R-FFT: Function Split at IFFT/FFT in Unified LTE CRAN and Cable Access Network

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Abstract—The Remote-PHY (R-PHY) modular cable network for Data over Cable Service Interface Specification (DOCSIS) service conducts the physical layer processing for the transmissions over the broadcast cable in a remote node. In contrast, the cloud radio access network (CRAN) for Long-Term Evolution (LTE) cellular wireless services conducts all baseband physical layer processing in a central headend unit and the remaining physical layer processing steps towards radio frequency (RF) transmission in remote nodes. Both DOCSIS and LTE are based on Orthogonal Frequency Division Multiplexing (OFDM) physical layer processing. We propose to unify cable and wireless access networks by utilizing the hybrid fiber-coax (HFC) cable network infrastructure as fiber fronthaul network for cellular wireless services. For efficient operation of such a unified access network, we propose a novel Remote-FFT (R-FFT) node that conducts the physical layer processing from the Fast Fourier Transform (FFT) module towards the RF transmission, whereby DOCSIS and LTE share a common FFT module. The frequency domain in-phase and quadrature (I/Q) symbols for both DOCSIS and LTE are transmitted over the fiber between remote node and cable headend, where the remaining physical layer processing is conducted. We further propose to cache repetitive quadrature amplitude modulation (QAM) symbols in the R-FFT node to reduce the fronthaul bitrate requirements and enable statistical multiplexing. We evaluate the fronthaul bitrate reductions achieved by R-FFT node caching, the fronthaul transmission bitrates arising from the unified DOCSIS and LTE service, and illustrate the delay implications of moving part of the cable R-PHY remote node physical layer processing to the headend. Overall, our evaluations indicate that the proposed R-FFT node to reduce the fronthaul bitrate requirements of the existing CRAN structures.

Index Terms—Broadcast cable, Cable access network, Cellular wireless network, Delay, DOCSIS, Internet access.

I. INTRODUCTION

A. Motivation: Modular Cable DOCSIS and Cellular LTE Architectures

The architectures of both the broadcast cable DOCSIS access network and the cellular wireless LTE access network have recently been evolving towards modular architectures. In broadcast cable networks, the Modular Headend Architecture version 2 (MHAv2) [1] implements the Cable Modem Termination System (CMTS) functions in a modular fashion. Specifically, in the R-PHY architecture [2]–[4], a digital fiber links the headend with distributed Remote PHY nodes (RPDs).

An RPD can be located close to the cable modems (CMs), improving the signal quality on the broadcast cable. The RPD conducts all the physical layer processing for the transmissions to and from the CMs, while the higher layer processing is conducted centrally at the headend.

Similarly, in cellular wireless access, the Cloud Radio Access Network (CRAN) architecture splits communication functions between centralized Base Band Units (BBUs) that conduct the baseband signal processing and Remote Radio Units (RRUs), which conduct the passband processing for the physical RF transmissions. A central BBU can support multiple RRUs and thus provide a common platform for centralized resource management. BBUs are typically flexibly implemented in software on generic computing hardware [5], [6] and are amenable to implementation on cloud computing resources. Also, conducting the baseband processing in the BBU reduces the complexity and cost of the RRUs, which is particularly advantageous for large-scale small cell deployments.

Importantly, both DOCSIS 3.1 [7] and LTE are based on OFDM physical layer processing, which requires an IFFT/FFT module as main last step of the baseband processing. In the downstream direction, the FFT module produces the time domain I/Q samples that the LTE CRAN transports over the fronthaul link from BBU to RRUs.

B. Challenge: Fronthaul for CRAN

A critical challenge of CRAN operation is the fronthaul transport of the time domain I/Q samples between BBU and RRUs, which require low latency and high bitrates [8]. A low-latency high-bitrate connection must constantly be maintained between BBU and RRUs, regardless of the actual user traffic. That is, the analog RF signals must be transmitted and received at all times, even when there is no wireless user activity. For instance, the passband signal with the cell broadcast information and reference or pilot tones must always be transmitted. Thus, the I/Q samples of the RF passband must be transported at the constant rate at all times. Moreover, the transmission requirements over the optical fiber increase linearly with the number of remote nodes. Therefore, numerous techniques, such as [9]–[12], have been proposed to dynamically compress the RF I/Q samples for effective transmissions over the optical fiber. However, the compression techniques are lossy because of the RF signal quantization, reducing the sensitivity of the receiver in the upstream. Nevertheless, the data rate requirements between BBU and RRUs typically lead to dedicated costly deployments of optical fiber connections and static allocations of transmission resources.
C. Solution: Unify Cable DOCSIS and CRAN LTE Networks

We address the LTE CRAN fronthaul challenge by exploiting the fiber capacity between the cable headend and the cable remote nodes in the installed hybrid fiber-broadcast coax networks. In particular, we propose a novel Remote-FFT (R-FFT) architecture, see Section [III], that co-locates the LTE RRUs with the cable remote nodes, while the LTE BBU are co-located with the cable headends (or outsourced to a cloud resource). The R-FFT node includes the IFFT/FFT module as well as the conventional RRU processing modules towards the RF transmission. Both cable DOCSIS and wireless LTE share the IFFT/FFT module in the R-FFT node. Thus, both DOCSIS and LTE frequency domain I/Q samples are transmitted over the fiber link between cable headend and remote nodes. In order to further reduce the fronthaul bitrates in the downstream direction, we propose to cache repetitive QAM symbols in the remote nodes in Section [IV]. Our evaluations in Section [V] present the bitrate reductions achieved by the QAM symbol caching in the remote node. We also evaluate the fronthaul bitrates required for the unified DOCSIS and LTE operation and the delay implications of the transition of an existing R-PHY cable remote node to an R-FFT remote node.

D. Related Work

Our study relates to modular access network strategies that have so far mainly been studied in isolation for broadcast cable networks and for wireless cellular networks as well as to caching strategies in access networks. Broadcast cable access networks have been extensively studied for providing wired broadband Internet access to residential users [13]–[22]. Recent studies have examined the impact of the distance between the remote node and cable headend on the medium access control (MAC) performance of the R-PHY modular architecture (which conducts all physical layer processing in the remote node and the MAC in the headend) and the R-MACPHY architecture (which conducts all physical layer processing plus the MAC in the remote node) [2]. The studies found that the modular R-PHY architecture gives good throughput-delay performance for short headend-to-remote node distances up to around 100 km. We consider the R-PHY modular architecture as starting point for our R-FFT node development and move some of the physical layer processing to the headend.

A very extensive set of literature has examined modular wireless cellular access network architectures. Extensive CRAN studies have demonstrated the advantages and challenges of conducting the LTE physical layer baseband processing in the BBU [23]–[29]. The high transmission bitrate requirements for transporting the time-domain I/Q samples produced by the baseband processing at the BBU to the RRU have spurred research on fronthaul transport strategies, see e.g., [30]–[32], and alternative function splits between BBU and RRU [8], [33]–[42]. Complementary to this extensive research, which has examined cellular wireless access in an isolated manner and typically considered abstract models for the fronthaul between BBU and RRU, we propose to unify cable and wireless access networks. More specifically, we pursue a specific function split at the IFFT/FFT module that (i) reduces the fronthaul transmission bitrate requirements compared to the conventional CRAN time domain I/Q sample transmission, (ii) shares the IFFT/FFT module in the remote node among DOCSIS and LTE, and (iii) shares the fiber infrastructure between cable headends and remote nodes for DOCSIS transport and LTE cellular wireless fronthaul.

Mechanisms to reduce the carbon footprint of access networks have recently been investigated in wireless networks [43]–[49] as well as cable networks [50]–[52]. This line of energy saving research has included studies on the caching of application layer content items in or near the RRUs, e.g., [53]–[55]. In contrast to the caching of application layer content items, we examine the caching of repetitive PHY layer QAM I/Q symbols at the RRU.

Only few studies have explored supporting wireless services with cable networks. In particular, the channel propagation characteristics of indoor femto cells that are supported over cable links have been modeled in [50], [57]. The economic benefits of general infrastructure sharing by residential wired and cellular wireless networks have been explored in [58]. The economic benefits of integrating LTE and DOCSIS have been discussed in [59], [60], while general fiber cost sharing has been studied in [61]. We note for completeness that the application layer performance of LTE wireless access has been compared with wired DOCSIS access in [62]; however, the study [62] did not seek to unify LTE and DOCSIS networks. In contrast to the existing studies, we seek to efficiently unify DOCSIS cable and LTE wireless access networks through the sharing of the cable headend-to-remote node fiber infrastructure and the sharing of the IFFT/FFT module in the remote node. At the same time, the PHY layer function split at the IFFT/FFT module reduces the high fronthaul bitrate requirements of the conventional CRAN with PHY layer baseband processing at the BBU, while still allowing for extensive softwarized physical layer processing at the BBU or headend.

