Proceedings of the 2015 IEEE/SICE International Symposium on System Integration, pp.817-822, December 11-13, 2015

Time Domain Characteristics of Multiple UWB 2D Communication Tiles

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***Abstract*—In this paper, we analyze time domain characteristics of multiple ultra-wide band (UWB) two-dimensional communication (2DC) tiles. The time domain characteristic, especially a root-mean-square (RMS) delay spread is important to properly design a physical layer protocol. In the tile system, signals propagate twice in a sheet-like communication medium at a source tile (signal transmitter unit) and a sink tile (signal receiver unit) that have the same communication characteristics. The signal propagation path indicates that the delay spread of the entire system can be estimated from one-tile characteristics. In order to clarify the delay property, the tile system is modeled and the delay spread are numerically simulated. The simulation results show that the delay spread of the total signal path is about 1.41 times longer than that of the source tile. As the next step, the delay spread of the multiple tiles are evaluated in experiments, which show consistency between the simulation and the measurements. These results provide the estimation on the RMS delay spread of the multi-tile system.**

I. Introduction

Recent technological trends of indoor wireless communication represented by Internet-of-Things (IoT) where everything is networked require increasing communication capacity. A large number of devices including video devices need a wider bandwidth than the limited ISM band. Use of ultra-wideband (UWB) [1] is a potential solution to this problem because of such a wide bandwidth, 3.1 GHz-10 GHz. However, the regulation that restricts the transmitted power under −41.3 dBm/MHz is a high hurdle for stable connections.

A two-dimensional communication (2DC) [2] is one of solutions to the physical connection problem of UWB technology. In the 2DC, signals propagate in a sheet-like waveguide called a 2DC sheet. The sheet structure is similar to a parallel plate waveguide, except that the top layer has a mesh-pattern of a conductor not a plane plate. An evanescent field can be generated above the top layer if the wavelength is longer than the mesh pitch. Devices with a specialized coupler are put on the sheet and the coupler transmit/receive signals to/from the sheet with a proximity connection. Because signals exist only in the vicinity of the sheet, the 2DC system has following characteristics. The first one is that signals are not obstructed by general objects since they propagate in the sheet. The second one is that data communication and wireless power transmission [3] can be integrated in the same sheet. The other is that the transmission efficiency can be larger than free-space propagation [4].

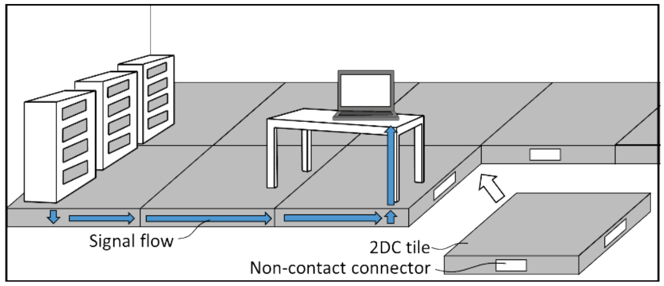

Fig. 1 Concept diagram of the UWB 2DC tile system. The tile is a floor unit that include a sheet-like waveguide and signal relay devices. The system is comprised of multiple tiles, which are connected with non-contact connector. Signals propagate in the waveguide, not in the air. They are also relayed to neighboring tiles via the signal relay devices. The specialized coupler are put on the tile to transmit/receive signals to/from the tile with proximity connection.

A UWB 2DC tile [5] is a practical way to implement a room-size 2DC network. This tile is based on the 2DC technology and enables the stable UWB communication. The concept diagram of the tile system is shown in Fig. 1. The UWB 2DC tile is a floor unit that includes the 2DC sheet and a signal relay component called a base layer as described in the next section. The structure and effort of laying are similar to an ordinary free-access floor although the 2DC sheet is included and the base layer has some electrical circuits and connectors. A signal connection between the 2DC and the base layer is established in a non-contact manner.

