**Comparison of Analogue and Digital Fronthaul for 5G MIMO Signals**

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*Abstract*— This paper investigates architectural and capacity issues associated with analogue and digital radio over fibre fronthaul for MIMO in 5G cellular systems. The capacity of both systems is evaluated in terms of a static system deployment and also with varying traffic load. The results show that in a leased line scenario, the analogue systems offer an opportunity to reduce the cost of fibre infrastructure by more than 93% due to the more efficient use of bandwidth. but since the ARoF equipment is currently more expensive than the DRoF equivalent, there is a trade-off between CAPEX and OPEX for a given deployment.

Keywords—: 5G, Fronthaul, eCPRI, WDM, MIMO, Radio over Fibre

# Introduction

The continued evolution of cellular systems towards and beyond the fifth generation (5G) includes significant changes to both the system architecture and the radio technology used to connect the end users (mobile devices). Two important concepts that will help to deliver increased capacity with scalability and flexibility while still maintaining an economically viable cost models are Multiple Input Multiple Output (MIMO) antenna systems [1] and Cloud Radio Access Networks (CRANs) [2]. Essentially, MIMO allows the use of multiple antennas to increase the capacity of a radio link and CRAN allows some functionality of a base station to be located at a central hub and connects to the antenna site via a so called “Fronthaul” network.

Mobile network operators face a number of design and deployment choices about how best to implement these concepts. These choices are explored in this paper in terms of capacity, scalability, flexibility and relative costs.

Obviously, any deployed system must have sufficient capacity to carry the peak traffic in the network. That capacity, however, should also be able to be increased dramatically in scale as the demands of users is expected to increase by orders of magnitude as mobile data services proliferate. It should also be able to be used in a flexible way, so that the radio channels that carry the user’s data can be moved from a lightly loaded cell to one where there is higher demand. Such flexible radio resource management is a major motivator for the CRAN concept so that signal processing capabilities can be pooled in a central resource and shared between multiple cells.

The total cost of ownership of a CRAN system is composed of a number of fixed assets that are located at the central pool and the distributed antenna sites. The network connecting the elements of the CRAN system, however, can either be owned by the operator and therefore contribute significantly to the Capital Expenditure (CAPEX) or they can be leased from a third party and contribute to the Operational Expenditure (OPEX). Different models are possible for this leased arrangement and the suitability of the different technical implementations are explored in that light.

For clarity, this paper describes the downlink direction only and it is assumed that similar technology would be used for the uplink from the antenna system towards the core network.

# CRAN Architecture

## Cloud RAN

The CRAN concept relies on optical networking to provide fronthaul connectivity from centralised radio resources to remote cell sites. Two key ways to implement these fronthaul connections are: - analogue radio over fibre (ARoF) [3] and digital radio over fibre (DRoF) such as the enhanced Common Public Radio Interface (eCPRI) [4].

Since MIMO systems require different radio signals to be transmitted at the same frequency from different antennas at the same cellular base station, the fronthaul network must carry multiple versions of the radio signal for each cell. A common implementation of MIMO in cellular systems uses 8 antennas at each cell site so that the optical bandwidth required for the fronthaul network increases dramatically to accommodate eight times more radio channels.

The various technology options explored here are each set in a typical metropolitan optical ring network similar to those described in [5]. Within this context, technical constraints will be introduced for the different aspects of the total system and mapped onto the fronthauling technology options.

## Fronthaul Architecture

The CRAN concept uses a centralised pool of Base Band Units (BBUs) that are based on General Purpose Processors (GPPs) typically based on a standard multicore X86 processor which is augmented by Graphics Processor Units (GPUs) to accelerate the parallelisable aspects of signal processing such as Fast Fourier Transforms (FFTs). The BBU’s may also include high speed Field Programmable Gate Arrays (FPGAs) to execute some of the complex filtering functions.

The signals produced by the BBU are then a digitised stream of complex valued samples of the desired radio base-band signal composed of In-phase and Quadrature components (I(t) & Q(t)). These radio signals are then sent via the fronthaul network to Remote Radio Heads (RRHs) for transmission.

