FPGA-based Implementation and Evaluation of Realtime OFDM Phase Compensation in 5G

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***Abstract*—In the New Radio (NR) standard which is standardized by 3GPP as a candidate for 5G mobile communication system, Orthogonal Frequency Division Multiplexing (OFDM) has been selected as the waveform for the air interface. Unlike the 4G Long Term Evolution (LTE), where the carrier frequency between the transmitter and receiver are always at the same locations, in NR, they can be at different frequencies. In such case, this leads to the phase ramped up at the receiver which cannot be recovered if the OFDM symbol is not equipped with reference signal for channel estimation and equalization. In this paper, we present our model for this issue and how to eliminate it by compensating the phase difference at both transmitter and receiver. We also implement this approach in Field Programmable Gate Array (FPGA) and validate it in real hardware testbed. The result show that with phase compensation, the received signal constellation is significantly improved.**

Keywords—5G, OFDM, New Radio, Phase Compensation, FPGA

I. Introduction

Orthogonal Frequency Division Multiplexing (OFDM) is the waveform used for New Radio (NR) standard, which is standardized by 3GPP as candidate for the air interface for 5G mobile communication system due to its robustness to time dispersion and flexibility in designing different physical channels and signals in time – frequency domain.

OFDM also is the waveform used in 4G Long Term Evolution (LTE) system, however unlike LTE, where the center of the RF frequencies are the same at the transmitter and the receiver, in NR, the receiver is not known in advance the center frequency of the transmitter, the transmitter and receiver can operate at different RF frequencies simultaneously. This lead to the phase rotation at the receiver which cannot be recovered if the OFDM symbol is not accompanied with the De-Modulation Reference Signal (DMRS). Therefore, the unknown phase rotation seen at the receiver must be compensated at both the transmitter and the receiver so that transmitted signal can be reconstructed at the receiver. In this paper, we present in detail the phase rotation shows up at the receiver due to the difference of the RF frequencies at the transmitter and the receiver. This phase rotation is calculate in closed form as a function of the RF frequency and the OFDM symbol index. We show how to eliminate this phase rotation by pre and post compensating it at the transmitter and receiver respectively.

We validate the effect of the approach using hardware testbed, standard testing data, and in realtime using FPGA implementation. The phase compensation processing block in the FPGA processor consists of two main parts. The phase compensation generator block and phase compensation multiplier block with IQ data. To minimize the FPGA system resources, the phase compensation generator block is processed in the operating system kernel running on ARM core of the FPGA processor. We validate our design using hardware testbed consists of server running on x86 Intel processor to generate standard test vector data, FPGA processing kit, ADRV9009 RFIC for analog processing and commercial Vector Signal Analyzer (VSA) to analyze the transmitted signal. The results show that without phase compensation, the received signal constellation is severely rotated and cannot be recovered while with phase compensation, the received signal is significantly improved on VSA.

This paper is organized as follows. In section II, we present a brief overview about the overall transmission structure of the NR standard, then we present the possible phase rotated of the signal at the receiver due to this structure, and the phase compensation approach to eliminate this phenomena. In section III, we present our realtime FPGA implementation and the experimental results using commercial vector signal analyzer. Finally section IV concludes the paper.

II. OFDM Phase Compensation

In this section, we first provide a brief overview about the transmission structure of the New Radio (NR) specifications standardized by 3GPP. Then we model the phase rotated seen at the receiver due to this transmission structure and the solution to eliminate this issue.

A. NR Transmission Structure Overview

In the time domain, the transmission is divided into frames of 10 ms, each frame consists of 10 equally sized subframes of length 1 ms each. One subframe is further divided into a number of slots, each of which consists of 14 OFDM symbols for normal Cyclic Prefix (CP) or 12 OFDM symbols for extended CP [1], the length of each slot depends on the subcarrier spacing (Δf) used for the transmission as illustrated in Fig. 1 for normal CP case. In frequency domain, the system bandwidth is divided into subcarriers, the number of subcarriers depends on the system bandwidth and subcarrier spacing used [5]. As in LTE, one subcarrier and one OFDM symbol construct one Resource Element (RE) which is the smallest resource can be allocated for physical channel or signal [1].

