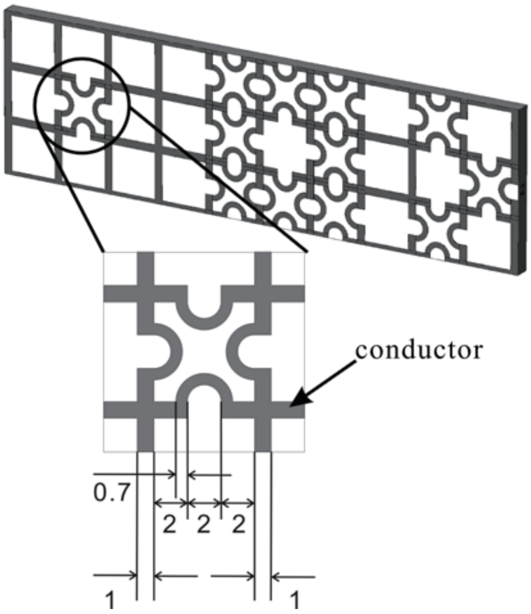


Fig. 4 One of the simulation models of a 2DC sheet for analyzing the electromagnetic field above the surface of the sheets. In this model, a marked block is realized with winding lines.

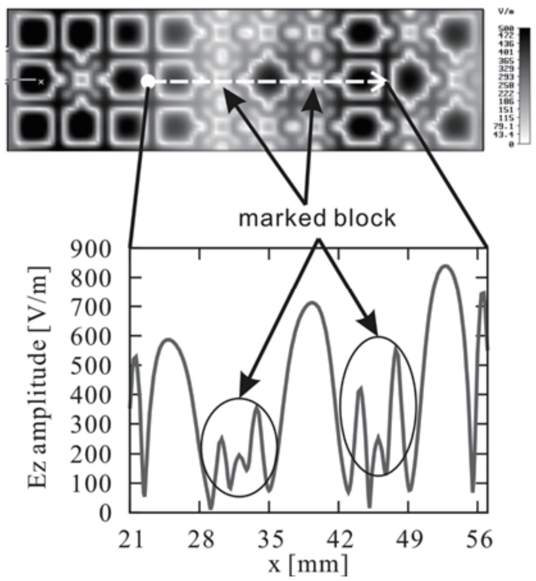


Fig. 5 The result of the simulation. The model is shown in Fig. 4. Upside: The time average of the vertical electric field 1 mm above the sheet surface is shown. The contrast of E_z amplitude in the single gird is apparently different between the plain and marked block. Downside: The E_z amplitude on the dash line shown in upside.

can arrange 2^9 Units laterally and 2^8 lengthways. If we assume a d = 7 mm pitch mesh sheet as used in [1], one Unit occupies the area of 49 × 49 mm^2, including the Boundary zone. Hence, the maximum area covered with the sheet is about 25 × 12.5 m^2. This is sufficiently large for our purpose of localization for room scale networks.

In addition, we evaluated the minimal size of the detector that always covers at least one whole Unit. From the simulations, we concluded that a 11 × 11 cm^2 detector can cover one whole Unit everywhere on the sheet regardless of the orientation. The detector size is almost enough small for our design goals.

Once the detector finds a whole Unit, it can detect its own precise position and orientation from the alignment of blocks as well as identifying the code. The accuracy of detected position depends on the spatial resolution of the detector. Sub-mesh precision is possible by a high-resolution detector.

4. PATTERN READING

4.1 Measurement principle

In our localization scheme, we detect the position information encoded on the 2DC sheet with the electromagnetic field measurement. The electromagnetic field above the 2DC sheet surface is written in forms as

$$f(x,z) = A\exp(-jkx)\left(\sum_{n=-\infty}^{\infty} B_n(z)\exp\left(j\frac{2\pi n}{d}x\right)\right)$$
$$= AC_0\exp(-jkx)\exp(-k_1 z)$$
$$+ A\exp(-jkx)\sum_{n\neq 0} C_n \exp\left(j\frac{2\pi n}{d}x\right)\exp\left(-\frac{2\pi n}{d}|z|\right) \quad (1)$$

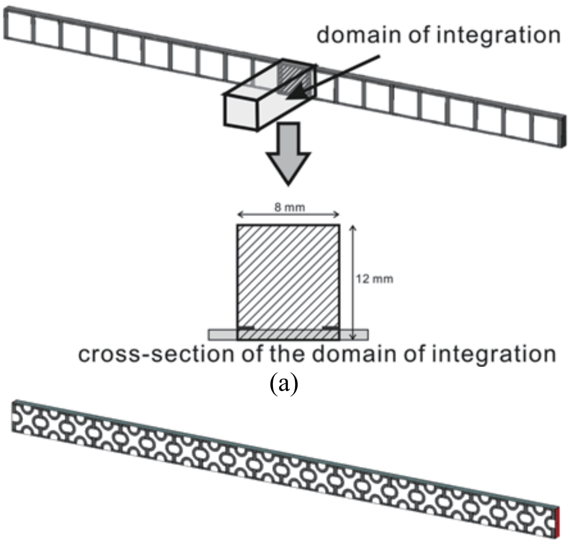
along the surface, where $d << 2\pi/k$, the electromagnetic waves run along x direction, and k is the wavenumber of the two dimensional electromagnetic wave. The difference of conductor shape between the plain and the marked blocks corresponds to the difference of C_n ($n \neq 0$).