In our previous works, feasibility of the tile communication between one tile and a device on it was confirmed from the point of transmittance values at a few points and an waveform distortion [5][6][7]. However the communication properties of the entire system where the multiple tiles are connected are different from those of one tile because the signals propagate in multiple separated tiles. In the purpose of this paper is to clarify the communication characteristics of the entire system. Especially, the time domain characteristic, a root-mean-square (RMS) delay spread is focused on. This is because the RMS delay spread represents available bandwidth and a data rate of the system. An inter symbol interference (ISI) is avoided by a protocol design properly considering the RMS delay spread, which is critical to minimize an irreducible bit error rate (BER) [8].

This work was supported in part by the Strategic Information and Communications R&D Promotion Programme (SCOPE) 155103003.

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First, the system is modeled and numerically simulated. The delay spreads are compared between the following two cases: 1) a source device (signal transmitter) and a sink device (signal receiver) are put on an identical tile and 2) the source tile and the sink tile are not identical. Then, measurements are conducted to verify validation of the model and the simulation results.

The rest of this paper is organized as follows. In the next section, a summary of the tile system are described and the signal propagation in the tile system are modeled. The RMS delay spread is numerically simulated. In section III, the measurements with the multiple tiles are examined to verify the simulation results. Finally we will conclude this paper in section IV.

II. THE TILE SYSTEM AND THE SIGNAL PROPAGATION

A. Summary of the tile system

The tile system is established by connecting the tiles. The schematic diagram of the cross-section is shown in Fig. 2 (a). The tile is typically a 500 mm square, with a standard tile size of a raised OA floor and consists of three layers: a surface layer like a carpet tile, the 2DC sheet, and the base layer. As shown in Fig. (b), the 2DC sheets consists of three layers: an inductive layer with conductive mesh, a dielectric layer, and a ground layer. The inductive layer and the ground layer are shorted at sheet edges so that the neighboring tiles are electrically independent. (An open boundary is also possible if the leak from the sheet is acceptable.) The base layer is a hollow block that includes the buffer circuit and the non-contact interfaces [9] that are necessary to connect the neighboring tiles. The signals are amplified with the buffer circuit so that signal intensity can be maintained between the tiles. Signals are transmitted/received to/from the sheet with the proximity connection between the sheet and the specialized coupler put on or in the tile. In this paper, we define the coupler on the surface layer as a "surface coupler" and the coupler in the base layer as a "back-face coupler".

The signal propagation from a "source tile" where the signal transmitter is put on to a "sink tile" where the signal receiver is put on is as follows. The input signal from the surface coupler propagates in the 2DC sheet of the source tile first. Then it is transmitted to the base layer via the back-face coupler and amplified at the buffer circuit. The signals propagated to the neighboring tiles via the interfaces are transmitted both to the next neighboring tile and to the 2DC sheet on it. In order to prevent oscillation by the amplifiers, we divide an uplink signals and a downlink one by their frequency shifts in the prototype system [10].

