CarpetLAN: A Novel Indoor Wireless(-like) Networking and Positioning System

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Abstract. CarpetLAN is a novel indoor wireless(-like) broad-band networking and positioning system. It uses the floor surface and the human body as an Ethernet-cable, and weak electric fields as the transmission media. Portable and wearable devices can connect to the network while the user stands or walks on the floor; connection speed is 10Mbps. Home and office appliances can also access the network if they are just put on the floor. CarpetLAN also provides an indoor positioning function, which is urgently needed for realizing "ubiquitous" communication. This electric field based transmission system yields ultra-micro communication cells, so the positions of humans and appliances can be detected with about 1 meter accuracy.

1 Introduction

In the last ten years, the time we spend accessing the network in our daily life has been greatly expanded by the miniaturization of information devices and improvement of wireless networking systems. In the near future, people will "wear" many devices at all times and utilize networked information and processors as their own knowledge and brain. The "ubiquitous" world will start to emerge, which means all surrounding objects as well as humans and computers will be connected to the network, and we can grasp all events and situations around the world in real-time.

Nowadays, many buildings and rooms already have networking systems. However, for realizing the ubiquitous world, every human and all surrounding objects in the location should be connected to the network constantly. In this case, it is unrealistic to connect all items with cables because it is too much of a bother and destroys mobility. Thus, the "last 1 meter (/foot)" is the important issue of how to connect people and objects to the each room's network outlet.

Radiowave-based local networking systems such as wireless-LANs and Bluetooth seem likely candidates for solving the last 1 meter problem. However, radiowaves often scatter beyond the intended space and interfere with other devices. Therefore, the communication bandwidth allocated to one user will be

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extremely small when many people and objects occupy a small area such as a crowded station or event space. In this case, it is effective to lay many access points which have a small service area (called micro-cell) for assuring bandwidth per user. However, it is impossible to create tiny cells (of less than a few meters) with no dead space between them, even if transmission power control and directional antennas are used. Optical communication is another candidate since it minimizes interference with surrounding devices. Unfortunately, it is also difficult to ensure many peer-to-peer communications with many randomly moving users.

Another unresolved requirement for realizing the ubiquitous world is highly accurate indoor positioning. GPS provides meter-level accuracy on a global basis, but it cannot be used indoors. Wireless-LAN based systems are commonly used, but their positioning accuracy is on the order of 10 meters, when only one access point is used as positioning. Some systems use the strength of radiowaves from multiple access points for increasing accuracy[1]. It is somewhat unstable in operation, however, because of interference with household furniture and the human body. There are highly accurate pointing systems that use ultrasonic sound or infrared rays. Ultrasonic-based systems[2] provide centimeter-level accuracy, though the service area is relatively narrow and they are weak against obstacles. Infrared-based systems[3] can provide both positioning and high-speed data links, but the service area is very narrow and thus it is only being used at information posts or kiosks. As a result, there is no known effective method for realizing both indoor high-speed networks and accurate positioning systems, which is needed for realizing the ubiquitous world.

This paper describes a new method that uses the floor and human body as transmission media (called CarpetLAN) that resolves the above issues. Wearable devices are connected to a tile-carpet style network via the floor's surface and the human body, so that wireless "-like" communication is realized. Objects such as computers and home appliances can also be connected to the network just by "putting" them on the floor. CarpetLAN is a contact-based communication system that uses weak electric fields so that interference caused by signal leakage into adjoining cells is greatly suppressed. Micro-cells of 1 meter size are easily realized by shrinking the tile-carpet size, and sufficient communication bandwidth can be assured even when many users occupy the same room. In addition, a positioning function of about 1 meter accuracy indoors is also realized using CarpetLAN's micro-cell capability. Therefore, CarpetLAN can solve both issues of the last 1 meter and indoor positioning.

Section 2 describes the communication method of CarpetLAN. Extended communication distances and high-speed data links are enabled using high-sensitivity Electro-Optic (EO) sensors. The electric field distributions of some communication situations are shown in simulations. A prototype is shown to offer 10Mbps communication speed and 1-meter level micro-cell capability.

Section 3 introduces the networking and positioning method of CarpetLAN. Simply laying the carpet-units contiguously forms a self-organized network. Each carpet-unit operates as a small gateway, so the positions of mobile devices can be acquired and appropriate packet routing provided. Effective traffic control that matches the user's movements is also established by predicting the user's position based on prior movements.

Finally, an example of the CarpetLAN prototype in operation and remaining issues are shown.

1.1 Related Works

Some surface-based sensing and networking systems have been proposed. *SmartSkin*[4] and *DiamondTouch*[5] detect touching position (and area) with a finger, hand, or arm using an electric field or capacitive sensing system. *WeightTable*[6] and *Active Floor*[7] detect positions of objects on the table and humans on the floor using signal computation of multiple load-cells embedded under the table and floor. *MagicCarpet*[8] uses a PVDF wire matrix to detect human foot positions. Though these systems can detect position(s) on the floor and table, sensors and connecting wires are not modularized, making it difficult to fit real rooms which have various sizes and shapes.

A brick- or tile-based modular system has scalability and easy-installation capability. It also provides an understanding of the entire room shape by gathering connection information of each module. *Z-Tile*[9] enables the detection of pressure and location information by covering the floor with networked sensor units. *Triangles*[10] also detects the connection topology of multiple tiles. However, ordinary systems just detect sensor data and connection information, and do not provide any data transmission between the floor and objects or humans.

