Wireless Channel Measurement System Using Zynq UltraScale+ RFSoC for MIMO and D2D Communication Systems

Haruki Inaba, Hiroshi Tsutsui, and Takuya Yasugi
Graduate School of Information Science and Technology, Hokkaido University

***Abstract*—In this paper, we present a wireless channel measurement system using Zynq UltraScale+ RFSoC for D2D communication systems. In order to achieve highly effective frequency utilization considering recent wireless communication progresses such as 5G and IoT systems, much more adaptive and sophisticated approaches are highly demanded. One chip solution such as RFSoC where an RF analog-to-digital signal chain is integrated might be a breakthrough for such demands. We developed a channel measurement system targeting MIMO and D2D IoT systems. In this paper, we present two measurement results, IEEE 802.11n OFDM frame transmission and the EVM measurement using a simple sine wave with various carrier frequencies.**

I. Introduction

In recent years, the number of wireless communication devices are increasing due to the wide spread of smartphones and IoT devices. When many devices communicate using a close frequency band, they interfere with each other and the throughput deteriorates. Considering that most of them are mobile devices, the radio wave propagation environment changes dynamically. In the near future, in addition, it is expected that enormous IoT devices will exchange data with each other to realize much more sophisticated applications. Considering these cases, efficient frequency utilization may become a much more important key for successful developments. Under the conditions where many communication devices exist in a limited space, it is necessary to investigate the actual antenna propagation environments to develop systems with highly efficient frequency utilization, where sophisticated communication methods are adaptively selected depending on the channel conditions. We may call such systems cognitive radio systems. With the recent progresses of semiconductor manufacturing technologies, FPGA chips with integrated RF functions such as Xilinx's RFSoC have appeared. In the near future, it is expected that cognitive radio systems may become truly practical.

To realize cognitive radio, the frequency sensing and software defined radio (SDR) [1] are indispensable key technologies. By sensing other users' communication status, the white space might be fully shared and utilized. From the sensed channel information, we can select the communication method that maximizes the throughput using SDR approaches. To develop such cognitive communication methods, it is necessary to utilize not only the simulation results, but also the actual experimental results using real antenna propagation conditions. In general, however, experiments using the actual radio waves require high-end equipment, development, and implementation costs. The FPGA approaches may alleviate the cost.

In this paper, we present a wireless channel measurement system using Zynq UltraScale+ RFSoC (RFSoC) [2, 3] to measure the propagation characteristics in an actual antenna propagation environment. The goal of our research is to realize highly efficient cognitive communication systems, which will be reported in other papers. In order to develop the cognitive systems considering the actual antenna propagation environment, devices that can transmit and receive radio waves in a wide band are required. We believe that RFSoC is suitable for such development because the RF modules are integrated with FPGA in one-chip. In this paper, we present a channel measurement system using RFSoC which has been developed as a first phase of cognitive radio system development.

The rest of this paper is organized as follows. Sec. II explains the direct down conversion, which is one of the key features of RFSoC. Sec. III explains the channel measurement system using RFSoC. Sec. IV describes the measurement results of the IEEE 802.11n OFDM frame using our system and the error vector magnitude (EVM) measurement results when the carrier frequency is changed. Finally, Sec. V concludes this paper.

II. RFSoC direct down conversion

This section describes the advantages of RFSoC over regular RF converters. One of the most significant key features of RFSoC is a wide bandwidth, which may cover many wireless communication standards.

According to the Shannon-Hartley theorem, the data amount that can be sent on the channel without error depends on the channel bandwidth and the SNR. The communication capacity used for wireless communication is rapidly increasing at a rate of 50 % every year, and will reach 30 exabytes in 2020. Therefore, the bandwidth specified in communication standards tends to be expanded. The maximum bandwidth of 100 MHz for 4G LTE has increased to 400 MHz for 5G. This trend may continue in the future.

In general, wireless communication systems include down conversion systems. The down-conversion system is designed to convert the input RF signals to intermediate frequency (IF) signals. A general down conversion system is shown in Fig. 1. On the other hand, the direct down conversion system

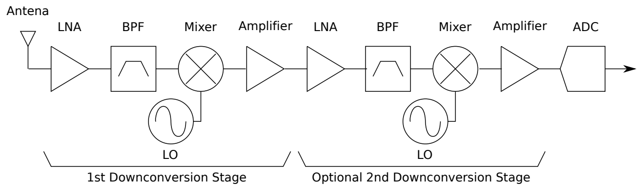


Fig. 1. General down conversion system.

