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UWB Wireless LAN by 2D-Communication Tile system Based on Direction-Dependent Frequency Shift

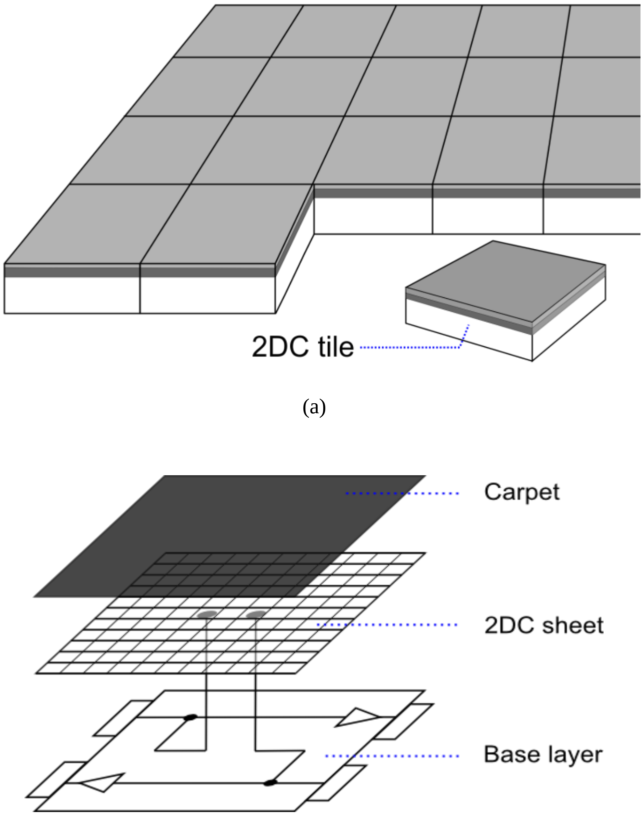
Yudai Fukui, Akihito Noda and Hiroyuki Shinoda

***Abstract*— To overcome the lack of bandwidth due to increase of wireless devices, using ultra-wideband (UWB) technology is attractive. However, a problem is the signal transmission power of UWB is restricted to as small as -41.3 dBm/MHz. To enhance the communication range, two-dimensional communication (2DC) technology is effective. UWB 2DC environment can be extended to cover the entire room by laying the 2DC sheet over the floor. As 2DC tile system behaves as just a physical medium, conventional communication protocols including Wi-Fi can be used. A previous study proposed to use the frequency range allocated for UWB radios as an alternative spectrum resource for conventional wireless local area network (WLAN) system in the 2DC environment. Devices on the 2DC tile can use the system by attaching an adapter. The adapter consists of couplers and a circuit that converts 2.4-GHz WLAN signals to UWB frequency range signals. In this paper, we propose direction-dependent frequency shift (DDFS) scheme for active tile 2DC. Experimental results demonstrate that the WLAN connection through prototype system can achieve 60% of throughput compared to the original 2.4-GHz WLAN connection, where at most 40-dB signal attenuation in the 2DC sheet and the coupler is assumed.**

I. INTRODUCTION

Use of wireless communication is more and more increasing. As well as the communication of mobile PCs, tablets, and smartphones, increasing wireless devices in Internet of Things (IoT) and Machine–to-Machine are causing the lack of bandwidth. To overcome the problem, unused higher frequency band such as millimeter waves, terahertz waves and ultra-wideband (UWB) [1] are attractive. The next generation wireless local area network (WLAN) standard, IEEE802.11ad, is designed for 60-GHz band [2].

UWB is another attractive frequency resource. UWB radio systems can use a wide frequency range (e.g. 3.6 - 10.6 GHz in US and 7.25 – 10.25 GHz as "UWB high-band" in Japan). A problem in UWB communication is that its signal transmission power is restricted to -41.3 dBm/MHz and signals are easily occluded by object in the air, due to propagation straightness. Free space propagation loss with transmitter/receiver antenna gains of 0 dB is given as follows by Friis's law [3]:



(a)

(b)

Fig. 1: (a) 2DC tile concept and (b) the structure of the tile. The room floor is covered with 50-cm square 2DC tiles. The tile consists of 3 layers: carpet, 2DC waveguide sheet and base layer. The base layer includes an active circuit to connect to adjacent tiles and to compensate signal loss. Signals can be evenly transmitted to every tile.