Some communication and power supply systems use magnetic coupling between the floor surface and objects. *Magic-Surfaces*[11] provides not only position and orientation detection but also bidirectional communication with floor-mounted objects. It is difficult, however, to communicate with hand-held or head-mounted objects, since the human body cannot be utilized as the transmission route of magnetic fields.

2 System Structure

This section details the communication method of CarpetLAN. **Figure 1** illustrates the basic principle of the communication.

There are two types of transceivers: one is a mobile device such as wearables, PDAs, and appliances; the other is a floor-device mounted in the floor carpet-units. A pair of electrodes is placed on the body-contact side (WB) and the opposite (untouched) side (WG) of a mobile transceiver. Another pair of electrodes is placed on the foot-contact side of the carpet-unit (FB) and the surrounding (untouched) part (FG) of the carpet-unit[3]. Every carpet-unit is a network-node, and all nodes are connected to each other, while groups of carpets are connected to outside networks via one or more room gateways.

[3] 'W'earable-device, 'F'loor-device, 'B'ody-side-electrode, 'G'round(return)-side

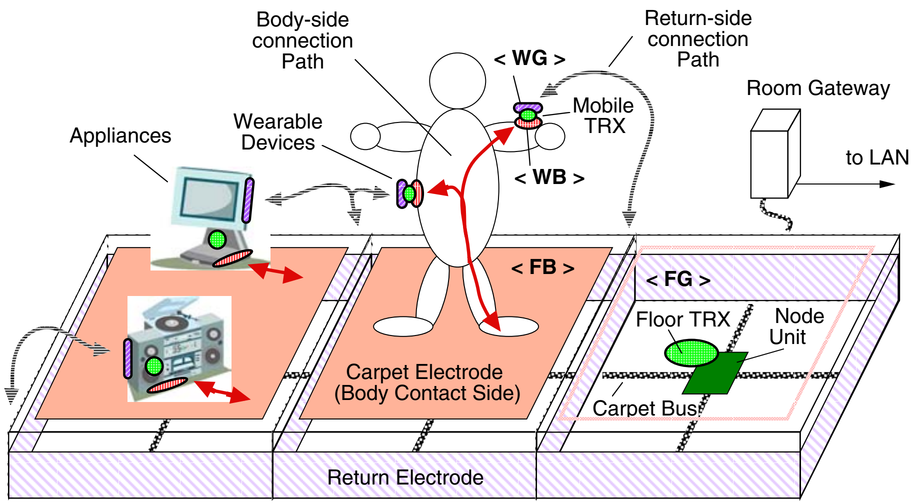

Fig. 1. System architecture.
Each carpet-unit works as a network cell.

To transmit a signal from a mobile device to the floor device, a high-speed switching voltage signal is applied across the mobile transceiver's electrodes (WB–WG). The current system uses a 10Mbps baseband signal, the same as Ethernet (10Base-T); signal voltage is 25V. The electric field surrounding the mobile transceiver is changed by the signal. The human body offers good conductivity for high-frequency (over 10kHz) electric signals, and so it acts as an electric wire. Thus, part of the electric field from the WB is conveyed through the body to the floor electrode FB. At the same time, the electric field from WG leaks into the surrounding space and reaches the floor electrode FG via air. Therefore, the transmitted signal can be decoded from the electric field that appears between the floor electrodes (FB–FG). When a signal is transmitted from the floor-side, the reverse process occurs.

However, most of the generated electric field is closed between the transmitter's electrodes (WB–WG). Thus a high-sensitivity electric field sensor is needed to realize this communication method.

2.1 Intrabody Communication

Electric field based communication methods are usually called "Intrabody Communication". Most systems use FET (Field Effect Transistor) -based devices as the electric field sensor. Since the sensitivity of FETs is not so high, operation constraints are usually severe such as demanding the use of shoe-insert transceivers[12] or short transmission distances[13][14][15]. Another problem with FET devices is the reduction in operation bandwidth seen when the earth ground floats. The maximum communication speed of an ordinary FET-based system is about 40kbps[16].

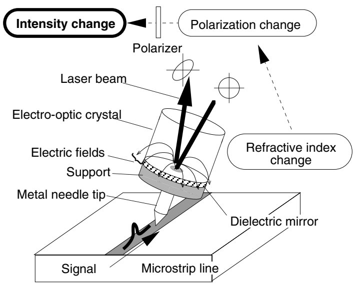

Fig. 2. EO Sensor
Laser-beam is used for sensing.

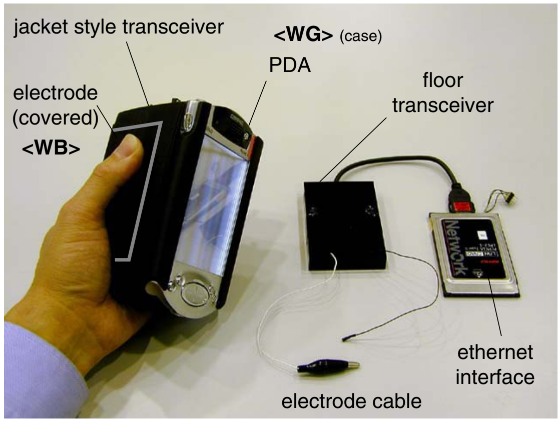

Fig. 3. Transceivers
(L) Handy trx (in PDA's jacket) / (R) Floor trx

CarpetLAN can overcome these problems using an Electro-Optic (EO) device as the electric field sensor. The EO device detects electric field as the polarization change of a laser beam, and it has high sensitivity and high-speed operation capability[17][18] (**Figure 2**). PDA-style and floor-mounted transceivers are shown in **Figure 3**. All transceivers are 10Base-T (half-duplex) Ethernet compatible.