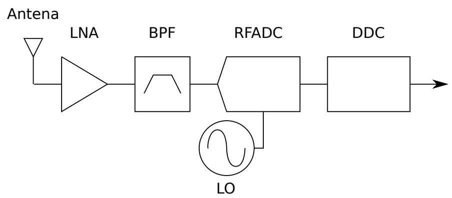


Fig. 2. RFSoC direct down conversion system.

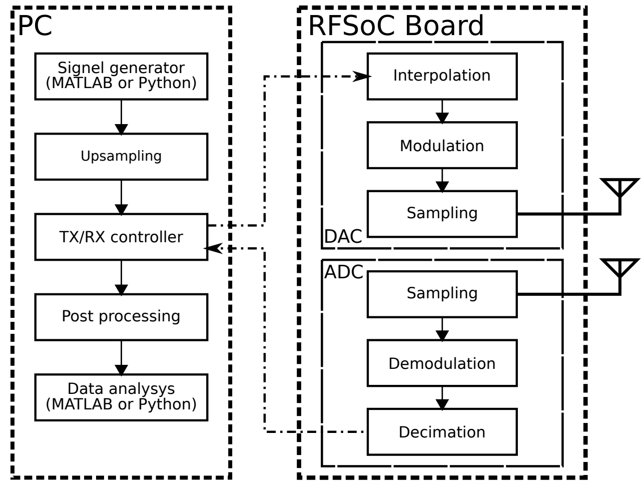


Fig. 3. Block diagram of the channel measurement system using RFSoC.

of RFSoC is shown in Fig. 2. RFSoC uses a digital down converter (DDC) for the down conversion. DDC is a digital processing approach for down conversion, where the ADC samples the input signal with several times higher frequency than the input one. As a result, the aliasing filters can be used with desirable characteristics, and the number of analog conversions can be reduced. In addition, the decimation filters can be applied while maintaining the information contained in the spectrum.

General dedicated RF converters support only specific sampling frequencies. On the other hand, the maximum sampling frequency of RFSoC ZU28DR is up to 4,096 MHz and 6,554 MHz for the ADC and DAC, respectively. Signals with a frequency band lower than 2 GHz can be transmitted and received using the direct conversion approach. Moreover, assuming the superheterodyne with additional RF converters, any IF signals lower than 2 GHz can be utilized. This may cover all of the communication standards currently used. To utilize Wi-Fi radio frequency ranges such as 2.4 GHz and 5 GHz, we newly developed RF boards for RFSoC. One of these boards is used for the OFDM frame transmission measurement in this paper, which will be shown in Sec. IV-A.

III. Channel measurement system using RFSoC

This section describes the channel measurement system using RFSoC. In the following, we assume the ZCU111 evaluation board with RFSoC ZU28DR.

A. *System overview*

Fig. 3 shows the block diagram of the channel measurement system using RFSoC. The RFSoC is controlled using a PC, which is connected to RFSoC via Ethernet.

The core software running in the PC is written using Python. The data to be sent is generated using Python or MATLAB. Since RFSoC's sampling rate is usually higher than that assumed in the signal generation, the data is upsampled to the corresponding sampling rate of RFSoC. The data ready to be transmitted to RFSoC is sent to RFSoC. The received data by RFSoC is transmitted to the PC. The data is applied some post-processing and analyzed.

Linux is running on RFSoC utilizing its ARM based processing system (PS). Therefore, the PC and the RFSoC can communicate with each other easily using TCP/IP. The programmable logic (PL) in RFSoC can be controlled from the PS. A daemon process running in PS controls PL, and play a role as an interface with the PC using TCP/IP. Utilizing a DDR memory on the RFSoC board, we can prepare experiment data up to 128 MB.

B. *Upsampling*

The maximum sampling rate of the RFSoC DAC is 6.554 GHz. Baseband signals usually do not require such a high sampling rate. Although the DAC has a functionality for interpolation up to 8 times, the effective sampling rate is still high. Therefore, we apply upsampling before sending data to RFSoC. Fig. 4 shows an example of upsampling for transmitting an OFDM frame whose number of samples is 6,400 at 40 MSPS (samples per second). The target sampling rate is 400 MSPS, which is 10 times upsampling. Besides the upsampling, we added zero signals to make it easier to see the data position in the received data since the current system repeatedly sends/receives the data. When $8\times$ interpolation is used in the DAC, the 400 MSPS data is regarded as 3.200 GHz data.

