Experimental Investigation of New Fronthaul Concepts for 5G

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Abstract

The evolution to a centralized radio access network (C-RAN), where multiple base band units (BBU) are co-located to jointly serve multiple remote radio heads (RRH), results in a more efficient use of radio resources [1]. Nevertheless, it also imposes more stringent requirements on the transport network connecting the BBU pool to the RRHs, also known as fronthaul. Especially the increasing demand for higher data rates in the fronthaul challenges current solutions based on protocols like the widespread common public radio interface (CPRI).
In this paper, we investigate two promising approaches to reduce the optical bandwidth utilization in the mobile fronthaul of next-generation cloud radio access networks. We experimentally analyze and compare the performance of an analog radio-over-fiber fronthaul and a new digital fronthaul. The analog system consists of four π/4-shift DQPSK modulated sub-channels with a data rate of 2.5 Gbit/s each and originates from a custom millimeter-wave system. The digital fronthaul approach utilizes On-Off-Keying (OOK) and is based on 10 Gigabit Ethernet.

Kurzfassung

Die Entwicklung hin zu zentralisierten Radio Access Networks (C-RAN), also die Zusammenlegung von Basisbandsignalverarbeitung (Base Band Units, BBU) zur Versorgung mehrerer entfernter Basisstationen (Remote Radio Heads, RRH), führt zu einer effizienteren Nutzung von Netzwerkressourcen [1]. Allerdings stellt diese Technologie strikte Anforderungen an das Fronthaul genannte Transportnetzwerk, das die BBU mit den RRHs verbindet. Insbesondere der Bedarf für immer höhere Datenraten auf dem Fronthaul stellt für gängige Protokolle wie Common Public Radio Interface (CPRI) eine Herausforderung dar.
In diesem Paper untersuchen wir zwei vielversprechende Ansätze mit dem Ziel, die optische Bandbreite des Fronthaul in C-RANs der nächsten Generation zu reduzieren. Die Leistungsfähigkeit eines analogen Radio-over-Fiber Fronthauls und eines weiterentwickelten digitalen Fronthauls wird experimentell ermittelt und verglichen. Das analoge System besteht aus vier mit π/4-shift DQPSK modulierten Kanälen mit einer Datenrate von je 2,5 Gbit/s, und ist von einem Millimeterwellensystem abgeleitet. Der digitale Fronthaul-Ansatz nutzt On-Off-Keying (OOK) und basiert auf 10 Gigabit Ethernet.

1 Introduction

The structure of the radio access network (RAN) in upcoming mobile communication systems is chaning from a distributed setup to a centralized one. The new so-called cloud-RAN (C-RAN) places the baseband signal processing from multiple base stations into central locations and connects remote radio heads (RRH) to them via fronthaul. This fronthaul usually consists of a digital optical connection and transports digitized baseband waveforms in the form of I/Q-samples. As every sample is represented by a number of serial bits, the bandwidth of the digital fronthaul signal is more than one order of magnitude higher than the transported baseband signal's sampling frequency.
With the transition to 5G networks and ever-growing bandwidths, this represents a serious problem. As an example, a signal with a sampling rate of 1 GS/s would require a data rate on the fronthaul of around 30 Gbit/s [2]. With multi-antenna and multi-carrier setups, this rate will grow further, and quickly reach an impractical magnitude. Thus, alternative solutions have been developed for the fronthaul: one of them, based on analogue transmission of fronthaul signals, converts multiple analogue baseband signals to separate intermediate frequencies (IF) that are modulated onto a common optical carrier for transport on the fronthaul. A new digital solution, referred to as next generation digital fronthaul here, partly reverses the centralization of signal processing in the RAN by moving some functions, in our case the complete physical layer baseband processing, into to the RRH. Since the baseband radio signal is now generated on the RRH side, the required data rate on the fronthaul is significantly lowered. Furthermore, the optical point-to-point link to connect baseband unit (BBU) and RRH, as required for the common public radio interface (CPRI) and analog solutions is replaced by a more flexible Ethernet network. The distribution of signal processing blocks between BBU and RRH can also vary: the split in the processing chain can be inserted at different points inside the physical (PHY) layer, between the medium access control (MAC) and PHY layer, or even in higher layers. As mentioned above, in this paper we regard a split point between the MAC and PHY layers.
Both the analogue and next generation digital fronthaul concepts are reproduced in our experiments by transmit-