$$L = \left(\frac{\lambda}{4\pi r}\right)^2, \tag{1}$$

where L, λ and r are the propagation loss, the wavelength and the propagation distance over the air, respectively. UWB transmitted signals are attenuated by 70 dB in roughly 10 m and received signal power is comparable to the thermal noise power -114 dBm/MHz at the room temperature 290 K. In a conventional WLAN system, signal-to-noise ratio (SNR) is required 20 dB or greater in order to achieve the maximum

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Yudai Fukui, Akihito Noda and Hiroyuki Shinoda are with the Department of Graduate School of Frontier Sciences, University of Tokyo, Tokyo, Japan (Tel: +81-4-7136-3777; E-mail: fukui@hapis.k.u-tokyo.ac.jp, Akihito_Noda@ipc.i.u-tokyo.ac.jp, hiroyuki_shinoda@k.u-tokyo.ac.jp)

data rate. If we use a similar modulation and the same bandwidth in UWB requiring 20 dB SNR, a simple calculation tells us the radius of the coverage is as short as 1 m approximately.

Using two-dimensional communication (2DC) [4], [5] can be effective for reliable UWB signal transmission. 2DC is realized with a thin waveguide sheet and proximity couplers. The waveguide sheet guides microwave along itself and generates evanescent field around its surface. Devices laid on the sheet can transmit/receive microwaves into/from the sheet via proximity couplers without electrical contact.

Moreover 2DC environment can be enhanced to the entire floor of a room based on the 2DC tile concept [6], [7]. 2DC tile system is shown in Fig. 1. Tiles have the uplink (UL) that receives signals from 2DC sheet on each tile and transmits them to the next tile, and have the downlink (DL) that transmits signals to every tile evenly. We can construct 2DC tile environment just to lay tiles by using non-contact couplers between adjacent tiles [8]. Each tile has amplifiers to compensate the signal attenuation due to the connection part between adjacent tiles, in order to transfer signals evenly to arbitrary number of tiles.

2DC tile system is the communication physical layer. This system does not restrict communication protocols, because tiles behave as just a physical medium by copying signals inputted into a tile to the adjacent tile. Thus, this system can use conventional communication protocols including Wi-Fi.

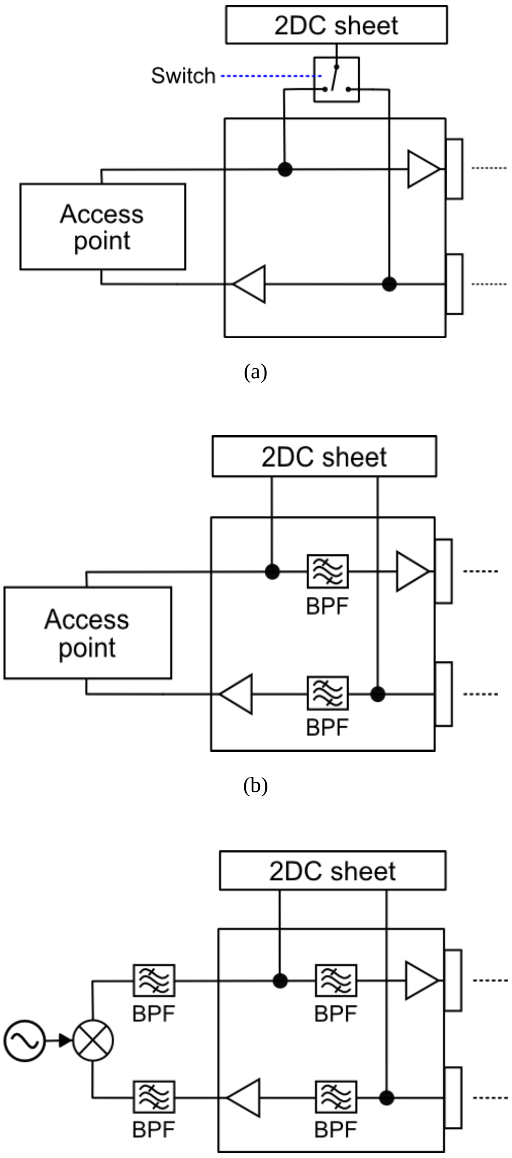
The system proposed in [9] uses the frequency range allocated for UWB high-band radios as an alternative spectral resource for conventional wireless local area network (WLAN). In the system, existing 2.4-GHz WLAN devices can transmit/receive UWB high-band signals via the 2DC tiles, by attaching a 2DC proximity coupler and an adapter that converts 2.4-GHz signals to another frequency in UWB high-band.

