Demonstration of Analog Millimeter-wave Fronthaul Link for 64-QAM LTE Signal Transmission

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Abstract—Centralized baseband architecture is believed to be cost efficient and to offer high performance. The fronthaul network, connecting the centralized baseband to distributed remote radios, requires high capacity and low latency transport links, due to the stringent specifications of the data interface, known as common public radio interface (CPRI). Today, fronthaul links are mostly based on digital CPRI over fibers, and it is possible to realize CPRI over wireless technology, but with the drawback of poor bandwidth efficiency. In this paper, we propose an analog wireless fronthaul concept to enable bandwidth efficient and scalable fronthaul networks. The basic idea is to transport narrow band analog radio signals over millimeter-wave bands instead of multi-gigabit digital signals. The phase and frequency impairments introduced by high frequency carriers are effectively reduced using an analog pilot-based mitigation technique. As a proof-of-concept demonstration, an analog fronthaul link is implemented, and the link performance is verified for 20 MHz 64-QAM LTE transmission over 70/80 GHz (E-band) with measured error vector magnitude (EVM) of about 3\% and 10\% pilot bandwidth overhead.

Keywords—Centralized baseband; millimeter-wave transmission; fronthaul; phase noise mitigation;

I. INTRODUCTION

Driven by the exponential growth in mobile broadband subscriptions and mobile data traffic, the requirements on mobile networks are continuously increasing. Network densification is an efficient tool for improving capacity and coverage, where low power small cells are deployed as a complement to existing macro cells. Since a large number of small cells are foreseen to be deployed to meet the demanding end-user expectations, mobile operators are interested in cost- and energy-efficient solutions. Centralized baseband, also referred to as the centralized radio access network (C-RAN), has been proposed accordingly [1].

In centralized baseband architecture, baseband processing units (BBUs) are separated from the radio access units, and are placed in a central office or BBU pool for centralized processing and management. The cell sites are simplified compared to conventional integrated ones with remote radio units (RRUs) only. Therefore both space requirement and power consumption are reduced to lower the operational cost. In addition, centralized baseband processing enables advanced coordination among the cells for interference mitigation using coordinated multi-point transmission (CoMP) [2].

However, the fronthaul network, connecting the centralized baseband to the distributed remote radios, is very critical. A network as such should be low cost and energy efficient, and in addition support Gbps capacity, low latency and multiple radio access technologies. The most used interface between the BBU and the RRU is known as common public radio interface (CPRI), which transfers digitized radio signals as I/Q samples [3]. Although the CPRI standard does not specify the transmission medium, optical fibers have been used almost exclusively as the fronthaul technology because of the demanding CPRI date rate. For example, to support one LTE sector with 20 MHz bandwidth and 2x2 MIMO, 2.5 Gbps data rate is required by the CPRI [2]. In future densified networks, small cells are likely to be deployed on street level at places such as lampposts, where installing fibers is not viable. Millimeter-wave (mm-wave) radios provide a low cost and flexible alternative to fiber links. Technology-wise, it is possible to realize digital CPRI over mm-wave as demonstrated in [4], where an E-band radio link at 70/80 GHz can support 2.5 Gbps CPRI transmission. However, the drawback is low bandwidth efficiency, where at least a few hundreds of MHz spectrum is needed for 2.5 Gbps transport. Bandwidth efficiency in wireless technology is a key figure of merit for operators to consider as the frequency spectrum is a rare and expensive asset.

In this paper, we propose an analog wireless fronthaul concept to enable bandwidth efficient and scalable fronthaul networks. The basic idea is to transport narrow band analog radio signals over millimeter-wave bands instead of multi-gigabit digital CPRI. Because the signals are transmitted in the analog format, multiple radio services can coexist in the fronthaul by multiplexing multiple radio carriers, while the digital CPRI transmission typically only supports one service at a time. Mm-wave with a large available bandwidth is attractive for analog fronthaul to allocate more carriers. However, it is challenging to implement analog fronthaul links at high frequency, since phase and frequency impairments also increase as the carrier frequency increases which degrades the quality of analog signals.

