Development of TV White-Space LTE Devices Complying with Regulation in UK Digital Terrestrial TV Band

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Abstract. Recently, white-space communication system has been widely promoted as one of the spectrum sharing technologies for further efficient use of spectrum resource. In particular, white-spaces in the TV bands (TVWS, TV white-spaces) have attracted attentions worldwide and regulations have been established in the U.S.A, the U.K., Singapore, etc. In the U.K., pilot program has been started based on regulations established by the Ofcom and trial operation of TVWS communication systems in cooperation with authenticated white-space databases has been performed from July 2014. In this trial, to avoid interference with primary users such as TV broadcasters and wireless microphones, draft rules established by ETSI are employed as specifications of radio characteristics. In this study, to verify the feasibility of spectrum expansion of mobile communication systems by utilizing the TVWS, the authors have developed TVWS LTE devices complying with the Ofcom rules and performed field experiment in the U.K. Prototyped devices have been licensed by the Ofcom and TVWS LTE system has been successfully demonstrated in London urban area. As a result, it is confirmed that the existing LTE system can be operated in the U.K. TVWS without interference with the primary users. This is the first report on prototype of TVWS LTE devices conforming to the ETSI draft specification.

Keywords: LTE · Spectrum sharing · TV white-spaces · Frequency conversion · Field experiment

1 Introduction

Recently, wireless communication services such as video streaming and social networking have been widely used with the explosive spread of portable devices such as smart phones and tablet computers, and thus, the demand for high-speed and large-capacity communications are increasing day by day. In such a situation, data traffic in

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mobile communication will continuously increase and further expansion of the assigned frequency bands is strongly required. ITU (International Telecommunication Union) estimated that a bandwidth (BW) of 1,280–1,720 MHz including current allocated frequency bands is necessary for mobile communication system by 2020 [1]. However, it is difficult to squeeze out a wide space from current crowded frequency bands, especially under 6 GHz that is suitable for mobile communication system. Therefore, technologies which allow more efficient use of limited spectrum resource are entreated and the white-space access is expected as one of such technologies. In particular, white-spaces in TV bands (TVWS, TV White-spaces) have attracted attentions due to a wide allocated frequency band for TV broadcasters and superior radio wave propagation and penetration characteristics in the UHF band, and thus, TVWS communication systems have been globally researched and developed. Furthermore, operational rules for practical use of the TVWS have been established in the U.S.A, the U.K. and Singapore, etc [2]-[4].

Toward the next generation of mobile communication system, TVWS utilization is also one of significant options, and operational scenarios, use cases and simulation-level system evaluations about LTE (Long Term Evolution) communication systems have been studied [5]-[8]. Furthermore, prototype of TVWS LTE system including devices was reported in 2013 [9]. This system incorporates spectrum sensing technology for enabling TVWS communication, however, white-space database (WSDB) approach is mainly employed as a basic direction in established rules.

In the U.K., the Ofcom (Office of Communication) has conducted a pilot program for trial operation of TVWS communication systems in cooperation with the WSDB based on the established rules from July 2014, and a series of trials have been performed [10]. In this study, the authors have also prototyped TVWS LTE eNB (enhanced Node B) and UE (User Equipment) conforming to the Ofcom rules, based on the frequency conversion technology [11]. Prototyped TVWS devices are licensed by the Ofcom and developed TVWS LTE system including the devices is operated in cooperation with the WSDB authenticated by the Ofcom. Also, by participating in the Ofcom trial, field experiment was performed in the King's College London (KCL), Denmark Hill Campus. In this trial, prototyped TVWS LTE system has been successfully demonstrated in London urban area.

The rest of this paper is organized as follows. TVWS regulation in the U.K. is summarized in Section 2. Performance of prototyped TVWS eNB and UE are characterized in Section 3. Prototyped TVWS LTE system and results of field experiment in London are described in Section 4. Section 5 is conclusion.

2 TVWS Regulation in the U.K

2.1 Requirements for TVWS Devices

In the U.K., a frequency band of 470–790 MHz is allocated to the digital terrestrial TV (DTT) and its channel BW is 8 MHz. In the pilot program for the secondary use of TVWS, TVWS devices are required to comply with the Ofcom regulation, and TVWS communication system is also required to operate in cooperation with the

WSDB authenticated by the Ofcom. Requirements for TVWS devices are defined by the draft specification developed by ETSI (European Telecommunications Standards Institute) and TVWS devices are licensed by the Ofcom based on this ETSI draft specification [12].

