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Wireless LAN on 2-D Communication Tiles Using Ultra-Wideband as an Alternative Spectrum Resource

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***Abstract*—To meet the ever increasing demand for wireless local area network (WLAN) connectivity, we propose to use the frequency range allocated for ultra-wideband (UWB) radios as an alternative spectral resource for conventional WLAN systems. Since the maximum permitted emission of UWB radios is 50-dB smaller than that of conventional WLAN devices, aerial communication range will be shortened to less than 1 m. To enhance the communication range while reducing the emission, two-dimensional communication (2DC) technology can be used. The low power UWB signals can be transferred along a 2DC-tiled floor with acceptably low loss, and can be received at arbitrary points on the floor of a room. This paper presents a scheme to use the UWB 2DC system for WLAN signal transmission. An adapter device is attached to each of WLAN access point and client station. The adapter upconverts WLAN's 2.4-GHz signal to 8-GHz (in UWB's frequency range), and downconverts the received 8-GHz signal to 2.4-GHz. The adapter is connected to the antenna port of the WLAN device, and no other modifications to the circuit, firmware, and software of the WLAN device are needed. The upconverted UWB signal is attenuated to the UWB's permitted emission level before sending. Experimental results demonstrate that the WLAN connection through prototype converters and a 2DC sheet can achieve the same order of throughput as the original 2.4-GHz aerial WLAN connection. Since each converter can choose individual upconversion frequency from the UWB's frequency range, the WLAN devices in the system virtually share the UWB's bandwidth up to 7 GHz, much wider than the 80-MHz bandwidth originally allocated for 2.4-GHz WLAN devices.**

Keywords*—*Two-dimensional communication, ultra-wideband, wireless local area network.

I. INTRODUCTION

Wireless local area network (WLAN) traffic, in the 2.4-GHz and 5-GHz bands, is getting more and more congested in daily life. Emerging technologies such as Internet of Things (IoT) and machine-to-machine communications (M2M) will cause ever increasing demand on the capacity for densely populated WLAN devices within a small area, such as a living room.

Today, we often experience WLAN getting slow down where extreme number of WLAN clients exist densely in a place such as large lecture/presentation halls, exhibition halls, and stadiums. Improving network capacity in such high-density WLAN environments is a major challenge.

One promising approach is the use of higher frequency electromagnetic waves, including millimeter waves and terahertz waves. The next generation WLAN standard, IEEE 802.11ad, is designed for 60-GHz band [1]. Much shorter wavelength of the 60-GHz millimeter wave than that of the 2.4/5-GHz microwaves is suitable for high-density WLAN environment, because it can propagate as a narrow, focused beam and enables fine-grained communication range control.

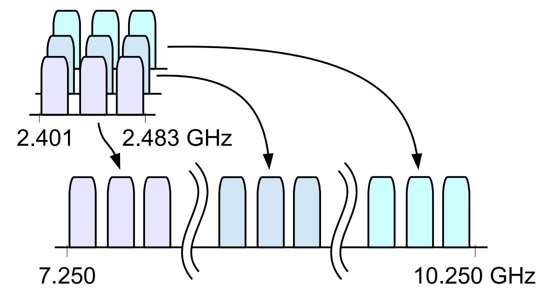


Fig. 1: 2.4-GHz-to-UWB frequency conversion. By appropriately allocating the channels in the UWB frequency range, significantly greater number of WLAN channels than the original WLAN band can be supported without interference among the channels.

As another approach to support high-density indoor WLANs while keeping the use of off-the-shelf WLAN devices, we propose to use the frequency range allocated for ultra-wideband (UWB) radios as an alternative spectral resource for conventional WLAN systems. In the proposed scheme, existing 2.4/5-GHz WLAN devices can be used by attaching a adapter that converts 2.4/5-GHz signal to another frequency in UWB radio's frequency range (e.g. 3.1–10.6 GHz in US and 7.25–10.25 GHz as "UWB high-band" in Japan). Since the UWB's frequency range is significantly wider than that of the 2.4/5-GHz bands, greater number of WLAN channels can operate simultaneously without interference, by properly choosing the converted frequency to be sent at each device, as shown in Fig. 1. Thus, the scheme can support higher-density WLAN.

