Radio-over-fibre for ultra-small 5G cells

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ABSTRACT

The need of a wireless network with a very low latency, a high bandwidth, and a high cellular density is paramount for serving futuristic applications. For this purpose, we design a very dense wireless network, consisting of radio cells of less than 10 m^2 . To serve these small cells, a backbone network implemented over a radio-over-fibre (RoF) based architecture can be an ideal solution. In this paper we propose different RoF architectures that are varying in architectural complexity, flexibility, supported user densities (depending on the sharing ratio of the optical transceivers between cells) and the number of users per cell. We indicate their main challenges and propose some specific scenarios where they can be applied. Not only there are architectural challenges to design the RoF network to bring a high capacity to every small cell, but also a medium access control (MAC) protocol is needed to confirm the quality of service (QoS) bounds of a low latency, seamless handovers, and a high throughput. We differentiate between two approaches to design such a MAC protocol, either distributed or centralized mechanisms.

Keywords: radio-over-fibre, optical backhauling, architecture, MAC protocol.

1. INTRODUCTION

Data transfer has always been a bottleneck in wireless communication, and as today's applications are becoming more and more demanding (e.g., video calls, remote computing), a significant increase of the capacity would certainly be useful. In this paper, we focus on the backbone network required for wireless connectivity in ultra small 5G cells - less than 10 m^2 , e.g. in the order of 1 m^2 or even smaller - at very high peak data rates of 10 Gb/s per cell, as specified for 5G [1][2]. These high data rates have to be combined with a low latency (below 1 ms) and a high-density cellular network connection. The design of a backbone network involves two main issues:

- First, designing a suitable architecture to meet the requirements of bandwidth and cellular density.
- Second, developing a suitable medium access control (MAC) protocol to assure the quality of service (QoS) requirements, like low latency and seamless handovers.

For the backbone network, we select a radio-over-fibre (RoF) architecture as it is a highly promising access network solution, taking advantage of its potential to bridge the last-meter wireless connection with ultra-fast optical signals [3]. The use of RoF is additionally strengthened by the establishment of an emerging fibre infrastructure as the dominant last-mile access technology. The deployment of e.g., passive optical networks (PONs) brings Gb/s-supporting access points closer to residential end-users, and can be used as optical backhaul network for the next generation (5G) wireless broadband connections.

In section 2, we discuss different RoF architectures that could be used for feeding ultra small radio cells. The RoF architectures will also need a dynamic bandwidth allocation (DBA) algorithm to distribute the resources among the users in a fair and an efficient way. We discuss the design challenges for the DBA algorithm in section 3. Finally, we present the conclusions of the work in section 4.

2. RADIO-OVER-FIBRE ARCHITECTURES

The technique of modulating the radio frequency (RF) subcarrier onto an optical carrier for distribution over a fibre network is known as radio-over-fibre (RoF) technology. As the optical fibre works in a different frequency range (around 200 THz) compared to radio transmission (from 3 kHz to 100 GHz), this requires translation of the wireless RF signal into optical frequencies. For our case, we consider an analogue RoF system which transports analogue optical/wireless signals carrying digital data through modulation in order to minimize the complexity at the remote antenna unit (RAU) as no analogue-to-digital conversions and no digital signal processing are needed at the optical-wireless interface. However, typical wireless modulation schemes require a high signal-to-noise (SNR) ratio due to the limited available wireless bandwidth and thus we have to minimize the insertion loss in the RoF architectural design. Several design options are discussed in this section.

2.1 Parameters

Table 1 gives an overview of the parameters used throughout the description of the different RoF architectures. A first classification of the RoF architectures can be based on the relationship between the number of cells and the number of optical transceivers (TRX), where we distinguish between $M = N$ and $M > N$:

- $M = N$: High capacity (good for scenarios with a high user density)

- $M > N$: Requires sharing of optical TRXs, eventually combined with fibre sharing (good for scenarios with low or medium user density). To implement this sharing, two possible solutions are:
 - Local broadcast by passive split, which offers a simple way of TRX and fibre sharing.
 - Flexibility through central optical switches, which offers a better flexibility.

The above classification leads to three main architectural designs that will be discussed in the next subsections.

Table 1. Parameter overview.