II. BACKGROUND ON FUNCTION Splits IN LTE AND CABLE NETWORKS

A. Wireless Downstream vs. Upstream Transmissions

1) Upstream: In the upstream direction, the RRU receives the RF signal transmitted from the users. This analog passband signal is down-converted to the baseband and digitized for the transmission to the BBU for baseband processing. Unlike the cable link in traditional cellular networks and antenna infrastructures, the CRAN connects the BBU and RRU with a digital optical fiber. The cable link in traditional infrastructures added significant attenuation to the upstream signal, which is especially harmful due to the low signal levels received from the user devices. In contrast, the digital fiber does not contribute towards the attenuation loss as it carries the signal in digital form. Extreme care is needed at the RRUs for digitizing the uplink signal from the users as any additional loss should be avoided due to the low level of the uplink RF signal at the RRU. For example, if the cable link accounts for 2 dB of loss and the noise floor is –120 dB, then the received
Fig. 1. The Cloud RAN (CRAN) implements the RAN functions on the cloud-based Baseband Unit (BBU), where baseband signals are processed and digital information is transmitted to a remote radio node, the Remote Radio Unit (RRU). The RRU generates the passband signal for the physical transmission of the wireless RF signal over the antenna. The RAN protocol stack towards the UE, especially at the MAC and PHY layers can be flexibly split between BBU and RRU to relax the data rate and latency constraints on the optical fiber.

signal at the RRU connected to a BBU over a cable link must be ≥ −118 dB for successful detection. The received signal can be as low as −120 dB if the RRU is connected to a BBU through a digital fronthaul link, thus the digital fronthaul link increases the dynamic range of the system by 2 dB. Although the Single Carrier Orthogonal Frequency Multiplexing (SC-OFDM) uplink modulation format is used in typical deployments, the technology is advancing towards uplink OFDM systems, especially for MIMO applications [63], [64]. Therefore, we focus on symmetrical OFDM systems in both the upstream and downstream directions in this article. The processing of the upstream signals for the detection and extraction of information from the RF uplink signals can be centrally executed in the cloud based BBU on generic hardware, such as the general purpose processors.

2) Downstream: In the downstream direction, the BBU sends the information to the RRUs for the generation of the passband signal to transmit over the physical antennas. The RRUs can easily set the transmit power level gain states for RF signals. In contrast to the upstream direction, there is no significant difference in terms of power level of the signal generation or the dynamic range of the systems between cable and digital fronthaul links. Similar to the centralized processing of the upstream in the cloud based BBU, the information is centrally processed on generic hardware, such as general purpose processors, to generate the baseband downstream signals.

B. Function Split in LTE

Figure 1 shows the conventional CRAN deployment in comparison to traditional cellular deployments. A radio base station protocol stack, e.g., the LTE protocol stack at the eNB towards the UE, can be functionally split and implemented flexibly over radio remote node and BBU. The conventional CRAN transports the baseband time domain I/Q samples over optical fiber to the RRUs. The number of supported RRUs is limited by the amount of traffic over the optical fiber. Let $R_o$ [bit/s] denote the capacity of the fronthaul optical connectivity and $R_u$ denote the data rate required by RRU $u$. Then, the maximum number of RRUs $N$ that can be supported over the fronthaul link is the largest $N$ such that $\sum_{u=1}^{N} R_u \leq R_o$. In present CRAN deployments, the fronthaul link resources are typically statically allocated. Therefore in symmetrical and homogeneous deployments with equal RRU data rates, i.e., $R_1 = R_2 = \cdots = R_N = R_o$, the fronthaul link can support at most $N = R_o / R_u$ RRUs. The main bottleneck for CRAN deployments is the delay and capacity of the fronthaul link.

To understand the RRU fronthaul requirements, we estimate the data rates required by the conventional CRAN, where the baseband I/Q samples are transported from the BBU to the RRU, which is the most common LTE deployment scenario. General data rate comparisons of various function split approaches in the LTE protocol stack have been conducted in [8], [35], [36]. Complementary to these existing evaluations, we closely examine the data rate requirements based on the implementation specifics of the protocol stack. That is, we track the information flows across multiple LTE protocol stack layers and identify the key characteristics that govern the fronthaul link requirements. Based on the computationally intensive FFT operation, the data flow between BBU and RRU can be categorized into two types: 1) time domain samples, and 2) frequency domain samples. Table I summarizes the main parameters for the evaluation of the fronthaul optical link requirements connecting RRU and BBU in the LTE context. We consider in the following evaluations an LTE system with 20 MHz system bandwidth, which has a $f_s = 30.72$ MHz sampling frequency and can support an LTE transmission bit rate of $R_L = 70$ Mbps.

1) Time Domain I/Q Sample Forwarding: The time domain I/Q samples represent the RF signal in the digital form either in the passband or the baseband. The digital representation of the passband signal requires a very high data rate that depends on the physical transmission frequency band. Thus, passband time domain I/Q sample forwarding is usually non-economical. For example, in an LTE system, the passband signal is sampled at
twice the carrier frequency $f_c$, with each sample requiring $K = 10$ bits for digital representation. Although the LTE deployment norm is to use $W = 2$ or more eNB antennas, for clarity and simplified comparison of multiple function split mechanisms, we set the number of antennas to $W = 1$. The resulting passband I/Q data rate over the fronthaul link is

$$R^P = N \times W \times 2 \times f_s \times K$$
$$= 1 \times 1 \times 2 \times 2 \cdot 10^9 \text{ Hz} \times 10 \text{ bit} = 40 \text{ Gbps}.$$  \hspace{1cm} (1)

The baseband signal for an OFDM symbol in the time-domain consists of a number of time samples equal to the number of OFDM subcarriers because of the symmetric input and output samples of the IFFT/FFT structure. The cyclic prefix is added to the OFDM signal to avoid inter-symbol interference. In order to reduce the constraints on the RF signal generation at the RRU, the baseband signal is sampled at a frequency of $f_s = 30.72 \text{ MHz}$, with each sample requiring $K = 10$ bits for digital representation, and an oversampling factor of 2. The resulting baseband I/Q data rate is

$$R^B = N \times W \times 2 \times f_s \times 2 \cdot K$$
$$= 1 \times 1 \times 2 \cdot 30.72 \cdot 10^6 \text{ Hz} \times 2 \cdot 10\text{bit}$$
$$= 1.23 \text{ Gbps}.$$  \hspace{1cm} (2)

Although the baseband I/Q data rate $R^B$ is significantly lower than the passband I/Q rate $R^P$, the baseband I/Q data rate $R^B$ scales linearly with the number of antennas and the bandwidth. Thus, for large numbers of antennas $W$ and wide aggregated bandwidth, the baseband data rate $R^B$ can be very high.

2) Frequency Domain I/Q Sample Forwarding: In a 20 MHz LTE system, the duration $T_s$ of one OFDM symbol, including the cyclic prefix, is 71.4 $\mu$s, which corresponds to 2192 time samples for each $T_s$. The useful symbol duration in the OFDM symbol duration $T_s$ is 66.7 $\mu$s or 2048 samples, out of which the cyclic prefix duration is 4.7 $\mu$s or 144 samples. Thus, each set of 2048 samples in an OFDM symbol (excluding the cyclic prefix) corresponds to $B_{sub} = 2048$ subcarriers when transformed by the FFT. However, only 1200 of these subcarriers are used for signal transmission, which corresponds to 100 resource blocks (RBs) of 12 subcarriers; the remaining subcarriers are zero-padded and serve as guard carriers. This leads to $(2048 - 1200)/2048 = 0.41 = 41\%$ of unused guard carriers. Each OFDM subcarrier is modulated by a complex value mapped from a QAM alphabet. The LTE QAM alphabet size is based on QAM bits, such as 64 QAM and 256 QAM. The resulting frequency domain subcarrier data rate $R^F$ is proportional to the number of subcarriers $B_{sub}$. That is, a vector of complex valued QAM alphabet symbols of size $B_{sub}$ needs to be sent once every OFDM symbol duration $T_s$, resulting in the data rate

$$R^F = N \times W \times B_{sub} \times T_s^{-1} \times 2 \cdot K$$
$$= 1 \times 1 \times 1200 \times (66.7 \cdot 10^{-6} \text{ s})^{-1} \times 2 \cdot 10 \text{ bit}$$
$$= 360 \text{ Mbps},$$  \hspace{1cm} (3)

which is a 70\% reduction compared to the time domain baseband I/Q data rate $R^B$.  