The most significant problem with the scheme is the extremely low power emission of UWB radios. The maximum permitted emission of UWB radios is -41.3 dBm/MHz in terms of equivalent isotropically radiated power (EIRP). This is 50-dB lower than that of conventional WLAN devices.

If the proposed scheme is implemented as a conventional over-the-air communication system, the communication range will be approximately 1 m, as estimated below. To achieve fairly high speed as high as tens of megabits per second in WLAN, roughly 20-dB or greater signal-to-noise ratio (SNR) is required at the receiver. Suppose that WLAN signal

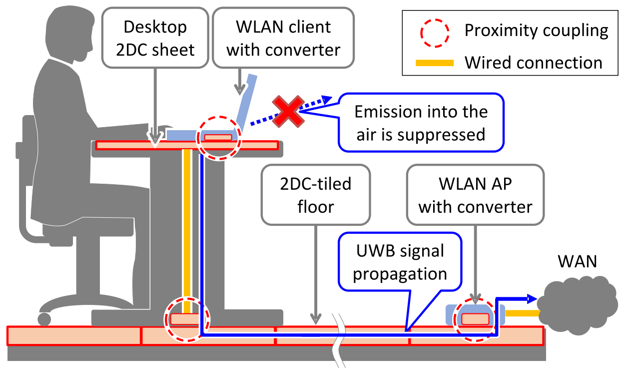


Fig. 2: Concept of WLAN on 2DC. A frequency converter (adapter) is attached to each of WLAN AP and client, and converted signal propagates along 2DC sheets, while the emission into the air is suppressed.

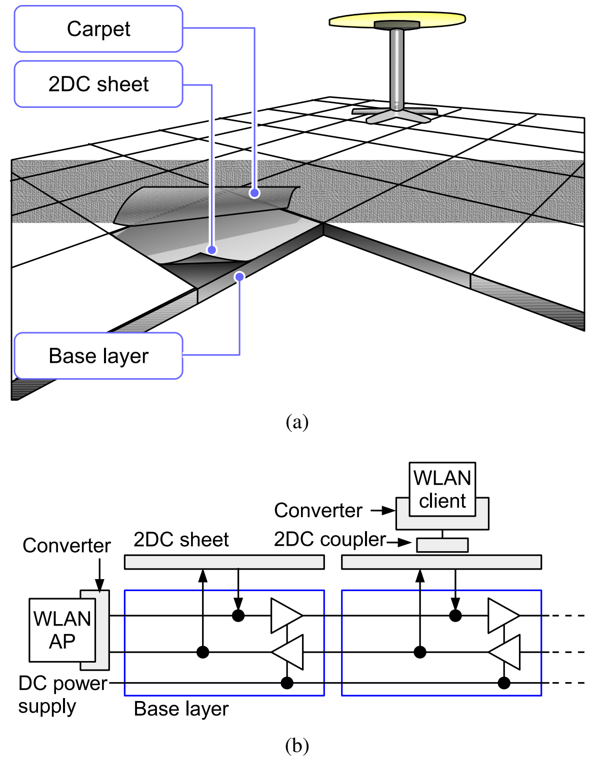


Fig. 3: (a) 2DC-tiled floor concept. The floor of a room is covered with 50-cm square 2DC tiles. Each tile consists of 3 layers: carpet, 2DC waveguide sheet, and base layer. (b) 2DC tile system schematic diagram. Active circuit is embedded in the base layer of each tile. Each base layer is integrated with amplifiers to compensate the signal loss between the adjacent tiles. Signals can be evenly received on every tile on the floor.

bandwidth is 20 MHz, i.e., a single channel is used without bonding. To achieve 20-dB or higher SNR, the received signal strength have to be -80 dBm or higher, since the thermal noise power at the room temperature 290 K is approximately -100 dBm for 20-MHz bandwidth. The signal converted into the UWB's frequency range is attenuated to -28.3 dBm, for conformity to the -41.3-dBm/MHz spectrum mask. Thus, the acceptable path loss from the transmitter to the receiver is roughly 50-dB, where 0-dBi antenna gains for both transmitter and receiver are assumed. The corresponding communication distance for the 50-dB path loss is approximately 1 m or shorter at 7 GHz or higher frequencies.