Active tiles compensating signal attenuation by amplifier have a problem that a positive feedback path can be formed in the base layer connection. The positive feedback path with a gain greater than 1 will cause oscillation and will disable communication through the path. This point is not explicitly considered in [9].

In this paper, we propose a scheme to avoid the positive feedback loop in the active tile 2DC system. Descriptions of 2DC active tile systems and an overview of possible configurations to avoid the positive feedback loop will be presented in Section II. Section III and IV presents the experimental system and evaluation experiments. The paper will concluded in Section V.

II. Overview of UL/DL Separation Scheme

In an active tile 2DC system, two separated transmission lines are needed. Signals in the two transmission lines are transferred in the direction opposite to each other. These two lines are referred to as an uplink (UL) and a downlink (DL). Since each line includes amplifiers to compensate signal loss, direct connection between them will form a positive feedback loop with a gain greater than 1. To avoid the loop, the two lines have to be separated. Possible approaches to separate the UL and the DL can be classified into three types as follows.



(a)

(b)

(c)

Fig. 2: Three possible configurations of 2DC active tile system. (a) DDTS-based (b) DDFS-based, AP type. (c) DDFS-based, ad-hoc type.

1. Direction-dependent time slot (DDTS).
2. Direction-dependent frequency shift (DDFS).
   2-a. Access point type. (DDFS/AP)
   2-b. Ad-hoc type. (DDFS/AH)

DDTS-based 2DC tile is shown in Fig. 2 (a). By connecting a Wi-Fi access point (AP) between the UL and the DL, those two lines are separated in the time domain. Every connection between the 2DC sheet and the UL/DL is switched by synchronizing with the AP’s receiving/transmitting operation. Therefore, direct connection between arbitrary two stations on the tiles system is not supported, but only connection between the AP and another station on the tiles is supported in this configuration.

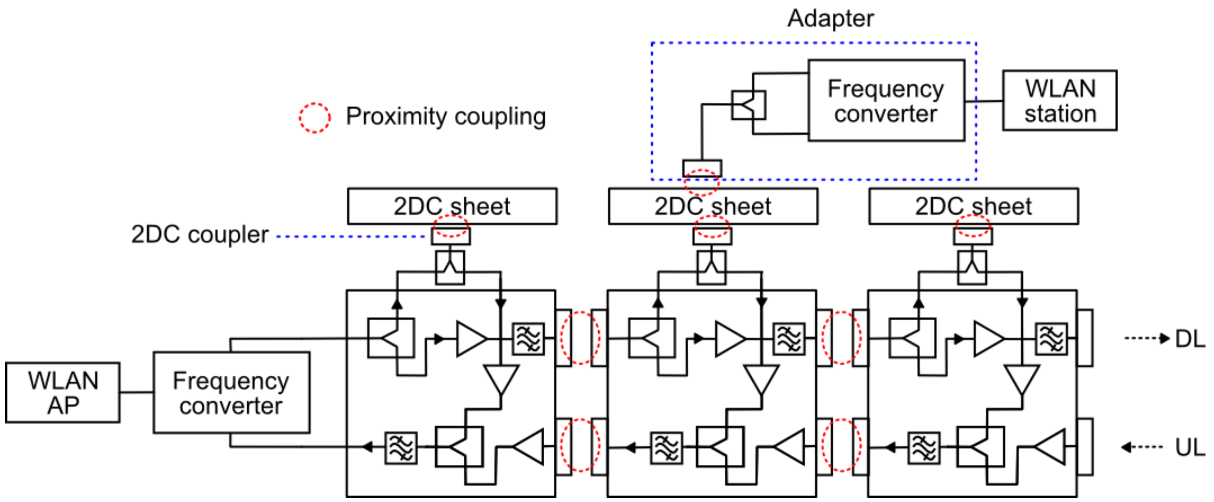


Fig. 3: UWB WLAN 2DC system based on DDFS. Three connections that is between a device on the tile and the 2DC sheet, the 2DC sheet and the base layer, and tile connection are connected by the proximity coupling. In one end of tiles (the left hand side in the figure), the WLAN AP is connected. WLAN stations with the adapter can connect to the AP through the 2DC system. Carrier frequency used in the UL and the DL are different.