C. Function Split in Cable Distributed Converged Cable Access Platform (DCCAP) Architectures

The traditional HFC network CCAP architecture implements the CMTS at the headend and transports the analog optical signal to a remote node over the optical fiber. The remote node then converts the optical analog signal to an electrical RF signal for transmission over the broadcast cable segment. However, the analog signal is prone to attenuation in both the optical fiber segment as well as the cable segment. If the remote node is deployed far from the headend, then the attenuation of the optical signal will dominate; conversely, if the remote node is deployed far from the CMs (users), then the attenuation of the RF signal in the cable will dominate.

The Modular Headend Architecture (MHA) overcomes the analog optical signal attenuation in the CCAP architecture by splitting the CMTS functions, i.e., by modularizing the implementation of the CMTS functions. The implementation of modular CMTS functions in a distributed manner across multiple nodes results in distributed DCCAP architectures. As shown in Fig. 2 the DCCAP architecture defines a remote node that is connected to the headend through a digital Ethernet fiber. The digital connection between the remote node and the headend eliminates the optical signal attenuation, allowing the remote node to be deployed deep into the HFC network. The remote node deployment deep into the HFC network reduces the cable segment length, which in turn reduces the analog RF signal attenuation and improves the overall Signal to Noise Ratio (SNR) at the CM. The network connecting the remote node to the headend is referred to as Converged Interconnect Network (CIN). The MHA version 2 (MHAv2) architecture defines two DCCAP architectures: Remote-PHY and Remote-MACPHY.

In the R-PHY architecture, the DOCSIS PHY functions in the CMTS protocol stack are implemented at the remote node, which is referred to as Remote-PHY Device (RPD). All higher layers in the CMTS protocol stack, including the MAC as well as the upstream scheduler, are implemented at the headend. A virtual-MAC (vMAC) entity can virtualize the DOCSIS MAC on generic hardware, which can be flexibly deployed at either the headend or in a cloud/remote data center. The RPD is simple to implement and hence has low cost.
III. PROPOSED UNIFIED ACCESS NETWORK ARCHITECTURE FOR LTE AND CABLE NETWORKS

The digital optical remote node in the DCCAP architecture is deployed close to the CMs (users). The close proximity of the remote node to the residential subscribers can be exploited for establishing wireless LTE connectivity through deploying an LTE eNB RRU at the remote node site, as illustrated in Fig. 3. With the establishment of LTE connectivity by the cable system operator, users can be wirelessly connected to the cable system core network for Internet connectivity, increasing the cable system service capabilities. The LTE eNB RRU at the remote node reuses the existing HFC infrastructure, enabling cable system operators to provide additional LTE services with low costs.

A. PHY Function Split at IFFT/FFT

LTE and DOCSIS 3.1 share similar PHY transceiver characteristics for the OFDM implementation. We propose to exploit these PHY transceiver similarities to simultaneously support LTE and DOCSIS over the HFC network. The general overview of the physical layer for LTE and DOCSIS is shown in Fig. 4. In the downstream direction, the data from the MAC layer is processed to form PHY frames and mapped to OFDM resource locations, which are then converted to frequency domain QAM I/Q symbols (see Sec. II-B2) based on the modulation and coding schemes. The QAM I/Q symbols are then IFFT transformed to obtain the complex time domain samples. These time domain samples (see Sec. II-B1) are then converted to an analog RF signal for transmission. In a conventional CRAN, the remote node conducts the DAC/ADC and the onward processing steps towards the RF transmission; the conventional CRAN remote node is therefore also referred to as R-DAC/ADC node.

The I/Q information undergoes different DOCSIS and LTE protocol specific processing before (to the left of) the IFFT/FFT module as well as after (to the right of) the IFFT/FFT module. However, the same IFFT/FFT module can be used for the I/Q processing of both DOCSIS and LTE, as illustrated in Fig. 4. Thus, we can separate (split) the functions at the IFFT/FFT module. That is, the IFFT/FFT and the processing steps between IFFT/FFT and RF are implemented at the remote node; whereas the steps towards the MAC layer are implemented at the headend. This function split at the IFFT/FFT node can simultaneously support LTE and DOCSIS over the HFC network.

B. Common IFFT/FFT for LTE and DOCSIS

The LTE and DOCSIS protocols both employ OFDM as the physical layer modulation technique. The OFDM modulation relies on FFT computations [67]. The fact that both LTE and DOCSIS require the same IFFT/FFT computations for each OFDM modulation and demodulation can be exploited by using the same computing infrastructure. The implementation of parallel FFT computations, i.e., FFT computations for multiple protocols, on a single computing infrastructure yields several advantages. Utilizing the same computing infrastructure for the LTE and DOCSIS FFT computations reduces the power consumption and design space [68]–[71].

Thus, the main motivation for computing the FFT at the remote node is to exploit a common remote node platform while flexibly realizing the different OFDM transmission formats for heterogeneous OFDM based protocols at the headend. Figure 5 illustrates the R-FFT remote node architecture for LTE and DOCSIS. By reusing the IFFT/FFT computing structures used for multiple OFDM based technologies, e.g., for LTE and DOCSIS, the actual IFFT compute times \( \tau_L \) and \( \tau_C \) for cable can span from a few microseconds to several tens of microseconds. Consequently, there are typically long idle time periods in the FFT module inbetween the FFT computations. Thus, we can interleave the I/Q input in time such that same IFFT/FFT module can be used for multiple OFDM based technologies, e.g., for LTE and DOCSIS. By reusing the IFFT/FFT computing structures we can reduce the complexity of the hardware, be more power efficient, and reduce the cost of the remote node.
DOCSIS OFDM
Computational
Symbol
traffic. We believe this is an important characteristic of the FFT rate required over the fiber is directly proportional to the user capacity. The advantages of the proposed FFT implementation modifications if the remote node has enough spare computing FFT/IFFT with relatively modest modifications or without so that existing DAC/ADC remote nodes can take over the node in existing conventional CRANs requires some digital circuitry, such as a CPU, for the DAC and ADC control. The software implementations at the headend can be easily upgraded while retaining the R-FFT blocks common platform hardware, such as elementary DAC/ADC technology upgrades. That is, the R-FFT node has minimal impact on technology advancements because the R-FFT blocks combining multiple R-FFT nodes, each supporting DOCSIS and LTE services, as illustrated in Fig. 3. In addition, the proposed mechanism enables the implementation of the complex PHY layer signal processing at the headend. Examples of the signal processing operations include channel estimation, equalization, and signal recovery, which can be implemented with general-purpose hardware and software. Moreover, the processing of digital bits, such as for low density parity check forward error correction, can be implemented at the headend. Thus, the proposed R-FFT approach reduces the cost of the remote nodes and increases the flexibility of changing the operational technologies. The software implementations at the headend can be easily upgraded while retaining the R-FFT node hardware since the node hardware consists only of common platform hardware, such as elementary DAC/ADC and FFT/IFFT components. Thus, the proposed approach eases technology upgrades. That is, the R-FFT node has minimal impact on technology advancements because the R-FFT blocks are elementary or independent of most technology advances.

C. Proposed Shared Remote-FFT (R-FFT) Node

In the uplink direction, the proposed R-FFT remote node converts the incoming DOCSIS RF signal from the CMs to an encapsulated data bits format that can be transported over the digital fiber link for additional processing and onward forwarding at the headend. In a similar way, in the downstream direction, RF signals are generated from the incoming formatted data bits and sent out on the RF cable link to the CMs. For LTE, an eNB can use a wide range of licensed spectrum with a single largest carrier component of 20 MHz; the bandwidth can be further extended by carrier aggregation techniques to obtain larger effective bandwidths. The R-FFT node effectively converts the upstream LTE RF signal from the wireless users to a digital signal for transport over the digital fiber link to the BBU/CRAN. In the downstream direction, the R-FFT node converts the digital information to an LTE RF signal for wireless transmission to the users.