Parameter	Symbol	Parameter	Symbol
number of cells	M	number of radio frequencies	V
number of optical transceivers	N	number of users	U
number of RF modulators	N'		

As every user is typically connected to a dedicated optical TRX, the number of TRXs (N) is in the order of the number of users (U). However, to support soft handovers (i.e. a handover where a user is simultaneously connected to two cells during the handover procedure), an additional fraction of optical TRXs will be needed, meaning that M will be slightly higher than U . Further, for simplicity reasons, we can assume that the number of RF modulators (N') is equal to the number of optical TRXs (N), which is a valid assumption as all modulated RF signals have to be mixed with an optical wavelength to transmit it to the RAUs. The number of radio frequencies (V) is typically much lower than the number of RF modulators, as there will be spectrum reuse between the cells.

2.2 RoF architecture with dedicated resources per cell

Figure 1 shows a point-to-point RoF architecture for the case where each cell or RAU has its own dedicated optical TRX in the central gateway (i.e. $M = N$). The digital signals carrying the user data are first modulated on the right RF. A first electrical space switch (dimension of $U \times N$) is needed to steer the user data to the right RF modulator. The modulated user data is then transmitted to an optical TRX, where it is modulated on an optical wavelength, e.g. λ_0 . The optical TRX has a direct fibre connection towards the cell where the user is located. To steer the signal to the right optical TRX, a second electrical space switch (dimension of $N \times N$) is used. Both space switches are controlled through a control plane, that will run a MAC protocol as discussed in section 3. At the RAU, an optical to electrical (O/E) converter and a band pass filter (BPF) are used to extract the RF signal, which is then transmitted to the end user by the local antenna of the RAU.

Figure 1. RoF architecture without optical TRX sharing and a dedicated fibre per cell.

This architecture is simple and well-suited for a scenario with a high user density demanding a very high capacity, as every cell can simultaneously be used at its maximum capacity. If two or more users, however, are located in the same cell, they should be time shared, leading to a reduced data rate per user. In case of scenarios with user densities far below 1 user/cell, this architecture will be overdimensioned as it does not allow any sharing of optical TRXs among cells. For that reason the architectures of the next subsections are introduced.

2.3 RoF architecture with shared resources among cells and passive splitting

The architecture on Figure 2 implements the resource sharing in the last-mile fibre network, by adding a passive power splitter (PS) on the fibre path between the central gateway and the RAUs. This is a simple way of sharing optical TRXs among cells. Further, this architecture is identical to the one of Figure 1.

Figure 2. RoF architecture with optical TRX sharing & last-mile fibre time sharing.

The drawback of this architecture, however, is that cells connected to the same PS are typically neighbouring cells, meaning that if there are users in both cells, the data rate per user will be reduced due to time sharing.

2.4 RoF architecture with shared resources among cells and flexible optical switching

Figure 3 depicts a RoF architecture where the number of optical TRXs is smaller than the number of radio cells or RAUs (i.e. $M > N$). This means that the optical TRXs have to be shared among the cells. For that reason, the second space switch is asymmetrical and is located after the optical TRXs. By consequence, an optical space switch is required which could be implemented as an automated fibre patch panel, assuming that the switching times are fast enough (cf. discussion in section 3.2). Otherwise, a broadcast and select (B&S) switch, as presented in Figure 4, might be needed. This architecture assumes that the number of RF modulators is equal to the number of optical TRXs ($N' = N$). If this assumption is not valid, an additional space switch between the RF modulators and the optical TRXs would be needed. As each RAU is connected by a dedicated fibre to the central gateway, no user selection is needed at the RAUs, but this implies that only one user per cell can be served.

Figure 3. RoF architecture with optical TRX sharing & a dedicated fibre/cell carrying data from only one user.

The architecture on Figure 4 is similar to the one on Figure 3, but the optical space switch is replaced by an optical B&S switch, consisting of N ($1 \times M$) semiconductor optical amplifier (SOA) switches, and M ($N \times 1$) arrayed waveguide gratings (AWGs). Note that the AWGs could also be replaced by passive PSs. This would make the switch cheaper, but will come at the penalty of a higher insertion loss due to the power splitting. These B&S switches allow steering multiple optical signals to the same fibre - directly connected to one specific RAU - provided that all optical signals are on a different optical wavelength. One RAU could then be shared by multiple users, as long as different radio frequencies are used. Furthermore, this architecture supports fibre sharing among multiple RAUs by connecting them in a passive way to the same fibre, as indicated by the additional RAUs on Figure 4. In this way, the RoF architecture consists of several parallel PONs with multiple 1:2 splitting stages. To limit the power difference between the first and the last RAU, asymmetrical splitting ratios are preferred at each RAU. This architecture also needs tuneable optical filters at the RAUs to select the appropriate wavelength.