For avoidance of interference with the primary users, limitation of adjacent channel leakage power (ACLP) is defined as one of required specifications for TVWS devices, but different in each country and region. For example, the limitation of ACLP is defined by the absolute value according to operational conditions in the U.S.A [2]. On the other hand, the limitation of ACLP is defined by the relative value to the output power, in the U.K. [12]. In the ETSI draft specification, the adjacent channel leakage power ratio (ACLR) is defined as the relative value of following equation.

$$P_{\mathrm{OOB}}\ (\mathrm{dBm}/(100\ \mathrm{kHz})) \le \max\{\, P_{\mathrm{IB}}\ (\mathrm{dBm}/(8\ \mathrm{MHz})) - ACLR\ (\mathrm{dB}),\ -84\ (\mathrm{dBm}/(100\ \mathrm{kHz}))\,\}, \quad (1)$$

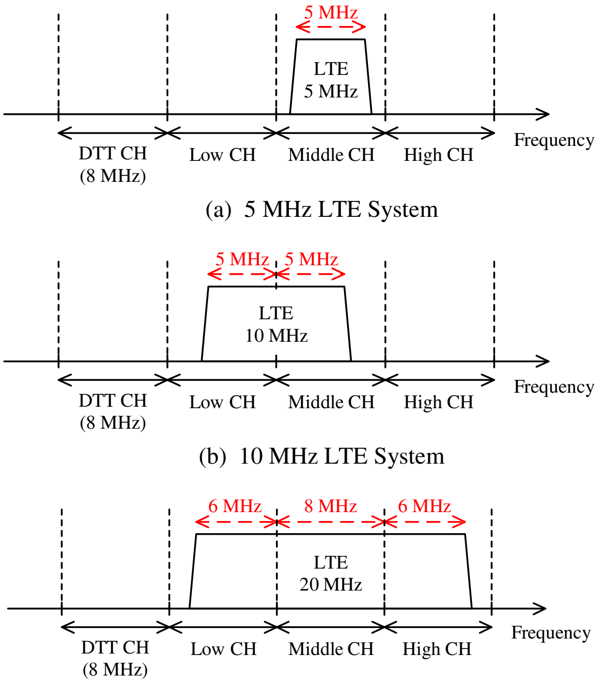
where P_{OOB} is leakage power in a 100 kHz BW outside using DTT channel and P_{IB} is output power in a 8 MHz BW of using DTT channel [12]. Here, the ACLR is defined by the suppression ratio of P_{OOB} to P_{IB}. Table 1 shows required ACLR specification. Depending on the ACLR performance, TVWS devices are classified into five “Device Emission Classes,” i.e. device classes. In the pilot program in the U.K., before starting radio communication in the TVWS, TVWS devices inform the WSDB of device information including geo-location and the device class, and then, receive an available DTT channel list including information of permitted maximum power for each channel from the WSDB. At this time, received parameters vary according to the device class.

Table 1. ACLR for different device emission classes [12].

Where P_{OOB} falls within nth adjacent DTT channel	ACLR (dB)				
	Class 1	Class 2	Class 3	Class 4	Class 5
$n = \pm 1$	74	74	64	54	43
$n = \pm 2$	79	74	74	64	53
$n \ge +3, n \le -3$	84	74	84	74	64

In the case that the signal BW is wider than 8 MHz and multiple DTT channels are used, limitation of P_{OOB} is calculated from (1) with the lowest P_{IB} in used channels. Fig. 1 shows channel allocation of TVWS LTE system to DTT channels with a signal BW of 5 MHz, 10 MHz and 20 MHz. Here, it is required to use 2 and 3 contiguous DTT channels for 10 MHz and 20 MHz LTE system, respectively. In the case of 20 MHz LTE system, center DTT channel is fully occupied, while a BW of only 6 MHz is occupied in two DTT channels at both ends, and thus, P_{IB} of DTT channels at both ends is theoretically 1.25 dB decreased in comparison with the center DTT channel. Therefore, limitation of P_{OOB} is calculated from P_{IB} in DTT channels at both ends.