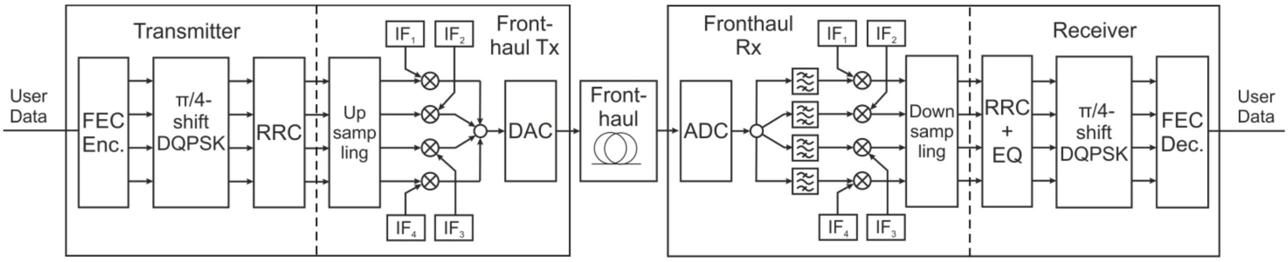

Figure 1 Signal processing for analog fronthaul

ting a fronthaul signal over a fiber of varying length and assessing the impact of the fronthaul transmission on signal quality. We regard the fronthaul link only in downlink direction in order to assess general feasibility. In the uplink direction, the principle is generally identical, but further problems arise specifically for the analog fronthaul, such as multiplexing of up- and downstream signals, power control, and different noise levels. These problems are addressed in [3].

In this work, we are focusing on transmission at 1550 nm, due to the expected use of dense wavelength division multiplexing (DWDM) for access and the availability of hardware. At these wavelengths, chromatic dispersion (CD) is one of the main limiting aspects, which has to be taken into account for the fronthaul links. The use of 1310 nm systems, that face virtually no dispersion effects in a standard single mode fiber (SSMF), would principally also be possible. However, the multiplexing of several fronthaul connections over a single fiber would require some sort of wavelength division multiplexing, optimally DWDM. Hardware for such systems is more widely available for 1550 nm, due to its common application in long-haul core networks and lower costs.

2 Reference System

The reference system for the experiments is a custom real-time 5 Gbit/s millimeter-wave (mm-wave) transceiver as described in [4]. This system concept provides the background for a 10 Gbit/s system, however not in real-time. The data rate of 10 Gbit/s is chosen with respect to 10 Gigabit Ethernet, which is widely used in access networks and also considered for realization of the next generation digital fronthaul [5].

The extended mm-wave system transports four channels at a data rate of 2.5 Gbit/s each. A π/4-shift DQPSK (π/4-SDQPSK) modulation is used with a symbol rate of 1.25 GBd per channel. To minimize bandwidth usage, a channel spacing of 1.5 GHz together with pulse shaping and bandpass filtering is applied. The digital signal processing (DSP) at the transmitter (Tx) and receiver (Rx) is realized in Matlab. The following steps are taken in the Tx separately for each channel: first the user data is encoded for forward error correction (FEC), then modulated using the π/4-SDQPSK modulation scheme, and filtered using a root-raised cosine (RRC) filter with a roll-off factor of 0.25 for pulse shaping. In this step, the sampling rate of the baseband signals is increased to 2.5 GS/s.

At the Rx, a frequency domain equalizer is applied to each baseband channel along with another RRC filter. In this step, the oversampling is removed, so that the sampling rate is 1.25 GS/s again. Afterwards, previously to demodulation and FEC, the error vector magnitude (EVM) of the π/4-SDQPSK symbols is estimated.

In this reference system both fronthaul concepts are integrated between the π/4-SDQPSK transmitter and receiver and are experimentally evaluated.

