Energy-Aware Technology Comparisons for 5G Mobile Fronthaul Networks

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***Abstract*— Communication networks are not only important to society, they also consume a lot of energy. Recent years research has focused on Cloud-Radio Access Network (C-RAN) to decrease the energy consumption of mobile networks. Hence, this work investigates how to lower the energy consumption in the fronthaul network by choosing the right C-RAN functional split and the right type of fronthaul network. Different functional splits assign different loads to the fronthaul network, and this work considers how much impact the data load has on the fronthaul network's energy consumption. At the same time different types of fronthaul network impact the energy consumption in different ways. The paper provides models to be used for calculating the energy consumption in different network types and for the choice of different functional splits. Results show huge differences in energy consumption between especially wired and wireless technologies. Considering the same functional split, the difference between the most energy consuming transport technology and the least energy consuming is 99.5% for LTE and 99.6% for 5G. For the Ethernet overlay alone, the difference in energy consumption between the, with regard to energy consumption, best and worst case scenario is 99.3% per switch.**

Keywords- Energy consumption; green networking; Ethernet; fronthaul; C-RAN; functional split; 5G; PON; PtP; CWDM.

I. INTRODUCTION

This paper is an enhanced version of [1]. The Information and Communications Technology (ICT) sector counts for over 2% of the world's carbon emissions nowadays [2]. However, the energy consumption of the ICT sector is forecasted to increase by 8% by 2030 in the best case scenario, and by 20% in the worst case scenario [2]. The ICT sector covers many areas and one of them being mobile networks. Mobile networks are growing the most, among all ICT sectors, in terms of number of subscribers, traffic demand, connected devices and offered services [3]. The trend in mobile networks is that more and more capacity is required and the coverage should be everywhere. Hence, base stations are widely deployed to cover the largest area possible, in order to satisfy the users' needs. The next generation of mobile networks, the 5th Generation (5G), is approaching and promises more capacity and higher bitrates. Thus, an important parameter to consider is how this growth will affect the energy consumption in mobile networks.

In the mobile network's base stations, the power amplifier takes up most of the energy consumption, next comes the baseband processing and then the cooling [3]. Cloud-Radio Access Network (C-RAN) architectures have been introduced to lower these parameters. In C-RAN, the radio frequency and

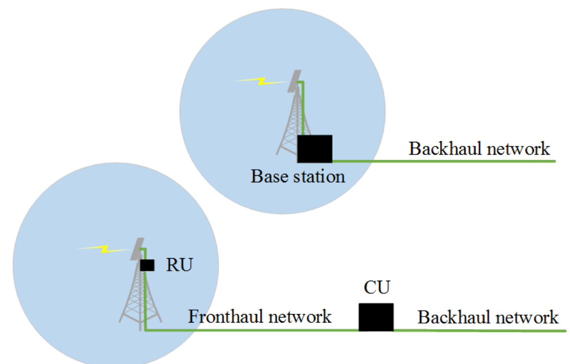


Figure 1. Comparison of traditional base station and C-RAN.

baseband processing functions from the base station are split in two units referred to as the Radio Unit (RU) and the Centralized Unit (CU). The concept is illustrated in Fig. 1. The RU is located close to the antenna at the antenna mast, thereby it is convection cooled and settles for a smaller amplifier. The CUs from several cells can be gathered in a datacenter, where it is possible for them to share processing powers when not used at the same time. Hence, C-RAN will have the possibility of saving energy consumption in the three most energy consuming parameters of the traditional base station. The RU and the CU are connected by a network segment called the Fronthaul (FH) network [4]. Originally, only the radio frequency functions were present in the RU, as the FH network required very large bitrates in order to transport a constant stream of raw In-phase and Quadrature (IQ) data blocks. These blocks of raw IQ data were transported using a special protocol, for example Common Public Radio Interface (CPRI). Recently, the concept of Functional Splits (FS) has been scrutinized, leaving more processing functions in the RU. The more functions are left locally in the RU, the lower the bitrate on the FH network, and gives the possibility of a bitrate varying with user load, but also a larger and more complex RU. Additional information regarding the FSs can be found in [4], which provides an in-depth analysis of the FSs including latency and impact on FH network. Selected FS options are illustrated in Fig. 2. Fig. 2 shows the RU and CU separated by the FH network, which is illustrated by a green dotted line. To the right in Fig. 2, the Long Term Evolution (LTE)/LTE-Advanced(LTE-A)/5G protocol stack illustrates the location of the different FSs selected for this paper. The LTE/LTE-A/5G protocol stack consists of, from the bottom up: the Radio Frequency functions (RF), the physical processing (PHY), the Media Access Control (MAC), the Radio Link Control (RLC) and the Packet Data Convergence Protocol (PDCP). Further description of the protocol stack layers can be found in [4]. On the right side of the figure is a table stating the FH bitrates for LTE, LTE-A and 5G considering different FSs. These FH bitrates are based on calculations in [5] and extended using the parameters stated in Table I, to also include LTE and 5G. The FH bitrates are only considered for the Downlink (DL) direction. The FH bitrates reveal how extremely capacity demanding the FH is, it puts large requirements to the network carrying it.