## Optical System

The different fronthaul architectures considered in this work are shown in Fig. 1 in the context of a Wavelength Division Multiplexed (WDM) ring topology. The DRoF architecture shown in Fig 1(a) relates to a standard 100GbEthernet deployment using 50GHz wide WDM channels where multiple transponders will be required to support the bit rates required here. The ARoF architecture in Fig 1(b) illustrates a possible system using an optical comb source to carry the eight versions of the radio signals required for the MIMO implementation. By selecting the comb spacing carefully, the entire radio band can be carried on each of the comb lines so that one comb source transponder can serve all the requirements for one cell site.

In both architectures, the BBU pool sends the radio signals using optical channels, and the ROADMs are used to “drop” appropriate channels to the required RRHs while the remaining channels carry on to the next node in the ring. The ROADM’s selectivity, therefore, defines or constrains the possible bandwidth of the WDM channels. A common implementation uses a minimum ROADM bandwidth of 12.5GHz and multiple channels can be combined to provide wider channels of 25GHz, 37.5GHz or 50GHz.

## Radio System

To realistically model the radio aspects of the system, each cell site hosts three cells, each of which uses an 8 element MIMO system. The specification of the 5G New Radio (5G-NR) allows for radio channel bandwidths up to 100MHz in 15 channels defined between two bands 3.3GHz to 4.2GHz and 4.4GHz to 5GHz [6]. For the purposes of this work, the minimum load is one NR channel per cell (i.e. 3 per cell site) and the maximum load is five NR channels per cell (i.e. 15 per cell site).

The International Telecommunications Union (ITU) states that a 100MHz wide 5g-NR channel with an 8 antenna MIMO configuration would require a raw bit rate of 40Gbps with some additional overhead required for the transport technology used (e.g. eCPRI) [7]. This corresponds to two streams at the CPRI 10 rate of 24.33Gbps including overhead.

Since the radio resources (blocks) that are transmitted within the radio channel to multiple users are fixed for a given 10ms period, each RRH is paired with one BBU for that period. The radio resources may then be reconfigured for the next 10ms period and consequently, the optical resource allocation follows the same periodicity.

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| Fig. 1: Example Fronthaul Architectures (a) DRoF system using a multicarrier transponder to transport multiple Ethernet-based flows and (b) ARoF system using multiple comb sources to transport the signals. |

# eCPRI DRoF Fronthaul

## eCPRI Overview

The eCPRI specification (2019) [4] enables the transfer of multiple radio signals as a series of digital, complex valued (I & Q) samples between the paired BBUs and RRHs. The eCPRI specification also includes provision for buffering at each end of the fronthaul link so that multiple CPRI streams can share a high capacity physical network path in either a time-slotted or contention-based way.

The specification allows for a number of different points where the processing chain for each base-station is split. In this work it is assumed that the CPRI split point is located as close as possible to the antenna so that the centralisation benefits of the system are maximised (denoted split point “E”). The RRH therefore simply contains an optical receiver that can decode the digital streams and arrange the bits correctly into streams of words that can be used to generate the analogue radio signal for each antenna using a pair of Digital to Analogue Converters (DAC’s) and an electrical IQ modulator with a local Oscillator (LO) tuned to the required radio channel frequency. For the 8x8MIMO scenario, this hardware will be repeated eight times.

The initial analysis here assumes that each BBU/RRH pair in the system uses the highest load, of two CPRI 10 streams for each of the 15 possible radio channels, yielding a traffic load of 730Gbps to each cell site. In this work, two options for sharing optical network capacity are explored and explained below.

## Using 50GHz Channel spacing

In the system envisioned here, each WDM channels uses 25 Gbaud DP-QPSK modulation to yield a line rate of 100Gbps which can accommodate four CPRI 10 streams for full load conditions. Under light load the CPRI streams can be directed to four cell sites where the receiver then decodes all four streams but only uses the one that is addressed to it. The Ethernet Frames denoted TS1 to TS4 indicated in Fig 1(a) show how these data frames will be interleaved in time.