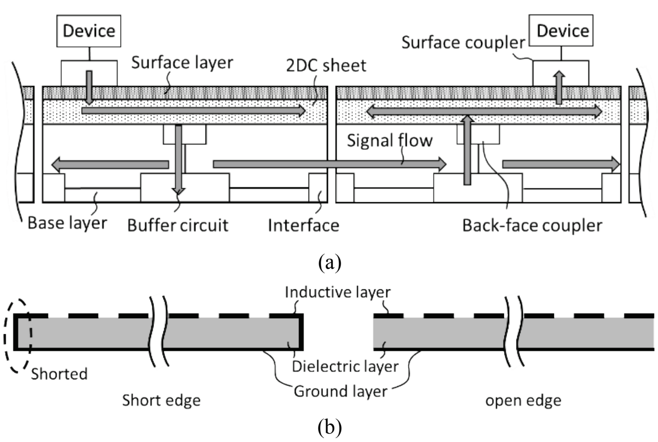


Fig. 2 (a) Schematic diagram of the tile system and flows of the signal propagation. The tile consists of three layers and the neighboring tiles are connected via non-contact interfaces. The signal propagates from a "source tile" where a transmitter is put on to a "sink tile" where a receiver is put on. The device transmits/receives signals to/from the sheet through a "surface coupler" that is put on the surface layer. A "back-face coupler" set under the 2DC sheet relays signals between the sheet and the buffer circuit. (b) Structure of the 2DC sheet. The sheet consists of three layers. A top layer and a bottom layer are shorted in the short boundary sheet.

B. Signal propagation model

Fig. 3 shows the model of the signal propagation mentioned above. The input signal $x(t)$ to the tile system propagates in the source tile that corresponds to Tile 1 and some of them are transmitted to the sink tiles, Tile 2 and Tile 3, through the base layer. The received signal of another coupler at the source tile $y_{source}(t)$ is described as follows.

$$y_{source}(t) = x(t) * h(t) \quad (1)$$

$h(t)$ denotes an impulse response of the tile. For a simple and rough estimation, we assume that all of the following three types of paths show the same impulse response: 1) from the transmitter surface coupler (Tx coupler) to the receiver surface coupler (Rx coupler) on the source tile, 2) from the Tx coupler to the back-face coupler on the source tile, and 3) the back-face coupler to the Rx coupler on the sink tile. Because the input signal to each sink tile is $y_{source}(t)$ and the tiles have the same impulse response, the received signal $y_{sink}(t)$ of each coupler put on Tile 2 and Tile 3 is the same and expressed as

$$y_{sink}(t) = h(t) * (x(t) * h(t)). \quad (2)$$

No reflections among the tile connections are assumed in Eq. (2). The number of the impulse response that the signals propagate from the source tile to the sink tile is the same among the sink tiles. Therefore, the communication characteristics of the overall system can be estimated with the one-tile property as shown in Eq. (2).

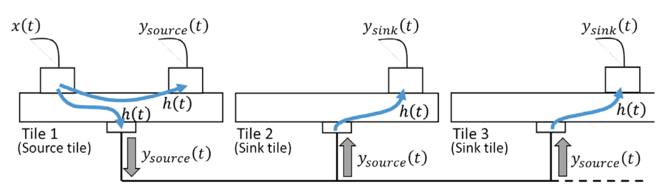


Fig. 3 Schematic diagram of the tile-system model. An impulse response of three paths: from the transmitter surface coupler to another surface coupler or the back-face coupler on the source tile and from the back-face coupler to the receiver surface coupler on the sink tile, is assumed to be the same. Input signals to each sink tile from the back-face couplers are the same. Therefore the received signals of each tile are also the same.

C. *Numerical simulation of the RMS delay spread*

The RMS delay spread is numerically simulated with the model to quantitatively evaluate a relation between the delay spread of the source tile and that of the total path. In the UWB 2DC tile, multipath signals are generated because the tile has reflective characteristics [5]. Since the impulse response of the multipath environment is generally expected to have exponential-attenuation property [11], the impulse response in the simulation is assumed as

$$h(t) = e^{-\alpha t} \tag{3}$$

where α denotes decaying factor. If the input signal $x(t)$ is an ideal impulse and the impulse response is expressed as Eq. (3), $y_{source}(t)$ and $y_{sink}(t)$ can be numerically simulated as shown in Fig. 4.