In addition, transmitter unwanted emissions outside the TV band, transmitter intermodulation and receiver spurious emissions are defined as well as common radio standard, in the ETSI draft specification [12].



(a) 5 MHz LTE System

(b) 10 MHz LTE System

(c) 20 MHz LTE System

Fig. 1. TVWS LTE channel allocation to DTT channels (based on 8 MHz wide channels).

2.2 ACLR Requirement in 3GPP Standard

Prototyped TVWS eNB and UE employs frequency conversion technology which allows LTE communication in the TVWS by converting the frequency band of existing LTE system to the UHF band [11]. In our TVWS LTE system, 2.6 GHz LTE system is used as an existing LTE system. Therefore, RF characteristics of prototyped TVWS eNB and UE comply with the existing LTE standard regulated by 3GPP, and ACLR characteristics are also based on the existing LTE system. Table 2 shows ACLR requirement for UE in 3GPP standard in comparison with that in the ETSI draft specification for the TVWS. In the 3GPP standard, 29.2 dB is defined as the ACLR limit for 5 MHz, 10 MHz and 20 MHz LTE system [13]. However, measurement frequency, i.e. frequency offset (Δf), and measurement BW are different between the 3GPP standard and the ETSI draft specification. As easier comparison, by converting ACLR of the 3GPP standard to that with a 100 kHz measurement BW, ACLR(/100kHz) is calculated to 46.2 dB. This is about 3.2 dB lower than that in the ETSI draft specification. This means the possibility of TVWS utilization by existing LTE system, although Δf in the

3GPP standard is larger than that in the ETSI draft specification. In addition, the ACLR of eNBs in the 3GPP standard is more stringent than that of UEs, and thus, the ACLR of eNBs also complies with the ETSI draft specification.

Table 2. Comparison of ACLR requirement [12],[13].

Signal BW	3GPP standard			ETSI specification		
	Δf	ACLR	Measurement BW	Δf	ACLR	Measurement BW
MHz	MHz	dB	MHz	MHz	dB	MHz
5	5	29.2	4.5	4-12	43	0.1
10	10	29.2	9	8-16	43	0.1
20	20	29.2	18	12-20	43	0.1

3 RF Performance of Prototyped TVWS Devices

We prototyped TVWS eNB and UE as shown in Fig. 2 by utilizing the frequency conversion technology, as reported in the previous work [11]. To comply with the TVWS regulation in the U.K., some alterations have been made to previous design; e.g. channel allocation to the DTT bands as depicted in Fig. 1. In our system, therefore, the FDD (Frequency Division Duplex) LTE system with a signal BW of 20 MHz can be operated, when 2 blocks of 3 contiguous DTT channels involving a moderate duplex spacing are available.

In this section, performance of the prototyped TVWS eNB and UE in the TDD (Time Division Duplex) mode are characterized for each signal BW, and licensed by the Ofcom based on measured RF characteristics. Device class of each device is "Class 5." Table 3 summarizes required specification and typical measurement result of prototyped TVWS UE in the TDD mode. Detailed measurement processes and results are described in each sub-section. All characteristics are basically measured in the measurement processes elaborated in [12], except for transmission intermodulation.

(a) eNB (b) UE

Fig. 2. Prototyped TVWS LTE devices [11].

3.1 Output Power

Output power is measured by spectrum analyzer (SA) with the following settings: a resolution BW (RBW) of 10 kHz, a video BW (VBW) of 30 kHz, RMS (Root Mean Square) detector and max hold trace mode. Measured frequency range is set to 470 MHz + RBW/2 to 790 MHz – RBW/2. Measurement result is compensated by comparing the summation of measured power for all the sampling points to the power measured by a calibrated power meter for the entire TV band. Subsequently, P_{IB} is calculated as summation of measured powers for all the sampling points in each DTT channel with a BW of 8 MHz. P_{OOB} and P_0 that is power spectral density in a BW of 100 kHz are calculated by adding up 10 contiguous measured powers at an arbitrary frequency.

