All-Optical Network Capacity for 5G Cellular Fronthaul

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ABSTRACT

In this paper, we have investigated the use of fast wavelength switching optical transmitters and a wavelength selective space switching all-optical network for cellular fronthaul applications. System capacity is calculated by using hard-deadlines that arise from the radio requirements and the physical constraints of the optical network. The results show that the approach proposed can reduce hardware costs by 50% while satisfying the stringent latency requirements of evolving 5G fronthaul systems. An analysis of the impact of varying the switching times of the transmitter and the reconfiguration time of the space switch reveals the limits (1us and 1ms respectively) where the system offers potential benefits compared to fixed networks.

**Keywords**: Fronthaul, fast switching networks, ultra-low latency, 5G, CPRI.

# INTRODUCTION

Mobile telecommunications systems are evolving towards fifth generation (5G) mobile networks with increasing bandwidth requirements. This evolution includes the concept of Cloud Radio Access Network (C-RAN) [1] (also referred to as a Centralised RAN), where the base station is split into two logical parts, the Base Band Unit (BBU) and the Remote Radio Head (RRH). The BBUs can be pooled in a central point and use ultra-low latency “Fronthaul” connections to the RRHs using the Common Public Radio Interface (CPRI) specification [2] to transport a digitised version of the Radio Frequency (RF) signals between each BBU/RRH pair.

CPRI has worked well for 3G and 4G mobile systems and is typically deployed using optical Ethernet to provide low latency fronthaul links with sufficient bandwidth to support the sampled RF signals. However, the increased bandwidth required by evolving 5G systems and the push to millimetre wave frequencies is expected to push the optical bandwidth required to a level that cannot be easily supported by existing technologies [3]. Moreover, some of the new radio access technologies that will be used in evolving 5G networks require ultra-low latencies of less than 1ms which motivates the removal of electrical routing from the fronthaul paths. The use of all-optical switching and wavelength-based routing is the prime candidate for achieving these ultra-low latencies [3].

The CPRI specification sends the digitised RF signal in a frame-based protocol that has a strict periodicity where the bitrate required is adjusted by varying the payload of each frame. Since there are currently only nine allowable frame sizes, a CPRI-based fronthaul network lends itself to an analysis based on deterministic models. In this work we will explore the capacity of such a network using techniques that have been proposed for datacentre networking [4] and access networking applications [5] in an All-Optical Network using superchannels composed of 100Gbps subchannels [6]. In particular, we will find the system capacity when constrained by hard-deadlines arising from the CPRI standard and the requirements of 5G cellular systems.

…

Burst

Assembler

TRX 1

WSS 1

Space

Switch

Cell Site 2

…

Burst

Assembler

Burst

Assembler

Burst

Assembler

TRX 2

WSS 2

TRX 3

WSS 3

TRX 4

WSS 4

Cell Site n

**Cell Site 1**

Buffer

Buffer

Buffer

Super-channel

Ethernet Switch

RRH 1

RRH 3

RRH 2

BBU 1

BBU 2

BBU 3

BBU 4

BBU 5

BBU 6

BBU n-2

BBU n-1

BBU k

**BBU Pool**

Further BBUs connected to remaining TRX s

Figure System Architecture and example of the internal arrangement of the cell site equipment.

# System Architecture

In this work, we assume a C-RAN deployment with a single BBU pool that has a bank of wavelength tunable transceivers (TRXs) to provide the connectivity to and from the cell sites, as shown in Figure 1. Each TRX can use a variable number of 100Gbps optical channels to provide increased capacity and reduced latency as required by the network traffic. These multiple channels are bonded together to create a superchannel. A set of *k* BBUs send their CPRI frames to a “Burst assembler” that arranges the frames in a queue towards a specific TRX which are then sent in a transmission burst on a superchannel tuned to particular wavelength associated with a specific cell site. It is also assumed that each of the *n* cell sites hosts three cells and each cell uses a single RRH/BBU pair, so that the RRHs and BBUs are logically grouped in threes and hence *k=3.n*.

In the downlink direction, the optical paths from each TRX are created by configuring a Space Switch and a Wavelength Selectable Switch (WSS) to route a particular set of wavelengths to each of the cell sites being served. A number of cell sites therefore share the capacity of the optical TRX by transferring CPRI data to the desired cell site during the period when the TRX is tuned to the correct wavelengths for that cell site. Each cell site has one optical superchannel termination on an Ethernet switch that forwards the individual CPRI streams towards each of the three RRHs within the cell site. The output ports of the Ethernet switch will have a buffer to hold the CPRI data until the RRH is ready to use it.

The maximum bit rate on each CPRI link corresponding to a fully loaded cell is 12.1651Gbps [7] and since this architecture assumes that each cell site contains three cells, then the maximum bit rate for each cell site is 36.5Gbps. A single channel 100Gbps TRX can therefore only accommodate 2 cell sites, while a superchannel arrangement with 5 subchannels can theoretically accommodate 13 cell sites.

