Design Principles for Fibre-Wireless Integration in the Mobile Communication Networks

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ABSTRACT
Bandwidth demand from existing and emerging applications is the main driver for the study of the fibre-wireless integration in future mobile communications networks. Despite commercial availability of 5G solutions fast advances in both fibre-optic communications systems and wireless communications support interest in a new methodology for fibre-wireless integration. With advanced features such as network MIMO and multi-user diversity, new fronthaul designs are in demand. Emerging and future technologies for broadband wireless communication networks will offer new opportunities for photonics technologies in the implementation of the next-generation integrated optical-wireless networks. In this paper we consider a fronthaul design to support multiple-beam array antenna for 5G application with continuous control over the steering angle of the beam. We discuss two optical beamforming approaches: at the base station, and at the remote radio units.
Keywords: optical communications, fibre-wireless integration, 5G, beamforming.

1. INTRODUCTION

To meet the performance metrics of the 5th generation mobile network (5G) such as cell capacity and user-end data rates, new spectral bands with larger available bandwidth will be required. For instance, $57 - 64$ GHz is one of the recommended bands for future telecommunication systems in the US [1]. This increase of the available bandwidth and data rate provides opportunities for implementation of new optical-wireless solutions. There are various enabling technologies for fibre-wireless integration, including radio-frequency-transparent photonic demodulation, the photonic vector mm-wave generation scheme, the integration of various multi-dimensional multiplexing techniques, and others. Larger bandwidth will make it possible to utilize the high-loss areas of the spectrum to manage smaller cells - micro- and pico-cells, which are adopted to overcome the challenge of the density of users. There are numerous advantages in going to higher frequencies beside greater data rates; the more signal power loss at these bands leads to a natural cell separation which makes it possible to have frequency reuse. Furthermore, the higher the frequency the smaller the antenna and RF devices which can be crucial in the implementation of 5G especially when it comes to communication features which require many antenna elements derived at the cell site. The latter is an important feature of 5G and beyond as it is necessary for pencil beam antenna radiation directed to each mobile user which can reduce interference and improve system capacity and efficiency. This beam-forming capability and other spatial diversity and multiplexing features of 5G all require dedicated data stream to each antenna element and entail significant available data rate at the fronthaul. On top of this high available spectrum bandwidth, a novel architecture for the whole communication network is required. An efficient system based on edge computing and cloud radio access network (C-RAN) helps to achieve these goals. C-RAN improves network performance through coordinated multi-point and more efficient use of resources. C-RAN can cope better with the volatile data traffic and make the best of it through statistical multiplexing. The statistical multiplexing gain of the centralised resource allocation is made possible in C-RAN where different demand distribution among various user data usage habits is exploited. In C-RAN, baseband processing (at baseband unit (BBU)) can be centralised in an intelligent service hub which follows the temporal state of data demand and its geometrical distribution leaving the radio frequency (RF) operations to the remote radio units (RRU). This centralisation also reduces the complexity of the RRU at the fronthaul the amount of which depends on the type of computation and tasks to move to the base station (BS) and the level of flexibility. The closer the split of functions to the RRU, the more complex RRU and higher required data rate in the RRU feed. In order to exploit all the benefits of C-RAN, it is highly preferable to have performed most of the computation at the BS [2]. The high user data rate entails using high capacity communication links between BS and RRUs such as optical fibre, commonly in the form of a packet-switched network architecture such as Ethernet. A solution to decrease the digital overhead of Ethernet-based fronthaul is to use analogue radio-over-fibre (A-RoF) [3,4] implemented to support massive MIMO and advanced beam steering techniques [4,5]. The beam-steering capability of an array antenna can improve the performance of the wireless system by improving the SNR and mitigating interference. Moreover, multi-beam transmission can simplify the architecture and reduce the complexity of resource allocation analysis. Exploiting the full capacity of a fibre link, it is possible to derive all antennas in the RRU using only one fibre link connecting the RRU to the BS or the aggregation point where not much processing is required [6,7]. Since one of our design principles is to have a single fibre link connecting the BS to each RRU, signals pertaining to each antenna element should be multiplexed in some way. They are various ways for multiplexing different antenna streams using a single fibre link with polarisation diversity being of the most widely proposed technique [7]. However, as the number of antennas increases the frequency multiplexing techniques show to be the most flexible and promising ones [6]. While a single fibre link is enough to serve a cell, the challenge is to reduce the cost and complexity of an RRU keeping the advanced features of the 5G fronthaul provided. In this work, based on the BS configuration of [8], we consider a fronthaul design (WDM-RoF) to support multiple-beam array antenna for 5G application with continuous control over the steering angle of the beam [8, 9, 10]. Focusing on the downlink, the wireless-optical conversion takes place using a wideband photodiode (PD) where the heterodyning an optical carrier and a properly spaced signal produces an RF signal to be amplified, probably processed, and feed an antenna element [8]. The processing of the RF signal may comprise filtering, up-conversion, amplification, and as the main concern of this paper, phased array antenna operations. Here we consider signal preparation to derive a uniform linear array antenna in order to achieve multi-beam emission. There are several scenarios in which the signal to feed each antenna element can be generated from the beam signal, the signal to be delivered to a particular mobile user. Operations like beam steering are usually deemed as the last stages of BS functions wherein splitting the BS are left to the RRU side [2]. However, here we are considering a scenario in which optical or electrical beamforming takes place at the BS and the resulting signals to derive each antenna element is sent to the RRU through an RoF ink. So, in general, the beamforming processing can take place i) in the BS or in the RRU, and/or ii) in the electrical or optical domain. The common way is an RF beamforming at the RRU site [4, 11]. This solution has serious disadvantages especially as the operating frequency goes further into the millimetre wave domain, such as time delay accuracy for wideband signals and electromagnetic interference, power consumption and size and weight [12,13]. Even when true-time delay (TTD) microwave beamforming networks are used, the problem of insertion loss, crosstalk ensued from leakage from microwave switches, and expensive and bulky implementation limit the applicability of such mmWave-based solutions [13]. An alternative is an optical beamforming which provides large bandwidth and immunity to electromagnetic interference all at lower power consumption and size [12,13,14]. The implementation of optical beamforming at the selected microwave band has made possible by the advent of continuously tuneable, wideband, optical signal delay lines with wide-range delay in the form of a linearly chirped fibre Bragg grating [13]. In the following, we investigate two approaches of optical beamforming: at the BS, and at the RRU.