LTE system using multiple DTT channels such as 10 MHz and 20 MHz LTE are required to calculate P_{IB} and P_0 for all using DTT channels as shown in Table 3. In the case of 20 MHz LTE system, occupied BW of three DTT channels are different, and thus, P_{IB} of a center DTT channel is theoretically about 1.25 dB higher than that of DTT channels at both ends. In the measurement result, there is about 2–3 dB difference between center DTT channel and others, and slightly higher than the theoretical value. This is mainly caused by unflatten spectrum of prototyped LTE devices.

3.2 ACLR

As abovementioned, ACLR in Table 3 is calculated from the lowest P_{IB} in all using DTT channels. As a result, it is confirmed that ACLR of prototyped TVWS LTE UEs complies with the ETSI draft specification for class 5 TVWS devices in all of 5 MHz, 10 MHz and 20 MHz LTE systems. Therefore, it is also confirmed that the existing LTE system can be used in the U.K. TVWS without interference with primary users, since the prototyped devices just convert the frequency of existing LTE system to the UHF band.

Fig. 3 shows typical spectrum mask of prototyped TVWS UE for 5 MHz, 10 MHz and 20 MHz LTE system in the TDD mode. Dashed lines are limited lines of P_{OOB} that are calculated from measured P_{IB} and ACLR requirement for class 5 TVWS devices shown in Table 1. Inclination is observed in measured spectrum masks. This asymmetry is mainly caused by frequency characteristics of the frequency conversion circuit including mixers and power amplifiers. In this study, limited lines of P_{OOB} are calculated from the lowest P_{IB} in using DTT channels in consideration of this asymmetry (P_{IB} in the low CH is used for ACLR calculation in 20 MHz LTE system). In addition, asymmetry is also observed in slopes of spectrum mask, inter alia, for 20 MHz LTE system. This is mainly caused by nonlinearity of power amplifier in the frequency conversion circuit. Since gain balance is different in each signal BW and gain of the power amplifier in the 20 MHz LTE system is higher than others, nonlinearity of power amplifier is notably emphasized in 20 MHz LTE system.

Table 3. Required specification and typical RF characteristics of prototyped TVWS UE in TDD mode.