All electrodes are covered by an insulator, and no metal parts contact the human body directly. In addition, induction current generated by the transceiver is very weak and less than that occurring in everyday life.

2.2 Simulations of Electric Field(EF) Distribution

Simulations were conducted to determine the electric field distribution in the space surrounding the floor and human body when a mobile device and floor device are communicating. Some electric field simulations of intrabody networking have been published[19]. Unfortunately, they considered only the small area between the human arm and hand, and no simulations examined the large area containing the whole human body and the floor.

Cell Separation: Figure 4-(a1) shows the basic structure of the carpet-units considered in our simulations. Each carpet-unit is 100 x 100 cm. The floor-side electrode FB (approximated as Cu ($\rho = 5.8\text{x}10^7$S/m)) is rather small (95cm x 95cm) to avoid shorting against the neighboring carpet-unit, and is 10cm above the earth ground. FB is covered with 10mm thick (smallest mesh size) of insulated material (approximated as natural rubber ($\varepsilon_r = 2.4$, $\rho = 0.067$S/m)). The earth ground is approximated as a 500 x 500 cm copper film, it also works as a return-side electrode FG. The nine carpet-units are aligned in a 3 x 3 pattern and are simulated by electromagnetic field analyzing software[4]. Analysis mesh

[4] Micro-Stripes

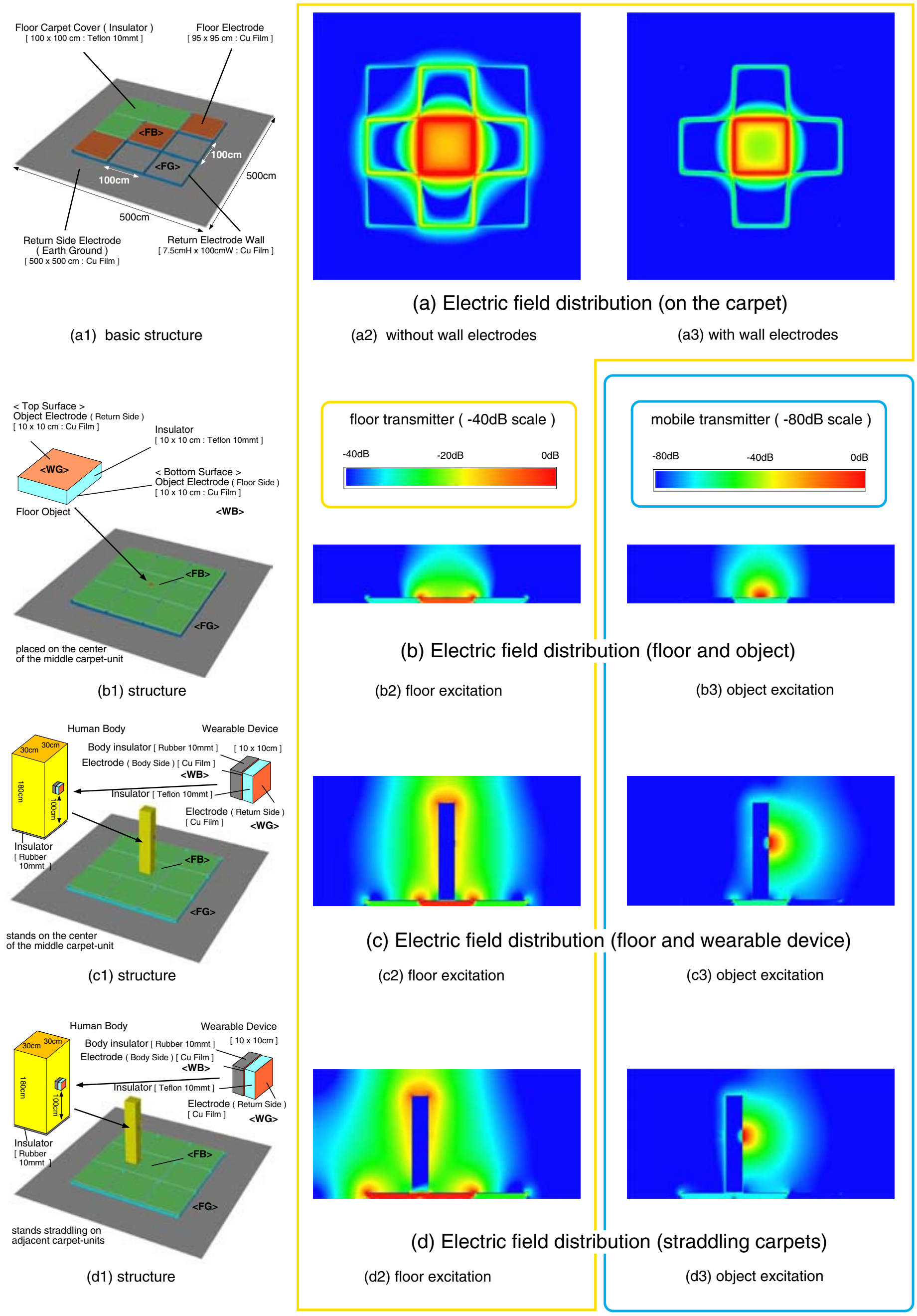

Fig. 4. Electric Field Simulations of CarpetLAN
Electric field generated by the floor-tx is about 30dB greater than by the mobile-tx.

size is 25mm for most of the volume, and 10mm in the vicinity of the electrode and insulators.