2. METHODS

There are several algorithms to design the beamforming. The calculated phase shifts or signal delays are then realised in the optical or electrical domain. Assume $x(t)$ and $y(t)$ are two optical signals to beat at the PD to generate a mmWave signal at 60 GHz. One of these two signals is only an optical carrier. In order to have the intended phase shift for the mmWave signal, only one of these two signals should be phase shifted. Here and for a linear array of isotropic antennas spaced at half-wavelength the imposed phase on the nth antenna to steer the ith beam at an angle θ_i is $\phi_n = (n-1)\sin\theta_i$. This is the phase of the incident field at the antenna element. One can deliver such a signal at the antenna port using heterodyning of two properly adjusted optical signals. Signal streams of each antenna can be separated from others by means of individual fibres after the phase-shifted signal of each beam is added to other beams [12]-[14]. If the optical phase shifts take place at the RRU, individual fibre paths are provided by separate tracks on photonic chips or short fibre links. This mean, the optical signal generated at the BS should be demultiplexed to separate signals of each beam. These signals then will be accompanied by a common locally generated optical. However, if the beamforming takes place at the BS, there should be as many fibre links as the number of antennas connecting each RRU to the serving BS. This is problematic not only because of the excess cost but also because of the difference between the characteristics of these independent channels. An alternative is to multiplex the antenna streams in the wavelength domain using a DWM multiplexer or frequency domain requiring narrowband AWGs. This approach entails taking into account the impact of fibre and transceiver mismatches on the relative phases of each antenna stream. We consider two configurations for deriving antenna elements using optical beamforming networks: i) OBF at the BS and separating signals for each antenna using different wavelengths on a WDM grid, ii) OBF at the RRU using beam streams on either separated wavelengths on the WDM grid or separated frequency bands on the same wavelength. The latter has the benefit of serving many RRUs using a shared fibre where each RRU's channel can be easily obtained using commercial WDM demux. These scenarios are depicted in Fig. 1a and Fig. 1b, respectively, for a case where two wireless beams are to be generated using a four-element antenna. Figure 1a shows how beam streams B_1 and B_2 modulate four optical carriers at wavelengths $\lambda_1 \dots \lambda_4$ where a phase shift takes place after removing the carrier using an optical filter. The carrier is then added to the signal again followed by a WDM MUX which generates the fibre input. At the RRU site, after a WDM demux different wavelengths are directed to PDs whose outputs are filtered, amplified and derive the intended antenna element. For case ii, here the beam streams of each RRU are in different frequency bands on the same wavelength. Figure 1b shows the modulation of wavelengths $\lambda_1 \dots \lambda_K$ carrying beam data for K different RRUs. Each B_k