2.1 Analog Fronthaul

The analog fronthaul is modeled by up-converting the four analogue baseband signals of the reference system to separate intermediate frequencies (IF) and transmitting them on a common optical carrier as shown in **Figure 1**. After baseband processing and oversampling to 20 GS/s, each baseband signal is up-converted to its respective IF, and then added onto a common signal vector. A random time offset is also added to every baseband signal in this step in order to avoid constructive interference between the training sequences used for synchronization. The used IFs are 1.25 GHz, 2.75 GHz, 4.25 GHz and 5.75 GHz for the four channels. The resulting signal vector is exported

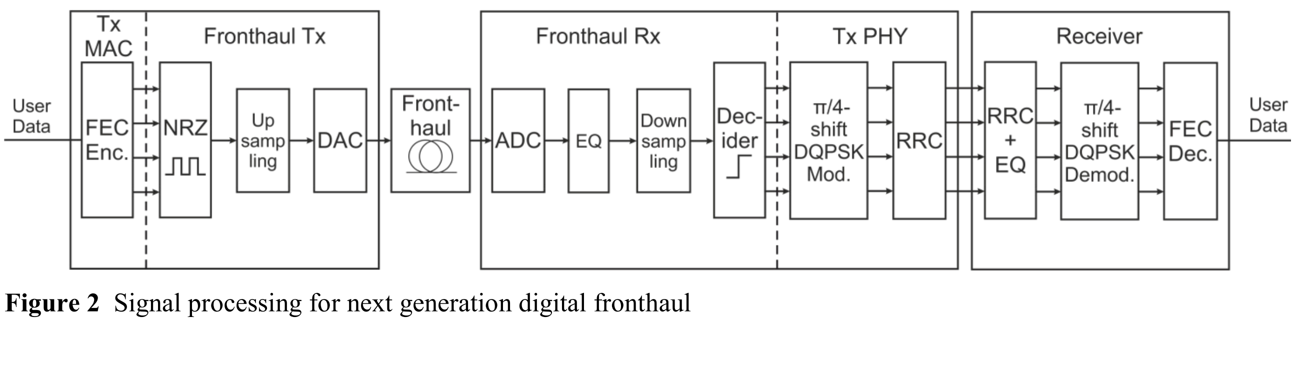

Figure 2 Signal processing for next generation digital fronthaul

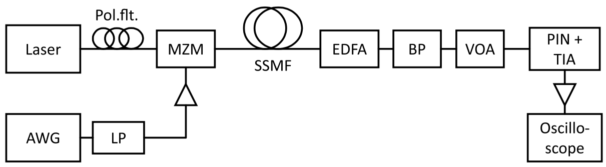

Figure 3 Experimental setup

and digital-analog converted with an arbitrary waveform generator (AWG). After transmission through the optical fronthaul link (please refer to section 2.3), the signal is recorded with a real-time oscilloscope at 80 GS/s. The Rx DSP consisted of bandpass filtering, to separate the four channels, down-conversion to baseband and RRC filtering. Afterwards the signals are further processed as specified for the reference system.

2.2 Next Generation Digital Fronthaul

The signal processing for the digital fronthaul is shown in **Figure 2**. Compared to the analog approach, here the fronthaul Tx is located after the FEC encoding. The FEC-encoded data from all channels is serialized as one data vector and OOK NRZ modulated at 10 Gbit/s. Afterwards the signal is up-sampled to 20 GS/s and a training sequence for the Rx equalizer is inserted. After digital-analog conversion with the AWG, the signal was transmitted over the optical link (please refer to section 2.3). At the Rx side, a simple finite impulse response (FIR) equalizer is applied, before down-sampling to the symbol rate. After hard decision, the FEC encoded user data is recovered. To evaluate the link performance, it is sufficient to determinate the BER after the decider (dashed line), since any accumulated errors are evenly distributed on the four wireless channels in the subsequent signal processing.

2.3 Optical Link

The fronthaul signals are transported over an intensity modulation / direct detection (IM/DD) link. **Figure 3** shows a block diagram of the setup: the beam from a DFB laser with a wavelength of 1550.52 nm is first passed through a polarization filter and then modulated using a Mach-Zehnder modulator (MZM). The MZM is driven using the output signal from the AWG, which is previously low-pass filtered and passed through an amplifier. The MZM is biased at the quadrature point to act as a simple intensity modulator. The launch power of the signal was around 2 dBm. After the MZM the signal is transmitted over various lengths of SSMF. Afterwards an Erbium doped fiber amplifier (EDFA) with a constant output power was used to achieve a sufficient signal level at the Rx. To vary the optical power, an additional variable optical attenuator (VOA) was applied in front of the Rx. The Rx consisted of a PIN photodiode with an integrated transimpedance amplifier (TIA). After electrical amplification, the signal was recorded using a real time oscilloscope at 80 GS/s.