IV. Measurement results

In this section, we show some results of sending and receiving data with RFSoC. In this paper, we show the results using the actual antenna propagation and the RF coaxial connection.

A. *IEEE 802.11n OFDM frame transmission*

We transferred and measured IEEE 802.11n OFDM frames whose band width is 40 MHz, subcarrier modulation scheme is 64 QAM, number of FFT points is 128 with 1/4 guard interval

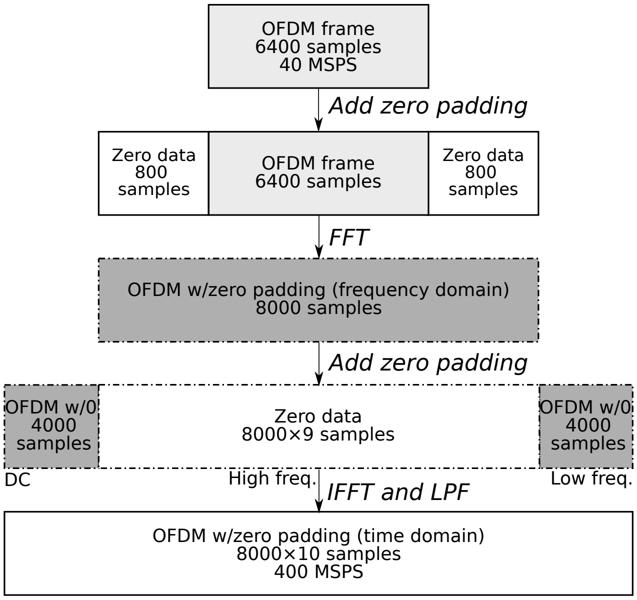


Fig. 4. Upsampling using FFT. An OFDM frame whose number of samples is 6,400 at 40 MSPS (samples per second) is upsampled 10 times resulting in 400 MSPS. The data order in the frequency domain is that commonly used in FFT libraries, where the first half contains the positive-frequency terms and the latter the negative-frequency terms.

(32 points). The number of data and preamble OFDM symbols are 38 and 2, respectively, resulting in a length of 6,400 points. The previously mentioned upsampling is applied for RFSoC.

Here, we used a superheterodyne approach for the transmission using a radio frequency of 5.2 GHz. For this purpose, we used one of our newly-developed RF boards for RFSoC. The baseband and intermediate frequencies are 40 MHz and 600 MHz, respectively. The measurement distance is 2.5 m and the measured transmission power is 7.18 dBm. As for the RFSoC DAC and ADC configuration, the sampling rate is 3194.88 MSPS, and the interpolation setting is 8×, resulting in the effective sampling rate of 399.36 MSPS.

Figs. 5 and 6 show the transmitted and received signal, respectively. BER is 7×10^{-4} and the SNR estimated using preamble symbols is 33.7 dB. Fig. 7 shows the EVM plot for each data symbol in each subcarrier.

B. EVM measurement

We carried out a simple error vector magnitude (EVM) measurement with various carrier frequencies from 100 MHz to 1400 MHz. The transmitted base band signal is a sine wave of 1 MHz as follows,

$$z = \exp(j2\pi ft) = \cos(2\pi ft) + j\sin(2\pi ft), \quad f = 1\,\mathrm{MHz}. \tag{1}$$

We denote a carrier frequency by f_c. The configuration of RFSoC is the same as the case of the OFDM frame measurement. The modulation of f_c by z is performed in RFSoC.

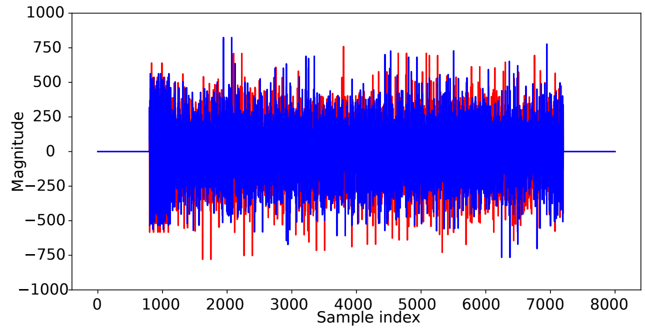


Fig. 5. Transmitted OFDM frame (baseband).