We address the high fiber data rate in conventional CRANs through a balanced split among the functions within the PHY layer while keeping the remote node simple. The R-DAC/ADC node in existing conventional CRANs requires some digital circuitry, such as a CPU, for the DAC and ADC control. The FFT/IFFT can be implemented very efficiently [72], [73] so that existing DAC/ADC remote nodes can take over the FFT/IFFT with relatively modest modifications or without modifications if the remote node has enough spare computing capacity. The advantages of the proposed FFT implementation at the remote node include:

i) flexible deployment support for LTE and DOCSIS

ii) requires lower data rate \( R^F \), see Eqn. (5), to transport frequency domain I/Q samples as compared to time-domain I/Q samples, which require the higher \( R^B \) rate, see Eqn. (4).

iii) data tones carrying no information are zero valued in the frequency I/Q samples, effectively lowering the date-rate over the fiber channel for both LTE and DOCSIS, thus enabling statistical multiplexing, and

iv) possible caching of repetitive frequency QAM I/Q samples, such as Reference Signals (RS) and pilot tones.

We emphasize that in the proposed R-FFT system, the data rate required over the fiber is directly proportional to the user traffic. We believe this is an important characteristic of the FFT function split whereby we can achieve multiplexing gains by combining multiple R-FFT nodes, each supporting DOCSIS and LTE services, as illustrated in Fig. 3. In addition, the proposed mechanism enables the implementation of the complex PHY layer signal processing at the headend. Examples of the signal processing operations include channel estimation, equalization, and signal recovery, which can be implemented with general-purpose hardware and software. Moreover, the processing of digital bits, such as for low density parity check forward error correction, can be implemented at the headend. Thus, the proposed R-FFT approach reduces the cost of the remote nodes and increases the flexibility of changing the operational technologies. The software implementations at the headend can be easily upgraded while retaining the R-FFT node hardware since the node hardware consists only of common platform hardware, such as elementary DAC/ADC and FFT/IFFT components. Thus, the proposed approach eases technology upgrades. That is, the R-FFT node has minimal impact on technology advancements because the R-FFT blocks are elementary or independent of most technology advances.

D. Interleaving Timing of FFT Computations

In this section we briefly outline the scheduling of the interleaving of IFFT/FFT computations on a single computing resource. Figure 6 illustrates the basic timing diagram to schedule the FFT computations on the computing resource for the case where (i) the LTE OFDM symbol duration \( T_L \) is longer than the DOCSIS OFDM symbol duration \( T_C \) and...
the DOCSIS FFT computation takes longer than the LTE FFT computation, i.e., $\tau_C > \tau_L$ (due to the larger DOCSIS FFT size compared to the LTE FFT). We note that the computation times $\tau_C$ and $\tau_L$ can include a guard time to account for the loading and reading. In Fig.6 $d$ and $l$ denote the indices for the independent DOCSIS and LTE periodic symbols, which start to arrive simultaneously at the left edge of the drawn scenario.

The scheduling of multiple periodic tasks on a shared resource has been extensively studied [74]–[77]. With pre-emptive scheduling, which may interrupt an ongoing computation task, tasks are schedulable if the sum of the individual ratios of task computation time to task period duration is less than or equal to one [78], i.e., in our context if $\tau_C/T_C + \tau_L/T_L \leq 1$. Non-preemptive scheduling requires an additional condition [79] Theorem 4.1, 2], which in our example context corresponds to $T_C \geq \tau_C$ in conjunction with $T_L \geq \tau_L + \tau_C$. Non-preemptive scheduling appears better suited for the R-FFT node so as to avoid extra load and read times. Non-preemptive earliest deadline first scheduling (EDF) can schedule the tasks that satisfy these preceding conditions. In particular, we set the deadline for completing the computation of a symbol arriving at time $dT_C$, resp., $lT_L$, to be completed by the arrival of the subsequent symbol at time $(d+1)T_C$, resp., $(l+1)T_L$. The non-preemptive EDF scheduler selects always the tasks with the earliest completion deadline and breaks ties arbitrarily. We note that other schedulers could be employed for the relatively simple scheduling of only two interleaved tasks, e.g., an elementary cyclic schedule [80], [81]. Additionally, scheduling techniques that consider energy-efficiency, e.g., [82]–[85], may be considered. The detailed examination of different scheduling approaches for the proposed R-FFT node is beyond the scope of this study and is and interesting direction for future research.

The sharing of the FFT/IFFT module by multiple technologies can be extended to include both upstream and downstream directions, i.e., the module can be shared by downstream DOCSIS and LTE as well as upstream DOCSIS and LTE, as the computations for the different directions are performed independently of each other, even for wireless full-duplex communications. Also, the FFT computation duration $\tau$ can represent the aggregate of multiple OFDM symbol instances. For example, in the case of carrier aggregation in LTE (or channel bonding in DOCSIS), there would be an OFDM symbol for each of the $\alpha$ carrier component, resulting in $\tau_L = \tau_1 + \tau_2 + \cdots + \tau_\alpha$. Similarly, computations resulting from multiple LTE eNBs at a single node can be aggregated and abstracted to a single $\tau_L$. The proposed approach can be readily extended to more than two technologies that conduct their FFT computations by sharing the remote node.

E. Transport Protocols

A protocol is required to coordinate the I/Q data transmissions over the transport network. The strict latency requirements for the CRAN and DCCAP architectures limit the choice of generic protocols over Ethernet. Some of the fronthaul protocols that could be employed for the transport of information between headend/cloud and remote node are:

a) Radio over Fiber (RoF): Radio over fiber (RoF) transports the radio frequency signal over an optical fiber link by converting the electrically modulated signal to an optical signal. RoF signals are not converted in frequency but superimposed onto optical signals to achieve the benefits of optical transmissions, such as reduced sensitivity to noise and interference. However, the analog optical signal transmission in RoF suffers from more attenuation as compared to the transmission of digital data over the fiber.

b) Common Public Radio Interface (CPRI): The Common Public Radio Interface (CPRI) [86]–[89] defines a protocol to transport the digitized I/Q data through encapsulated CPRI frames. As compared to RoF, CPRI provides a more reliable end-to-end connection between headend/cloud and the remote node. Dedicated TDM channels can be established to support multiple logical connections supporting different air interfaces. The disadvantages of the CPRI are the strict timing and synchronization requirements as well as support for only the fixed function split to transport time domain I/Q samples. The transport of the frequency domain I/Q samples in our approach would require an extension or adaptation of the existing CPRI, or the definition of a similar new protocol. We note that the development of a new CPRI protocol, the eCPRI protocol, is currently under way; possibly the transport of frequency domain I/Q samples could be integrated into the ongoing eCPRI development.

c) Open Base Station Architecture Initiative (OBSAI): The Open Base Station Architecture Initiative (OBSAI) [90] is similar to CPRI in that the digitized time domain I/Q samples are transported over a fronthaul interface. The OBSAI would need to be adapted for the frequency I/Q transport. In contrast to CPRI, the OBSAI interface is an IP based connection. The IP logical connection can be implemented.

---

**Algorithm 1: Caching and FFT Computation Procedure**

1. **CRAN/Headend**
   (a) Identify cachable I/Q samples.
   (b) Create caching rules.
   (c) Signal the rules and data for caching.
   **if** Cached I/Q samples require updating **then**
   | Signal remote node for cache renew or flush.
   **end**

2. **Remote Node**
   **foreach** OFDM Symbol in $T_C$ and $T_L$ **do**
   | **if** Caching is enabled **then**
   | | Read cache and I/Q mapping;
   | | Add cache-read I/Q to received I/Q;
   | **end**
   **if** FFT module is free **then**
   | Schedule I/Q for FFT;
   **else**
   | Schedule at completion of current execution;
over any generic Ethernet link, providing flexible connectivity between headend/cloud and remote node.

d) External PHY Interfaces: The Downstream External PHY Interface (DEPI) [91] and Upstream External PHY Interface (UEPI) [92] enable the common transport mechanisms between an RPD and the CCAP core. DEPI and UEPI are based on the Layer 2 Tunneling Protocol version 3 (L2TPv3). The L2TPv3 transparently transports the Layer 2 protocols over a Layer 3 network by creating pseudowires (logical connections).

IV. PROPOSED REMOTE CACHING OF QAM SYMBOLS

In order to further reduce the bandwidth in addition to the function split process, several techniques, such as I/Q compression [9], [10], [12], [93], can be employed. In contrast, we propose OFDM resource element (time and frequency slot) allocation based remote caching. If some part of the information is regularly and repeatedly sent over the interface, a higher (orchestration, in case of SDN) level of the signaling process can coordinate caching mechanisms. For example, there is no need to transmit the downstream I/Q samples of the pilot tones as they remain constant in DOCSIS. Figure [7] gives an overview of repetitive QAM symbols in LTE and DOCSIS. The stationary resource elements across the time domain, such as the system information block (SIB), typically change over long time scales on the order of hours and days. The cached elements can be refreshed or re-cached through cache management and signalling protocols, see Sec. [IV-D].