An important index of the channel characteristics in time domain is the RMS delay spread. It represents how long signals spread by propagating the communication environment and is considered to avoid ISIs when designing the physical layer protocol. The RMS delay spread is calculated as below [10].

$$\tau_{rms} = \sqrt{\overline{\tau_m^2} - (\overline{\tau_m})^2}, \tag{4}$$

where

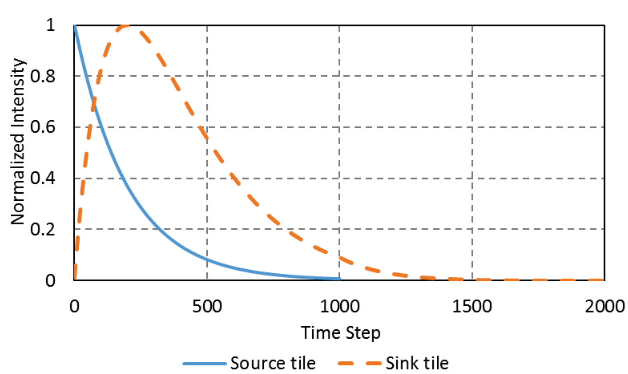
$$\overline{\tau_m} = \frac{\sum_k P(\tau_k)\tau_k}{\sum_k P(\tau_k)} \tag{5}$$

and

$$\overline{\tau_m^2} = \frac{\sum_k P(\tau_k)\tau_k^2}{\sum_k P(\tau_k)}. \tag{6}$$

τ_k represents excess delay time while $\overline{\tau_m}$ and $\overline{\tau_m^2}$ denote a mean excess delay time and a second central moment of the power delay profile $P(\tau_k)$ that is defined as the square of amplitude of the received signals.

We define the RMS delay spread of the identical tile path, from the surface coupler to another coupler as τ_{source}, and that of the total path, from the surface coupler on the source tile to the surface coupler on another sink tile as τ_{sink}. τ_{source} and τ_{sink} are 182 time steps and 257 time steps respectively from the simulation results shown in Fig. 4 and Eq. (4)-(6). The delay spread of the entire system τ_{total} is equal to τ_{sink}



Fig, 4 Simulation result of received signal y_{source} at the source tile and y_{sink} at the sink tile. It is assumed that the input signal is be an ideal impulse and the impulse response of the tile has exponential-attenuation characteristics.

because all of the sink tiles show the same delay spread. Therefore τ_{source} and τ_{total} are estimated to have the relation of

$$\tau_{total} \approx 1.41\tau_{source}. \tag{7}$$

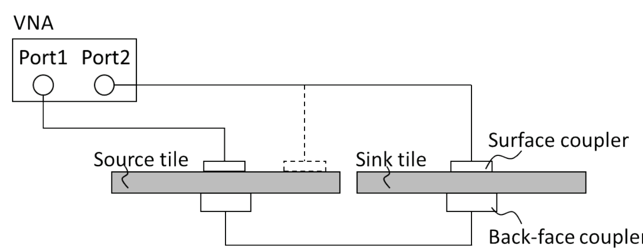
This result shows that the delay spread of the entire system is easily estimated if that of one tile is known.

III. Evaluation of Delay Spread of Multiple Tiles

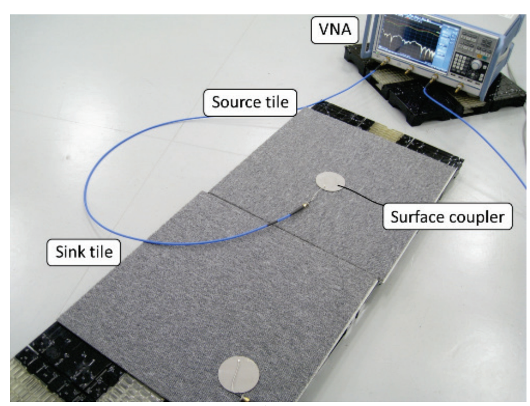
In this section, the relation of the delay spread between the tiles is examined by the measurement of the time domain signals with two patterns to verify the simulation results. First, the source tile and the sink tile are measured, then two sink tiles are measured.