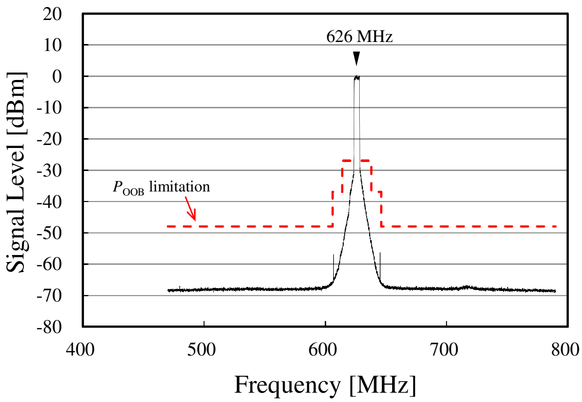
Item	Conditions	Unit	Spec.	5 MHz LTE			10 MHz LTE			20 MHz LTE		
Center frequency		MHz	–	482	626	762	494	630	758	498	634	738
Maximum output power		dBm	–	14.3	14.8	14.5	13.9	14.6	14.3	9.0	10.8	9.7
P_{IB}	Low CH	dBm/ 8 MHz	–				10.8	11.4	11.4	2.8	4.6	3.8
	Middle CH		–				10.9	11.7	11.2	5.6	7.5	6.4
	High CH		–				–	–	–	3.6	5.5	4.2
P_0	Low CH	dBm/ 100 kHz	–				–4.8	–4.5	–4.6	–13.3	–11.5	–12.2
	Middle CH		–	–1.8	–1.0	–1.3	–4.9	–3.8	–4.5	–12.5	–11.0	–11.8
	High CH		–				–	–	–	–12.7	–10.9	–12.0
ACLR	n=–1	dB	≥43	45.3	50.7	53.3	44.0	49.5	50.9	55.3	57.5	56.1
	n=+1	dB	≥43	45.4	49.9	53.8	44.9	51.6	52.9	50.0	51.4	51.3
	n=–2	dB	≥53	–	71.4	73.8	62.5	62.8	65.3	60.9	62.5	61.3
	n=+2	dB	≥53	62.8	69.6	72.9	62.1	60.4	63.5	56.0	56.7	57.5
	n≤–3	dB	≥64	–	81.7	79.7	–	71.7	73.9	–	67.1	65.8
	n≥+3	dB	≥64	74.4	81.8	80.2	68.8	69.7	72.2	65.3	67.1	66.5
Transmitter unwanted emissions outside TV bands	30–47MHz	dBm/ 100 kHz	≤–36	–59.8	–60.1	–56.1	–59.6	–59.6	–60.2	–57.5	–60.0	–59.6
	47–74MHz		≤–54	–58.8	–59.6	–56.4	–59.3	–59.4	–59.7	–57.1	–59.7	–59.0
	74–87.5MHz		≤–36	–59.8	–60.3	–56.2	–59.7	–60.2	–59.9	–54.4	–59.4	–60.1
	87.5–118MHz		≤–54	–58.9	–59.6	–56.5	–59.2	–59.5	–58.7	–55.8	–58.4	–59.6
	118–174MHz		≤–36	–59.2	–59.8	–56.0	–59.2	–58.4	–59.4	–59.4	–58.6	–59.3
	174–230MHz		≤–54	–57.5	–59.4	–54.9	–58.2	–59.0	–58.8	–58.6	–59.1	–59.1
	230–470MHz		≤–36	–38.8	–57.9	–55.1	–43.8	–58.4	–56.9	–38.8	–58.0	–58.2
	790–862MHz		≤–54	–58.9	–58.4	–54.6	–57.3	–58.2	–56.3	–58.5	–58.2	–56.4
	862–1,000MHz		≤–36	–48.4	–58.8	–54.8	–48.9	–58.3	–57.3	–49.2	–58.5	–58.1
	1–4GHz	dBm/ 1 MHz	≤–30	–48.7	–48.5	–43.2	–48.1	–45.6	–45.4	–37.4	–44.9	–55.4
3rd order reverse intermodulation attenuation (*RIM3*)	Lower	dB	≥45	48.4	56.2	57.0	53.0	59.3	62.3	55.6	58.9	56.0
	Upper	dB	≥45	46.8	51.3	55.0	52.6	57.8	59.8	50.0	50.5	49.6
Receiver spurious emissions	30MHz–1GHz	dBm/ 100 kHz	≤–57	–90.3	–89.8	–87.1	–93.2	–93.2	–92.3	–83.5	–89.2	–82.9
	1–4GHz	dBm/ 1 MHz	≤–47	–63.2	–69.2	–65.2	–70.2	–69.1	–56.4	–61.8	–65.8	–60.2

3.3 Unwanted Emissions and Intermodulation

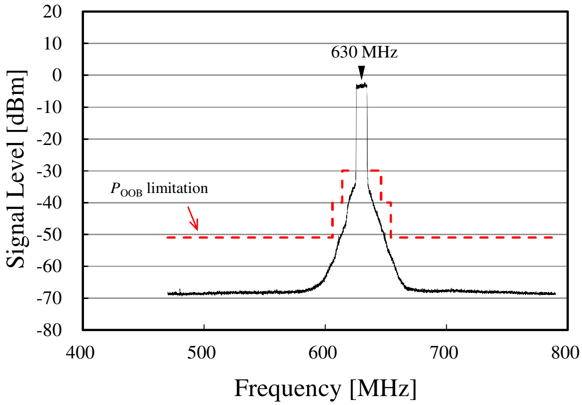
Transmitter unwanted emissions outside the TV band and receiver spurious emissions comply with the ETSI draft specification as shown in Table 3.

Transmitter intermodulation is measured by using a typical measurement system as shown in Fig. 4, in lieu of the measurement system in [12]. In this measurement, TVWS UE, signal generator (SG) for unwanted signal generation and SA are connected to each other through a power divider. Transmission frequency of the TVWS UE is set to f_w and output power is set to maximum output power in Table 3. Unwanted signal with a frequency of f_{un} is input from the SG and its signal level of P_u is set to –20 dBm, even though signal level of the unwanted signal is defined to 40 dB lower than that of transmission signal in the ETSI draft specification. During the measurement with this setup, 3rd intermodulation with a signal level of *PIM3* is observed at a frequency of $2 \times f_w - f_{un}$ on the SA. Then, the third-order reverse intermodulation attenuation of *RIM3* is calculated by substitution of P_{IB}, P_u and *PIM3* to the following equation.