## Narrow WDM channels

This system is rather similar to that presented in Fig 1 (a) except that the WDM spectral grid has a granularity of 12.5GHz. Two different cases are considered for this option. The first case considered is where a 100Gbps can be accommodated in a 37.5GHz WDM channel spacing using 25 Gbaud DP-QPSK [8]. Hence, the payload of four CPRI Option 10 streams can be accommodated in a 37.5GHz bandwidth. In the second case considered, 12.5GHz WDM channels are used. These can each carry 25Gbps using 6.25 Gbaud DP-QPSK, so that each of these smaller channels can accommodate one CPRI 10 stream which may offer increased flexibility and reconfigurability. At low load then, each cell site will require six of these WDM channels, whilst at high load, thirty such channels are required.

# ARoF Fronthaul

Since an 8x8 MIMO system is assumed here, we need 8 versions of each radio channel to be delivered to each cell. Two possible implementations of this are considered below.

## Transmission Frequency ARoF

This system modulates the RF signal at its transmission frequency which in the case of the popular 5G-NR bands is between 3.2GHz and 5GHz. A possible method to achieve this is by using an eight-channel optical comb source with 6.25GHz spacing between comb lines to carry the eight versions of the radio signals required. That is, all fifteen available radio channels or the subset of channels that are being used at that particular cell site, could be modulated onto each of the eight lines in the optical comb transmitter and then optically separated at the RRH to feed each RF channel to the required antenna. A stylised example of the first three sets of RF carriers in such a system is shown in Fig. 2, although the real signal would require eight sets of signals.

In general, then, the optical bandwidth (OBW) required by such a system will be dependent on the order of the MIMO system being used (denoted N here) and the frequency spacing of the comb (f) and given by:-

*OBW=N.f Eq 1*

In this case where f=6.25GHz and N=8, then OBW=50GHz, so this comb-based optical signal will fit into a 50GHz WDM channel (i.e. four 12.5GHz channels) that will be delivered to the correct cell site by appropriate configuration of the ROADM.

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| Figure 2 Transmission Frequency ARoF showing the first four optical comb lines spaced by 6.25GHz and the first three RF Signals between 3.2GHZ and 5GHz to the right of the optical lines. |

Since the system is purely analogue, it is not economically viable to use buffering that could allow the sharing of the optical channels. The optical aspects of this analogue version then, are fixed and cannot be reconfigured without causing an interruption to the radio service. It does, however, allow radio channels to be added, removed or altered without the need to change the network as such changes can be accommodated within the bandwidth of the comb spacing.

## IF-ARoF

This type of system modulates the analogue radio signal containing the 5G-NR channel onto a lower frequency carrier known as an Intermediate Frequency (IF) rather than at the transmission frequency. These IF signals can be arranged in the same spacing as the transmission frequency channels so that the RRH can simply convert the block of IF channels to the desired transmission frequency band of 3.2 to 5GHz. These combined IF signals are then used to modulate the intensity of an optical carrier using a Mach-Zehnder modulator and converted back to electrical signals at the optical receiver using a photodiode and sent to the antenna after some adequate amplification and filtering. The stylised spectrum shown in Figure 3 is for the case where an eight-line optical comb source with a spacing of 3.125GHz could be used, since the signal occupies less than 2GHz within the 3.125 GHz optical spacing.

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| Figure 3 Intermediate Frequency ARoF showing the first seven optical comb lines spaced by 3.125GHz and the first five IF Signals to the right of the optical lines. |

Separating and modulating the closely space lines of this optical comb approach will be challenging with current technologies, so an alternative approach envisages using groups of these IF signals modulated onto an electrical comb of RF subcarriers spaced by 2GHz using Sub-Carrier Multiplexing (SCM) [9]. This composite RF signal can then be modulated onto an optical carrier in a more attractive and bandwidth efficient scheme as shown in Figure 4. At the receiver, these SCM channels can be separated in the RF domain to yield the 8 versions of the block of 5G-NR channels that can be upconverted to the correct set of frequency channels and routed to the correct antennas.