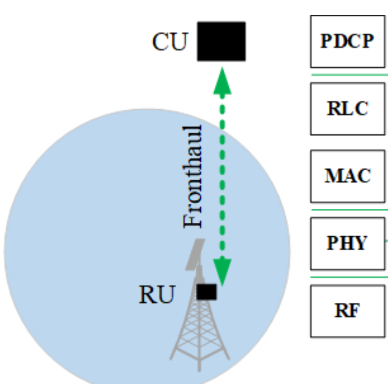
This work investigates how different FSs combined with different FH network types, impact the energy consumption in the FH network. The contribution of this paper includes new perspectives on energy consumption for different FH network options. The different FH network types considered in this paper are: point-to-point (PtP) fiber, Microwave Radio (MWR), Passive Optical Networks (PON) and Coarse Wavelength Division Multiplexing (CWDM) networks, all of these are compared with an over layer of Ethernet. These FH network types are chosen based on the overview in [6], where the physical layer technologies that can carry an overlay of Ethernet are chosen. This paper is organized as follows: Section II provides an overview of research in this field. Section III introduces FH networks in general. Section IV presents energy consumption in the physical layer including: PtP fiber, MWR, CWDM and PON FH networking. Section V presents Ethernet FH networking including a detailed model for energy consumption in the Ethernet FH network. In Section VI, the different layers energy consumptions are combined. Section VII discusses the results provided, considering how to obtain an energy efficient FH network for 5G. Section VIII concludes the paper. Compared to [1], then this work differentiates by introduction of Sections IV and VI. Remaining sections have been updated and modified.

TABLE I. PROPERTIES FOR FRONTHAUL BITRATE CALCULATIONS.

	RATs		
	LTE	*LTE-A*	*5G*
Bandwidth	20 MHz	100 MHZ	400 MHz
# Antennas	2	32	256
# Spatial layers	2	8	12
Modulation order	16 QAM	256 QAM	256 QAM
Sample rate	30,72 MHz	30,72 MHz	614,4 MHz
# Subcarriers	1200	6000	24000
# Resource element blocks	100	500	2000

II. State of the Art

C-RAN has been the topic of much research in recent years. A detailed description of the technology is found in [7]. Liu et al. state in [8] how PtP connections refer to the classical FH transporting IQ data blocks over what is now known as FS 8. Recent years research has looked into new FH opportunities, evolving the FH from PtP to shared connections. The Next Generation Mobile Networks (NGNM) provides in [6] a comprehensive study of the different options for FH transport including the five technologies selected for this paper: Ethernet, PtP, MWR, PON and CWDM networks. FH networks have been the topic of some energy efficiency investigations: Fathy et al. [9] present a power model for a RF/PHY split PON FH considering sleep mode and active RUs. They find that the average network power consumption is lower using their "greedy selection" algorithm. The work in [10] investigates the energy consumption in the RU considering different FSs, digital and analogue. In [11] Tan et al. analyze the energy consumption in RF/PHY split stating that 90 % of the energy is consumed by the RU, 9% by the CU datacenter and 1% by a 10G Ethernet PON FH network. The work in [12] by Kondepu et al. investigates the energy efficiency for the FH



FS	LTE DL FH Bitrate [Gbps]	LTE-A DL FH Bitrate [Gbps]	5G DL FH Bitrate [Gbps]
RLC/PDCP	0.4	4.0	160.0
PHY/MAC	0.4	4.1	160.8
PHY	0.5	86.0	2752.5
RF/PHY	4.9	157.3	25,165.8

Figure 2. The FSs considered and their corresponding FH bitrates for LTE, LTE-A, 5G. The FSs are illustrated in the LTE protocol stack with upper layer PDCP and lowest RF.