In contrast to the downstream, upstream information must be entirely transported to the headend to process all the signal components received by the R-FFT receiver.

In the evaluations of the overhead due to repetitive QAM symbols that can be saved through caching in this section, we evaluate the ratios (percentages) of number of repetitive I/Q symbols to total number of I/Q symbols. Subsequently, in the evaluations in Section [V] we evaluate the corresponding reductions of the fronthaul transmission bitrate.

A. LTE Networks

1) Reference Signal (RS) Tones Caching: RS tones are pilot subcarriers that are embedded throughout the operational wireless system bandwidth for channel estimation so as to equalize the impairments of the received wireless signal. Disturbances to the wireless signal are more prominent compared to signal propagation in the wired channel. Therefore RS tones are added in close proximity with each other in LTE to accurately estimate the channel characteristics, such as coherence-time and coherence-bandwidth.

For a single antenna, the RS tones are typically spaced six subcarriers apart in frequency such that eight RS tones exist in a single subframe (which consists of 14 OFDM symbols in the time dimension) and a single Resource Block (RB) (which consists of 12 LTE subcarriers in the frequency dimension). Thus, with a full RB allocation, i.e., for a relative payload data traffic load (intensity) of $\rho_L = 1$, approximately $8/(12 \times 14) = 4.7\%$ of I/Q transmissions over the digital fiber can be saved by caching RS tones at the remote node, regardless of the system bandwidth. In general, for a traffic intensity $\rho_L$, $\rho_L \leq 1$, the overhead due to RS tones in the LTE resource grid is

$$ RS\ Overhead = \frac{8}{\rho_L \times 12 \times 14} = 4.7\% \ (4). $$

When the user data traffic is very low, e.g., $\rho_L = 0.1$, the overhead is almost $47\%$, and similarly when $\rho_L = 0.01$ the overhead becomes $470\%$.

2) PHY Broadcast Channel (PBCH) Caching: The PHY Broadcast Channel (PBCH) carries the Master Information Block (MIB) which is broadcast continuously by the eNB regardless of the user connectivity. The MIB includes basic information about the LTE system, such as the system bandwidth and control information specific to the LTE channel. The PBCH/MIB always uses the six central RBs (i.e., 72 subcarriers) for the duration of 4 OFDM symbols to broadcast the MIB data. The PBCH space in the resource grid is inclusive of the RS tones used in the calculation of Eq. [4]; therefore, the RS tones need to be subtracted when calculating the MIB overhead. The PBCH/MIB occurs once every 40 ms and there exist four redundant MIB versions, which are broadcast with an offset of 10 ms. Thus, an PBCH/MIB occurs effectively once in every 10 ms (radio frame). The PBCH/MIB overhead for an entire 20 MHz system LTE system with 1200 subcarriers, 14 OFDM symbols, and 10 subframes is thus

$$ PBCH\ Overhead = \frac{6 \times 12 \times 4 - (8 \times 6)}{\rho_L \times 1200 \times 14 \times 10} = 0.142 \% \ (5). $$

Alternatively, for a 1.4 MHz system with 72 subcarriers (the lowest currently standardized LTE bandwidth, which would be used for IoT type of applications), the overhead increases to

$$ PBCH\ Overhead_{1.4\text{MHz}} = \frac{6 \times 12 \times 4 - (8 \times 6)}{\rho_L \times 72 \times 14 \times 10} = 2.3\% \ (6). $$

Future IoT related standardization efforts may lower the LTE rates below 1.4 MHz to better suit the needs of low-rate IoT applications, leading to further increases of the PBCH overhead.
(SSS), which are broadcast continuously by the eNB, regardless of the user connectivity. The PSS and SSS help with the cell synchronization of wireless users by identifying the physical cell ID and the frame boundaries of the LTE resource grid. The cell ID and frame boundary information are static for a given cell deployment. Thus, caching the PSS and SSS does not degrade the functioning of the LTE cell. The PSS/SSS occurs every 5 ms (twice per radio frame) and uses six central RBs over two OFDM symbols. Similar to Eqs. (5) and (6), the overhead due to the PSS/SSS in 20 MHz and 1.4 MHz systems are

\[
\begin{align*}
\text{SCH Overhead} & = \frac{6 \times 12 \times 4}{\rho_L \times 1200 \times 14 \times 10} = 0.171\%,
\text{SCH Overhead}_{1.4\text{MHz}} & = \frac{6 \times 12 \times 4}{\rho_L \times 72 \times 14 \times 10} = 2.8\%. \quad (7)
\end{align*}
\]

4) System Information Block (SIB) Caching: In a similar way, the caching mechanism can be extended to the System Information Blocks (SIBs) broadcast messages of the LTE PHY Downlink Shared Channel (PDSCH). There are 13 different SIB types, ranging from SIB1 to SIB13. SIB1 and SIB2 are mandatory broadcast messages, while the transmission of other SIBs depends on the relations between the serving and neighbor cell configurations. In a typical deployment, SIB3 to SIB9 are statically configured and can be combined in a single message block for the resource block allocation. Typical RB allocation configurations schedule the SIB1 and SIB2 transmissions over 8 RBs across 14 OFDM symbols in time (i.e., 1 subframe), with an effective periodicity (with redundant version transmissions) of 2 radio frames (i.e., 20 ms). The overhead from the SIB1 and SIB2 transmissions while subtracting the corresponding RS tones overhead of \(8 \times 8\), i.e., 8 tones per RB for 8 RBs, is

\[
\begin{align*}
\text{SIB Overhead} & = \frac{8 \times 12 \times 14 - (8 \times 8)}{\rho_L \times 1200 \times 14 \times 20} = 0.381\%,
\text{SIB Overhead}_{1.4\text{MHz}} & = \frac{8 \times 12 \times 14 - (8 \times 8)}{\rho_L \times 72 \times 14 \times 20} = 6.3\%. \quad (8)
\end{align*}
\]

Caching of higher order SIBs, i.e., from SIB3 to SIB9, can achieve further savings; however, the resource allocation and periodicity can vary widely and it is therefore difficult to accurately estimate the overhead.

B. Cable Networks

In DOCSIS 3.1, downstream pilot subcarriers are modulated by the CMs with a predefined modulation pattern which is known to all CMs to allow for interoperability. Two types of pilot patterns are defined in DOCSIS 3.1 for OFDM time frequency grid allocations: i) continuous, and ii) scattered. In the continuous pilot pattern, pilot tones with a predefined modulation occur at fixed frequencies in every symbol across time. In the scattered pilot pattern, the pilot tones are swept to occur at each frequency locations, but at different symbols across time. The scattered pilot pattern has a periodicity of 128 OFDM symbols along the time dimension such that the pattern repeats in the next cycle. Scattered pilots assist in the channel estimation. Typical deployments have 192 MHz operational bandwidth [94], corresponding to an FFT size of 8K with 25 kHz subcarrier spacing. A 192 MHz system has 7680 subcarriers, including 80 guard band subcarriers, 88 continuous pilot subcarriers, and 60 scattered pilot subcarriers. Therefore, the overhead due to guard band and pilot subcarriers, which can be cached at the remote node, is

\[
\text{Cable Over.} = \frac{80 + 88 + 60}{\rho_C \times 7680} = 2.9\% \quad (9)
\]

C. Memory Requirements for Caching

The caching of frequency domain OFDM I/Q symbols requires caching memory at the remote node. Each I/Q symbol that needs to be cached is a complex number with real and imaginary part. For the purpose of evaluation, we consider a 10 bit representation for each part of the complex number, resulting in 20 bit memory requirement for each frequency domain QAM symbol. The caching of LTE RS tones saves 4.7\% of the fronthaul transmissions as shows in Eqn. (4). Within each RB, 8 RS tones exist for every 12 subcarriers. A typical 20 MHz system with 1200 subcarriers, has thus \(8 \times 100\) RS tones. The total memory required to cache the RS tones QAM symbol data is

\[
\text{RS Tones Mem.} = (8 \times 100) \times 2 \times 10 = 16000 \text{ bits}. \quad (10)
\]