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| Figure 4 Intermediate Frequency ARoF using an electrical comb with 2GHz spacing and using SCM. |

In this case the optical bandwidth (OBW) required will be dependent on the bandwidth of the radio channels (RBW), the order of the MIMO system being used (N) and the guard band required between each version of the radio signal (GBW) and given by:-

*OBW=N.(RBW+GBW) Eq 2*

In the case where the system can accommodate all RF channels, RBW=1800MHz. To avoid low frequency noise in the system, we select GBW=200MHz and N=8, so that OBW=16GHz, so this RF comb-based optical signal will require 32% of the bandwidth required by the transmission frequency ARoF system for each 8x8 MIMO radio channel. If, however, the ROADMS are set for a 12.5GHz grid, then two such channels would be required, which is 50% of the optical bandwidth requirement as the Transmission Frequency ARoF.

# Hardware Comparison

As both DRoF and ARoF transmission use significantly different hardware at each node, it is worthwhile taking into consideration their potential impacts on operator CAPEX. Both RoF technologies have specific hardware requirements which are either inherent to their implementation or are required to guarantee a certain level of performance.

ARoF approaches, which negate the requirement for digital-to-analog converters (DACs) and analog-to-digital converters (ADCs) at the antenna site, are often considered as a means to reduce CAPEX (compared to currently deployed DRoF) in future network deployments with Ultra Dense (UD) antenna distribution [10]. However, ARoF’s susceptibility to non-linearity in the transmission path [11] ultimately leads to the requirement for linear components (RF amplifiers and optical sources/modulators), which represents a significant increase in deployment costs over existing solutions. Indeed, in comparing DRoF and ARoF link performances, [12] concludes that relatively low cost, and low linearity optical systems benefit from the use of DRoF modulation and transmission.

In the context of the ARoF systems described in this work, the high Peak-to-Average Power Ratio (PAPR) associated with multi-carrier analog signals is also problematic from a cost perspective [13]. Compared to DRoF, this effectively limits the RoF link power budget; enforcing reduced transmission distances/number of splits, or a higher sensitivity photo-receiver, in order to achieve the target performance for a given optical transmit power. Overall, whether DRoF or ARoF leads to relatively lower CAPEX will be decided by the level of network scaling required. ARoF significantly increases optical transmitter side costs but facilitates network scaling. The amount of equipment associated with current DRoF technologies increases with the expected vast proliferation of small cell antenna sites.

# Deployed Capacity

## Leased Fibre

From the foregoing discussion, it appears that the eCPRI fronthaul system can carry two 5G-NR-8x8-MIMO channels in a single 100Gbps optical channel (either 50GHz or 37.5GHz wide). If the optical system could also be configured to use 12.5GHz WDM channels, then a single CPRI 10 stream could be carried in each 12.5GHz channel and two such streams would be required for each 5G-NR 8x8MIMO channel. An ARoF system, on the other hand, can serve one cell site with one 25GHz WDM channel carrying all 15 radio channels.

The ARoF solutions tend to be less mature in their manufacturing integration so that they have a substantially higher CAPEX than a DRoF system using relatively more mature 100Gbit Ethernet equipment. If the cellular system operator leases a fibre in a metropolitan ring, then the number of cell sites that can be served by that fibre can be simply calculated. The results for each system are shown in Table 1 for minimum load (one radio channel per cell) and maximum load (five radio channels per cell), assuming a fibre with a capacity of 80 WDM channels (50GHz grid) or 320 WDM channels on a 12.5GHz grid. For example, the calculation for 50GHz channel DRoF assumes that at light load, each cell site requires three radio channels, which would require two 100GbEthernet links, so that a maximum of 40 cell sites can be served in a single fibre. For the maximum load in this case, each cell site would require 8 of these 100GbEthernet channels so that a single fibre can serve 10 cell sites. The ARoF systems require a fixed optical bandwidth for each cell site, irrespective of the radio load within the cells.