Figure 4. RoF architecture with optical TRX sharing & an increased flexibility allowing fibre sharing and/or multiple users per cell at full capacity.

3. MAC PROTOCOLS

A MAC protocol is required to register new users and then to provide good QoS to the registered users. The challenges required in providing good QoS to the registered users involve seamless handovers, and using proper multiplexing to avoid interference in the radio frequency. First we describe the different MAC protocol strategies, and next we discuss how the architectures can deal with fast handovers.

3.1 Distributed vs. centralized MAC protocol

Two strategies exist to design DBA algorithms for RoF networks, i.e. distributed and centralized mechanisms.

- A possible approach for designing a *distributed* control mechanism is adapting existing wireless MAC protocols - like IEEE 802.11 (Wi-Fi) with RTS/CTS (Request to Send / Clear to Send) exchange

mechanisms - to the RoF architectures [4]. This approach suffers from the drawback that the additional fibre delay deteriorates the performance. However, if the difference between the central controller and the RAUs is not significant, then this approach could be used.

- When using *centralized* protocols to allocate bandwidth both in the optical and wireless domain, all bandwidth decisions are taken at the central controller. An example of a centralized protocol is the Medium-Transparent (MT) MAC protocol [5]. Medium transparent signifies that the protocol does not care whether the medium is fibre/air. Centralized protocols may resemble to point coordination functions (PCF) in Wi-Fi and provide a better QoS control.

As the fibre distance in all architectures is the same, the choice of distributed or centralized mechanisms is not different for any architecture. The fibre delay, which in turn depends upon the coverage area, will decide the best mechanism: with the distributed mechanisms more suited for a shorter fibre delay. However, more flexible architectures (e.g., architectures in Figure 3 and Figure 4) will require more complex mechanisms, like choosing the right RF modulators and optical TRXs, and may be time sharing them among a few users.

3.2 Handovers

For the intended ultra-small cells, we aim at a latency below 1 ms, e.g., 100 μ s, as defined in the 5G specifications. To optimize the handover times for the proposed RoF architectures, new handover solutions should be developed making use of the concepts and technologies proposed in this paper. In [6], we described the concept of fast handovers in a RoF architecture designed for delivering broadband Internet access to trains. There, a RoF architecture was combined with a moving cell concept where the cell frequencies are following the train. It was illustrated that it is possible to implement these moving cells entirely in the optical domain, and this by reconfiguring some optical switches in the control station of the RoF network. The fast handovers for the ultra-small 5G cells should further exploit this initial idea. The steps in the handover process are selection of the new cell and hitless switching of the data stream to that new cell. This requires the synchronization with the wavelength and space switching in the different central switches. Electrical space switching should be possible in the order of 10 ns or lower, and the SOA switches used for broadcast & select in Figure 4, have a switching time in the order of 1 ns. The selection criterion of the next cell will be based on the movement of the user and could involve a prediction algorithm. We assume that users could be connected to two cells at the same time, enabling soft handovers to reduce the stringent time requirements on handover procedure.

4. CONCLUSIONS

This paper proposes different RoF architectures for serving ultra small 5G radio cells. Three main architectural categories are presented, each having their own application area. A *point-to-point* architecture with dedicated resources per cell is simple and well suited for scenarios with high user densities. As there is no sharing of optical TRXs, this architecture will be overdimensioned and too costly for user densities far below 1 user/cell, which will often be the case for ultra small radio cells. Sharing optical TRXs and RF modulators, and eventually fibre connections, among radio cells will be of a key importance to design cost efficient architectures for low or medium user densities. An architecture with a *passive fibre split* is the most simple option, but neighbouring cells will typically share bandwidth, leading to a reduced data rate per user. A more flexible - but more complex - solution uses *optical switching* to share resources at the central gateway, either by an optical space switch or by an optical broadcast & select switch. The latter is most flexible, and allows fibre sharing and/or multiple users per cell at full capacity. Finally, a MAC protocol is needed to confirm the QoS bounds of low latency, seamless handovers, and a high throughput. Two different MAC mechanisms are considered: importing standard (*distributed*) Wi-Fi protocols to RoF networks, or designing *centralized* medium-transparent protocols.

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