On the other hand, DDFS-based 2DC tile uses separated frequencies for the UL and for the DL (e.g. lower frequency band is assigned for the UL and higher frequency band is done for the DL). Using band-pass filters (BPFs), unintended feedback loop gains are reduced and positive feedback paths are eliminated. The DDFS-based 2DC includes two kinds of configurations.

One is AP-type, the same as the DDTS-based system, as shown in Fig. 2 (b). The destination of all signals transmitted from the tiles is the AP, and the signals transmitted from the AP are broadcasted to all the tiles. Ad-hoc communication between an arbitrary pair of stations is not supported. One of the advantages of this configuration to the DDTS is that the AP-synchronized switching circuit is not need.

The other one is ad-hoc type, the UL and the DL are connected with a frequency shifter, as shown in Fig. 2 (c). In this configuration, a signal transmitted from an arbitrary station is transferred to the frequency shifter through UL, and the frequency-shifted signal is broadcasted to all the tiles through the DL. Thus, arbitrary pairs of stations can directly communicate with each other, without AP (ad hoc mode is allowed).

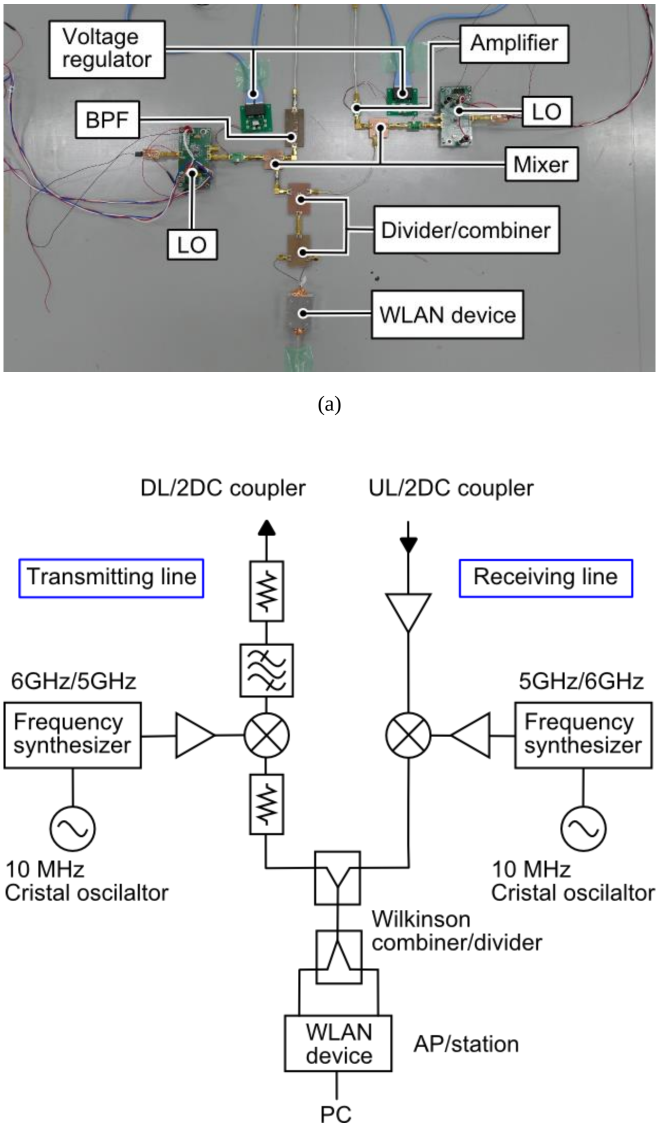
III. EXPERIMENTAL SETUP

The UWB WLAN 2DC tile system based on DDFS/AP is shown in Fig. 3. The device on the tile needs the adapter that consists of couplers attaching to the 2DC sheet and a frequency converter to convert separated frequency in transmitting and in receiving. The WLAN AP between the UL and the DL needs the converter.