To enhance the communication range without increasing the emission, two-dimensional communication (2DC) technology [2], [3] is employed in this work. The concept of WLAN on 2DC is illustrated in Fig. 2. 2DC is a unique form of communication physical layer, different from either ordinary over-the-air radio connection or wired connection. A waveguide sheet is used as the communication medium for 2DC. Devices laid on the sheet can transmit/receive radio waves into/from the sheet via proximity (non-contact) coupling. The transmission loss between the transmitter and the receiver through the sheet and the coupler can be less than 50 dB [3], [4]. The 2DC environment can be enhanced to the entire floor of a room based on 2DC tile concept [5] as shown in Fig. 3. Each tile is integrated with amplifiers to compensate the signal loss between the adjacent tiles. Signals can be evenly received on every tile on the floor. Signals picked up at floor surface can be forwarded to a desktop 2DC sheet with a cable. Thus, low power UWB signals can be transferred to/from arbitrary points on floor, desktop and other furniture surfaces, with acceptably low loss.

As shown in Fig. 2, 2DC devices are required to be touching or to be close to the sheet. Therefore, devices laid on the desktop, floor, and other surfaces where 2DC sheet is integrated can receive the benefit of the scheme. Although wearable devices including a smartphone held in one's hand are not supported, data traffic of non-wearable, semi-fixed devices, will be significant in the context of IoT and M2M.

This paper presents a design of adapter attached to WLAN devices and demonstrates the feasibility of the proposed concept through experiments.

The rest of this paper is organized as follows. The adapter design is described in Section **??**. Evaluation experiments on WLAN speed using the prototype adapter are presented in Section III. Finally, we conclude this paper in Section IV.

II. Adapter Design

This section presents a design of an adapter that converts frequency between the WLAN's original frequency band and another one in the UWB radio's frequency range.

In this paper, the 2.4-GHz band WLAN signal is used as the original signal. Suppose that a frequency band from 7.25-GHz to 10.25-GHz, specified as "UWB high-band" in Japan, is available for UWB-side frequency, as shwon in Fig. 1. The adapter circuit to achieve this 2.4-GHz-to-UWB (2.4G-UWB) conversion is shown in Fig. 4.

In the transmitting operation, the WLAN output signal frequency is converted by the mixer. For example, by mixing WLAN signal at 2.45-GHz and local oscillator (LO) signal at 5.55-GHz, 8.0-GHz and 3.1-GHz signal components are generated. Through the attenuator and the bandpass filter (BPF), the 3.1-GHz component is eliminated and the 8-GHz component with -41.3 dBM/MHz power density is obtained.

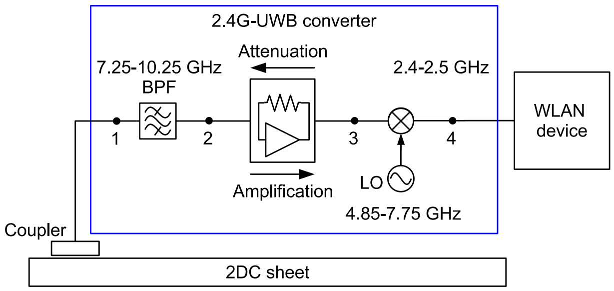


Fig. 4: The adapter schematics. It upconverts 2.4-GHz signal into UWB's frequency range and attenuates the signal to -41.3 dBm/MHz. On the other hand, UWB signal received from the 2DC tile is amplified by LNA before frequency conversion to 2.4-GHz.

The 8-GHz component is fed into the 2DC sheet through the dedicated UWB 2DC coupler [3].

In the receiving operation, 8.0-GHz signal picked up from the 2DC sheet by the coupler is amplified by a low noise amplifier (LNA). The LNA is required to avoid significant SNR degradation in the circuit beyond the LNA. Other noise components outside the frequency range used in the system is rejected by the BPF. From the amplified 8-GHz signal and 5.55-GHz LO signal, the original 2.45-GHz WLAN signal is reconstructed through the mixer. 13.55-GHz component, also generated at the mixer, is rejected at the BPF inside the WLAN device.

The actual prototype implementation is shown in Fig. 5. The WLAN device is sealed inside an aluminum shield case in order to suppress the 2.4-GHz original signal emission into the air. The WLAN antenna ports is connected to the intermediate frequency (IF) port of a double-balanced mixer, Hittite HMC220. The 5.55-GHz LO signal is generated by a frequency synthesizer, Linear Technology LTC6948.