Figure 4-(a2) shows the electric field distribution when applying 3V voltage between floor-side electrode FB and earth ground (= return-side electrode) FG of the middle carpet-unit. This figure shows the horizontal distribution on the upper surface of the insulator (height =11cm). The magnitude of the electric field is normalized to give 30V/m (applied voltage) = 0dB, full scale is −40dB. Analysis frequency is 10MHz, a typical frequency of the 10Base-T baseband signal. In this figure, an electric field of −3.5dB(20V/m) is generated at the edges of the middle carpet-unit, and −14dB(6V/m) seen at the center of the carpet. However, the electric field is not efficiently isolated, since an electric field of −17dB(4V/m) appears at the outside edge of the adjacent carpet-units.

Figure 4-(a3) shows the electric field distribution when adding a return-side electrode with double-cross shape (length=100cm, height=75mm; see also Figure 4-(a1)) on the borders of each carpet-unit. With this arrangement, the electric field leakage to the outside edge of the adjacent carpet-unit is reduced to −26dB(1.4V/m). In addition, leakage to the center position of the adjacent carpet-unit is reduced to under −40dB(450mV/m).

Thus, we can achieve a cell isolation of about 20dB between adjacent carpet-units using a wall-shaped return-side electrode. The remaining analyses assume the use of this return-side electrode.

Communication with Floor Object: We next simulated communication with a mobile device placed on the surface of the carpet. The mobile device's electrodes (WB and WG) were modeled as a pair of 10cm square copper film separated by a 10mm thick insulator (approximated as teflon $\varepsilon_r = 2.16$, $\rho = 0$S/m) placed at the center of the middle carpet-unit as the transceiver of an appliance-style mobile device (see also **Figure 4**-(b1)).

Figure 4-(b2) shows the electric field distribution when applying 3V between FB and FG of the middle carpet-unit. This figure shows the vertical distribution at the cutting plane of the mobile device's electrodes (WB and WG). The other conditions are the same as in the previous simulation (30V/m = 0dB, full scale is -40dB). In this figure, an electric field of −25dB(1.6V/m) appears between two electrodes of the mobile device. It means a voltage of roughly 16mV was generated between the 10mm separated receiver electrodes (WB–WG), and it follows that an electric field sensor with a sensitivity of a few mV could detect the carpet-unit's signal. Note that the electric field generated by the floor carpet-unit rises to about 100cm above the carpet's surface.

Figure 4-(b3) indicates communication from the mobile device to the carpet-unit, and 3V is applied between WB and WG. Though normalization was performed as in the previous simulation (30V/m = 0dB), full scale is expanded to −80dB, because only small signals appear in the field. In this figure, the electric field created by the mobile device is only −59dB(35mV/m) at the center position under the middle carpet-unit, and the corresponding voltage generated between FB and FG is just 3.5mV. This result is at least 30dB smaller than the value

seen in the opposite situation (from the carpet-unit to the mobile device), so the carpet-side receiver must offer higher sensitivity for realizing bi-directional communication. In addition, electric field leakage to the adjacent carpet-unit's receiver is under −80dB, thus over 20dB separation can be ensured. This means that the position of the mobile device can be detected with 1 meter accuracy.

Figure 4-(b2) also shows that a signal transmitted from the middle carpet-unit interferes with the adjacent carpet-unit's receiver. The leakage is about −31dB(850mV/m), a value that is about 30dB higher than the signal from the mobile device at the center of its own carpet-unit. This interference cannot be eliminated using a signal level filter. It can be eliminated, however, by the network node module installed in each carpet-unit through the use of techniques such as MAC address filtering. In addition, CarpetLAN automatically duplicates data packets from the carpet-unit to the mobile device for tracking human movement speed (described later), so this interference has no adverse effect.

Communication with Wearable Device: The next simulation examined communication with a wearable device. The human body was assumed to be a rectangular solid 180cm(H) x 30cm(W) x 30cm(D), and its material was approximated as human muscle ($\varepsilon_r = 81$, $\rho = 0.62$S/m)[19]. The wearable device was attached to the waist of the human body (100cm above the foot) and matches the mobile device of the above simulations (10cm square electrodes, 10mm thick insulator). Another insulator (10mm thick natural rubber) was installed under the human body's foot representing the shoe's insole. The same rubber was also placed between the human body and the wearable device, so no electrode contacted the human body directly (**Figure 4**-(c1)).

Figure 4-(c2) shows the electric field distribution when applying 3V to FB and FG of the middle carpet-unit. This figure shows the vertical distribution at the cutting plane of the wearable device's electrode. The other conditions are the same as in **Figure 4**-(b2) (full scale is −40dB). In this figure, the electric field lies around the human body, and about −19dB(3.5V/m) appears between WB and WG. Although the wearable device is some distance above the floor, the received signal is roughly twice that captured by the floor-mounted device (1.6V/m). This indicates that the human body works well as a signal transmission route.

Figure 4-(c3) indicates communication from the wearable device to the carpet-unit, and 3V is applied between WB and WG (full scale is −80dB). The electric field created by the wearable device is −58dB(39mV/m) at the middle carpet-unit. As with the floor-mounted mobile device, the received signal is very weak so that the carpet-side receiver must have high sensitivity.

Carpet Straddling: The final simulation examined the case of the human body straddling two carpet-units (**Figure 4**-(d1)). The other conditions are the same as in the previous simulation.