The converter is shown in Fig. 4. As DDFS-based 2DC tile system uses separated frequency for transmitting and for receiving, a line from WLAN device is divided into a transmitting line and a receiving line by a Wilkinson divider. In the WLAN AP between the UL and the DL, as it receives signals from the UL and transmits them to the DL, the receiving line signals are mixed with a 5-GHz local oscillator (LO) signal and the transmitting line signals are mixed with a 6-GHz LO signal. Unintended frequency signals, up-converted 12.4-GHz in the receiving line and down-converted 3.5-GHz in the transmitting line are generated. Through the BPF, only 8.4-GHz intended frequency signals pass to the DL in the transmitting line. In the receiving line, only 2.4-GHz intended frequency signals are accepted by the BPF inside the WLAN device. And an amplifier is connected in the receiving line in order to amplify signals picked up from the 2DC sheet by the coupler. In the transmitting line, attenuators are connected at the mixer’s intermediate frequency (IF) port to match the signal power with LO’s requirement and at the radio frequency (RF) port to adjust the signal power to the UWB power restriction of -41.3 dBm/MHz.

The converter specification is shown in TABLE 1. In the transmission line, the intended path is from the Wilkinson divider to the attenuator and the unintended path is the opposite direction. In the receiving line, the intended path is from the amplifier to the Wilkinson combiner and the unintended path is the opposite direction. As the Wilkinson divider divides signals into two lines equally, unintended signals are output from the receiving line. As those signals are much smaller than the intended signals and are used separated frequency, communication is not affected by them.

The adapter for the WLAN station on the 2DC tile is almost the same as one for the AP as it transmits signals to the UL and receives them from the DL, the only difference is the LO frequencies, 5-GHz for the receiving line and 6-GHz for the transmitting line.



(a)

(b)

Fig. 4: (a) Converter circuit overview and (b) its schematic diagram. The WLAN device is sealed inside an aluminum shield case in order to suppress the signal emission into the air. Two antenna ports of the WLAN device (it uses multiple-input and multiple-output (MIMO)), are combined by a Wilkinson combiner.

TABLE I
CONVERTER SPECIFICATION

	Transmitting line	Receiving line
Loss (intended path)	-34 dB	+2 dB
Loss (unintended path)	-34 dB	-50 dB
Output power	-43 dBm/MHz	-59 dBm/MHz (unintended)

IV. EVALUATION EXPERIMENT

In this section, the UWB WLAN communication is evaluated by using the prototype converter and attenuators in place of the 2DC sheet.

Experimental system is shown in Fig. 5. The WLAN AP transmitting and receiving lines are connected to the WLAN station receiving and transmitting lines with coaxial cables respectively. In each line, between the adapters of the AP and of the station, attenuators are connected instead of an actual 2DC sheet to evaluate acceptable loss in the sheet. Received signal power P_{R} at the point 10 is calculated as follows,

$$P_{\mathrm{R}} = P_{\mathrm{T}} - L_{\mathrm{Sheet}} + G_{\mathrm{Amp}} - L_{\mathrm{Others}} \tag{2}$$