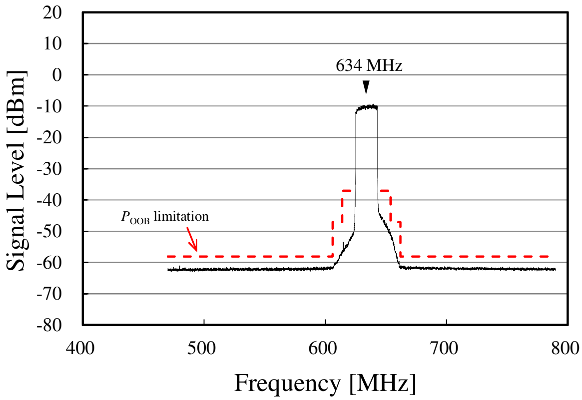
$$RIM3 = 2 \times P_{IB} + P_u - PIM3, \qquad (2)$$



(a) 5 MHz LTE System.



(b) 10 MHz LTE System.



(c) 20 MHz LTE System.

Fig. 3. Spectrum mask of prototyped TVWS UE in the TDD mode.

In this measurement, unwanted signal is normally input to the adjacent DTT channel; i.e. 8 MHz offset. However, in TVWS systems that use multiple DTT channels, 3rd order intermodulation will be generated in occupied frequency band. Therefore, f_{un} is set to f_w ± 12 MHz and f_w ± 16 MHz for 10 MHz and 20 MHz LTE system, respectively. For this measurement methods and results, consensus was obtained from the Ofcom.

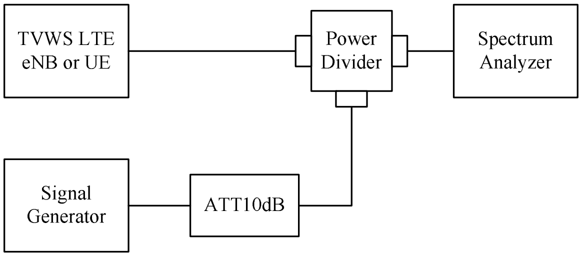


Fig. 4. Measurement system for transmitter intermodulation.

4 Field Experiment

Fig. 5 shows architecture of the developed TVWS LTE communication system demonstrated in the TVWS pilot program conducted by the Ofcom. As this platform is elaborated in more detail in [14], we briefly introduce the overview in this section. The TVWS eNB is operated as an LTE base station, and the TVWS UE is operated as an LTE terminal in this system. Therefore, the TVWS eNB is used as a fixed device and the TVWS UE is used as a non-fixed device. In conformance with the ETSI draft specification [12] and the Ofcom WSDB specification [15], TVWS devices are categorized into two types of "Master device" and "Slave device," and "Master device" should negotiate with the WSDB listing server and the WSDB before starting the TVWS communication. Procedures for the negotiation are generally as follows. First, "Master device" acquires a list of authenticated WSDBs from the WSDB listing server and select one WSDB for parameter exchange. Then, "Master device" informs the WSDB of "device parameters" including "device emission class," and receives "operational parameters" such as time validity and available maximal output power from the WSDB. Here, both devices are categorized as "Master device" in this system. In general, non-fixed devices are operated as "Slave devices," however, slave devices need to obtain "operational parameters" from master devices by using the TVWS communication system without directly access to the WSDB, and thus, slave devices cannot transmit any signal during the reception of "operational parameters." By categorizing both WS eNB and UE as "master devices," in this system, the existing LTE standard is used without any change while avoiding the difficulty to incorporate such parameter exchange in the current LTE system information.