A. *Source tile and Sink tile*

Fig. 5 shows the schematic diagram and the photo of the measurement setup. Two tiles are connected with the back-face couplers set under the ground layer of the 2DC sheet as shown in Fig. 6. The base layer are not implemented because influences of the buffer circuit and the interfaces is avoided. The couplers [12] are used as the surface coupler. They are connected to a vector network analyzer (VNA), Rhode & Schwarz ZNB-20. The inverse Fourier transform technique is used to obtain time domain signals from the measurement results. A frequency range is from 10 MHz to 10.25 GHz and the number of sweep points are 1001. These settings indicate time resolution and available time span are about 0.05 ns and 50 ns, respectively. Two signal paths are examined, 1) from the surface coupler on the source tile to another surface



(a)



(b)

Fig. 5 (a) Schematic diagram of measurement setup. The measurement is conducted to obtain signal propagation data of two paths: 1) from the surface coupler on the source tile to surface coupler on the sink tile and 2) from the surface coupler to another surface coupler on the source tile. The tiles are connected with the back-face couplers under the ground layer. (b) Photo of the setup.

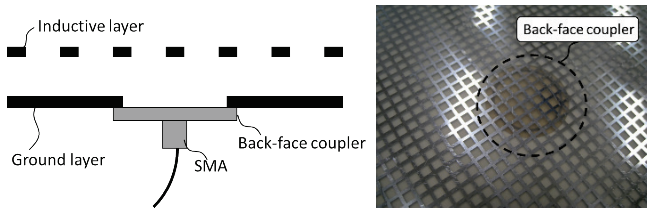


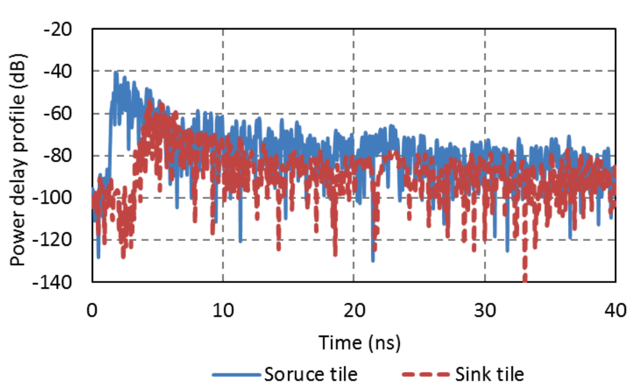
Fig. 6 (a) Cross-section of the back-face coupler under the ground layer. The ground layer around the coupler is eliminated to resonate between the coupler and the sheet. (b) Photo of the setup of the back-face coupler. The hole size of the ground layer is about 30 mm

coupler on the source and 2) from the surface coupler on the source tile to one on the sink tile. The five-hundred measurements are conducted at a half area of each tile in the consideration of symmetry of the sheet.

A composition of the 2DC sheet is as follows. The sheet size is 500 mm square. A line width and a pitch of the inductive layer are 1mm and 4mm respectively. A material of the inductive layer and the ground layer is aluminum. Thickness and the material of the dielectric layer is 1mm and polypropylene whose relative permittivity is 2.1. These sheet settings are employed from the point of performance and availability and are typical in our previous works. In this experiment, the edge of the sheet is open. This is not critical because the open edge also has reflective property. The surface layer of the tile is a commercial carpet tile, the model number YS 1004 manufactured by Teijin Limited. The size is 500 mm×500 mm×6 mm.

Fig. 7 shows examples of the measured power delay profile in dB unit. The signals of Source tile has exponential characteristics and the received signals of Sink tile are more gradually excited compared to Source tile. These properties match with the numerical simulation.

Fig. 8 shows cumulative density function (CDF) of the RMS delay spread. Table I shows the statistical delay spread values and a ratio of the delay spread of Sink tile to that of Source tile. $\tau_{rms,}$ 10%, $\tau_{rms,}$90%, and τ_{rms}, 100 % denote the RMS delay spread values when the CDF is equal to 0.1, 0.9, and 1. The value of τ_{rms}, 100% is almost the same as that of the simulation results and the other results are also comparable. These results show the consistency between Eq. (6) and the experimental results. Therefore, the relation of the delay spread between the source tile and the neighboring tiles are ensured.