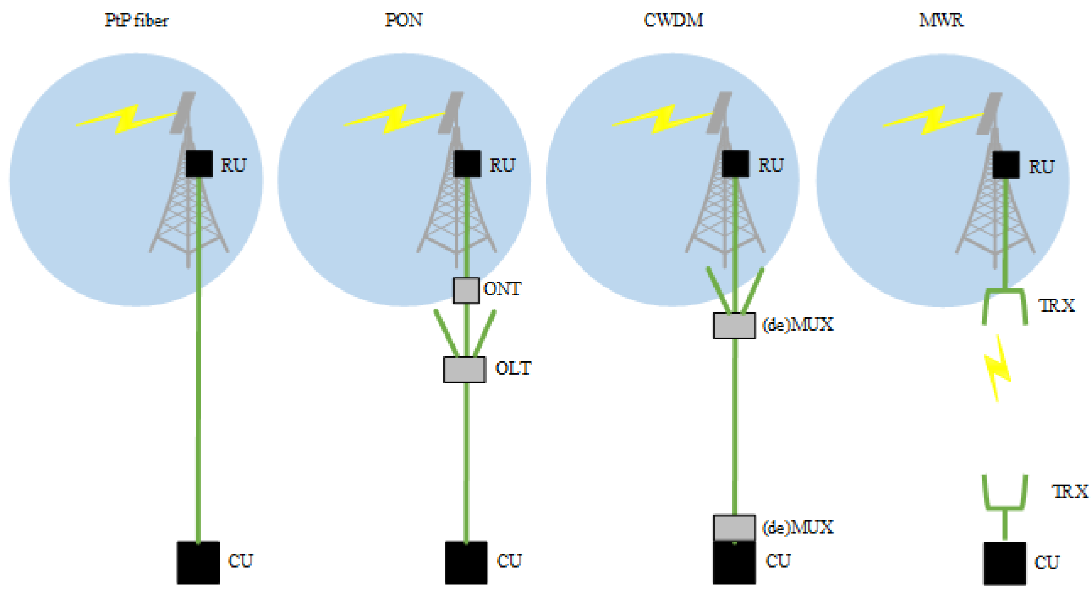


Figure 3. Illustration of different solutions for FH transport technologies: PtP, PON, CWDM and MWR

network for a flexible FS, by switching on and off resources using Software Defined Networking (SDN).

With regard to the findings provided in this section, this work represents an uninvestigated area of looking into the FH energy consumption of multiple FH options while considering different FSs individually.

III. FRONTHAUL NETWORKS

FH transport can use many different types of technologies, wired and wireless. The FH network consists of different elements, depending on the type of network. Networks operate in layers, and technologies must be evaluated based on, which layer they operate. The network types considered for the physical layer in this work covers fiber PtP, MWR, PON and CWDM. On top of this, in the data link layer, this work considers Ethernet. The layered transmission considered in this work is illustrated in Fig. 4. The figure illustrates how the transmission paths are determined by Ethernet but the physical transmission, or moving of data is performed in the physical layer.

In the future 5G network, the RAN will be expanded with more antennas. This will increase the demands to the FH network even more, as not only higher bitrates shall be transported, but also more streams are present from the higher numbers of RUs and antennas. Our model (1) estimates the amount of RUs in an area covered by one CU assuming a circular coverage area. Equation (1) takes the area of the coverage area and divides it by the area of each cell, then sums up for all RATs:

$$N_{RU} = \sum_{RAT} \frac{\pi \cdot D_{MAX}{}^2}{\pi \cdot RAT_n{}^2}, N_{RU} \in \mathbb{N}_0 \qquad (1)$$