First, we examined that which component of the electromagnetic field is favorable to detect the difference between the marked and the plain blocks. The simulation and experiment results suggested that the vertical component of the electric field E_z is suitable for the measurand. E_z is the only component whose amplitude pattern is insensitive to the direction of the signal wave propagating in the 2DC sheet. Additionally, E_z provides clear difference in $C_{\pm1}$, while the magnetic field was found to have small energy in $C_{\pm1}$. That is, E_z amplitude pattern contains a larger low spatial frequency component than the magnetic field has. This means that we can read E_z pattern with a lower resolution detector. This feature is preferable for our purpose in terms of the simplicity of the sensor.

4.2 Design of the marked block

Based on the discussion in 4.1, we designed the shape of a marked block through electromagnetic field simulations. We use the MW-STUDIO software (AET Japan Inc.) for the analyses.

The achieved design is shown in Fig. 4. We express a marked block by curving the grid line. We show the result of the simulation conducted by using the model in Fig. 5. The details of the analysis model are follows. As to the dielectric layer, the relative permittivity ε_r was 1.5 and the thickness was 2.0 mm. At the bottom of the di-



(a)

(b)

Fig. 6 The simulation models to evaluate the inductance of the proposed marked block. (a) is the basic model with all plain blocks. In (a), the region for the volume integration of magnetic energy density is shown. The dimensional parameters were chosen so that the sheet inductance of model (b) was the closest to that of the normal mesh (a). The detailed configuration is shown in Fig. 4.

electric layer, perfect conductive boundary condition was used, instead of modeling the physical conductive layer. The top conductive mesh layer was a d = 7 mm pitch mesh with 1 mm width conductor. 2.4 GHz electromagnetic waves were applied from the one side of the 2DC sheet model. We assumed no reflection occurs at the edge of the sheet.

The result shown in Fig. 5 is the vertical component amplitude of the electric field 1 mm above the 2DC sheet model surface. The result shows the apparent difference in C_1 between the plain and the marked blocks, that is, the contrast of E_z amplitude in the single block is apparently different between both cases. The difference can be detected by spatial sampling with a period smaller than $d/2$.

In addition, we tuned the marked block shape to avoid the unexpected reflection of electromagnetic waves at the boundary of the plain and the marked blocks. To achieve this, the macroscopic sheet inductance of the top conductive layer should be kept constant [1]. The sheet inductance is evaluated by the magnetic field energy

$$U_{\mathrm{B}} = \int_{\mathrm{v}} |\mathbf{B}|^2 d\mathbf{v} \qquad (2)$$

induced by the given surface current I. We conducted some simulations to evaluate the sheet inductance. The analysis models are shown in Fig. 6. A line of blocks was used to obtain the inductance of a block. In the model, the domain of the integration in (2) is the rectangular solid shown in Fig. 6(a). This solid is the height of 12 mm from the bottom of the sheet within a single block area. We obtained the value of U_{B}/I^2 in this single block region. We changed the line width of the marked block shown in Fig. 4, and found that the parameters shown in Fig. 4 realize the closest value to that of the plain block.

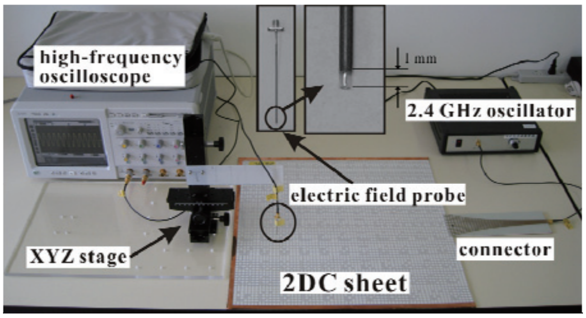


Fig. 7 The setup of the experiment. The size of the 2DC sheet is 50 cm squire. We applied 2.4 GHz 2 W microwaves to the 2DC sheet through the connector with a horn structure. The detection of the electric field on the sheet surface is realized with a miniature electric field probe. The probe is fabricated by peeling the metallic shield of a semi-rigid cable. We recorded the output with a high-frequency oscilloscope.

5. EXPERIMENT

We conducted an experiment to confirm that the designed meshed block actually modulates the vertical electric field amplitude.

The setup for the experiment is shown in Fig. 7. The 2DC sheet includes marked blocks whose shape is designed in Section 4. We used a miniature electric field probe as a sensor. It detects only one component (axial direction) of an electric field. We connected the probe to a high-frequency oscilloscope and recorded the root mean square value of the output. We scanned in the measurement region shown in Fig. 8 with the single probe.