Fig, 7 Examples of the power delay profile of the two tiles. The signal of Sink tile rises more gradually than that of Source tile. This trend corresponds to the simulation result.

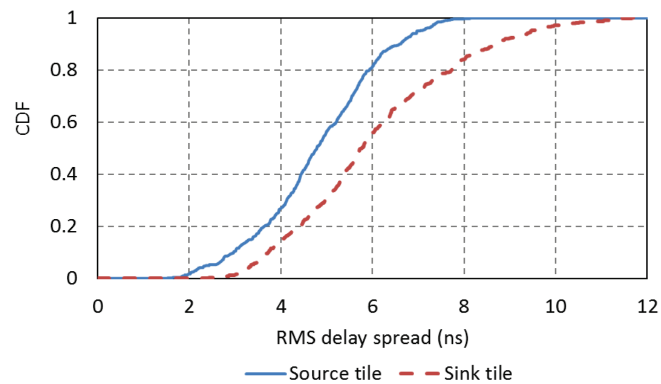


Fig. 8 Cumulative density function (CDF) of the RMS delay spread of Source tile and Sink tile. The delay spread values of Source tiles is shorter than that of Sink tile.

TABLE I
STATISTICS OF THE RMS DELAY SPREAD OF THE SOURCE TILE AND THE SINK TILE

	τ_{rms}, 10% [ns]	τ_{rms}, 90% [ns]	τ_{rms}, 100% [ns]
Source tile	2.97	6.6	8.14
Sink tile	3.74	8.7	11.67
Ratio	1.26	1.32	1.43

B. Two sink tiles

This measurement is conducted to ensure the relation among the delay spread value of the multiple sink tiles. Because the signals among the sink tiles are theoretically the same, the RMS delay spread values are considered to be the same or comparable.

Fig. 9 shows the schematic diagram and the photo of the measurement setup. Three tiles are used, one is the source tile and the others are the sink tiles. The same signal power is provided to Sink tile 1 and Sink tile 2 by using a divider. The VNA settings and the composition of the tiles are the same as the former experiment. The transmittances between Source tile and Sink tile 1 and between Source tile and Sink tile 2 are measured at 500 points in the half area of each tile. Then the data are processed to time domain signals.

Fig. 10 shows examples of the measured power delay profiles at the same position of the two sink tiles. The similar profiles indicate the similar signals are input to the sink tiles. Fig. 11 shows the CDF of the delay spread. The trend is almost comparable with each other. Table II shows the statistical delay spread values. These values indicate that the delay spread of Sink tile 1 and 2 is almost the same and also indicate the consistency with the former experiment results. Therefore the delay spread values of the multiple sink tiles can be considered to be the same and have the same relation with the source tile.