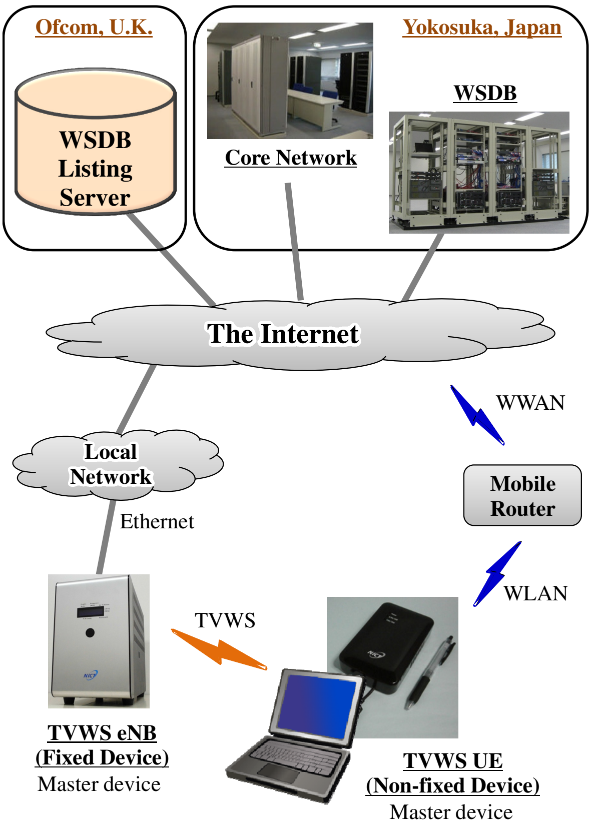


Fig. 5. Developed TVWS LTE communication system in the Ofcom TVWS pilot program.

Field experiment with TVWS eNB and UE was performed in the London urban area. Connectivity and maximum throughput were measured in the Denmark Hill Campus of the KCL where the TVWS eNB was placed on the rooftop of the seven-story building and the TVWS UE moved campus area around the building. Fig. 6 shows maximum downlink throughput in the TDD mode as a function of RSRP (Reference Signal Receiver Power) in the conditions of a signal BW of 20 MHz and a SISO (Single-Input Single-Output) communication link. Despite the high-interference and high-temperature environment resulting in the performance degradation, a maximum downlink throughput of 19.5 Mbit/s was successfully achieved in the field experiment. In the FDD mode, a maximum downlink throughput of about 45.4 Mbit/s was obtained in the same measurement conditions. In addition, a downlink throughput of more than 2 Mbit/s was achieved with a line-of-site distance of 250 m in the TDD mode with a signal BW of 5 MHz, while the TVWS UE was moving in the campus.

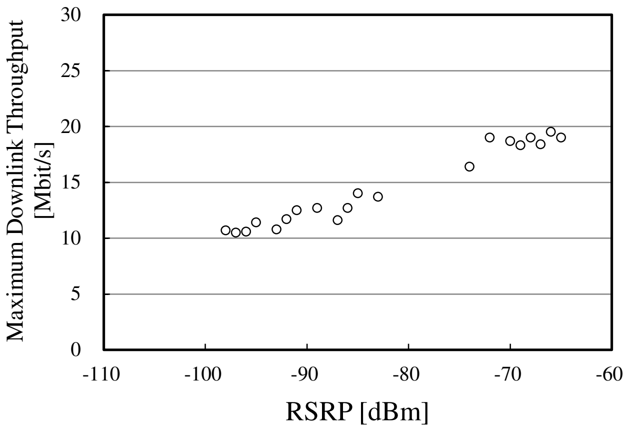


Fig. 6. Maximum downlink throughput as a function of RSRP.

5 Conclusion

In this study, TVWS eNB and UE complying with the ETSI draft specification were developed by utilizing frequency conversion technology, and licensed by the Ofcom. Even in the 10 MHz and 20 MHz LTE systems that use multiple DTT channels, it was confirmed that all the RF characteristics including ACLR complied with the ETSI draft specification.

Also, the TVWS LTE system, which can operate in the cooperation with the WSDB authenticated by the Ofcom, was developed and trial operation of this system was performed in London urban area by participating in the Ofcom pilot program. Although measured maximum throughput was degraded due to tough measurement environment, decent maximum throughputs of 19.5 Mbit/s and 45.4 Mbit/s were achieved in TDD and FDD modes, respectively. Consequently, it is also confirmed that the existing LTE system can be operated in the U.K. TVWS without any interference with the primary users and TVWS LTE system is expected as one of the technologies to extend spectrum access opportunities towards new generation of mobile communication system.

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