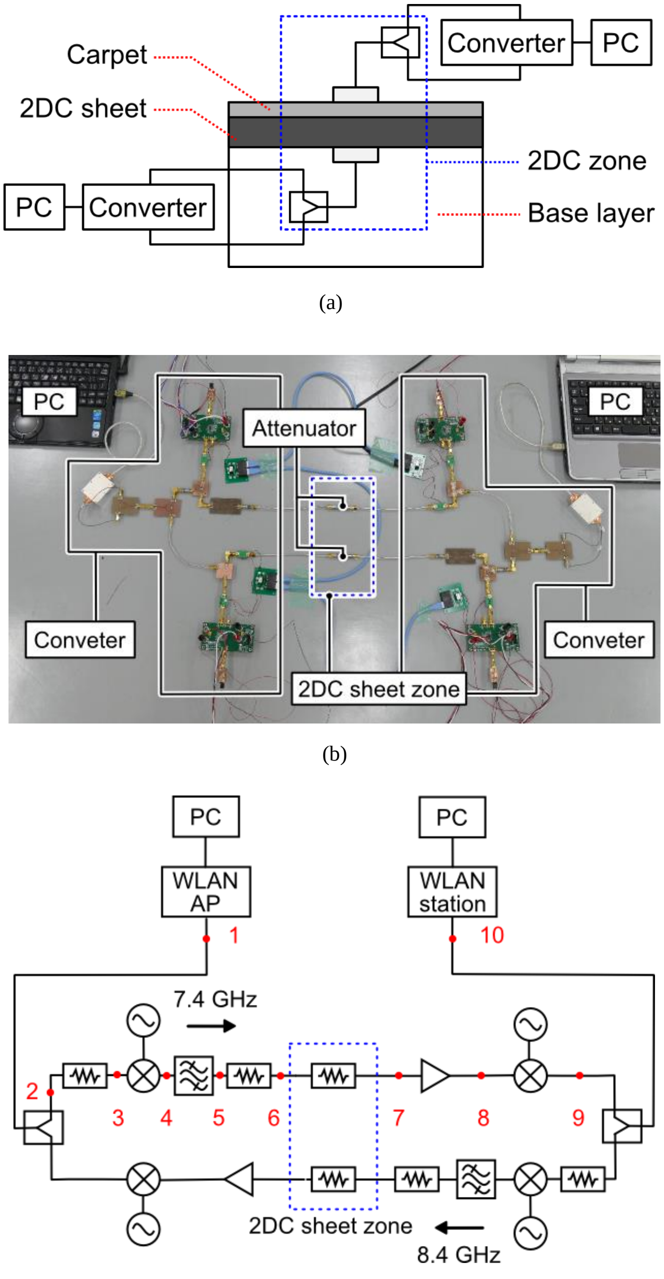
where P_{T}, L_{Sheet}, G_{Amp} and L_{Others} respectively represent the transmission power at end of the transmission line (at the point 6) in the converter (-43 dBm/MHz, as shown in Table 1), the loss through the 2DC sheet and couplers, the amplifier gain and the loss of other component (such as the mixer, the combiner and the line loss), and they are expressed in dB.

Fig. 6 shows the signal power density, the noise power density (at the room temperature 290 K) and their SNR when L_{Sheet} = 0 dB in the experimental circuit shown in Fig. 5. As the point 6 is the output point to the 2DC sheet, its power is adjusted below the UWB power restricted, by tuning the attenuation between points 5 and 6. In the receiving line, the amplifier gain is adjusted to compensate the loss of the mixer and the divider (roughly $G_{\mathrm{Amp}} = L_{\mathrm{Others}}$).

The relationship between the throughput and the sheet loss L_{Sheet} was evaluated with PCATTCP [10] in the experimental system shown in Fig. 5. The result is shown in Fig. 9. For instance, throughput of the original 2.4-GHz connection, evaluated with the system shown in Fig.8, is also shown in the figure. The signal power incident on the attenuator L_{Sheet} was tuned to be identical for the both cases.

The dots show the average of the 30 trials for each condition and error bars show the standard deviation. The WLAN connection was based on IEEE802.11n in the 2.4-GHz band and channel bandwidth was 40 MHz. Throughput achieved more than 40 Mbps up to 40 dB attenuation and it is roughly 60% throughput of the2.4-GHz original WLAN connection. It significantly decreased in case of 50 dB attenuation. In this case, the received signal power density is approximately -93 dBm/MHz and the noise is -109 dBm/MHz at 290 K. Thus, SNR is 16 dB.

According to the experimental result, for high-speed communication faster than 40 Mbps, the SNR should be higher than 25 dB and the maximum acceptable L_{Sheet} is 40 dB



(a)

(b)

(c)

Fig. 5: (a) Emulated environment, (b) Experimental system overview and (c) its schematic diagram. The 2DC sheet zone is emulated a path that passes couplers and 2DC sheet . Attenuators are used in place of the loss through the sheet