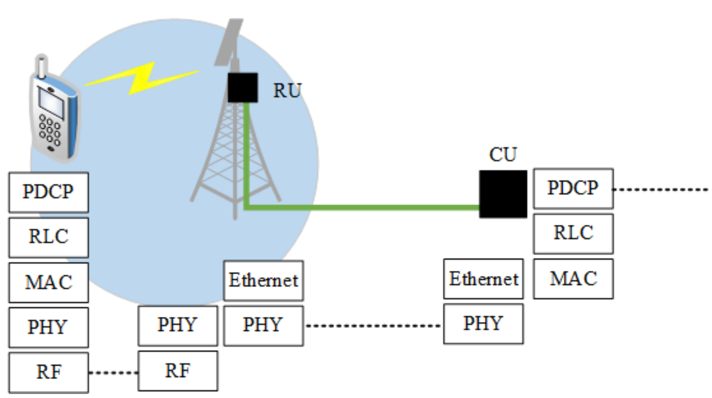


Figure 4. FH transmission over PHY layer, which could be PtP, PON, CWDM or MWR with Ethernet on top. The FS illustrated in this figure is PHY/MAC.

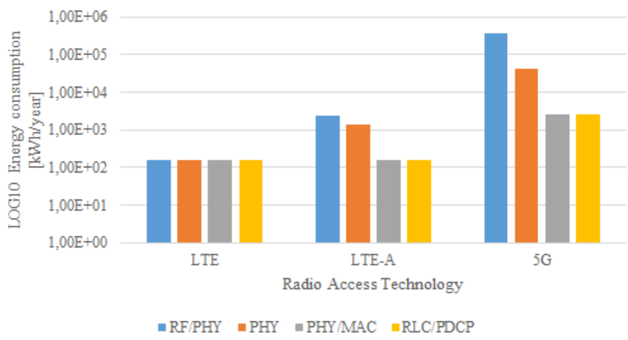


Figure 5. Energy consumption by RAT for one RU-CU connection using PtP/CWDM FH.

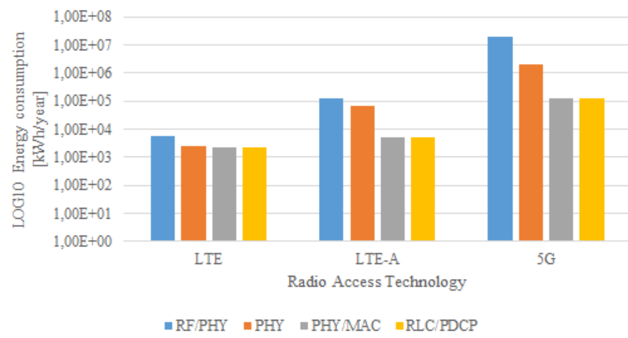


Figure 6. Energy consumption by RAT for one RU-CU connection using MWR FH.

D_{MAX} is the maximum distance between the CU and the RU due to FH latency constraints. RAT_n is the maximal transmission distance for one single antenna per Radio Access Technology (RAT). The RATs describe whether 3rd Generation (3G), LTE, LTE-A etc. are present in the current area, as each RAT requires its own RU. Equation (1) summarizes the amount of RUs for all RATs present, because different RATs have different cell sizes.

IV. Energy Consumption in the Physical Layer

This section introduces different options for physical layer FH transport and corresponding energy consumption models.

A. PTP Fronthaul

The traditional C-RAN FH network establishes a single PtP fiber transmission link between the CU and RU. The only energy consuming elements in this setup are the Small Form-factor Pluggable (SFP) modules and the media converter. The SFP modules are transceivers that connect the CU and RU to the fiber in each end of the connection, the media converter converts the signal to Ethernet before transmission.

1) PtP energy consumption

This work uses SFP+ modules for reference consuming 1.5 W each with a capacity of 10 Gbps [13]. For media converter a 10 Gbps capable media converter consuming 7.2 W is used for reference [14].

The amount of SFPs in PtP is dependent of the SFP capacity. For those FSs having a bitrate higher than the SFP capacity, the data stream will be split out on more channels, hence more SFPs. The number of SFPs per RU, SFP_{RU}, is calculated in (2), and is always at least one:

$$SFP_{RU} = \left\lceil \frac{B_{FH}}{Cap_{SFP}} \right\rceil , \; SFP_{RU} \in \mathbb{N} \qquad (2)$$

In (2) B_{FH} is the FH bitrate, which can be found in Fig. 2, and cap_{SFP} is the capacity per SFP. The total number of SFPs can be calculated as, SFP_{PtP}.

$$SFP_{PtP} = SFP_{RU} \cdot N_{RU} \cdot 2 \, , \; SFP_{PtP} \in \mathbb{N}_0 \qquad (3)$$