In the downlink, the physical signals and channels are organized as in Fig. 2. The Primary Synchronization Signal (PSS), the Secondary Synchronization Signal (SSS) and the Physical Broadcast Channel (PBCH) form the SS/PBCH Block (SSB), this block is used for UE to search for the frame timing and acquire basic system information, e.g., system frame number and the location of the Remaining Minimum System Information (RMSI), which contains the most

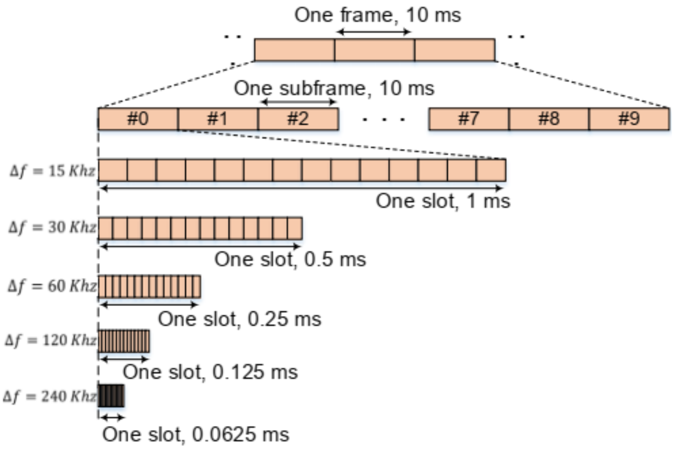

Fig. 1. Time and frequency structure

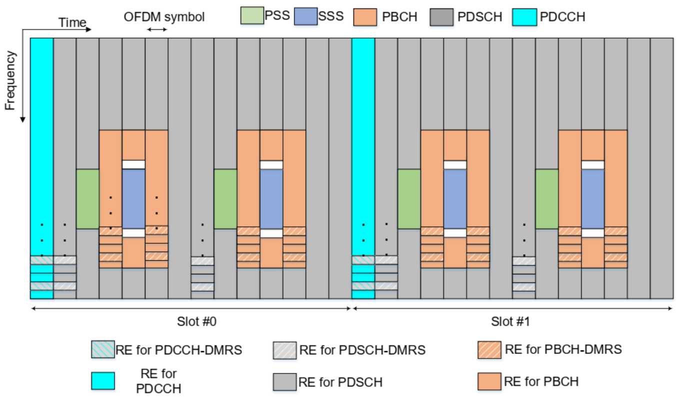

Fig. 2. Physical signals and channels in time and frequency domain

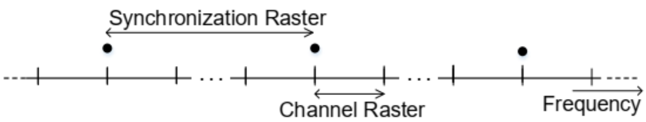

Fig. 3. Channel and synchronization raster in NR

important information for the User Equipment (UE) to access the network [3]. The Physical Downlink Control Channel (PDCCH) transfers the information, e.g., the location of the resources allocated for data, the modulation so that UE can decode the Physical Data Share Channel (PDSCH), which is the channel carrying user data. Each physical channel has its own DMRS (De-Modulation Reference Signal [1]) for channel estimation and equalization. In each OFDM symbol, there are possible REs for carrying data (for PDCCH, PDSCH and PBCH) and REs for physical signal, e.g., PSS, SSS, and DMRS as depicted in Fig. 1.

In the NR standard, the channel raster is defined as the point in the frequency domain which the center frequency of the carrier can be located while the synchronization raster is the point where the center of the Synchronization Signal Block (SSB) can be occupied [2]. In LTE, the synchronization and channel raster are at the same locations, however in NR, due to the very large bandwidth required, the synchronization raster is much sparser than the later so that the complexity and time required for the UE to search the SSB can be reduced.