Similarly, caching of the PBCH, SCH, and SIB data requires

\[
\begin{align*}
\text{PBCH Mem.} & = (6 \times 12 \times 4 - (8 \times 6)) \times 2 \times 10 \text{ bits} = 4800 \text{ bits}, \quad (11)
\text{SCH Mem.} & = (6 \times 12 \times 4) \times 2 \times 10 = 5760 \text{ bits}, \quad (12)
\text{SIB Mem.} & = (8 \times 12 \times 14 - (8 \times 8)) \times 2 \times 10 \text{ bits} = 5760 \text{ bits}. \quad (13)
\end{align*}
\]

For DOCSIS, the cache memory requirement for the continuous and scattered pilots is

\[
\text{Pilot Tones Mem.} = (80 + 88 + 60) \times 2 \times 10 \text{ bits} = 4560 \text{ bits}. \quad (14)
\]

Thus, based on Eqs. (4)–(9), total savings of approx. 7\% to 18\% can be achieved in the fronthaul transmissions when the full resource allocation \((\rho = 1)\) over the entire bandwidth is considered in both LTE and DOCSIS. For lower allocations, i.e., when there is less user data \((\rho < 1)\), the caching can achieve much more pronounced fronthaul transmission bitrate reductions. In the extreme case, when there is no user data, all the cell specific broadcast data information can be cached at the remote node and the fronthaul transmissions can be completely suspended. The total memory for the caching required at the remote node based on Eqs. (10)–(14) is less than 37 Kbits. The implementation of less than 5 KBytes cache memory at the remote node appears to be relatively simple and no significant burden for the existing remote nodes. Therefore, we believe that fronthaul transmission bitrate reductions of more than 7\% with almost negligible implementation burden is a significant benefit.

D. Signalling and Cache Management Protocol

The signalling and cache management protocol involves: i) transporting the caching information to the remote nodes, ii)
traffic rate is \( \rho \), which can be evaluated as the fronthaul transmission bitrate required for the payload data. Each complex and real part of a QAM I/Q symbol, \( R \), modulate the fronthaul transmission bitrate \( R \) found in Eqn. (9). The actual payload traffic rates are based on continuous and scattered pilots, approximating the 2.9\% savings for the LTE fronthaul I/Q requirements for the same link capacity compared to 6.54\% savings for the DOCSIS fronthaul I/Q requirements for the same link capacity. Higher code rates reduce the fronthaul requirements by lowering the total data rate.

V. PERFORMANCE EVALUATION

A. Reduction of Downstream Fronthaul Bitrates due to Caching

Tables II and III compare the downstream fronthaul transmission bitrate requirements for I/Q transmissions in an FFT-split system without and with caching of the repetitive I/Q QAM symbols for different packet traffic payloads (intensities) \( \rho_L \) and \( \rho_C \) and code rates of 0.9, 0.7, and 0.5, for the LTE and DOCSIS systems, respectively. Tables II and III also report the corresponding transmission bitrate reductions (in percent) achieved by caching the repetitive I/Q QAM symbols. Based on the evaluations in Sec. IV, we consider an I/Q QAM symbol overhead of 7\% in LTE, including RS tones, PBCH, PSS/SSS, and SIB, for a system with a bandwidth somewhat below 20 MHz. For DOCSIS we consider a 3\% overhead due to continuous and scattered pilots, approximating the 2.9\% found in Eqn. (9). The actual payload traffic rates are based on wireless and cable link capacities of \( R_L = R_C = 1 \) Gbps, e.g., for the traffic intensity \( \rho_L = 0.01 \), the actual LTE payload traffic rate is \( \rho_L \times R_L = 10 \) Mbps. The fronthaul I/Q data rate originating from the payload traffic depends on the QAM size and code rate of the system, with \( K = 10 \) bits required to represent each complex and real part of a QAM I/Q symbol, the fronthaul transmission bitrate required for the payload data can be evaluated as

\[
R_{\rho,\text{Payload}}^F = \frac{\rho \times R}{\text{Code Rate} \times \text{QAM Size}} \times 2 \cdot K. \tag{15}
\]

And the excess I/Q transmission bitrate required due to the overhead (non-payload) can be evaluated as

\[
R_{\rho,\text{Overhead}}^F = \text{Overhead Percentage} \times R_{\rho=1,\text{Payload}}^F. \tag{16}
\]

The total required fronthaul transmission bitrate is the sum of bitrates arising from overhead and payload I/Q transmissions, i.e.,

\[
R_{\rho,\text{Total}}^F = R_{\rho,\text{Payload}}^F + R_{\rho,\text{Overhead}}^F. \tag{17}
\]

Note that the system bandwidth \( R_F \) from Eqn. (7) provided by the employed subcarriers must be high enough to accommodate the fronthaul transmission bitrate \( R_{\rho,\text{Total}}^F \) arising from the payload traffic intensity \( \rho \), i.e., \( R_{\rho,\text{Total}}^F \leq R_F \).

Form Table III, we observe that the reductions of the total I/Q fronthaul data rates with caching are proportionally higher for lower offered loads \( \rho_L \). This is because the overhead data rate \( R_{\rho,\text{Overhead}}^F \) is fixed at a value corresponding to the fully loaded \( \rho_L = 1 \) LTE system, whereas the I/Q payload bitrate varies with the actual payload. Caching eliminates the overhead rate \( R_{\rho,\text{Overhead}}^F \) and thus reduces the total fronthaul bitrates. For example, for the code rate = 0.9, for \( \rho_L = 0.01 \), the total data rate without caching is 0.296 Gbps, which is nearly 30 times of the offered load \( \rho_L R_L \); when \( \rho_L = 1 \), the total fronthaul data rate with caching is 3.962 Gbps, which is nearly four times of the offered load \( \rho_L R_L \). However, when caching is employed, for both loads \( \rho_L = 0.01 \) and 1, the total data rates are 3.7 and 3.33 times of the offered load, respectively. Higher bitrate savings can be achieved at lower loads as compared to higher loads. For \( \rho_L = 0.01 \), the total savings is 87.50\%, compared to 6.54\% savings for \( \rho_L = 1 \).

For both data rates, with and without caching, we observe linear increases with decreasing code rates. For example, for \( \rho_L = 0.01 \), the data rate without caching is increased from 0.296 Gbps for the code rate 0.9 to 0.390 Gbps for the code rate 0.7, i.e., the data rate is increased by a factor of \( 0.9/0.7 = 1.27 \). Since both the data rate with caching and the data rate without caching scale linearly by a constant factor with the decreasing code rate, the bitrate savings achieved from the overhead caching is independent of the code rates. However, the choice of code rate for fronthaul I/Q generation significantly affects the total data rates. Higher code rates reduce the fronthaul requirements by lowering the total data rate.

The throughput requirements for the DOCSIS fronthaul I/Q transmissions presented in Table III show similar behaviors as the LTE results presented in Table II. However, as compared to the LTE fronthaul I/Q requirements for the same link capacity of \( R_C = R_L = 1 \) Gbps, the DOCSIS protocol requires relatively lower bitrates. This is because, the DOCSIS protocol supports a higher QAM size of 4096 (212) than LTE; thus, DOCSIS transports more bits per I/Q symbol transmission. The DOCSIS overhead percentage arising from the continuous and scattered pilot, which can be cached at the remote node, is 3\%. Therefore, the effective savings in DOCSIS are relatively smaller compared to LTE. Nevertheless, the fronthaul bitrate savings are 2.9\% for a fully loaded (\( \rho_C = 1 \)) DOCSIS system and 23\% for a 10\% (\( \rho_C = 0.1 \)) loaded system.