Figure 4-(d2) shows the electric field distribution when applying 3V to FB and FG of the middle carpet-unit (full scale is −40dB). This figure indicates that the electric field surrounding the human body is reduced slightly, but it is

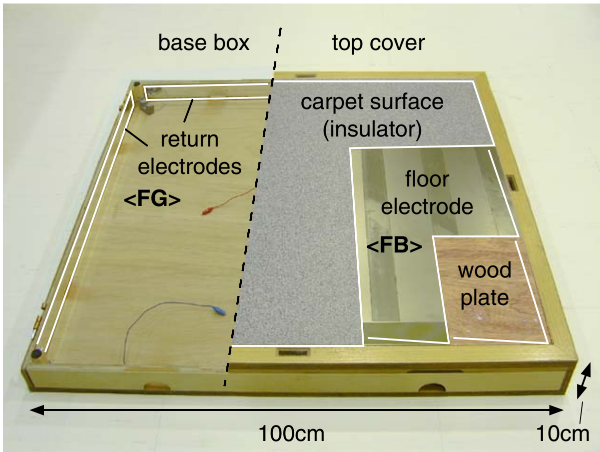

Fig. 5. Carpet Box
(left) Return electrode strips / (right) Floor top electrode (covered)

sufficient for communication. However, interference to the left carpet unit has occurred via the human body. It is difficult to reduce interference in the physical layer; some network-level protection such as packet filtering is needed.

Figure 4-(d3) indicates communication from the wearable device to the carpet-units, and 3V is applied between WB and WG (full scale is −80dB). The electric field of −64dB(18mV/m) appears at the two carpet-units and is about half the single carpet condition. If the floor-side receiver has sufficient sensitivity, the “straddling” condition can be detected while two carpet nodes receive the same signal. It can be utilized for more accurate positioning of mobile and wearable devices.

2.3 Prototype Carpet Unit

Prototype carpet-units were made based on the above simulation results. **Figure 5** shows one carpet-unit. The carpet box is made of wood, and its dimensions are 100cm square and 10cm thick. The floor-side electrode (FB) is a copper sheet (90cm square, 0.3mm thick), and is covered by an insulator (vinyl flooring: 90cm square, 2.3mm thick[5]). Four return-side electrodes (FG) are metal plates (90cm long, 5cm high, 0.3mm thick) that are installed along the inner lateral sides of the box.

The nine carpet-units were aligned in a 3 x 3 grid following the simulations, and a 10MHz sine wave was transmitted from the middle carpet-unit. **Figure 6** shows the measured signal strength[6] at the center of each carpet-unit(a) and the waist position (height=100cm) of a standing human body(b). This figure

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[5] Insulator is thinner than simulation, so the generated electric field may be much larger.

[6] Maximum value is normalized to 0dB.

(a) At the floor-surface (dB)

-26.5	-27.5	-27.0
-28.3	**-5.2**	-28.3
-26.8	-28.0	-26.7

(b) At the human-waist (dB)

-26.5	-26.9	-26.0
-26.5	**0**	-27.6
-26.7	-26.3	-26.7

Fig. 6. Electric field strength
About 20dB separation is achieved.

Type	Object (floor surface)		Wearable (waist)	
Direction	floor → object	object → floor	floor → wearable	wearable → floor
Error rate	**4%**	**23%**	**3%**	**12%**

Fig. 7. Packet error rate
Measured using 100 UDP packets

indicates that a cell isolation of about 20dB can be achieved between neighboring carpet-units. It also follows the simulation results in that the signal strength at the human waist is greater than at the floor's surface.

Figure 7 shows the packet error rate when a PDA-style transceiver (shown in Figure 3) was placed on the center of the floor's surface(left) and at the waist position of the standing human body(right). 100 UDP packets (64bytes length) were transmitted from the PDA and from the carpet-side in turn, and the error rate was measured. The results show that most packets to the PDA were received, while 10% to 20% of the packets to the carpet were lost. It is noted that the signal level at the carpet-side receiver is about 30dB smaller than that at the PDA-side receiver, as shown by the measured and simulation results. Packet loss can be reduced by improving the carpet-unit's receiver sensitivity[7].

3 Networking and Positioning System

CarpetLAN can provide a "network reachable" environment across entire indoor spaces such as rooms and buildings by covering the floors with these carpet-units. This section describes suitable approaches to carpet-networking and positioning system realization. Ordinary unit-based floor network systems use common shaped cells and a bucket-brigade style packet forwarding method[9][10]. However, some issues appear when realizing a practical network system in real rooms and passages.

- Forwarding delay:
  Forwarding delay becomes serious when a large-scale network is built using single-layer bucket brigade forwarding. Assuming that 1 hop forwarding time is 1msec, a communication delay of about 200msec will occur between the opposing corners of a 100m square room paved with 1m square cells. This means that realtime communication services such as IP phones or TV phones are problematic.
- Shape flexibility:
  There are various room shapes. It is difficult to cover the entire space using just one standard cell such as a rectangle or hexagon. Decreasing the cell size offers more flexibility, but forwarding delay is increased.

[7] The measured error rate is much higher than is expected in a regular wireless LAN system. The main reason is that the baseband modulation used by the current prototype transceiver is susceptible to interference by surrounding noise. Packet loss can be greatly reduced using a more robust modulation method.

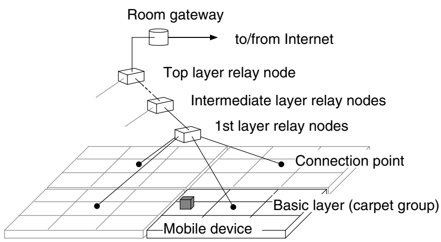


Fig. 8. Structure of CarpetLAN Network
Grouped carpet and layered relay nodes.