To demonstrate the feasibility of analog mm-wave fronthaul, a test link is designed and implemented at 70/80 GHz (E-band) with analog phase noise mitigation by applying an RF-pilot as the phase reference to restore the signal at the receiver [5]. Thanks to the pilot-based noise mitigation, 20 MHz 64-QAM LTE uplink and downlink transmission is demonstrated over E-band with measured error vector.
magnitude (EVM) of about 3% at the cost of 10% pilot bandwidth overhead.

II. CONCEPT OF ANALOG FRONTHAUL

Comparing analog fronthaul with digital fronthaul shows the difference in the implementations of the fronthaul link as well as the RRUs. As main functional blocks outlined in Fig. 1, the digital wireless fronthaul is a replacement of the optical fiber, carrying digital baseband (I/Q samples) with CPRI radio interface. However, the analog fronthaul relays analog radio signals over mm-wave carriers between the centralized BBU and RRUs. Taking the downlink as an example, digital radio signals are generated at the BBU, and the analog fronthaul converts the signals to analog format which is then up converted to mm-wave over the air. At the cell site, received signals are first down converted from mm-wave to radio frequency (RF) and then amplified to communicate with user terminals. Therefore, the function of the RRU is simplified with only the mm-wave front-end for up/down frequency conversion and RF amplification.

As opposed to digital fronthaul where hundreds of MHz bandwidth is required for 2.5 Gbps CPRI to support one LTE sector, the analog fronthaul links only carry the LTE radio signal in 20 MHz over the air. Since the required bandwidth of CPRI is much higher than the bandwidth of the actual radio signals, digital CPRI transmission is not appropriate to support multi sectors and MIMO for capacity upgrade in future mobile networks. The analog fronthaul, however, as a bandwidth efficient solution, is data-rate scalable by frequency multiplexing narrow band radio signals on a mm-wave carrier. In addition, the analog fronthaul is protocol transparent due to transmission of analog radio signals, and therefore allows simultaneous transport of multiple radio access technologies (e.g. 2G/3G/4G/WiFi) in multi-band. Fig. 2 illustrates the deployment of remote radios from a macro site for capacity and coverage enhancement. Analog radio signals are generated at the macro site and transmitted to RRUs through analog fronthaul links using point-to-point or point-to-multipoint connection. For RRUs without line-of-sight condition to the macro (e.g. RRU4 in Fig. 2), the fronthaul connection is established by using the mm-wave carrier to distribute radio signals through line-of-sight links in a daisy chain fashion.

Despite cost advantages of the analog fronthaul, there are also technical challenges. Since it is the analog radio signal to be transmitted rather than digital baseband, high linearity is required for the analog links. For short links of few hundred meters, the radio transmitters can operate in the linear region due to the relatively high gain of the mm-wave antennas. However, nonlinearity compensation should be considered to improve system gain for longer transmission links and/or better reliability. Mm-wave bands offer wider bandwidth than microwave and RF frequencies to enable high link capacity. However, radio impairments such as phase noise and frequency error also increase proportionally to the carrier frequency. For example, phase noise increases as much as 30 dB when the carrier frequency is shifted from 2.6 GHz to 80 GHz. The baseband digital signal processing in conventional radio base stations and user terminals is not capable of handling high frequency noise as such. Thus, the added signal noise over the mm-wave fronthaul link must be minimized to maintain the performance of the radio access signals so that users should not experience any service degradation.

Figure 1. Comparison of end-to-end fronthaul link implementations, (a) digital wireless fronthaul, and (b) analog wireless fronthaul.

III. IMPLEMENTATION OF ANALOG FRONTHAUL AT 70/80 GHz

An analog phase noise mitigation method has been proposed to reduce both phase and frequency impairments of an arbitrary mm-wave signal using an RF-pilot [5]. The pilot is co-transmitted with the data signal over the mm-wave channel so that it is distorted in the same way as the signal by high frequency noise due to up and down conversion. Therefore, the pilot can be used as a phase reference at the receiver side to restore the signal by noise cancellation using frequency multiplication.