carries all beam streams of the kth RRU and appropriately positioned optical carriers. At the RRU, optical carriers are separated, and beamforming takes place. The carriers are added to the antenna feed signals which input a PD. The mmWave signal at the output of the PD is then filtered and amplified an excite the antenna element.

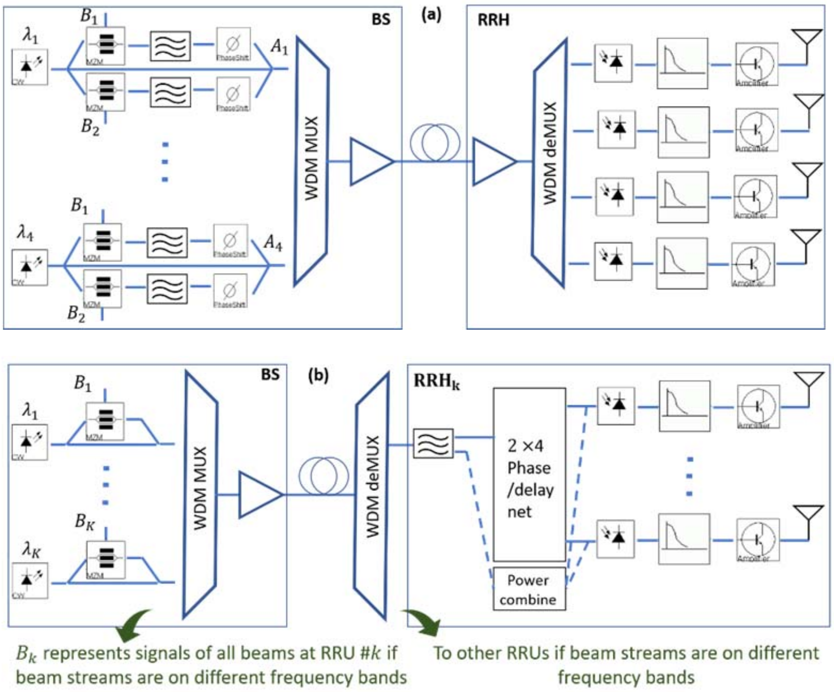

Figure 1. Scenarios for optical beamforming at: a) the BS, and b) the RRU.

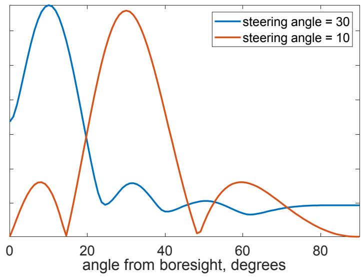

Figure 2. Radiation pattern of an array of 8 isotropic antennas.

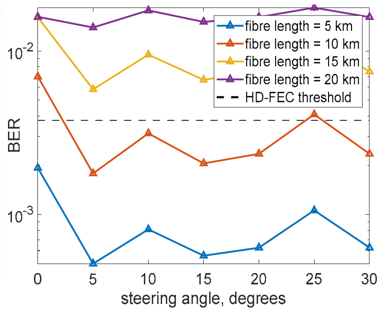

Figure 3. R=10 m, $BR = 2.5$ GBaud, $L = 5, 10, 15, 20$ km.