Measured gain/loss of the components used in the prototype circuit is shown in Table I. The gain/loss of the amplifier/attenuator is shown in Fig. 6. Relative signal strength at points 1–4 shown in Fig. 4 is calculated from these values and is shwon in Fig. 7.

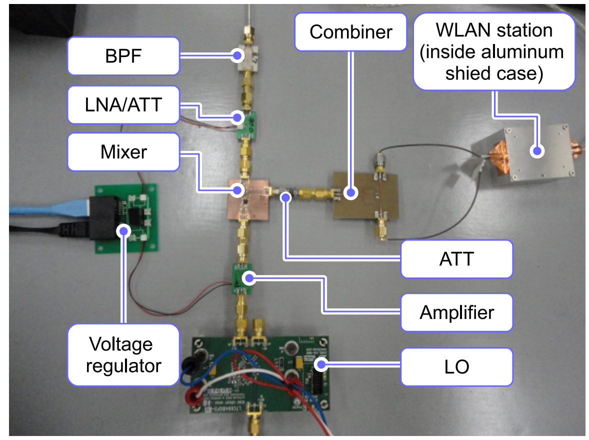
III. Evaluation Experiment

In this section, the frequency-shifted WLAN communication is evaluated by using an actual 2DC sheet and the prototype adapter. The 2DC sheet and the coupler used in the experiment are shown in Fig. 8.

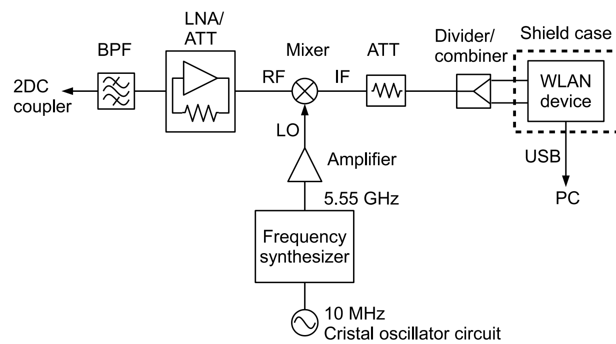
Experimental system was configured as shown in Fig. 9 and Fig. 10. Signal strength calculated at points 1–5 in Fig. 9

TABLE I: Gain/loss of each component (dB)

Component	at 2.45 GHz	at 8.0 GHz
BPF	-47	-2
Attenuator	-40	-30
Amplifier	$+20$	$+16$
Mixer	-11	-9



(a)



(b)

Fig. 5: (a) Converter circuit overview and (b) its schematic diagram. The WLAN device is sealed inside an aluminum case. The two antenna ports of the WLAN device (originally used as multiple-input and multiple-output (MIMO) antenna ports) are connected to a Wilkinson combiner.

is shwon in Fig. 11. The attenuator inserted between points 1 and 2 is for adjusting signal strength at point 3 to be -41 dBm/MHz. The transmittance between points 3 and 4, the 2DC sheet and couplers, is supposed to be -30 dB at 8 GHz and -45 dB at 2.45 GHz, as a representative value from measurement results. Actually this value significantly depends on frequency and coupler position, due to multipath fading in 2DC sheet.

The calculated minimum signal strength, -71 dBm/MHz in the downlink (DL) and -76 dBm/MHz in the uplink (UL), is roughly 40-dB higher than the thermal noise power at 290 K, -114 dBm/MHz. Thus, the system can achieve sufficiently high SNR for high-speed WLAN communication. The throughput was evaluated with the experimental system shown in Fig. 10. Although only a single piece of the sheet is used in the experiment, the system can be enhanced to the 2DC-tiled floor with large number of 2DC sheets, and can achieve room-size mid-range communication.

In the system, there are two major frequency components, the original 2.4-GHz component and the converted 8-GHz component. The signal propagation in the system can be divided into two spatial paths, the 2DC sheet path and over-the-air path. Hence, there are four combinations of these two