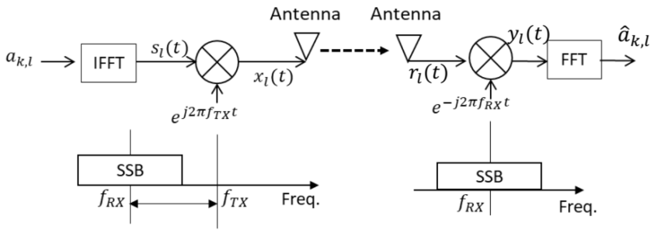

Fig. 4. System model

When an UE tries to access the network, it has no information about the system parameter, e.g., the information about the carrier frequency used by the transmitter as well as the frame timing of the system. It will first jump into each synchronization raster and try to acquire the SSB to find the timing of the frame structure, read the PBCH and subsequently decode further system information in order to initiate the random access procedure [3]. Due to the fact that the synchronization and channel raster can be at different locations in the frequency domain, there is a possible phase rotation at the receiver which cannot be recovered in the symbol without DMRS, and therefore the SSB cannot be decoded. In the next section, we elaborate this problem and the approach to eliminate the phase ramped.

B. OFDM Phase Compensation

In this section, we present the analysis about the phase rotated seen at the receiver due to the transmission structure of the NR we mentioned previously. We consider a system consists of one Base Station (BS) and one UE, each one is equipped with one antenna for simplicity (Fig. 1). The BS is configured to periodically broadcast the SSB for downlink synchronization. As we have mentioned before, when UE tries to access the network, it has to be synchronized with the BS by searching and decoding successfully the SSB. Considering the case when the center frequency of the SSB (which is the frequency UE uses to receive the RF signal from the BS) and the center of the carrier are not at the same location as in Fig. 1, let $a_{k,l}$ is the data (e.g., data of the SSB) after modulation, it is mapped to the input of the Inverse Fast Fourier Transform (IFFT) before up converted by the RF frequency f_{TX}. At the receiver, the RF signal is down converted by the frequency f_{RX} before going through the FFT for signal reconstruction. Note that unlike LTE, f_{TX} is not necessarily as the same as f_{RX} in NR.

Let $s_l(t)$ is the baseband signal after the IFFT, then it is given by

$$s_l(t) = \sum_k a_{k,l} e^{-j2\pi k \Delta f (t - T_{CP,l})},$$

where k and l are the subcarrier and OFDM symbol index respectively, $0 \le t \le T_{sym} + T_{CP,l}$ is the time within one OFDM symbol, T_{sym} is the length of the symbol without CP, $a_{k,l}$ is the data transmitted by the resource element (k, l), $T_{CP,l}$ is the length of the cyclic prefix of OFDM symbol l^{th}, Δf is the subcarrier spacing. Let f_{TX} is the center frequency of the BS, after up conversion, the transmitted signal is given by

$$x_l(t) = e^{j2\pi f_{TX}(t + t_{start,l})} s_l(t),$$

where $t_{start,l}$ is the start of OFDM symbol t^{th} and given by

$$t_{start,l} = \begin{cases} 0 & l = 0 \\ t_{start,l-1} + T_{sym} + T_{CP,l} & \text{otherwise} \end{cases}.$$

For simplicity, the effect of the channel to the transmitted signal is not included in the analysis, at the receiver the baseband signal after down conversion is given by

$$y_l(t) = r_l(t)e^{-j2\pi f_{RX}(t+t_{start,l})}$$
$$= x_l(t)e^{-j2\pi f_{RX}(t+t_{start,l})}$$
$$= x_l(t)e^{2\pi(f_{TX}-f_{RX})(t_{start,l}+T_{CP,l})}.$$

Where $r_l(t)$ is the RF signal received at the receiver, then the baseband signal after the FFT is given by

$$\hat{a}_{k,l} = \underbrace{e^{j2\pi(f_{TX}-f_{RX})(t_{start,l}+T_{CP,l})}}_{\text{Phase rotation}} \sum_k x_l(t)e^{j2\pi k\Delta f(t-T_{cp,l})}$$
$$= e^{j\phi}a_{k,l}. \qquad (1)$$