# CPRI Requirements

The specifications for LTE systems require a high degree of synchronisation between transmissions from all antenna systems which places particularly stringent requirements on a fronthaul system in terms of both latency and jitter. Thus, fronthaul systems are typically deployed with dedicated optical links between every BBU and its associated RRH. This, in turn, means that the CAPEX associated with these circuit-oriented deployments is substantial and as the systems evolve towards higher bit rate requirements, the costs will become prohibitive [8].

The CPRI standard uses a well-defined framing structure [7], where a BasicFrame contains a block of RF signal samples and has a duration of 260.416ns. The size of these BasicFrames is usually quoted in octets and depends on the CPRI option that is required to support the radio channels in the cell (see Table 1). Exactly 256 BasicFrames are then encapsulated in a CPRI HyperFrame which has a duration of 66.67us. These HyperFrames are logically embedded in a CPRI SuperFrame which has a duration of 10ms, which is exactly synchronised with the 10ms LTE frame duration that is used on the radio interface.

# System Constraints

Since the radio resources in each cell are assigned for the duration of each LTE frame, then it also holds that the CPRI requirements are fixed for this period and hence the wavelength sharing regime for the optical network is static during this period. In this work, then, it is assumed that the WSS can be reconfigured at the end of each SuperFrame which, in turn means that all of the SuperFrames must be transferred to the RRH’s buffer before the reconfiguration begins. This sets a constraint on the system that all SuperFrames must be delivered in a time equal to 10ms minus the time required for reconfiguration.

During wavelength switching events, there is a pause in data transmission which reduces system efficiency. The most convenient time to switch wavelength is at the end of an integer number of HyperFrames and here this is assumed to be one HyperFrame to minimise the system latency. Since each cell site hosts 3 cells, the optical network bursts will contain three HyperFrames, the time taken to transmit a HyperFrame (*Thf*) is given by:

*Thf = Ncs x (Burst size/Superchannel rate + Wavelength switching time) (1)*

where Ncs is the number of cell sites being served. The first HyperFrame in a SuperFrame will experience the longest delay which is given by *Thf\_MAX = Thf + (WSS reconfiguration time)* and should be less than 1ms [3]. Since a SuperFrame contains 150 HyperFrames, the longest time taken to transmit a single SuperFrame to each of the cell sites *(Tsf)* can be simply calculated and must be less than the LTE Frame duration of 10ms. That is:

*Tsf = 150 x Thf + WSS reconfiguration time < 10 milliseconds (2)*

Equation (2) therefore defines the first constraint on system capacity. The second constraint is that the TRX cannot use more than 80 wavelength channels [6].

# Capacity Calculation

A numerical model based on these equations was developed in MATLAB where the number of cell sites being served by a single flexible TRX is incremented and the number of subchannels is increased when the latency constraint is violated. Thus, the capacity is found when the total number of channels will exceed 80 if another cell site is added. In this first example, the WSS reconfiguration time is set to 50us and the wavelength switching time is 100ns [4, 5] to reflect state of the art optical switching capabilities. The data shown in Table 1 indicates the CPRI traffic parameters that were used to generate a constant load from a bank of BBUs. The table also shows the maximum number of cell sites that can be served by a flexible TRX (i.e. the system capacity) with the number of subchannels per superchannel when the maximum capacity is reached. The results also show that the maximum latency experienced by a HyperFrame is always less than the 1ms target for 5G [3]. At the maximum capacity for CPRI option 9, the TRX can serve 13 cell sites (i.e. 39 BBU/RRH pairs) by using superchannels composed of 6 subchannels. Interestingly, a bandwidth based calculation would suggest that 13 cell sites would require a maximum bit rate of 474.5Gbps and can therefore be served by a superchannel TRX with only 5 subchannels. The loss in efficiency caused by the switching events simulated in this paper however, causes the superchannel to require 6 subchannels.

These results suggest that a system can be designed that uses a single flexible TRX to replace 13 single channel TRXs. Assuming that the flexible TRX contains 6 lasers to create the superchannel in this case, it is possible that this approach could yield a CAPEX saving of the order of 50%. In figure 1, the WSS and Space switches are shown as separate entities to emphasise the need to separate the channels in wavelength and in space. It is expected that further cost savings could be possible as the system lends itself to integration including the use of integrated optical comb sources [9].

Table 1. System Capacity and Performance Summary.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| CPRI Option | Bit Rate (Mbps) | BasicFrame Size (octets) | Maximum HyperFrame Latency (us) | Number of Sub-Channels | Number of Cell Sites Served |
| 1 | 614.4 | 20 | 115.1 | 1 | 49 |
| 2 | 1228.8 | 40 | 103.2 | 2 | 40 |
| 3 | 2457.6 | 80 | 93.5 | 3 | 26 |
| 4 | 3072.0 | 100 | 103.7 | 3 | 26 |
| 5 | 4915.2 | 160 | 101.2 | 4 | 20 |
| 6 | 6144.0 | 200 | 113.4 | 4 | 20 |
| 7 | 9830.4 | 320 | 114.5 | 5 | 16 |
| 8 | 10137.6 | 330 | 112.3 | 5 | 15 |
| 9 | 12165.1 | 396 | 114.6 | 6 | 13 |