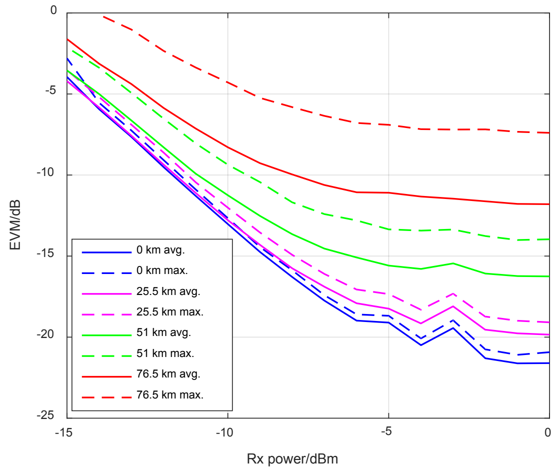

Figure 4 Estimated EVM for analog fronthaul over Rx power and for different fiber lengths

The fiber used in the experiments had a dispersion coefficient of ~17 ps/(nm·km) and an attenuation of ~0.2 dB/km. Three patches of 25.5 km length each were used to achieve total fiber lengths of 25.5, 51.0, and 76.5 km. For a fronthaul scenario in the access network, 25.5 km are considered as sufficient. The higher distances of 51.0 and 76.5 km address e.g. large scale BBU pooling and fronthaul transmission in the metro network.

3 Results

In the following, the experimental results for both fronthaul solutions are presented.

3.1 Analog Fronthaul

Figure 4 shows the EVM over the received power for optical back-to-back (btb), 25.5, 51.0, and 76.5 km of SSMF. The solid lines depict the average EVMs over all

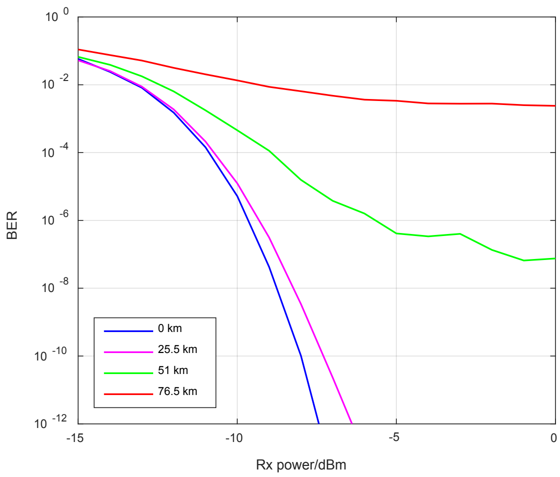

Figure 5 Estimated BER for analog fronthaul over Rx power and for different fiber lengths

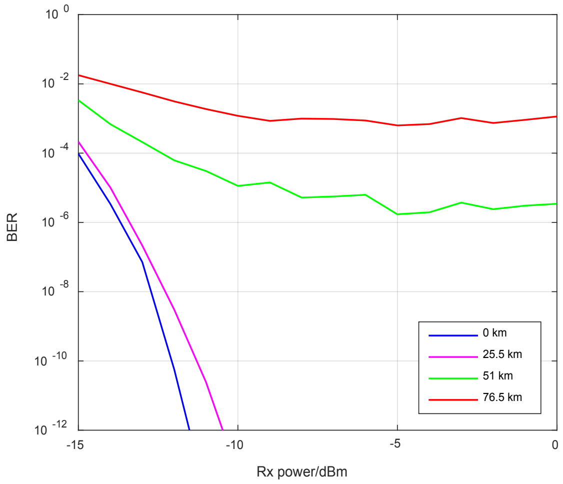

Figure 6 Estimated BER for digital fronthaul over Rx power and for different fiber lengths

four channels, the dashed lines represent the maximum EVMs observed at any channel.