Where the phase ramped up at the receiver is given by

$$\phi = 2\pi\left(t_{start,l} + T_{CP,l}\right)(f_{TX} - f_{RX}).$$

It can be seen that the phase rotation at the receiver is a function of the RF frequency and the OFDM symbol index. Therefore, for symbols with DMRS signal this phase ramped can be corrected by channel equalization. However, for symbol without DMRS, then this phase ramped cannot be compensated, it severely affects the received constellation (it is rotated, as we will show later in real hardware measurement). In fact, without phase compensation, commercial signal analyzer will be unable to decode the SSB.

The approach is that both transmitter and receiver need to compensate this phase ramped before and after up and down conversion respectively, i.e., the transmitter applies a phase pre-compensation term

$$e^{-j2\pi f_{TX}(t_{start,l}+T_{CP,l})}. \qquad (2)$$

The receiver applies a phase post-compensation term

$$e^{j2\pi f_{RX}(t_{start,l}+T_{CP,l})}.$$

So that the phase rotation term in (1) will be canceled out each other at the receiver. In this approach, the transmitter and receiver only need to know their own RF frequencies, the receiver is not necessarily know the RF frequency of the transmitter.

III. FPGA IMPLEMENTATION AND VALIDATION

A. FPGA Implementation

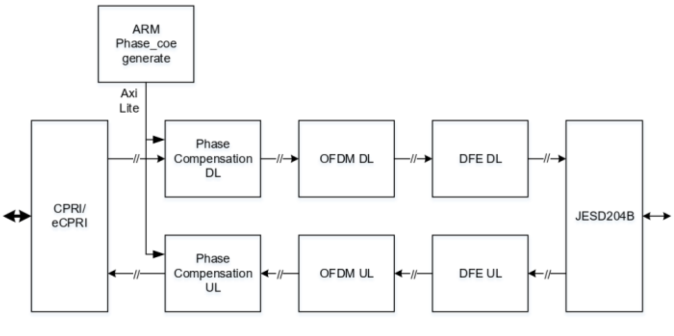

Fig. 5. The block diagram DL/UL processing

In this section, we present our FPGA design for the phase compensation. The phase compensation processing is simply multiplying the 14 phase offset coefficients as calculated in (2) with the IQ data of 14 OFDM symbols, the processing is carried out in frequency domain (before OFDM modulation as in Fig. 5). The phase compensation processing block consists of two main parts. Phase compensation generator block and phase compensation multiplier block with IQ data. To minimize the FPGA system resources, the phase compensation generator block is processed on the operating system kernel running on the ARM core of the FPGA processor (Fig. 5). After receiving the input parameter as the desired transmission frequency, the block will automatically calculate 14 sets of corresponding coefficients and bring these 14 coefficients down to the FPGA through an Advanced eXtensible Interface (AXI) lite protocol (as in Fig. 6) for communication between ARM and FPGA. The phase compensation multiplier block with the desired data is processed on the FPGA. After receiving 14 phase compensation coefficients from ARM, the processor will determine the IQ data is coming from which OFDM symbol for appropriately selecting the corresponding phase compensation coefficients based on the 10ms trigger, 0.5ms trigger and input valid signal (Fig. 7). The data of OFDM symbols sequentially from 0 to 14 in one slot will be multiplied by the phase offset of that symbol.