3. SIMULATION RESULTS

We have simulated a transmission with CS-SSB OFDM signals for two mobile users at different distances from the RRU using VPIphotonics Design Suit and Matlab Phased Array System toolbox. The impact of chromatic dispersion on the system performance in terms of experienced BER by a mobile user is investigated. Signal baud rate is 2.5 GBaud for 4QAM symbols on 32 subcarriers with 0.125 cyclic prefix over different lengths of fibre and steering angels. The RF frequency is 60 GHz with SNR=30 dB. At the mobile device a noise figure $NF = 5$ and noise temperature $T = 290^o$ is considered. The optical modulator is a dual-electrode MZM where a phase difference of 90^o is applied between the two RF electrodes to generate an SSB signal more resilient to the fibre chromatic dispersion. The modulator is biased at $\frac{V_\pi}{2}$ with the extinction ratio of 30 dB. The parameters of the SMF link is as the following: $\alpha = 0.2$ dB/km, $D = 16\ \mathrm{s/km^2}$, nonlinear index $n_0 = 2.6 \times 10^{-20}\ \mathrm{m^2/W}$, and core area $A_0 = 80 \times 10^{-12}\ \mathrm{m^2}$. The wireless transmitter antenna array comprises of 8 isotropic antenna elements placed at a half-wavelength distance. The optical beamforming can take place in different ways in numerical simulations. The most straightforward approach is to use Xcouplers with adjustable coupling factor. Another method is to introduce TTD by means of length-controlled waveguides [13]. As the steering angle increases the side lobes grow which can increase the incident interference and lower the SNR. The array antenna pattern for steering angles 10^o and 30^o is shown in Fig. 2 which shows this effect. Therefore, the steering angle of the RRU array antenna can have some impact on the quality of the received signal at the mobile device. Figure 3 illustrates this dependency for different fibre lengths for a mobile user at 5 m distance from the RRU. Figure 4 shows the BER versus fibre length for three wireless distances, $R = 5, 10, 15$ m for 4QAM transmission with baud rate $BR = 2.5$ GBaud and when the steering angle is 20^o. Increasing data rate increases the BER as is depicted in Fig. 5 for different fibre lengths. Figure 6 compares the receiver constellation of the middle subcarrier of the OFDM signal for four cases when the fibre length is $L = 5{,}10$ km and the mobile range is $R = 5{,}10$ m.

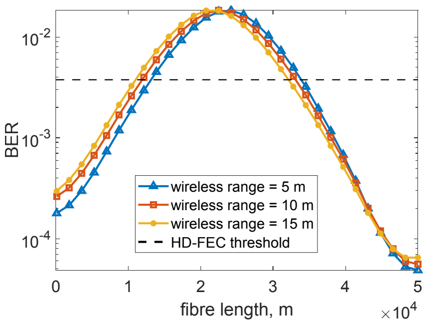

Figure 4. 5 Gb/s transmission to an azimuthal angle of 20^o *and distance 5, 10 and 15 m from the RRU.*

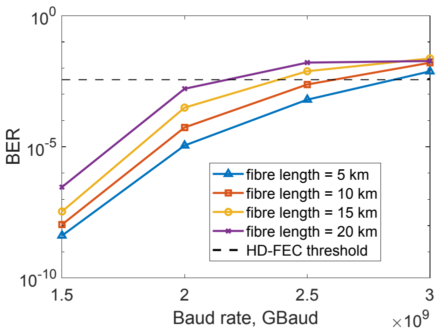

Figure 5. performance with the azimuthal angle of 20^o *and distance 10 m from the RRU.*

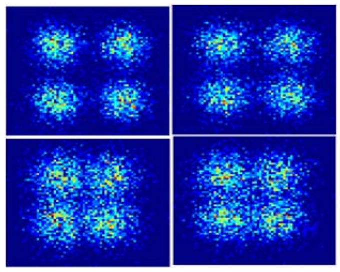

Figure 6. top-left) $L = 5\ km$, $R = 5\ m$, *top-right)* $L = 5\ km$, $R = 10\ m$, *bottom-left)* $L = 15\ km$, $R = 5\ m$, *and bottom-right)* $L = 15\ km$, $R = 10\ m$.

4. CONCLUSIONS

We have investigated the performance of a wireless-fibre WDM-RoF interface in a fronthaul of a communication system equipped with beamforming at the final stage of delivering the signal to the mobile user. Our simulation results made it evident that the RoF system with SC-SSB OFDM signal can support a 5 Gb/s data rate over a fibre link of 20 km and deliver error-free communication to a mobile device at 10 m from the RRU site using optical beamforming at the RRU using only one 100 GHz WDM channel. Other scenarios of performing the beamforming at the BS to further push the functional split of the BBU to the BS is left for future works.

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