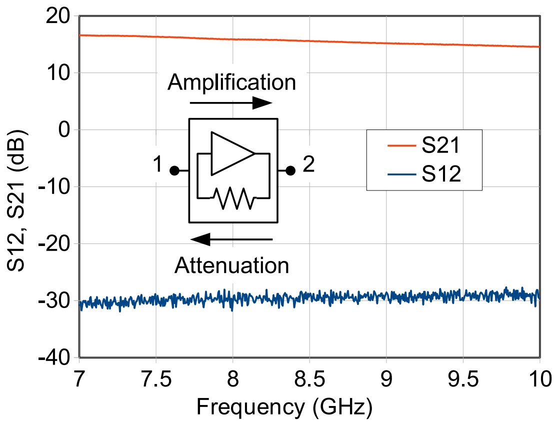
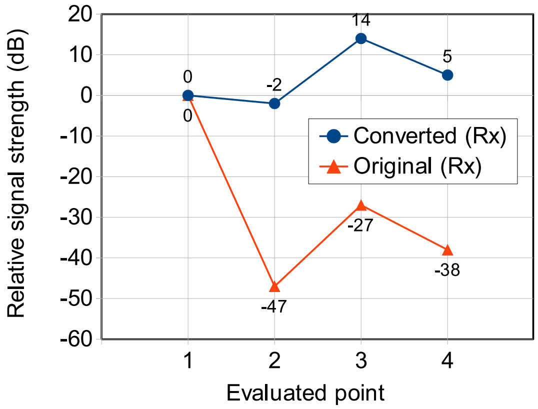
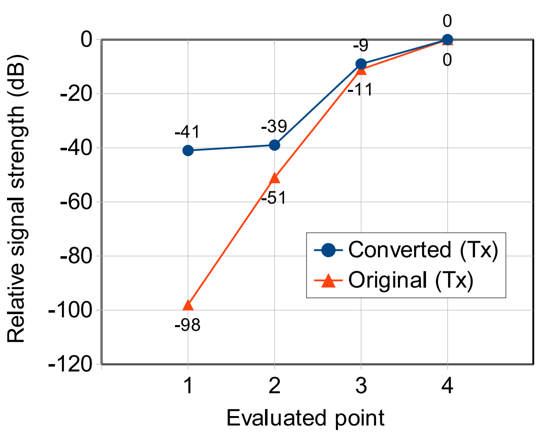


Fig. 6: Measured S_{12} (attenuator loss) and S_{21} (amplifier gain) of the amplifier/attenuator circuit.



(a)



(b)

Fig. 7: Relative signal strength of the original 2.4-GHz signal and the converted 8-GHz signal at points 1–4 shown in Fig. 4. (a) Receiving operation (signals propagate rightward) and (b) transmitting operation (leftward).

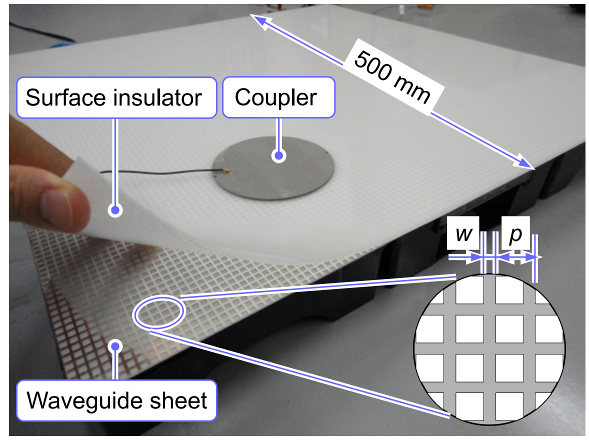


Fig. 8: 2DC sheet and coupler used in the experiment. The sheet design is the same as one reported in [6]. The sheet is 1-mm thick and the conductor mesh pitch and the line width are $p = 4$ mm and $w = 1$ mm, respectively. The surface insulator layer is a 1-mm thick polyethylene sheet.

frequency components and two spatial paths, as shown in Fig. 12. We expect that only the path denoted as (a) in the figure works well, and all other paths are disabled.

To examine the system operation, the throughput of the system is evaluated under four different conditions as described below.

1) Normal condition, as shown in Fig. 9.
2) 2DC-disconnected condition, the client coupler is removed away from the 2DC sheet.
3) Unmatched LO condition, the client-side LO frequency is changed to 5.65-GHz, different from 5.55-GHz AP-side LO frequency.
4) Converter-less condition, the 2.4G-UWB converters are removed from both AP-side and client-side, the points 2 and 5 in Fig. 9 are connected with a coaxial cable and 40-dB attenuator, which correspond to the free space path loss across 1-m distance.