B. Total LTE + Cable Fronthaul Bitrate for Different Function Splits

The downstream fronthaul transmission bitrate requirements to concurrently support LTE and DOCSIS deployments over a shared optical infrastructure are shown in Table IV. The FFT split, baseband, and passband fronthaul bitrates are evaluated based on Eqns. (15)–(17) and (1)–(3). For the purpose of the evaluation, we consider \( W = 1 \) antenna, a code rate (CR) of 0.9, carrier frequencies of \( f_c = 2 \) GHz and 1 GHz, sampling frequencies of \( f_s = 30.72 \) MHz and 204.8 MHz, symbol durations of \( T = 66.7 \) \( \mu \)s and 20 \( \mu \)s, link capacities of \( R = 1 \) Gbps, and cached overhead of 7\% and 3\% for LTE.
TABLE II
Downstream LTE fronthaul bitrates without caching ($R_{e,\text{TOTAL}}^P$; Eqs. (15)) and with caching ($R_{e,\text{PAYLOAD}}^P$, Eqn. (17)), as well as bitrate reductions due to I/Q caching with 7% overhead in FFT-split LTE system with QAM size 64 ($2^6$), for different payloads $\rho_L$ and code rates 0.9, 0.5, and 0.7.

| LTE Load $\rho_L$ | LTE FFT-Split Fronthaul I/Q Data Rate (Gbps) | % Sav. |
|------------------|-----------------------------------------------|--------|
|                  | Code Rate = 0.9 | Code Rate = 0.5 | Code Rate = 0.7 | w/o cach. | w/cach. | w/o cach. | w/cach. | w/o cach. | w/cach. | w/o cach. | w/cach. | w/o cach. | w/cach. | w/o cach. | w/cach. |
| 0.01             | 0.296           | 0.380           | 0.533           | 0.096       | 87.50     | 0.047     | 0.476     | 1.133     | 0.466     | 41.17     |
| 0.1              | 0.629           | 0.809           | 1.133           | 0.466       | 87.50     | 0.476     | 1.133     | 0.466     | 41.17     |
| 0.2              | 1.000           | 1.285           | 1.800           | 1.333       | 25.92     | 0.952     | 1.800     | 1.333     | 25.92     |
| 1                | 3.962           | 5.095           | 7.133           | 6.666       | 6.54      |

TABLE III
Downstream cable fronthaul bitrates without caching ($R_{e,\text{TOTAL}}^C$) and with caching ($R_{e,\text{PAYLOAD}}^C$), and bitrate reductions due to I/Q caching with 3% overhead in FFT-split DOCSIS system with QAM size 4096 ($2^{12}$), for different packet payloads $\rho_C$ and code rates 0.9, 0.5, and 0.7.

| DOCSIS Load $\rho_C$ | DOCSIS FFT-Split Fronthaul I/Q Data Rate (Gbps) | % Sav. |
|---------------------|-----------------------------------------------|--------|
|                     | Code Rate = 0.9 | Code Rate = 0.5 | Code Rate = 0.7 | w/o cach. | w/cach. | w/o cach. | w/cach. | w/o cach. | w/cach. | w/o cach. | w/cach. | w/o cach. | w/cach. |
| 0.01                | 0.074           | 0.185           | 0.309           | 0.033       | 75.00     | 0.023     | 0.333     | 0.033     | 23.07     |
| 0.1                 | 0.240           | 0.309           | 0.333           | 0.333       | 23.07     | 0.238     | 0.333     | 0.333     | 23.07     |
| 0.2                 | 0.425           | 0.547           | 0.476           | 0.666       | 13.04     | 0.676     | 0.666     | 13.04     |
| 1                   | 1.907           | 2.452           | 2.380           | 3.333       | 2.91      |

TABLE IV
Total downstream LTE + cable fronthaul bitrates for different splits: PHY (entire PHY processing at remote node), R-FFT (proposed, with and without caching for coding ratio 0.9), baseband (conventional CRAN), and passband split for range of LTE and DOCSIS payload traffic intensity levels $\rho_L$ and $\rho_C$ for LTE and DOCSIS capacities $R_L = R_C = 1$ Gbps.

| Fronthaul Traffic (Gbps) | PHY Split, payload intensity ($\rho$) | FFT split $R_{e,\text{TOTAL}}^C$, Eqs. (15) and (17) | Baseband split $R_B^H$, Eqn. (2) | Passband split $R_P^H$, Eqn. (1) |
|--------------------------|-------------------------------------|-------------------------------------------------|---------------------------------|---------------------------------|
|                          | $\rho_L, \rho_C$ | w/o cach. (CR = 0.9) | Total | w/o cach. (CR = 0.9) | Total | LTE | DOC. | Total | LTE | DOC. | Total | LTE | DOC. | Total |
| 0.01                     | 0.01                 | 0.037           | 0.055 | 0.296           | 0.074 | 0.370 | 18.45 | 8.192 | 26.642 | 40   | 20   | 60   |
| 0.10                     | 0.10                 | 0.370           | 0.555 | 0.629           | 0.240 | 0.869 | 18.45 | 8.192 | 26.642 | 40   | 20   | 60   |
| 0.20                     | 0.20                 | 0.719           | 1.110 | 1.000           | 0.425 | 1.425 | 18.45 | 8.192 | 26.642 | 40   | 20   | 60   |
| 1.00                     | 1.00                 | 3.333           | 6.184 | 3.926           | 1.907 | 5.833 | 18.45 | 8.192 | 26.642 | 40   | 20   | 60   |

and DOCSIS, respectively. We observe from Table IV that the bitrates decrease as the position of the function split is moved from passband (i.e., remote DAC/ADC) to remote-PHY (i.e., from right to left in Fig. [4]).

The passband bitrates $R_{e,\text{TOTAL}}^P$ = 40 Gbps [Eqn. (1)] evaluated with $f_c = 2$ GHz and $R_{e,\text{TOTAL}}^P = 20$ Gbps [Eqn. (1)] evaluated with $f_c = 1$ GHz] are independent of the offered payloads $\rho_L$ and $\rho_C$. Similarly, the baseband bitrates $R_{LTE, 20 \text{ MHz}}^B = 1.23$ Gbps [Eqn. (2)] evaluated with $f_s = 30.72$ MHz and $R_{DOC}^B = 8.19$ Gbps [Eqn. (2)] evaluated with $f_s = 204.8$ MHz] for baseband I/Q time sample transport are independent of the offered payloads. The LTE baseband bitrate $R_{LTE, 20 \text{ MHz}}^B = 1.23$ Gbps is evaluated for a 20 MHz system, which can typically support baseband bitrates up to around $R_L = 70$ Mbps with a single antenna. Therefore, to support the payload bit rate (capacity) of $R_L = 1$ Gbps, the LTE system needs to be scaled up by a factor of at least 15, e.g., to an LTE system with 2 antennas, 256 QAM, and 100 MHz bandwidth, which can support the 1 Gbps bitrate [55]. Thus, the effective LTE baseband bitrate to support 1 Gbps payload is $15 \cdot R_{LTE, 20 \text{ MHz}}^B = 15 \cdot 1.23 = 18.45$ Gbps. The FFT split fronthaul bitrates with and without caching are derived from Tables II and III. We observe from Table IV that for a system (without caching) loaded at 10% ($\rho_L = \rho_C = 0.1$), the R-FFT approach reduces the fronthaul bitrate to 0.87 Gbps compared to 26.64 Gbps with the conventional baseband split; thus, the R-FFT approach reduces the fronthaul bitrate to one third compared to the conventional CRAN baseband split for this lightly loaded scenario. For a fully loaded ($\rho_L = \rho_C = 1$) system, R-FFT reduces the fronthaul bitrate to roughly one fifth of the baseband split.

C. Delay Evaluation

We proceed to illustrate the delay implications of the proposed R-FFT deployment in comparison to the existing R-PHY deployment. In particular, we consider transitionning a DOCSIS cable system from R-PHY to R-FFT operation, while sharing the fronthaul link with a fixed LTE CRAN deployment that transmits a prescribed traffic load (intensity) $\rho_B$ (relative to the transmision bitrate $R_n$ of baseband time domain I/Q sample data. We developed a simulation framework in the discrete event simulator OMNET++ to model the DCCAP cable architecture of the HFC network. A remote cable node, R-PHY or R-FFT node, is connected to the headend through an optical fiber with distance $d$ and transmission bitrate $R_n = 10$ Gbps. 200 cable modems (CMs) are connected to the remote node through an analog broadcast cable. Each CM generates self-similar traffic with varying
levels of burstiness controlled by the Hurst parameter $H$ with an average packet size of 472 bytes. The Hurst parameter $H = 0.5$ corresponds to Poisson traffic, and the burstiness increases for increasing $H$. The DOCSIS 3.1 protocol coordinates the cable transmissions in the broadcast cable with the transmission bitrate $R_C = 1$ Gbps in each direction. The Double Phase Polling (DPP) protocol [96] schedules the upstream transmissions of the 200 distributed CMs over the shared broadcast cable. For R-PHY, DOCSIS PHY frames are digitized and transported over the Upstream External PHY Interface (UEPI) with prioritized CIN transmission of the upstream transmission requests. For R-FFT operation, the upstream cable data is converted to frequency I/Q symbols and transported in generic UDP packets. An FFT size of $4K$ which corresponds to $T_C = 40 \mu s$ and QAM size of 12 bits with code rate 0.9 are used for converting the upstream data to frequency domain I/Q symbols. Each complex number representing an I/Q symbol is digitized with $2 \cdot N = 20$ bits.