The power consumed by PtP can then be calculated as P_{PtP}, including the power per SFP, P_{SFP} and the power per media converter, P_{MC}, which is the same amount as the SFPs:

$$P_{PtP} = SFP_{PtP} \cdot P_{SFP} + SFP_{PtP} \cdot P_{MC} \, , P_{PtP} \in \mathbb{R} \qquad (4)$$

2) PtP Results

One PtP connection consumes 17.4 W for FS RLC/PDCP. This corresponds to 152.4 kWh per year. Fig. 5. Illustrates the energy consumption for one PtP fiber CU-RU connection. The figure illustrates how the energy consumption is the same for all FSs in LTE. But when considering LTE-A and 5G bitrates, the energy consumption starts to scale. The decrease in energy consumption between RF/PHY split and PHY/MAC split is 99.3 % for 5G and 93.8 % for LTE-A.

B. MWR Fronthaul

The MWR FH establishes a wireless PtP connection between the CU and RU. In a MWR link, the RU is connected via a cable to the baseband processing part, which is then connected to one or more Transceivers (TRX), depending on required FH capacity. Each of the TRXs are then connected to an antenna. The antenna transmits radio waves to another antenna located close to the CU. This antenna is connected to a TRX and a baseband processing part, connected to the CU. As each TRX requires another TRX at the receiving side, these will in the following be referred to as TRX pairs. The energy consuming elements in a MWR FH consists of the baseband processing part and the TRXs in each end of the link.

1) MWR energy consumption

To provide information about MWR energy consumption, energy measurements were performed using an Ericsson Mini link MWR setup [15]. The system power was measured using a Rohde and Schwarz power Analyzer HMC8015. The configuration considered in this example is 28 MHz bandwidth and 1024-QAM modulation [15]. The baseband processing and one TRX in each end of the link consumes in total 250 W, and additional TRX pairs add 20 W on top of that [15]. These numbers assume that the TRXs are transmitting at the highest power. The capacity of each TRX

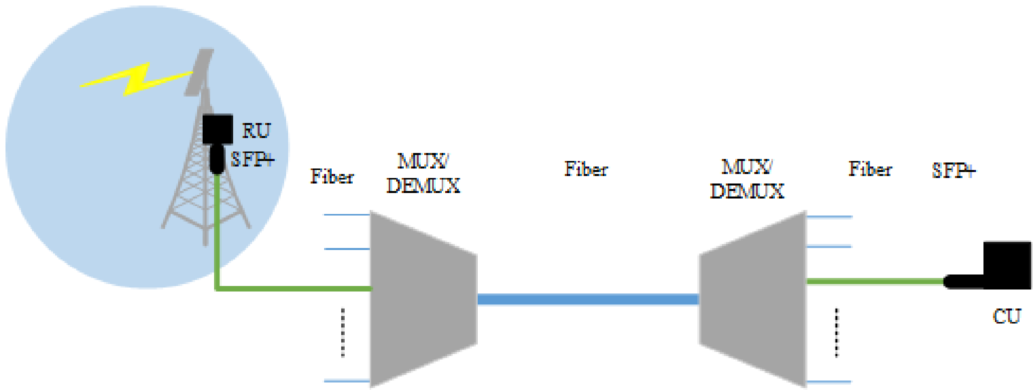


Figure 7. The CWDM system, multiplexing several fibers into one, and demultiplexing them again.

pair is 225 Mbps [15]. Studies show [15] that the power consumption of MWR links does not increase significantly with the user load. But another factor to consider is the transmission power, which when increasing also increases the energy consumption. The transmission power depends on the distance between the antennas, obstacles and weather conditions.

In MWR each CU-RU connection is a wireless PtP connection. The capacity necessary for transmission of one link is described by the number of TRX pairs. Calculating the total number of TRX pairs T, is done using the FH bitrate B_{FH} and the max capacity per TRX pair TRX_{cap}:

$$T = \left\lceil \frac{B_{FH}}{TRX_{cap}} \right\rceil, T \in \mathbb{N}_0 \qquad (5)$$

The power consumption for the whole MWR FH, P_{MWR} is then calculated using the power consumption of the baseband with one TRX pair included P_{BB} and the power consumption of additional TRX pairs, P_{TRX}:

$$P_{MWR} = P_{BB} + (T-1) \cdot P_{TRX}, P_{MWR} \in \mathbb{R} \qquad (6)$$

2) MWR Results

Fig. 6 illustrates the energy consumption for one RU-CU connection using the bitrates provided in Fig. 2. Note Fig. 6 uses a logarithmic scale on the Y-axis. The figure shows the large differences in energy consumption between the different RATs. In 5G the difference between RF/PHY split and RLC/PDCP split is a 99.3 % decrease, where in LTE the same decrease is only 59.7 %.