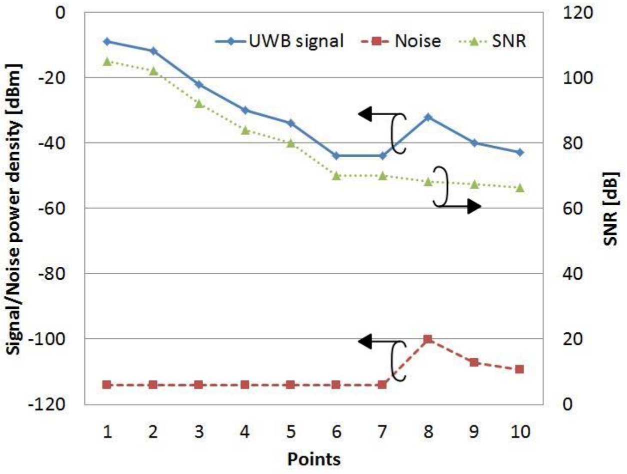


Fig. 6: Signal and noise level diagram are in left side axis and SNR is in right side axis where the signal attenuation in 2DC sheet is 0 dB at the point 7. As the point 6 is an output point to the 2DC sheet, Signal power is adjusted below -41.3 dBm/MHz of UWB restriction.

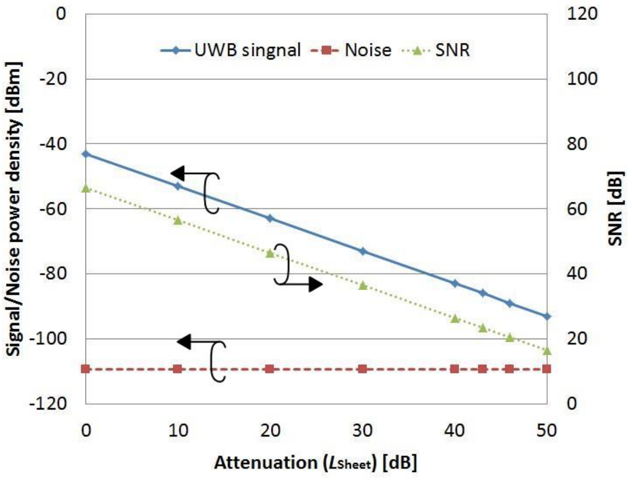


Fig. 7: Received signal power density (the point 10 in Fig. 5) and noise power density vs. the attenuation in the sheet, L_{Sheet}.

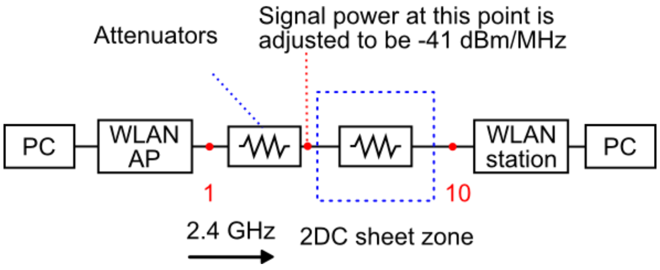


Fig. 8: 2.4-GHz non-conversion schematic diagram. The point 1 and 10 shown in Fig. 5 are connected directly by coaxial cables. Signals are adjusted to -41 dBm/MHz by attenuators.

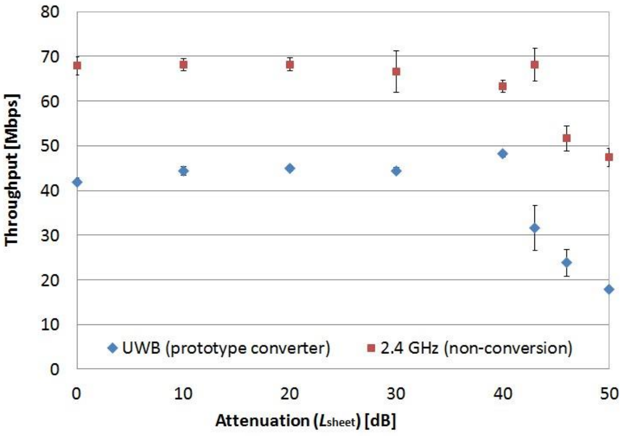


Fig. 9: Measured data transmission rate. The horizontal axis is attenuation of 2DC sheet. The dots show the average of 30 trials and the error bars show the standard deviation for each case.

V. CONCLUSION

In this paper, we proposed DDFS scheme for active tile 2DC system. Frequency converter applicable to DDFS 2DC was developed. We evaluated throughput using that converter in the DDFS-based WLAN 2DC tile system. In the converter, throughput achieved more than 40 Mbps where signal attenuation of 2DC sheet is less than 40 dB. It is roughly 60% of throughput of the 2.4-GHz original WLAN connection.

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