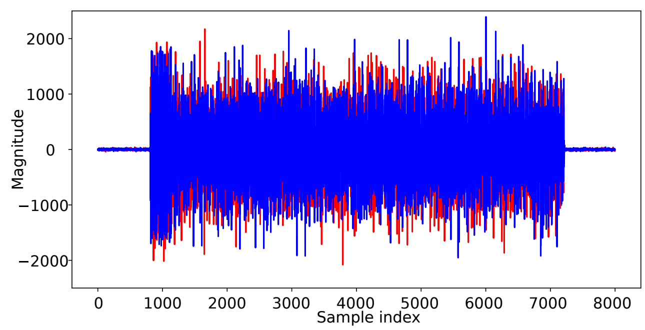


Fig. 6. Received OFDM after (baseband). The baseband, intermediate, and radio frequencies are 40 MHz, 600 MHz, and 5.2 GHz, respectively. The distance is 2.5 m, and the measured transmission power is 7.18 dBm. SNR and BER are 33.7 dB and 7×10^{-4}, respectively.

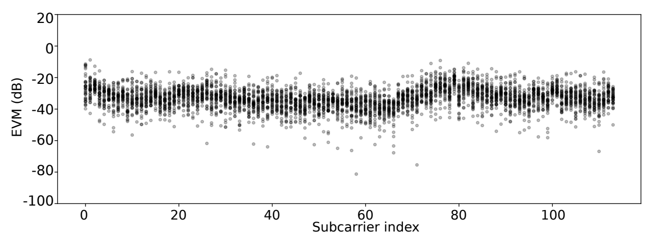


Fig. 7. OFDM channel measurement result in terms of EVM. Each dot shows an EVM value of a data OFDM symbol in a subcarrier.

In this experiment, the EVM values are calculated by

$$E_{\mathrm{EVM}} = 100 \times \frac{\overline{||z| - |z'||}}{\overline{|z|}} (\%), \tag{2}$$

where z and z' is the transmitted (ideal) signal and the received signal, respectively, and the overline means the average operation. Since $|z| = \overline{|z|} = 1$ according to (1), we first normalized the received signal under the constraint of $\overline{|z'|} = 1$.

The result is shown in Fig. 8. The minimum EVM is about 4 %. When $f_c \simeq 800$ MHz, the EVM is about 12%. When $f_c \simeq 100$ MHz and $f_c \simeq 1{,}100$ MHz, the EVM is about 25%. These results can be explained by the second and third harmonics.

Figs. 9 (a) to (d) explain the effects of the harmonics for the cases of $f_c = 100$ MHz, 400 MHz, 800 MHz, and 1,100 MHz, respectively. The modulated f_c signals contains harmonics whose frequencies are as twice and three times of f_c. These harmonics can be observed at the ADC side in addition to the modulated signals. We can ignore the harmonics whose order is higher than three since they cannot be observed.

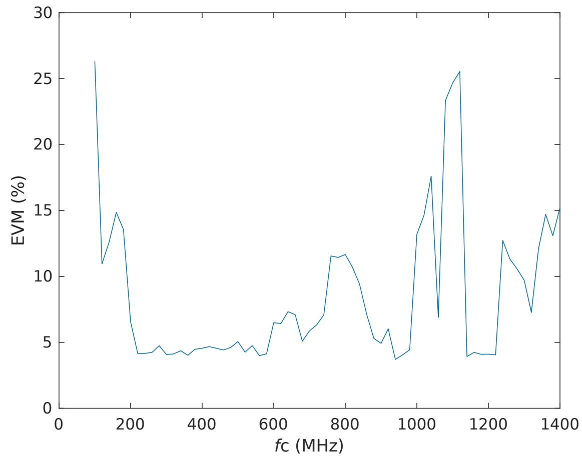


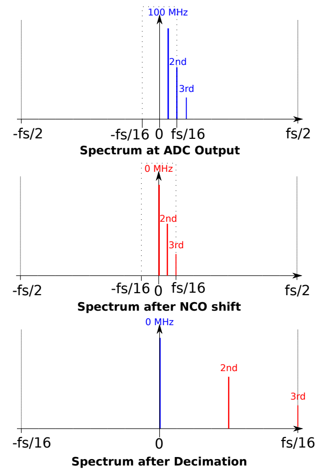
Fig. 8. EVM when modulating sine wave from 100 MHz to 1400 MHz.