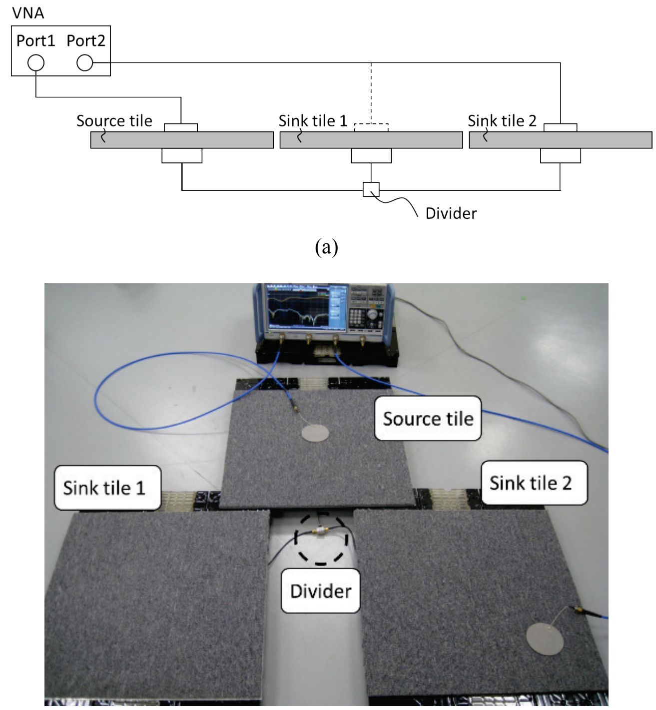


Fig. 9 (a) Schematic diagram of the measurement setup. A divider is used to provide the signals to Sink tile 1 and 2. (b) Photo of the measurement setup.

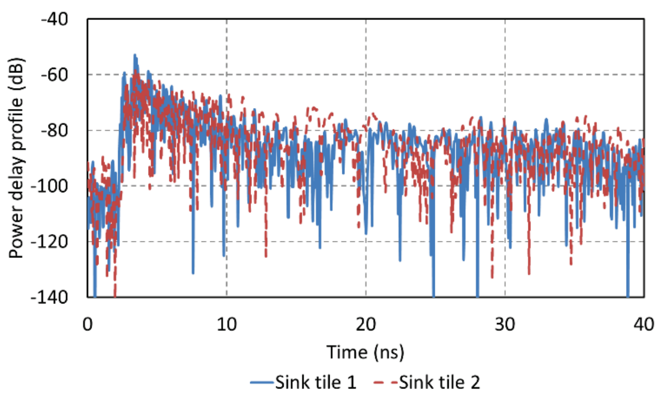


Fig. 10 Examples of the power delay profiles of the two sink tiles. The sample points on the tiles are the same. The similar trend indicates the same signals are input to the tiles.

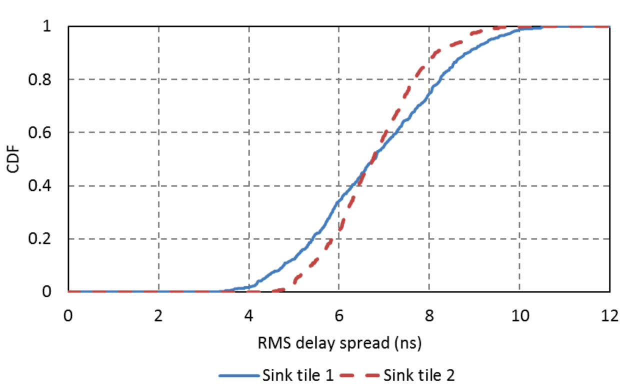


Fig. 11 Cumulative density function of the two sink tiles. The trend of both tiles is similar.

TABLE II
STATISTICS OF THE RMS DELAY SPREAD OF THE TWO SINK TILES

	τ_{rms}, 10% [ns]	τ_{rms}, 90% [ns]	τ_{rms}, 100% [ns]
Sink tile 1	4.77	8.85	10.53
Sink tile 2	5.37	8.13	10.06

IV. CONCLUSION

In this paper, we analyzed the time domain characteristic, especially the RMS delay spread of the multiple UWB 2DC tiles. First, the tile system was modeled and the delay spread was calculated with the numerical simulation. The delay spread of the entire system is determined with two tiles, the source tile where the transmitter is put on and the sink tile where the receiver is put on because the 2DC sheet in the tile affects the transmission property and the relay component like the base layer does little. The simulation results show that the delay spread of the total path from the transmitter to the receiver is about 1.41 times longer than that of one tile. The measurements of the delay spread were conducted with the two patterns 1) the source tile and the sink tile, 2) the two sink tiles. Each measurement results show the consistency with the simulation results.

These results enable the estimation of the delay property of the entire system with one-tile property.

ACKNOWLEDGMENT

We thank Yoshiaki Hirano and Machiko Oouchida, Teijin Limited for providing the sheet materials.

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