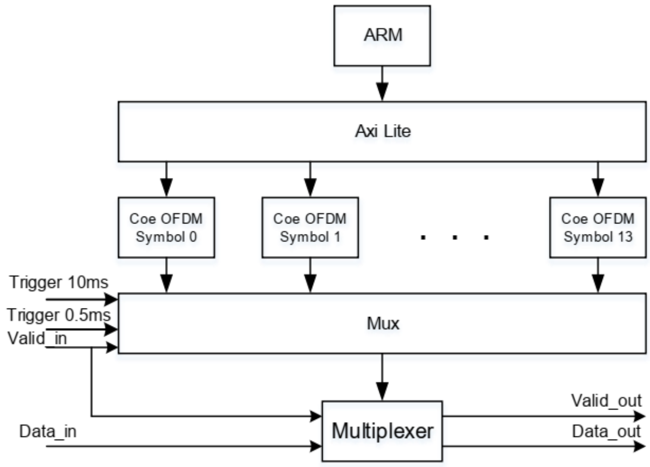

Fig. 6. Structure of the phase compensation block

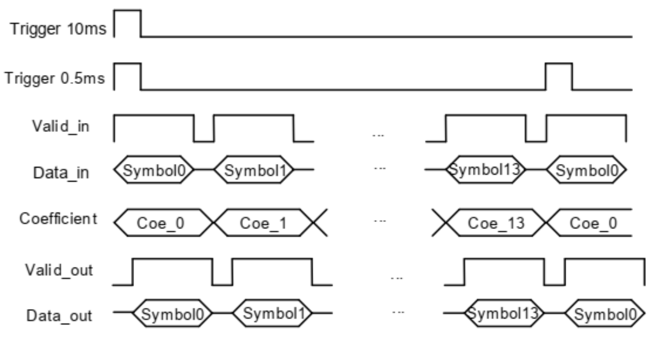

Fig. 7. Timing diagram

B. Experimental Results

The testbed system consist of three main parts, namely the baseband data generation, the Remote Radio Unit (RRU) which carry out the phase compensation, OFDM modulation and mixer to bring the digital signal to analog for transmission, and commercial Vector Signal Analyzer (VSA) to analyze the transmitted signal as in Fig. 7. The DU (Digital Unit) Intel x86 server will store 100MHz test data with full 273 RB (Resource Block [1]). The IQ data is generated using QAM-64, the TDD frame structure is selected as DDDSU where each D consists of 14 OFDM symbols for downlink, S is the guard period, U consists of 14 OFDM symbol for uplink. This test pattern is repeated after each 2.5 ms. In order for the server to communicate with the RRU via the CPRI interface, we design an FPGA-based transfer card that has the function of transmitting - receiving data from the server via the PCIe interface and sending it down to the RRU using one CPRI interface with a line rate of 9.8304 Gbps.

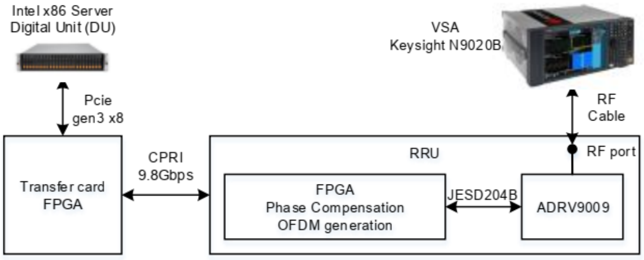

Fig. 8. Test system

The RRU receives 100 MHz test data from the server via CPRI interface, then calculate and multiply the phase compensation coefficients, perform OFDM modulation with IFFT size is 4096 to accommodate the 100 Mhz test data, and then send it to the RFIC ADRV9009 through the JESD204B interface. At RFIC ADRV9009 data is filtered, increased sampling rate, and converted from baseband to RF frequency of 3.6 Ghz. Then the RF signal is transmitted into the VSA via RF cable for measurement. The key performance indicator we evaluate here is the Error Vector Magnitude (EVM), which is to measure how far the received signal are from the ideal signal and is calculated as [104]

$$EVM = \sqrt{\frac{\sum_{t\in T}\sum_{f\in F(t)}|Z'(t,f)-I(t,f)|^2}{\sum_{t\in T}\sum_{f\in F(t)}|I(t,f)|^2}}$$

where T is the set of symbols with the considered modulation scheme being active within the test data, $F(t)$ is the set of subcarriers within the system bandwidth with the considered modulation scheme being active in symbol t, $I(t,f)$ is the ideal signal reconstructed by the measurement equipment in accordance with the relevant transmitted data, $Z'(t,f)$ is the modified signal under test. It simply calculates the error vector magnitude of the received signal compare to the transmitted signal.