Each subfigure in Fig. 9 shows the spectrums just after ADC, after the f_c mixer, and after the decimation, for a specific f_c. Hereafter, we denote the ADC sampling rate by f_s. In the case of this experiment configuration $f_s \simeq 3200$ MHz, and the Nyquist frequency $f_s/2 \simeq 1600$ MHz.

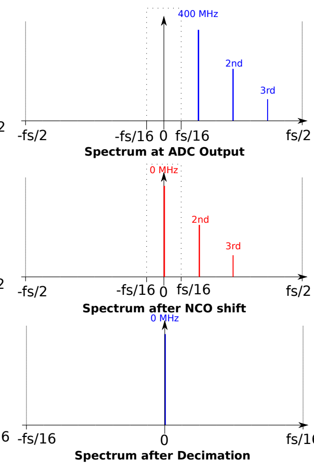
As for the spectrum just after ADC, the spectrum whose frequency exceeds the Nyquist frequency is folded and observed, like the cases of $f_c = 800$ MHz (Fig. 9 (c)) and 1,100 MHz (Fig. 9 (d)). The effects can be seen in the 1st graph of each figure. Mixing f_c to the received signals using the numerically controlled oscillator (NCO) of RFSoC, the spectrum is shifted down, which is regarded as the demodulation. This effect can be seen in the 2nd graph of each figure. After the decimation, the low frequency components are extracted similarly to low-pass filters (LPFs). Since the decimation is 8×, the frequency components higher than $f_s/16$ are removed.

Fig. 9 (a) is the spectrum with $f_c = 100$ MHz. In this case, since the 2nd and 3rd harmonics remain after the decimation, the EVM deteriorates significantly. Fig. 9 (b) is the spectrum with $f_c = 400$ MHz. Since there are no harmonics after the decimation, the EVM is relatively good. Fig. 9 (c) is the spectrum with $f_c = 800$ MHz. Since the folded third harmonic overlaps with the original signal, the EVM becomes worse. Fig. 9 (d) is the spectrum with $f_c = 1{,}100$ MHz. The EVM is greatly deteriorated because the second harmonic, which is folded when the ADC is applied, remains.

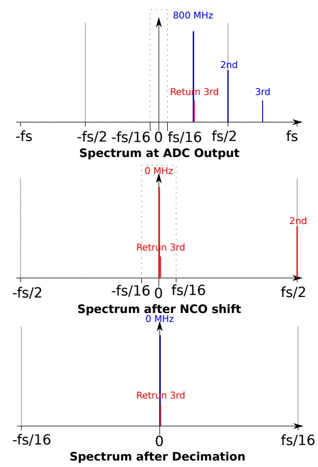
The effect of the harmonics can be removed by using LPFs. In some cases, however, it cannot be removed like the case of $f_c = 800$ MHz. It is necessary to select the appropriate DAC/ADC sampling frequencies and carrier frequency assuming the folding effect and the harmonics.



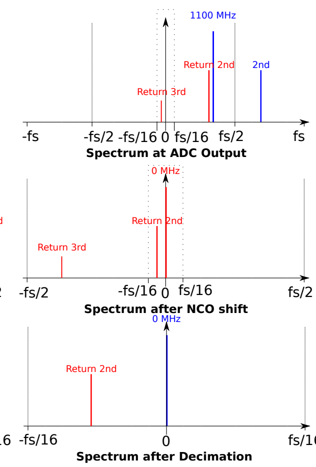
(a) $f_c = 100$ MHz.



(b) $f_c = 400$ MHz.



(c) $f_c = 800$ MHz.



(d) $f_c = 1{,}100$ MHz.

Fig. 9. Effect of the harmonics for the cases of (a) $f_c = 100$ MHz, (b) 400 MHz, (c) 800 MHz, and (d) 1,100 MHz.

V. Conclusion

We developed a channel characteristics measurement system using RFSoC. In this paper, we showed two measurement results, IEEE 802.11n OFDM frame transmission using the superheterodyne approach with our newly-developed RF board, and the EVM measurement using a simple sine wave transmission with coaxial cables. In addition, the effects of harmonics were discussed using the EVM measurement results with various carrier frequencies.

Acknowledgments

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