C. CWDM Fronthaul

CWDM is a multiplexing technique utilizing several optical wavelengths in the same fiber [16]. This is a very efficient way to transport data over great distances, as the only components requiring power along the transmission path are optical amplifiers [16]. CWDM transports up to 18 channels and for up to 60 km [16]. A CWDM network consists of a multiplexer that can combine data on several wavelengths, SFP modules, a fiber connection, one or more amplifiers along the path and a demultiplexer splitting the

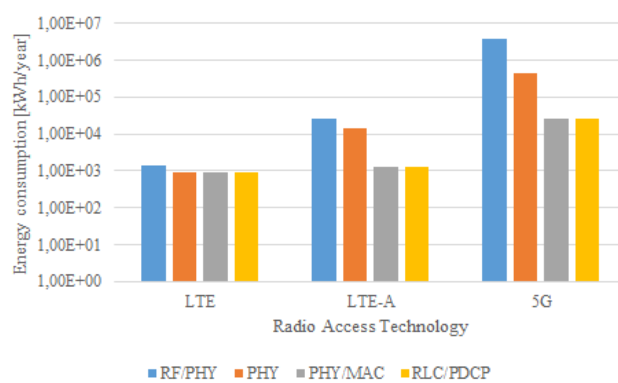


Figure 8. Energy consumption by RAT for one RU-CU connection using PON FH.

wavelengths out on the fibers connected to the individual RUs. The setup is illustrated in Fig. 7. Energy consuming elements in CWDM are the SFP modules, the media converters and the amplifiers along the transmission. The fiber medium does not consume any power itself and neither do the (de)multiplexers.

1) CWDM energy consumption

CWDM (de)multiplexers made with the newest technologies are passive and does not consume any energy themselves [17]. The transceivers considered for this CWDM system are CWDM SFP+ modules [13]. The CWDM 10 Gbps SFP+ modules consume 1.5 W each [13]. The media converter is 10 Gbps capable and consuming 7.2 W [14].

The energy consumption model for CWDM is equal to the one for PtP. This is due to the fact that the (de)multiplexers do not consume any power themselves, the energy consumption corresponds to the same as PtP.

2) CWDM Results

The CWDM power consumption corresponds to the power consumption in PtP.

D. PON Fronthaul

A PON network consists of one Optical Line Terminal (OLT) connected by fiber to one or multiple Optical Network Terminals (ONT). For this work the PON version Gigabit-

PON (GPON) is considered [18], this standard supports a 1.2 Gbps datarate on the FH link [18]. The process of transporting data from the OLT to the ONT is performed on a "transmit when there is something to send" basis, because the OLT is aware of all ONTs. The process of transporting the user data from the ONT to the OLT is more complex in PON, and a process referred to as Dynamic Bandwidth Allocation (DBA) is used for uplink scheduling. The DBA process assigns bandwidth to the individual ONTs when they request it [18]. The issue when considering PON as a FH transport medium arises in the uplink scheduling delay. This problem can be solved by creating a request message in the CU and this way send it on an earlier state to the OLT [19].

1) PON energy consumption

The products used for PON reference in this work is a Nokia ISAM FX-8 switch acting as the OLT using a 16 port line card, which means that this one device handles 16 OLTs at the time. Each of these OLTs connects up to 32 ONTs. The switch's power consumption is not included in this physical layer section. The GPON linecard consumes 89 W and optics are SFP B+ modules consuming 0.6 W per ONT.

The ONT considered for this work is an ICOTERA GPON FTTH ONT i5800-series with a maximum power consumption of 14.4 W [20].