In Fig. 9 and 10, we show the analyzed signal by the VSA, it can be seen that without the phase compensation at the transmitter, the received constellation is severely rotated, the EVM for PDSCH is about 12%, which is not satisfied the requirement of 8% [2] for QAM – 64, in addition, the EVM of PBCH is 112% which is too high, and in this case the analyzer is unable to detect the PBCH. By contrast, with phase compensation at the transmitter, the received signal is much more improved, with the EVMs of PDSCH and PBCH are 1% and 2% respectively, which is in compliance with the requirement [2], and the analyzer is able to detect the PBCH and PDSCH data. In addition, frequency error estimated on VSA with phase compensation is significantly lower than when phase compensation is turned off, this also will support the channel equalization at the receiver.

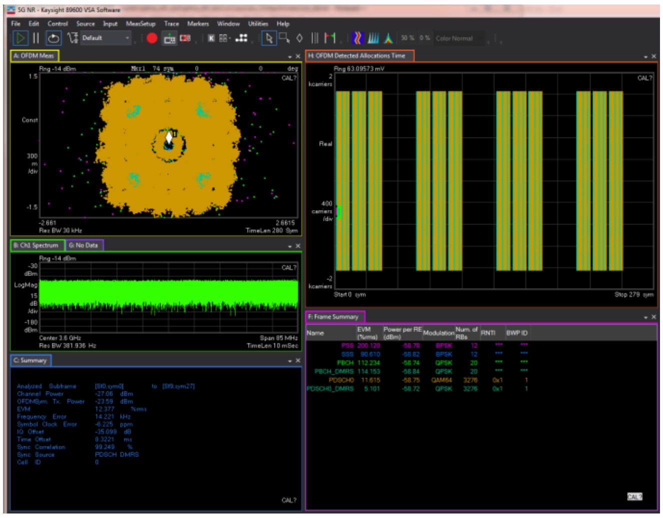

Fig. 9. Received constellation without phase compensation

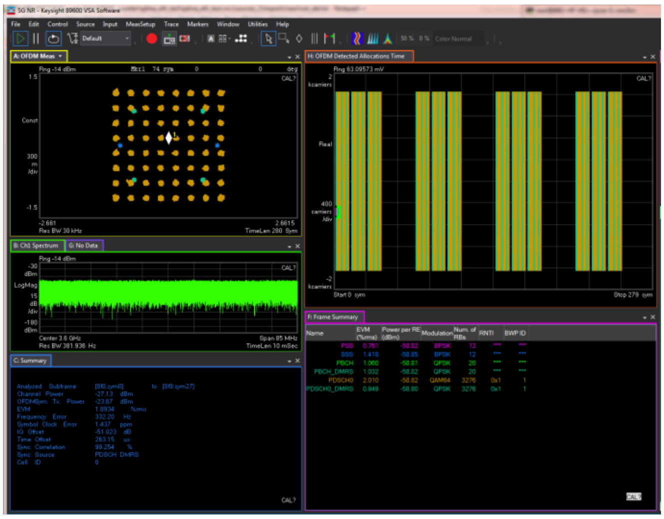

Fig. 10. Received constellation with phase compensation

IV. CONCLUSION

In this paper, we present the OFDM phase rotation issue as a result of the RF frequency mismatch between the transmitter and receiver in 5G mobile network. We then evaluate the approach on hardware testbed in realtime by using FPGA-based implementation. Our implementation consists of two main parts, the phase compensation generator block and phase compensation multiplier block with IQ data. To minimize the FPGA system resources, the phase compensation generator block is processed on the operating system kernel running on the ARM core of the FPGA processor. Measurement using commercial signal analyzer in realtime shows that the received signal constellation is significantly improved with phase compensation.

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