The throughput between the two PCs shown in Fig. 9 is evaluated by using PCATTCP [7]. The measured result is summarized in Fig. 13. The bars show the average of the 20 trials for each condition and the error bars show the standard deviation. The WLAN connection was based on IEEE 802.11n in the 2.4-GHz band and channel bandwidth was 40 MHz. The experiments were performed in a electromagnetically silent environment, i.e., other WLAN signals not related to the experiments almost did not exist.

Under the 2DC-disconnected condition, the intended and unintended paths (a) and (d) get disconnected. The measured throughput of zero indicates that the remaining unintended over-the-air paths (b) and (c) are negligible in this system. Under the unmatched LO condition, the signal frequency after both of upconversion and downconversion become different from the original signal frequency and cannot be accepted by the WLAN receiver, and only the unchanged original frequency signal transferred through paths (c) and (d) can be accepted. The measured throughput of zero indicates that unintended paths (c) and (d) are negligible in this system. Thus, only path (a) is available as expected.

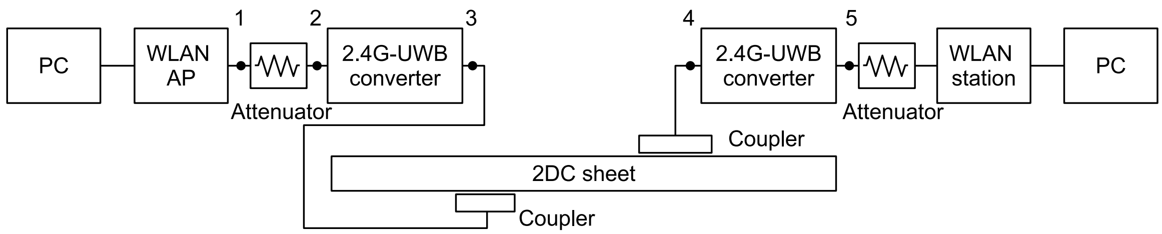


Fig. 9: Block diagram of the experimental system.

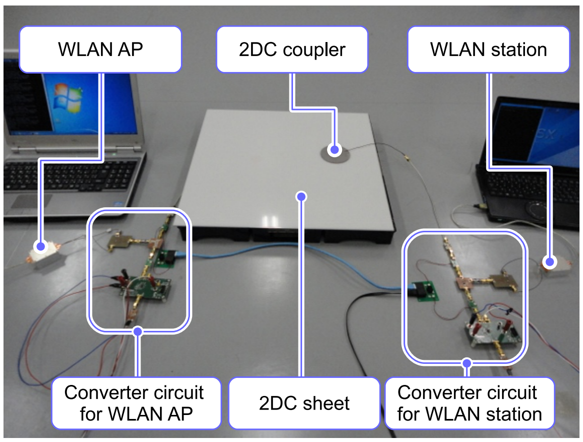


Fig. 10: Experimental system overview.

Comparing the throughput between the normal condition and the converter-less condition, they are almost the same. This result indicates that the 2.4G-UWB converter does not degrade the WLAN signal quality.

Thus, the unintended signal paths (b), (c) and (d) are negligible, and high-speed WLAN communication more than 50-Mbps was achieved through the proposed scheme.

IV. Conclusion

In this paper, we proposed a scheme to use UWB radio's frequency band as an alternative spectral resource for conventional WLAN systems. A 2.4G-UWB converter was designed and conventional WLAN devices' signals were carried as UWB signal through a 2DC sheet.

Through the converters and a 2DC sheet, WLAN communication speed was evaluated and a data rate higher than 50-Mbps, as high as the original WLAN device data rate in the experimental environment, was achieved. When the 2DC coupler was removed away from the 2DC sheet, the WLAN connection was failed or the data rate significantly degraded to lower than 1-Mbps. It indicates that the major WLAN signal path is in the 2DC sheet, and the unintended over-the-air path is disabled. The WLAN connection also failed when the LO frequencies in the Tx and Rx were different from each other. It demonstrates that the original 2.4-GHz WLAN signals are significantly suppressed and the converted 8-GHz signals work well, as we intend.