The result of the measurement is shown in Fig. 8. The difference between the marked and the plain blocks is clearly observed. We should notice the difference between the simulation and the experimental results. The simulation showed the contrast of E_z amplitude in a single block was different between the plain and marked blocks. The theory tells us that the average of E_z is common between both cases. On the other hand, the detected signal amplitude was strong simply over the metal area of the top layer pattern, in the experiment.

The disparity is ascribed to the interaction between the probe and the sheet surface. When the probe is placed near the sheet, electric field is expected to be induced between the probe conductor and the mesh conductor, which was not considered in the simulation. The property found in the experiment seems favorable for practical uses in which a low resolution detector detects the code stably. We can also obtain more accurate position by the conductor area pattern measured

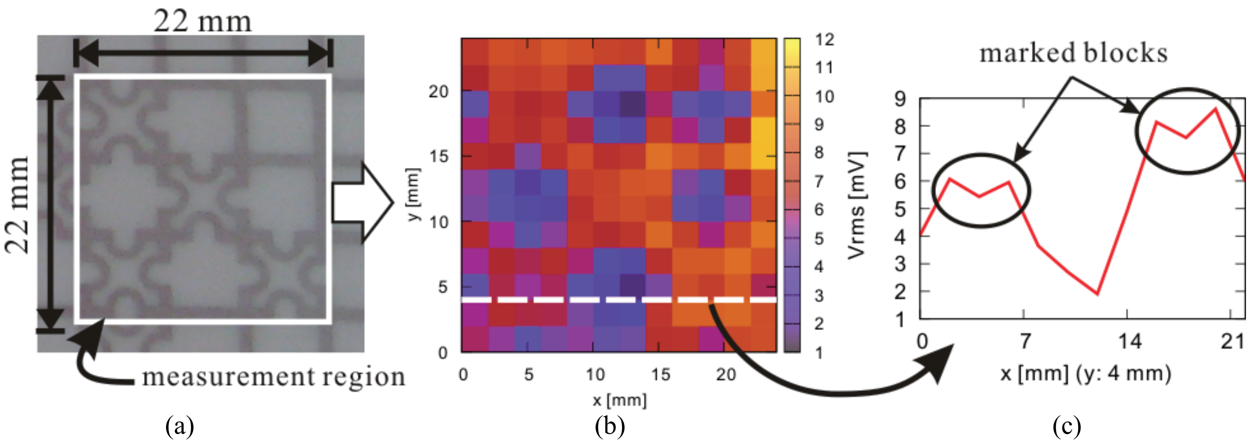


Fig. 8 The result of the experiment. The measurement region shown as a white box in (a) is 22×22 mm^2. In this region, we measured the vertical electric field 1 mm above the 2DC sheet surface with a 2 mm interval. (b) shows the distribution of the electric field amplitude. From this pattern, we can distinguish marked blocks from plain blocks clearly. The graph of (c) corresponds to one dimensional data on the white dashed line (y = 4 mm) shown in (b). One can decide the threshold between marked blocks and plain blocks. Since we can detect mesh conductor pattern, it is expected that we can obtain more accurate position information by the details.

with a higher resolution detector.

6. CONCLUSION AND FUTURE WORKS

In this paper, we proposed a method of self localization of sensor nodes distributed on the 2DC sheet. We showed our approach and the design goals, and described the scheme to encode the position information on the 2DC sheet. We confirmed that the scheme can achieve our design goals. Then, we described the physical detection of the position code on the 2DC sheet. We showed that the vertical component of the electric field E_z is favorable for detection of one bit of information that one block represents. We designed the marked block shape that modulates E_z amplitude effectively and do not affect the communication and powering properties of the existing 2DC sheet. Finally, we confirmed the validity of the design through the experiment. From the result, we can distinguish the difference between the marked and the plain block in the 2DC sheet.

In future, we should implement the electric field sensor array which does not need scanning to obtain the large area electric field amplitude pattern. The required resolution of the array is smaller than 2.47 mm, considering the rotation on the sheet. The diameter of the electric field probe used in Section 5 is 1.2 mm and enough thin to achieve the resolution. We are trying to downsize the measurement circuit. The diagram of the prototype we are currently developing is shown in Fig. 9.

The next issue is the reflection of the microwaves at the edge of the 2DC sheet. The reflection forms the standing waves in the 2DC sheet. Thus, the output range depends on the position on the sheet. As a solution, we will attach termination registers and the electromagnetic wave absorber at the edges to prevent the reflection.

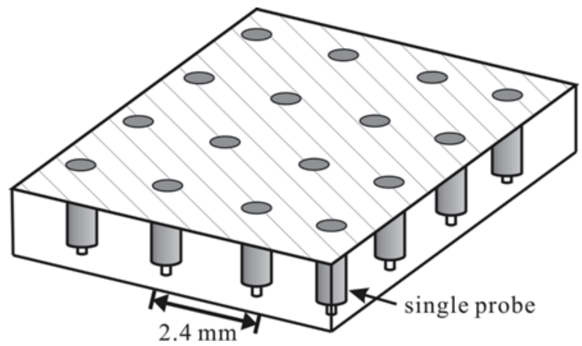


Fig. 9 The diagram of an electric field probe array.

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