In this paper, we apply the pilot-based noise mitigation in an analog fronthaul link at 70/80 GHz (E-band) to demonstrate 64-QAM LTE transmission. Moreover, the impact of the pilot overhead and the pilot signal strength on transmission performance is also investigated. The analog fronthaul link is implemented using commercial RF components and mm-wave
front-end modules, as shown by the photo in Fig. 3. The LTE uplink and downlink signals are generated from a vector signal generator, with 20 MHz bandwidth and 64-QAM modulation format. Signal quality is evaluated in a signal analyzer, which demodulates the LTE signals digitally and measures the EVM as performance indicator.

Fig. 4 presents the block diagram of the fronthaul link setup. At the transmitter side, a sinusoidal wave as the pilot tone \( f_P \) is added next to the LTE signal at around 1.8 GHz \( f_E \) by a power combiner. Frequency separation between the pilot and the signal spectrum is 2 MHz, which is defined as half of the signal bandwidth (e.g., 10 MHz in this case) subtracted from the separation between the pilot and the center of the signal spectrum. The pilot power is 10 dB lower than the signal power. The combined pilot and LTE signal are sent to the E-band Tx module for frequency up conversion to E-band low band at 73 GHz. In the lab experiment, the E-band Tx and Rx are connected through waveguide attenuator and without antennas, and the value of attenuation is adjustable. On the receiver side, the pilot and the signal are first down converted to the IF stage. And the pilot is selected after a second frequency down conversion using a band pass filter (BPF) with 2 MHz bandwidth and centered at 70 MHz \( f_c \). The selected pilot is then multiplied with the signal using a frequency mixer to cancel phase and frequency impairments introduced over the E-band by down converting the signal with \( f_c \). The frequency shift \( f_c \) to the signal carrier due to noise mitigation is compensated by setting different carrier frequencies for E-band Tx and Rx modules so that the received signal is centered at \( f_E + f_c \) after E-band up and down conversion as compared with the signal \( f_E \) at the transmitter. Due to conversion loss from the passive mixers in use, power amplification is needed in the pilot branch to ensure a good dynamic range for the noise reduction.

IV. EVALUATION OF TRANSMISSION PERFORMANCE

A. Demonstration of 64-QAM LTE over 70/80 GHz

20 MHz 64-QAM LTE transmission is demonstrated over a 73 GHz carrier for both uplink and downlink signals. Signal EVM is measured at the transmitter and receiver, respectively, as summarized in Table I together with captured constellation diagrams. The quality of the LTE signal directly from the generator is very high with EVM below 1%. The signal is distorted by phase noise due to frequency up and down conversion at E-band and the EVM is degraded to larger than 10%. Thanks to the pilot-based noise mitigation, the signal is restored with EVM of about 3%, well below the EVM requirement of 8% for 64-QAM as defined in the 3GPP technical specification [6]. Fig. 5 is a screen shot of a spectrum analyzer showing the pilot next to the 20 MHz LTE signal, where the pilot is 2 MHz separated from the signal spectrum with 10 dB lower in power.

LTE downlink employs OFDM-based multi-carrier modulation, while LTE uplink is single-carrier frequency division multiplexed, known as SC-FDM. The effect of phase noise on transmission performance is similar for both uplink and downlink as indicated with the measured EVM values. However, the phase noise impact on signal constellation is different between uplink and downlink. The uplink, as a single-carrier signal, has less embedded pilots for channel estimation and therefore is more sensitive to the common phase error which rotates the constellation diagram. For OFDM-based downlink signal, inter carrier interference is dominant which is shown as enlarged constellation points [7].
TABLE I. MEASURED SIGNAL QUALITY FOR 64-QAM LTE UPLINK AND DOWNLINK OVER 73 GHz CARRIER

<table>
<thead>
<tr>
<th></th>
<th>Signal input to E-band at ( f_s )</th>
<th>Signal over E-band at ( f_s + f_c )</th>
<th>Signal after noise mitigation at ( f_s )</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 MHz LTE uplink</td>
<td><img src="image1.png" alt="Signal input" /></td>
<td><img src="image2.png" alt="Signal over" /></td>
<td><img src="image3.png" alt="Signal after noise" /></td>
</tr>
<tr>
<td>EVM</td>
<td>~1%</td>
<td>~11%</td>
<td>~3%</td>
</tr>
<tr>
<td>20 MHz LTE downlink</td>
<td><img src="image4.png" alt="Signal input" /></td>
<td><img src="image5.png" alt="Signal over" /></td>
<td><img src="image6.png" alt="Signal after noise" /></td>
</tr>
<tr>
<td>EVM</td>
<td>~1%</td>
<td>~12%</td>
<td>~3%</td>
</tr>
</tbody>
</table>

Figure 5. The combined pilot and 20 MHz LTE signal measured in spectrum analyzer with 3 MHz resolution bandwidth and 200 MHz span.