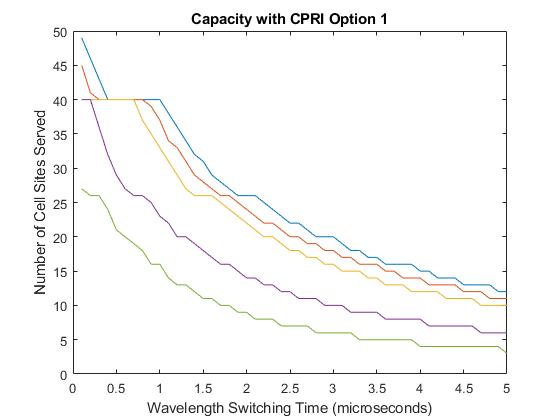
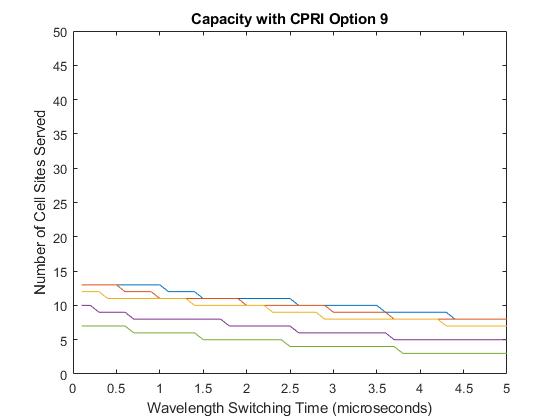
# Impact of Switching Speeds

Since slower switching devices are available at lower cost, it is interesting to explore the impact of these switching speeds on system capacity. The simulations presented in Figure 2 show how the capacity of the system for CPRI Options 1 and 9 depend on the switching times. The wavelength switching time is varied between 100ns and 5us and the WSS reconfiguration time is varied between 50us and 7ms (70% of the SuperFrame duration). The results show a “staircase” reduction in capacity with increasing wavelength switching time which is caused by the quantised nature of the constraints. For example, when an increase in switching time causes the SuperFrame delivery constraint to be violated then an additional subchannel is required in the superchannel to reduce the system latency. This in turn causes a step reduction in the number of superchannels that can be supported in the standard 80 channel WDM scenario.

The wavelength switching events occurs 150 times per cell site during a SuperFrame duration and can therefore have a significant impact on capacity. The results show that a value greater than 1us for the wavelength switching time begins to degrade the capacity significantly. The simulations with WSS reconfiguration times in excess of 1ms experience significant reduction in capacity and cause HyperFrame latency to increase above 1ms which is too high for many 5G applications [3]. Also, the simulations with WSS reconfiguration times of 5ms showed that the system would require superchannels with 22 subchannels, which is rather impractical. These results therefore indicate that the wavelength switching time should be less than 1us and the WSS reconfiguration time should be less than 1ms to maintain the system capacity at a reasonably practical level for the current range of CPRI bit rates. These switching speeds are easily achieved with current state of the art technology and may also be possible with more mature and lower cost technologies.

# CONCLUSIONS

This paper explores the capacity of a CPRI-based C-RAN fronthaul scenario using fast wavelength switching transmitters in an all optical network that includes the use of WSSs to reconfigure the switching routes. The capacity is constrained by both the total number of wavelength channels usable by a flexible optical transmitter and also by the latency limitations of a hard-deadline for the delivery of CPRI SuperFrames. These results show that a single wavelength-tunable superchannel TRX can support up to 13 cell sites (i.e. 39 BBU/RRH pairs) whereas a typical modern deployment using a single TRX for each cell site would require 13 TRXs. As the superchannel TRX is only required to support 6 subchannels, a CAPEX saving in excess of 50% is anticipated. Additional CAPEX savings are possible through the use of highly integrated implementations and the possibility to use comb-based TRXs [9].



WSS Switching

Time Increasing

WSS Switching

Time Increasing

Figure 2 System Capacity versus Wavelength Switching Time for CPRI Options 1 & 9. The WSS reconfiguration times are 50us, 1ms, 5ms, 6ms and 7ms.

Since these capacity figures are based on the full-load condition where all the cell sites use CPRI option 9, it may be possible to develop other, more flexible network architectures that exploit the fact that a flexible superchannel TRX can serve up to 49 cell sites during times when the cell sites are lightly-loaded (e.g. during the night when all cells are using CPRI option 1). Moreover, a larger network serving several hundred cells offers an opportunity to adapt the number of active TRXs to match the load across the set of cell sites with varying loads. It is expected that such a highly flexible arrangement may be able to provide considerable benefits in terms of OPEX and energy consumption.

Further work will focus on building a discrete time simulation of the system and to explore the dynamic behaviour of the system as the load changes through the movement of demand within the radio network. A scheduling mechanism to manage the resources in a more flexible network that lends itself to SDN implementation will be developed and evaluated.

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