Although the experiment shown in this paper was performed on a single piece of sheet, the devices can communicate

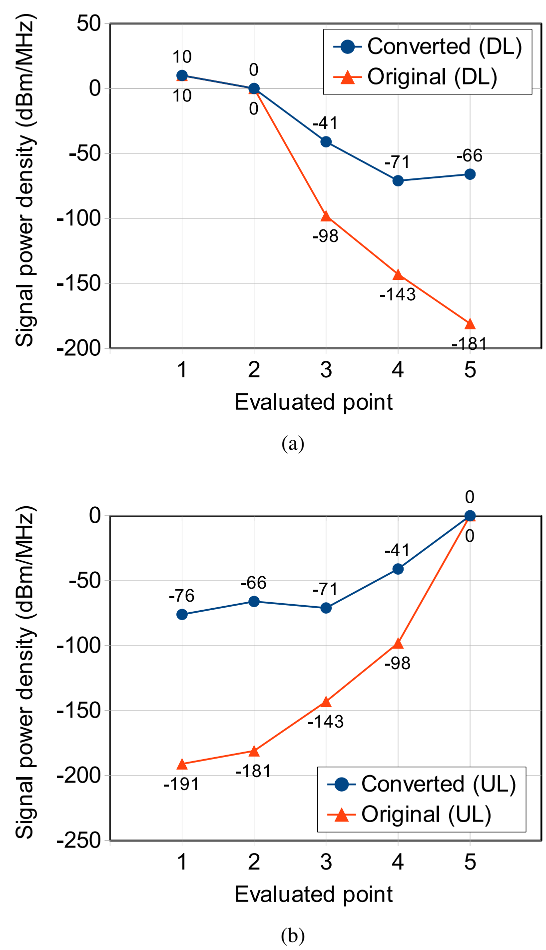


Fig. 11: Signal power density of the original 2.4-GHz signal and the converted 8-GHz signal at points 1–5 in Fig. 9. (a) Downlink (DL) operation (signals propagate rightward) and (b) uplink (UL) operation (leftward).

over several meters through multiple tiles. Fabricating such a larger system is one of our future works. We expect that high-speed mid-range radio communication as fast as the conventional WLAN connection will be achieved by using the low power UWB signals.

When a large number of WLAN devices simultaneously operate on the 2DC system, the signal frequency carried in the 2DC system can be evenly distributed over the UWB's frequency range by appropriately choosing the LO frequency of

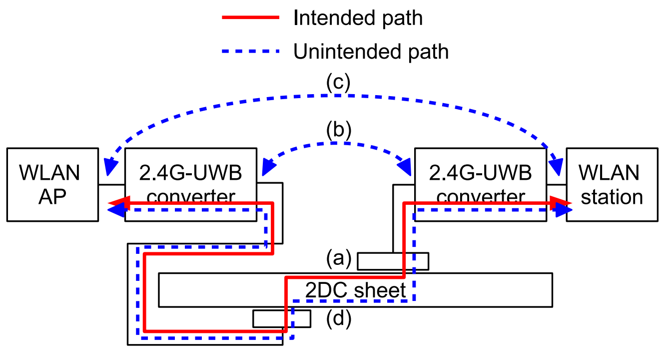


Fig. 12: Intended and unintended signal transmission paths. (a) Intended path of UWB signal, (b) unintended over-the-air path of UWB signal, (c) unintended over-the-air path of original signal, and (d) unintended 2DC path of original signal.

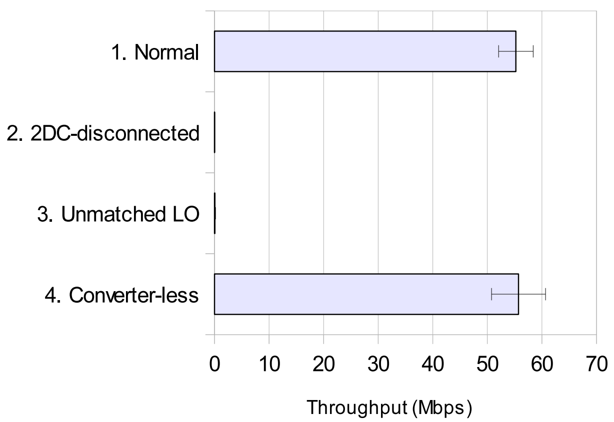


Fig. 13: Measured data transmission rate for the four conditions. The thick bars show the average of 20 trials and the error bars show the standard deviation for each case.

each converter. Demand on the frequency spectrum, currently concentrates at the 2.4-GHz band, can be evenly distributed to wider frequency range by the proposed scheme, in order to avoid spectrum shortage.

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