B. Performance Optimization

There are two critical parameters to optimize for system performance in the pilot-based noise mitigation: the bandwidth of the BPF for selecting the pilot and the pilot-to-signal power ratio (PSPR) [5]. Although the wider the bandwidth is, the more noise the pilot-based method can reduce, in practice, the filter bandwidth shall be relatively narrow so that a pilot can be placed as closely as possible to the signal spectrum. For the designed fronthaul link, a BPF with 2 MHz bandwidth is chosen as an acceptable trade-off between system spectral efficiency and performance. To avoid cross-talk between the signal and the pilot, the required frequency separation between the pilot and the signal spectrum (pilot-signal separation) is investigated as well as the PSPR is optimized with respect to the signal performance measured after the noise mitigation. Since the pilot is generated from a signal generator, the pilot frequency and the power strength can be easily tuned.

The impact of the pilot-signal spectrum separation on signal EVM for the LTE downlink is shown in Fig. 6. Four measured curves represent different PSPR values from -4 dB to -13 dB with 3 dB as a step. For instance, PSPR -4 dB means the pilot power is 4 dB lower than the total signal power. It is clear that all the curves demonstrate the same trend where the EVM is significantly reduced with an increased pilot-signal separation from 2 MHz to 4 MHz. Besides, increasing the pilot power also helps to improve the performance, which is obvious from the difference between the curve of PSPR -13 dB and the one of PSPR -10 dB. However, the improvement is minor with further increased pilot power due to performance saturation of the phase noise mitigation. Considering the trade-offs between performance and spectral/power efficiency, pilot-signal separation of 4 MHz and PSPR of -10 dB are chosen for the fronthaul link characterization.

![20 MHz OFDM-based LTE downlink signal](image7.png)

Figure 6. Impact of pilot-signal separation on signal quality in terms of measured EVM at different pilot power levels.

V. LINK CHARACTERIZATION

The fronthaul link is characterized using a 20 MHz OFDM-based LTE downlink signal in frequency division duplex scheme over E-band, where the low band is centered at 73 GHz and the high band is centered at 83 GHz. The input signal power to the E-band Rx is adjustable by varying the attenuation between the radio transmitter and the receiver. Signal quality after the noise mitigation is measured as a function of the varied Rx input power, as displayed in Fig. 7. Assuming EVM of 3% as the performance threshold, Rx sensitivity is measured to be -53 dBm for E-band low band and -51 dBm for the high band. The difference in sensitivity is due to the 2 dB higher in noise figure for the high band Rx module. Comparing with theoretical calculation of receiver sensitivity in [8], the fronthaul test link has a 3 dB implementation loss.

The rapid performance degradation in Fig. 7 at high input power is caused by the nonlinear effect of the commercial E-band Rx. In addition to improving linearity of the front-end circuits, such as the amplifier and the mixer, including automatic gain control in the receiver can also help to prevent overloading and thus increase the receiver dynamic range.
VI. CONCLUSION

A new wireless fronthaul solution is proposed, where the analog radio access signals are carried over millimeter-wave frequency, instead of being transported using multi-gigabit digital CPRI. The analog wireless fronthaul is considered to be much more bandwidth efficient than the conventional digital wireless fronthaul. Such analog fronthaul link is implemented and demonstrated at 70/80 GHz (E-band) for 20 MHz 64-QAM LTE transmission, equivalent to 1.25 Gbps digital CPRI traffic. To mitigate high frequency impairments of the analog link, an RF-pilot based phase noise mitigation technique is applied to the received signal. As a result, the quality of the LTE signal can be maintained about 3% EVM over E-band with 10% pilot bandwidth overhead. Based on the promising link performance and simplified cell/RRU set-up, the analog mm-wave fronthaul can potentially be a technology enabler for cost efficient and scalable fronthaul networks.

REFERENCES