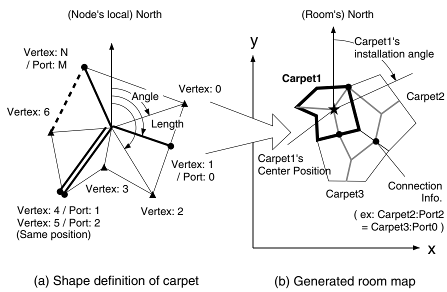


Fig. 9. Shape definition of carpet
Room map is generated by connections.

Table 1. Group and layer size and communication delay (65,536 carpets).
Carpet grouping and multi-layer network enables short communication delay.

Group size	256x256	128x128	64 x 64	32 x 32	16 x 16	**8 x 8**	**4 x 4**	2 x 2	1 x 1
Layer	1	2	3	4	5	**6**	**7**	8	9
Relay nodes	0	1	5	21	85	**341**	1365	5461	21845
Delay (ms)	512	258	132	70	40	**26**	**20**	18	16

3.1 Hierarchical Network Structure

As mentioned above, the single-layer bucket brigade network cannot minimize the forwarding delay if network scale is increased. CarpetLAN, however, suppresses the forwarding delay by combining the bucket brigade forwarding and a hierarchical network.

The basic network structure of CarpetLAN is shown in **Figure 8**. The carpet-units are connected to each other and constitute a mesh-style network (called the basic-layer). Connection points to the upper-layer network are placed at intervals on the basic-layer. Upper-layer relay nodes constitute a tree-structure network with multiple branches. The top-layer relay node is connected to the outside network via the room gateway, typically one per room.

Table 1 shows the maximum delay and required relay node numbers when 256 x 256 (total: 65,536) carpet-units are connected. In this table, it is assumed that each carpet-unit is square in shape, and all nodes have four connection ports for the mesh network. Network delay is calculated between opposing corners of the network area, as 1msec per 1 hop. This table indicates that forwarding delay can be suppressed to under 30msec even for a network at a scale of 65,000 units, when carpet-units are grouped into 8 x 8 units and a 6-layer relay node network is used. Thus, a CarpetLAN network can support 256m x 256m spaces such as large offices, warehouses, and stadiums when using 1m-square carpet-units.

3.2 Automatic Configuration with Free-Shaped Carpet-Units

It is difficult to cover all rooms using carpet-units of the same shape, since real rooms and buildings have various configurations. In CarpetLAN, each carpet-unit knows "its own shape", and shape information is reported to the upper-layer with connection information of surrounding carpet-units when laid. **Figure 9** shows the shape definition of one carpet-unit(a) and an example of the map information generated from connections between 3 carpet-units(b). The room gateway can understand the room's whole shape and network structure by gathering each carpet's shape and connecting information between carpet-units.

3.3 Routing Control

After all connection information is determined, the room gateway calculates routing information and downloads to each carpet-unit. At first, carpet groups of the basic-layer are configured. For each carpet-unit, the closest connection point to the upper-layer is found[8]. Then, carpet-units that have the same connection point are grouped. Upper-layer relay nodes constitute a tree-structure network.

Forwarding procedure is quite simple. Each carpet-unit and relay node forwards the incoming packets to "the output port that has the shortest route to the destination mobile device". As a result, packets are forwarded to the target device with minimum hop count. If the target device is not present in the room, the packet is delivered to the top node and forwarded to the outside network (other rooms or the Internet) via the room gateway.

3.4 Positioning

The room gateway knows the position information of each carpet-unit and all mobile devices in the room. Therefore, indoor positioning of humans and objects with 1m (cell-size) accuracy can be easily realized without additional devices. Even more accurate positioning is possible if the user straddles two or more carpet-units.

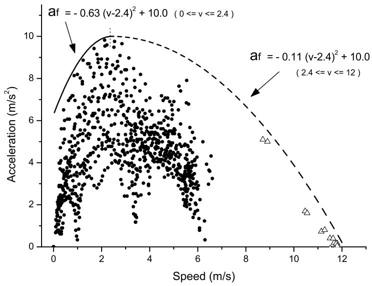
3.5 Routing with Position Estimation

CarpetLAN is a kind of mobile communication system because the users can communicate while moving around on the carpet-units. A mobile communication system must change the destination cell (called a handover) according to the movements of the target device. Handover is not so difficult in regular radiowave-based systems, since user movement speed is relatively low compared to cell size, and the boundary area between adjacent cells is overlapping. However, it is difficult for a CarpetLAN system that has large cell separation to deliver packets reliably to the fast moving target[9].

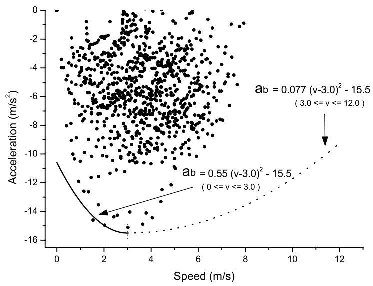
One solution is to deliver duplicated packets to the cells that the moving target is predicted to enter in the future. In this case, delivery mistakes can

[8] Hop count is used as the distance; the shortest route is identified using Dijkstra's method.

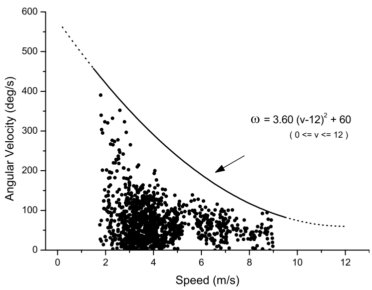
[9] For example, about 10 handovers are needed per second when a human runs across 1-meter carpet-units.