We consider the deployment of an LTE RRU at the remote cable node (R-FFT or R-PHY). The LTE RRU implements the conventional LTE CRAN baseband function split, i.e., injects the baseband time domain I/Q samples with bitrate $\rho_B R_o$ into the cable remote node. The LTE upstream traffic and the cable upstream traffic share the optical transmission bitrate $R_o$ from the remote node to the headend, where the BBU CRAN and the cable headend are implemented. We model a typical FIFO queue at the remote node to forward the LTE packets to the CRAN BBU.

Figure 8 compares the mean upstream DOCSIS and LTE packet delays when the cable remote node is operated as either R-FFT or R-PHY node. Figs. 8(a) and (c) show the mean cable (DOCSIS) upstream packet delay from the CMs to the headend as a function of LTE fronthaul traffic intensity $\rho_B$, which corresponds to the LTE I/Q sample bitrate $R^B = \rho_B R_o$ for different optical distances $d$ and traffic burstiness levels $H$. The cable traffic intensity is fixed at $\rho_C = 0.2$, which corresponds to the cable traffic rate $\rho_C R_C = 0.2 \times 1$ Gbps = 200 Mbps.

From Figs 8(a) and (c) we observe that the transition from operating the cable remote node as R-PHY node to R-FFT node slightly increases the mean DOCSIS packet delays for the bursty $H = 0.8$ traffic, whereas the mean DOCSIS packet delays are not visibly increased for Poisson LTE traffic loads below $\rho_B = 0.88$. However, for very high $\rho_B$ loads, the R-FFT DOCSIS delays shoot up to very high values at lower $\rho_B$ Poisson loads than the R-PHY DOCSIS delays.

The underlying cause for these observations is the increase of the cable bitrate due to the processes of I/Q conversion and digitization. For the 9/10 code rate, 12 bits QAM size, and $2 \cdot N$ bits for representing the real and imaginary parts of the I/Q samples, the cable bitrate is increased by a factor of $(10/9) \times (1/12) \times 2 \times 10 = 1.85$ [see Eqn. (15)]. There is some overhead in the uplink, e.g., for uplink pilot tones; however, there is no overhead due to broadcast of PHY layer attributes, such as MIB, SIB and PSS/SSS, in the uplink. We neglect therefore the uplink overhead, which is low compared to the 1.85 fold bitrate increase due to the I/Q conversion and digitization, in the uplink delay evaluation.

This 1.85 fold increase of the cable traffic portion on the fronthaul link results in negligible mean delay increases for low to moderate Poisson traffic loads. However, for high Poisson traffic loads, the increased cable traffic portion reduces
the LTE bitrate $\rho_B$ up to which low DOCSIS delays are achieved. In particular, for $\rho_C = 0.6$ considered in Fig. 8(c), the cable bitrate is increased from $\rho_C R_C = 600$ Mbps for R-PHY to 1.85-600 Mbps $\approx 1.1$ Gbps; accordingly, the tolerable LTE traffic load is reduced from close to $R_o = 600$ Mbps $= 9.6$ Gbps, i.e., $\rho_B = 0.96$, for cable R-PHY operation to only close to $\rho_B = 0.89$ for cable R-FFT operation. Similarly, for bursty self-similar traffic with $H = 0.8$, the increase of the cable traffic portion with R-FFT leads to more frequent temporary spikes of the total LTE plus cable bitrate above the $R_o$ fronthaul link capacity, increasing the mean DOCSIS packet delay compared to cable R-PHY operation.

Fig. 8(b) shows the mean LTE fronthaul packet delay for R-FFT and R-PHY operation of the cable remote node for different optical fronthaul distances of $d = 10$ and 50 km. We observe from Fig. 8(b) that the longer 50 km fronthaul distance increases the LTE packet delay compared to the 10 km distance due to the propagation delay increase [of 40 km/(2.10^8 m/s)] on the optical fiber. We also observe that the R-FFT cable node operation supports very slightly lower LTE traffic loads $\rho_B$ due to the increase of the cable traffic portion from the I/Q conversion and digitization. Fig. 8(d) shows the mean LTE packet delay as a function of the LTE fronthaul bitrate $\rho_B$ for Poisson ($H = 0.5$) and bursty ($H = 0.8$) traffic. We observe that the bursty traffic results generally in higher LTE mean packet delays and gives rise to pronounced delay increases for LTE traffic loads $\rho_B$ exceeding 0.5.

We note that the delay evaluations in this section considered the transition of the cable remote node from R-PHY to R-FFT operation while keeping the LTE CRAN operation unchanged. In particular, the cable traffic bitrate increased from the PHY payload $\rho_C R_C$ to the FFT split bitrate [which corresponds to $R_{p,\text{Payload}}^F$, Eqn. (15)], while the LTE traffic bitrate stayed unchanged at the baseband split rate $R_B^C$ [Eqn. (2)]. The presented delay results represent therefore a conservative assessment of the proposed R-FFT operation in that a consequent transition to R-FFT operation that includes the transition from the conventional CRAN baseband split to the proposed R-FFT split would reduce the LTE traffic portion. That is, the LTE traffic portion would be reduced from the baseband split bitrate $R_B^C$ to the FFT split bitrate, which is a substantial bitrate reduction. We also note that in such a consequent transition from the conventional R-PHY operation of the cable remote node and the CRAN (baseband split) operation of the LTE system to the proposed FFT split, the bitrate reduction of the LTE traffic (from baseband to FFT split) by far outweighs the cable traffic bitrate increase (from PHY split to FFT split). Thus, a consequent transition to the proposed FFT split will reduce the traffic bitrates on the fronthaul link and correspondingly reduce delays.

VI. CONCLUSIONS

We have developed a unified cable DOCSIS and wireless cellular LTE access network architecture with a novel Remote-FFT (R-FFT) node. The proposed R-FFT architecture supports both wired DOCSIS service to cable modems and cellular wireless LTE service over the installed hybrid fiber-broadcast cable infrastructure. More specifically, DOCSIS and LTE share the fronthaul fiber link from headend to R-FFT remote node as well as the IFFT/FFT module in the R-FFT node. The DOCSIS cable headend and LTE baseband unit send frequency domain I/Q symbols over the fronthaul fiber, reducing the bitrate compared to the conventional time domain I/Q symbol transmission. Also, the R-FFT node caches repetitive DOCSIS and LTE QAM symbols to further reduce the downstream bitrate requirements over the fiber link. Whereas conventional cloud radio access networks require the continuous transmission of time domain I/Q symbols over the fronthaul fiber, our R-FFT approach with caching can temporarily suspend or statistically multiplex the downstream transmission of frequency domain I/Q symbols if there is no downstream payload traffic. Our evaluations indicate that the bitrate savings achieved with QAM symbol caching increase substantially for low payload traffic levels. For typical DOCSIS scenarios, the caching savings increase from 2.9 % for a full DOCSIS load to 23 % caching savings with a 10 % cable traffic load. For LTE, the savings increase from 6.5 % for a full wireless traffic load to 41 % for a 10 % LTE traffic load.

Our evaluations also indicate that for a fully loaded system without caching, the R-FFT approach reduces the total fronthaul bitrate required for supporting cable and LTE wireless service to roughly one fifth of the bitrate for the conventional baseband approach of transmitting time-domain I/Q symbols. For 10 % cable and LTE traffic load levels, our R-FFT approach reduces the fronthaul bitrate in each direction (upstream and downstream) to approximately 1/30 of the conventional baseband approach. We have also demonstrated that transitioning a conventional R-PHY cable remote node to an R-FFT remote node (while keeping the LTE baseband operation unchanged) incurs only minute delay increases. The transition to cable R-FFT allows for the flexible efficient execution of all physical layer processing steps (except the FFT, DAC, and upconversion) in software on generic computing hardware at the headend, reducing the cost and complexity of the remote node.

There are several exciting directions for future research on unifying broadcast cable and cellular wireless access. One particularly important direction is to investigate how Internet of Things (IoT) applications and traffic flows, which consist typically of small intermittently transmitted data sets, can be efficiently served. Additional caching mechanisms may be useful in efficiently serving very large numbers of such intermittent IoT flows. Another direction is to examine and improve the interactions of the R-FFT remote nodes and headends (BBUs) with the corresponding metropolitan area and radio backhaul (core) networks.

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