1. Number of Cell Sites Served in One Fibre, where low load means that each cell requires One 5G-NR Channel and full load means that each cell requires Five 5G-NR channels

| System Type |  | Number of Cell Sites Served | |
| --- | --- | --- | --- |
| Optical WDM channel width | Low Radio Load | Full Radio Load |
| eCPRI | 50GHz | 40 | 10 |
| eCPRI | 37.5GHz | 53 | 13 |
| eCPRI | 12.5GHz | 53 | 10 |
| ARoF | 50GHz | 80 | 80 |
| IF-DRoF | 12.5GHz | 160 | 160 |

Typically, the fronthaul system needs to be dimensioned for the full load scenario for a defined number of cell sites in the service area. Thus, in a realistic deployment scenario, the 50GHz WDM eCPRI system would require up to sixteen times more fibres to be leased than an IF-ARoF equivalent. This would have a serious detrimental impact on the OPEX as the leasing costs is a major on-going cost [14].

## Flexible WDM Channel Leasing

With a leasing arrangement that allowed specific WDM channels to be leased on a dynamic “on-demand” way, then the OPEX could be reduced significantly in the DRoF case. To explore the dynamic capacity requirements, a traffic model was derived from a model for business and residential cells [15].

Here we use a cohort of 240 cells arranged in 80 cell sites, each with 3 cells per cell site. The model makes the offered load vary throughout the day for the 40 residential cell sites and 40 business district cell sites shown as dotted lines with triangle and square markers respectively in Fig. 5. The required bandwidth for each of the transport technologies is normalised to the equivalent number of 12.5GHz WDM channels that would be required to service the offered load.

The results show that if a dynamic leasing arrangement is possible, the number of WDM channels required will vary throughout the day and can lead to a reduced cost of leasing. The results indicate that the 12.5GHz WDM channels offer a slightly better use of bandwidth compared to the 37.5GHz or 50GHz variants. This is due to the increased flexibility of the smaller channels to provide a finer grained distribution of resources. In this case, the average number of 12.5GHz wide WDM channels required is 922 as opposed to 2400 for a fixed leasing policy.

The ARoF solutions do not dynamically change their WDM channel usage, so in this example, the regular ARoF approach would require 160 WDM channels and the IF-ARoF requires 80 such channels. So, despite their lack of flexibility, both these ARoF solutions will use much less WDM capacity than any of the CPRI based solutions with this load model, which would considerably reduce the OPEX for a fronthaul deployment using leased lines. Comparing the IF-ARoF requirements to the average number of channels required for the most efficient DRoF solution, the IF-ARoF approach uses less than 9% of the number of 12.5GHz channels in the WDM system for the given traffic model

Since the hardware cost of the ARoF solutions is considerably higher than the CPRI solutions, there is a trade-off between CAPEX and OPEX. This tradeoff will change if ARoF hardware become commoditized through higher levels of integration and larger volumes of manufacturing

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| *Fi*g.5: Daily variation of equivalent CPRI load per cell for residential cells and business district cells (dotted lines) and the associated number of WDM channels (12.5GHz) required to service the cohort of 120 of each type of cell (solid lines) for five types of network technology. |

# Conclusion

The capacity of ARoF, IF-AroF and eCPRI-based DRoF architectures for 5G MIMO signals were examined in terms of their flexibility and static capacity. The comparison used a leased-line metro ring architecture with reconfigurable bandwidth WDM channels with a resolution of 12.5GHz. The results indicate that the DRoF system would require 16 fibres to carry the same traffic as an IF-ARoF system. When this is cast in terms of the cost of leasing fibres to carry the traffic, the IF-ARoF system offers a saving of 93%.

The approaches were also evaluated using hourly traffic load for residential and business cell sites The results from our studies demonstrated that at all loads IF-ARoF used about 50% of the capacity required for a regular ARoF system. The DRoF system was able to adapt to the changing load throughout the day which could improve the OPEX if a flexible leasing arrangement were used compared to a DRoF system with a fixed leasing arrangement. The bandwidth required for the ARoF options was, however, significantly lower than any of the DRoF approaches at any load.

The choice of ARoF or DRoF will therefore depend on a CAPEX/OPEX trade-off for each specific deployment case and whether dynamic bandwidth pricing could be used to improve the cost of leased capacity in the DRoF case. The DRoF system also allows for other types of traffic to be opportunistically carried in the ring, while the ARoF systems do not lend themselves to capacity adaptation.

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