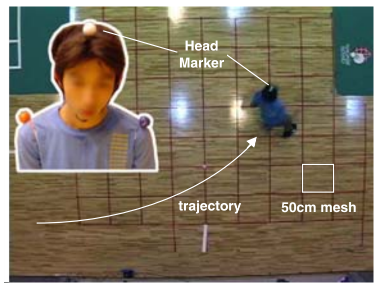
(a) Positive acceleration



(b) Negative acceleration



(c) Angular velocity



(d) Measurement space

Fig. 10. Performance limits of humans (acceleration and angular velocity)

easily be reduced by increasing the number of duplicated cells, though network load is also increased. Since the CarpetLAN system targets use by humans, estimation can be enhanced by understanding the typical movement patterns and limits of human beings.

Movement Limits of Humans: We conducted an experiment to determine the limits of human movements in which the positive and negative acceleration and sharp turns of humans were measured. A 6m x 4m measurement space overlaid by a 50cm mesh and a 10m long runway were set up (**Figure 10-**(d)). The subject wore a head marker (3.5cmϕ) that was captured by a DV camera mounted at the center of the measurement space (height=6m). The marker position was recorded at 30 times per second. The subjects were 12 adult males.

First, rapid acceleration patterns were gathered for determining positive acceleration limits. The subject moved from stationary to full speed and marker position was recorded; the subjects performed a total of 21 movements. Instantaneous speed vs. instantaneous positive acceleration was calculated at 1/30 second intervals[10]. Measurement results are shown in **Figure 10-**(a). Another acceleration data captured from split times of a 100m course run by an athlete[20] are also shown in the figure (marked with △).

[10] Moving averages using a 9-point window were calculated to suppress measurement noise such as head shaking.

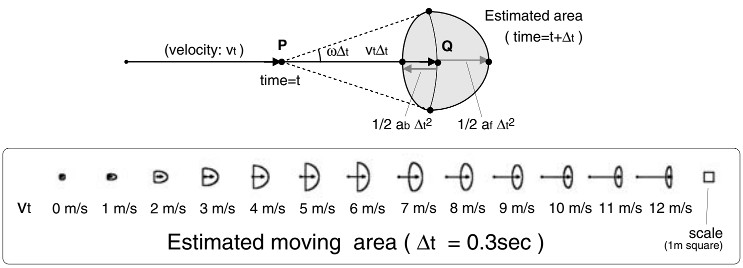


Fig. 11. Estimated area
Estimated area is changed by moving speed.

Next, rapid braking patterns were gathered to determine negative acceleration limits. The subject entered the measurement space at various speeds (from 8m/s to 2m/s) and tried to stop as quickly as possible; the subjects performed a total of 59 movements. Instantaneous speed vs. instantaneous negative acceleration was calculated at 1/30 second intervals. Measurement results are shown in **Figure 10**-(b).

Finally, rapid turn patterns were gathered to determine turn limits. The subject entered the measurement space at various speeds (from 9m/s to 2m/s) and made the tightest possible turn; the subjects performed a total of 50 movements. Instantaneous speed vs. instantaneous angular velocity was calculated at 1/30 second intervals. Measurement results are shown in **Figure 10**-(c).

Estimation of Moving Area: From measured data, the maximum values (human limit) of positive and negative acceleration, and angular velocity were determined, when human moves at specified instantaneous speed. The approximations[11] are also shown in **Figure 10**-(a,b,c). The human, whose movement vector is v_t, is expected to occupy the after-time period Δt as shown in **Figure 11**. This figure also shows the estimated moving areas of 0.3sec ahead for each speed.

4 Implementation and Discussion

4.1 CarpetLAN Node

Figure 12 shows prototype node units placed in each carpet-unit. Each node unit has a total 6 network ports: 4 ports for the mesh network, 1 port for connecting to the upper-layer, and 1 PCMCIA port for the electric field transceiver; all ports are Ethernet compatible. The node unit has an RISC CPU(VR5500), 16MB Flash-ROM, and 64MB SDRAM, and runs on the Linux-VR operating system. The same hardware and software is used for the carpet-units and relay nodes. Each node unit decides its operation mode according to the connections made to surrounding node units when starting up. In addition, one Linux PC is used as the room gateway.

[11] Quadratic approximations were used.

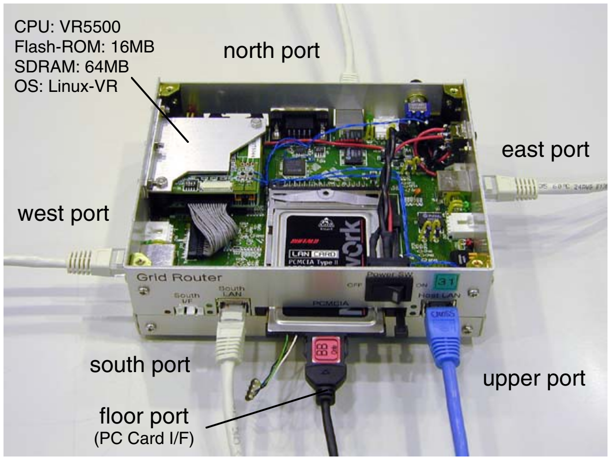


Fig. 12. CarpetLAN Node
Linux-based six-port node unit

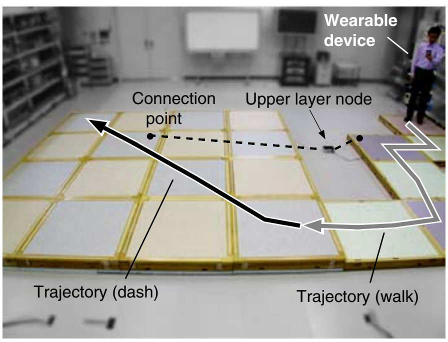


Fig. 13. Experiment network
Moving with hand-held PDA.