The PON FH energy consumption model is first calculating how many ONTs are necessary, per ONT-OLT connection in order to transmit the required FH bitrate, ONT_{pair}:

$$ONT_{pair} = \left\lceil \frac{BR_{FS}}{BR_{PON}} \right\rceil, ONT_{pair} \in \mathbb{N} \quad (11)$$

Where BR_{PON} is the PON maximum bitrate and BR_{FS} is the maximum FH bitrate of the current FS. Then the number of ONTs connected to each OLT is calculated, ONT_{OLT}:

$$ONT_{OLT} = \left\lfloor \frac{BR_{PON}}{BR_{FS}} \right\rfloor, ONT_{OLT} \in \mathbb{N} \quad (12)$$

Then the number of OLTs in PON are calculated, PON_{OLT}:

$$PON_{OLT} = \left\lceil \frac{N_{RU}}{ONT_{OLT} \cdot ONT_{pair}} \right\rceil, \ PON_{OLT} \in \mathbb{N}_0 \quad (13)$$

Here N_{RU} is the number of RUs in the area. Then it should be calculated how many linecards N_{LC} are necessary, where OLT_{LC} is the number of OLT ports on the linecard.

$$N_{LC} = \left\lceil \frac{PON_{OLT}}{OLT_{LC}} \right\rceil, \ N_{LC} \in \mathbb{N}_0 \quad (14)$$

Then it is calculated how many SFP modules are necessary:

$$SFP = (ONT_{OLT} + ONT_{pair}) + PON_{OLT}, \ SFP \in \mathbb{N}_0 \quad (15)$$

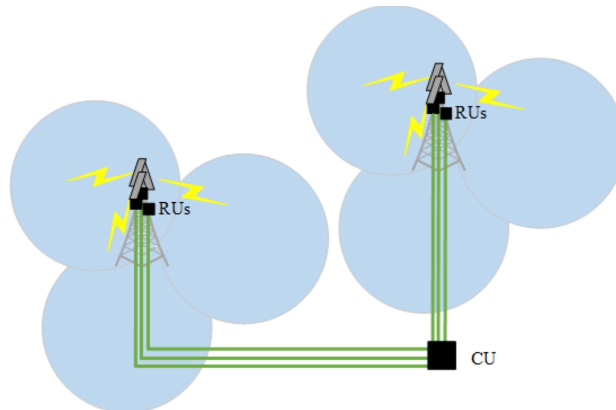


Figure 9. Illustration of several RUs connected to the same CU.

From this the total power consumption, P_{PON}, can be calculated:

$$P_{PON} = P_{LC} \cdot N_{LC} + P_{SFP} \cdot SFP + P_{ONT} \cdot (ONT_{OLT} + ONT_{pair}), \quad P_{PON} \in \mathbb{R} \quad (16)$$

In (16) P_{LC} is the power consumed by the linecard, P_{SFP} is the power consumed by each SFP module and P_{ONT} is the power consumed by each ONT.

2) PON Results

Fig. 8 illustrates the energy consumption by PON for one CU-RU connection considering different RATs and different FSs. Especially in the 5G scenario, the energy consumption is scaling much, here the decrease between split RF/PHY and PHY/MAC is 99.3 %. In LTE the decrease between the same FSs is 37.1 %.

E. Fronthaul networks comparison

This section considers a scenario where multiple RUs are connected to one CU. The situation is illustrated in Fig. 9 showing how multiple sites of 3-sectorized antennas are connected to one CU. In this use case, a FH network limited to 20 km by latency [7] using 3-sectorized antennas covering 13 km^2 per 3-sector, would need a total of 290 antennas/ RUs to cover the entire area calculated using (1). This example

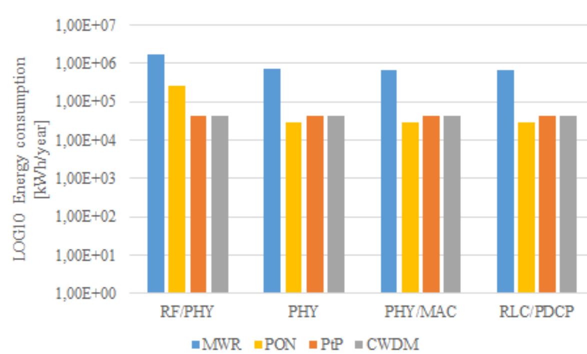


Figure 10. LTE FH energy consumption for different FH technologies considering an area with 290 RUs.