It can be seen that the penalty of 25.5 km fiber compared to btb is relatively low for higher received power, and virtually inexistent at lower power. However, even at 0 dBm received power, an EVM floor of around -22 dB for btb and -20 dB for 25.5 km occurs, due to general system limitations. While this is not problematic for the radio link considered here to operate at low SNR, it is difficult for the analog fronthaul when the radio link is operated at high spectral efficiency. After 51 km and 76 km of fiber, a clear impact of the CD can be seen. At 0 dBm received power the average EVM is -16 dB after 51 km, and -12 dB after 76 km. More notably, the maximum EVM increases drastically with distance: it is at -14 dB for 51 km, and at -7 dB for 76 km. As a reference, the EVM limit stated for QPSK by the LTE standard is 17.5%, or around -15 dB [6], which is only fulfilled on all channels for btb and 25.5 km, at a received power of at least -8 dBm.

EVM increasing with fiber length can be explained by the effect of chromatic dispersion, which accumulates over fiber distance and effectively causes signal fading at a certain frequency range, starting at high frequencies and moving to lower frequencies with increasing distance [7]. This also explains the discrepancy between average and maximum EVM in the analog system towards longer distances: since dispersion induced fading is frequency selective, it only affects some channels at a time.

Figure 5 shows the BER inflicted by fronthaul transmission, estimated from the EVM values of each channel and then averaged over all channels. For 25.5 km of fiber, only minor penalties compared to btb exist even at very low BERs. In detail this is 1 dB (-7 vs -6 dBm) at a BER of 10^{-12}. With 51 km fiber, the estimated BER is at least $\sim 10^{-7}$ for all power levels and with 76 km always above 10^{-3}. Below a BER of 10^{-4} all errors can be corrected by the applied FEC algorithm (Reed-Solomon 255/239). This condition is fulfilled for a received power of at least -10 dBm at btb and 25.5 km, for -8 dBm at 51 km, and not at all at 76 km.

3.2 Next Generation Digital Fronthaul

Figure 6 shows the BER of the received NRZ signal on the digital fronthaul over received power for the different fiber lengths. For btb and 25.5 km, the performance is similar and unproblematic for sufficient received power: at -10 dBm, the BER is below 10^{-12} for both distances. At 51 km fiber length, the BER ranges between 10^{-6} and 10^{-5} for powers greater than -9 dBm. An estimated BER of below 10^{-4} is achieved for received power greater than -14 dBm for btb and 25.5 km, and -12 dBm for 51 km. Again, transmission over 76 km produces errors for all received power levels.

4 Comparison

Both fronthaul solutions perform reasonably well over distances of up to 25.5 km for sufficiently high received power levels. Regarding the fronthaul alone, an acceptable error rate can be achieved for a higher received power at 51 km, too – however, this distance appears to be the limit of the system in both cases.

The necessary Rx power below the BER threshold of 10^{-4} is clearly lower for the digital fronthaul compared to the analog fronthaul. In detail, this is for digital vs. analog: -15 vs. -11.5 dBm for btb; -14.5 vs. -11 dBm for 25 km and -12.5 vs. -8.5 dBm at 51 km. This can be explained by the more robust modulation format of OOK compared to π/4-SDQPSK. Especially the far better peak-to-average power ratio (PAPR) of OOK compared to analog signals results in a significant gain.

For the distance of 51 km, the BER at high Rx power levels is better for the analog fronthaul. This can be explained by the smaller bandwidth of the analog fronthaul signal compared to the digital signal, which results in smaller penalties due to the CD. At 76.5 km, both fronthaul concepts experience severe penalties due to the CD, so only minor BER difference can be observed at high power levels.

5 Conclusions

The findings outlined above show that despite the larger signal bandwidth, the NRZ-based digital solution is more resilient, especially at low received powers as they might occur in a low-cost system without optical amplifiers on the Rx side. The analogue fronthaul significantly affects the transported baseband signal, especially for low received power levels. Both solutions, however, show little dependency on fiber length regarding dispersion effects, at least up to 25.5 km distance. In metro networks with covered distances of up to 100 km, the tested solutions do not hold up. Both reach their limitations at about 50 km distance.

6 Acknowledgements

This work has been funded by the European Union's Horizon 2020 project iCIRRUS (grant no. 644526).

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