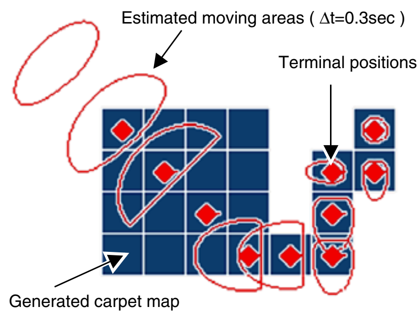


Fig. 14. Estimated areas
Each area shows estimated position 0.3sec ahead.

4.2 Experimental Network

Experimental network consists of 22 square cells (**Figure 13**). All adjacent cells are connected in a mesh network, and one relay node is used.

Automatic Network Configuration: It takes less than 1 minute after power-on to all node units to gather the connection structure and download the routing information to each carpet-unit[12]. We also confirmed that routing information is correctly updated when some node units are disconnected or new units are added.

[12] Most of this time is occupied by operating system booting; only a few seconds is needed for the shortest route calculation and downloading.

Network Access: Concurrent network access from multiple mobile devices was confirmed with experimental network. Three people holding PDA-style transceivers accessed the outside network (web browsing and TV-phone application) while roaming around on the carpet-units. Access with stand-straddling carpet-units and multiple-user access on one carpet unit was also confirmed. In this experimental network, each node can relay packets within 1msec, and network delay is under 10msec (10 hop count).

Estimation of Movement Area: The trajectory of an actual user holding a PDA-style transceiver and roaming around on the carpet is shown in **Figure 14**. Estimated movement areas (predicted ahead by 0.3 sec) are also shown. In this example, the user walks at the beginning but then starts to run. The results confirm that the estimated area changes with the user's speed.

4.3 Discussion

Here we present the remaining issues of the current prototype system and some possible solutions.

Interference with Adjacent Human Body: CarpetLAN may experience interference if several people stand close to each other. Especially, when people's bodies are directly touching each other in a crowded space, interference may reach beyond a few people. If people whose shoulder width is 50cm are crammed in 1m square cells, signals may reach two cells ahead. This means that cell size is expanded about 5m in diameter, and throughput and positioning accuracy may deteriorate. Throughput can be maintained using code or frequency interleaved modulation which is commonly used in radiowave-based wireless access. However, the structure of the transceiver and handover process become more complex.

Scalability: Networking delay does not increase using a hierarchical network structure, even if tens of thousands of carpets are used. However, packets for object tracking may increase when thousands of objects are moving on the carpets frequently. In the current system, all routing and location information packets are aggregated to the room server at any time when the mobile object moves to another carpet. The traffic of routing packets can be excessively reduced using the hierarchical routing information delivery method in which routing information packets are sent to the upper-layer only when a large movement to exceed the boundary of the local layer has occurred.

Energy Consumption and Cost: The current prototype node-unit is rather large (1000cc) and requires much power (8W). Its cost is also high, as it uses ordinary devices. However, the electric field communication method has low-power operation capability compared with other radiowave-based communication, since in principle very little current is needed for transmission. The size, cost, and power consumption of network processing parts can also be reduced by making a special LSI chip. It is not difficult to miniaturize the node unit into a card size that consumes only a few watts of power. However, this must be achieved under a few dollars and 100mW per node-unit to compete with wireless LAN systems that require hundreds of dollars and about 10W per room[13].

In addition, distribution of the electric field may vary when carpet size and thickness are changed. Additional simulation is needed to obtain appropriate electrode alignment of "tile-carpet" compatible units.

Timing Synchronization: In the current implementation, "packet sending time" is used for estimating the mobile device's speed. This is not perfect, as the carpet-units are not completely synchronized. NTP (Network Time Protocol) can synchronize many nodes, however, it is not precise, since dozens of milliseconds may be needed to distribute timing information to tens of thousands of carpet-units. One solution may be to superimpose a carpet-wide master clock on the power lines.

Easy Installation: Since the current prototype uses ordinary network connectors (RJ-45) and power-lines, installation is troublesome. The carpet-units should employ an easy "snap-in" style connection mechanism with one connector for all signals and power-lines. Non-contact connectors that use light or electromagnetic coupling are suggested for avoiding short-circuits due to spilled water.

Speed Up: The current backbone network between nodes use 10/100Base-T Ethernet, and the speedup is easy. However, it is hard to increase the connection speed of electric field communication above 10Mbps, since impedance control of the human body and large carpet electrodes is difficult.

5 Conclusion

This paper introduced a new indoor wireless(-like) networking system that uses the human body and floor surfaces as transmission media. Mobile devices can be accessed while either being worn on the body or put on the floor. Furthermore, the positions of people and objects can be detected with 1-meter accuracy, the current size of the carpet-units. CarpetLAN is effective for realizing a ubiquitous environment in homes, offices, transportation systems (installed on the floor of buses and trains), and event spaces. We are planning to downsize each component and create effective CarpetLAN applications. It is our goal that node-units are embedded in all "tatami" (Japanese straw mat) and tile-carpets, and all floors of the world are connected to the network.

[13] It is assumed that one room is 10m square and covered with 1m square carpet-units.

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