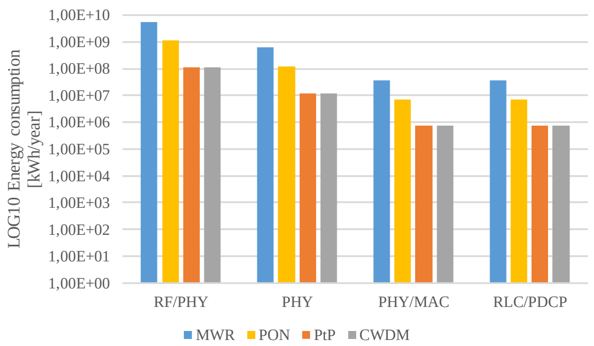


Figure 11. 5G FH energy consumption for different FH technologies.

only considers LTE as RAT. The results are summarized in Fig. 10 for LTE and Fig. 11 for 5G.

For both LTE and 5G, the largest energy consumption is consumed by the MWR connections, and the smallest energy consumption is consumed by PtP/CWDM. If changing from MWR FH to PtP/CWDM FH the energy consumption will be halved, regardless of the FS used. It is though interesting to observe that for the smallest FH bitrates in LTE, then PON is the least energy consuming solution.

V. ETHERNET FRONTHAUL

Ethernet is a data link layer transmission technology, which can act as overlay on top of the physical layer technologies already presented in this paper. Where the physical layer is just acting as pipes, Ethernet switches are forwarding Ethernet frames in the intended direction. As a FH network, Ethernet benefits in being flexible and already widely used in other network segments. Table II summarizes three options for FH transmission. The option of transmitting FH data using CPRI; this option is most beneficial for FSs located between the RF and the resource element mapper function, i.e., FSs having a constant bitrate on the FH link [4]. The same FSs can be transported over Ethernet using a gateway to encapsulate CPRI into Ethernet frames; this is referred to as CPRI over Ethernet. Another solution is FH transmission over Ethernet. This solution is preferred for FSs with a variable bitrate on the FH link, i.e., those having the resource mapper function included in the RU. Table II represents the current status of the network – the RUs connected using CPRI, and the Ethernet solutions as an option for the future 5G FH network.

The amount of RUs found in (1) can be used to find the estimated number of switches covering the current area. Hence, each RU is connected to one ingoing port in an Ethernet switch. Equation (17) expresses the lowest number of switches N_{sw} to cover an area:

$$N_{sw} = \left\lceil \frac{N_{RU}}{N_{port}} \right\rceil, N_{sw} \in \mathbb{N}_0 \tag{17}$$

In (17), N_{port} is the number of ingoing ports in each switch. Fig. 12 illustrates the composition of an Ethernet switch. An Ethernet switch consists of different components. Ethernet frames are received in input modules, which type depends on whether the network is optical or electrical. Then the Ethernet frames are sent into the switch via receiving ports. When entering the switch, the Frame Check Sequence (FCS) is checked and the frame is stored in a FIFO queue. Then the address field in the frame is read, and matched in an address lookup process to the right outgoing port. Afterwards the frame is again stored in a FIFO queue, before it is sent to the outgoing ports and transmitted via output modules. All of these processes consumes energy depending on the FH link bitrate found in Fig. 2.

A. Energy consumption

The calculations in this paper uses a Cisco Catalyst 9200 switch for reference. This switch has a standby power of 35 W [21]. The switch has a power consumption of 42,27 W in case of full port traffic and 100% load [21]. The difference between standby and full load is thereby 7.27 W. Dividing this number into four switch processes, those mentioned in the previous sub section (FCS, MAC, FIFO, FIFO), a rough assumption is that each process consumes 1.8 W. The switch is assumed to use 24 ports running 1 Gbps speed and transmitting/receiving via SFP+ modules consuming 1.5 W each [22].

TABLE II. COMPARISON OF CPRI, ETHERNET AND CPRI OVER ETHERNET FRONTHAUL.

	Selected FH options		
	CPRI	***CPRI over Ethernet***	***Ethernet***
What is transmitted?	Raw IQ samples.	IQ samples encapsulated in Ethernet frames.	Ethernet frames.
Quality of Service	Dedicated user channel.	Shared transmission. Ethernet control management necessary.	Shared transmission. Ethernet control management necessary.
Pros	Simple RU. Capacity, timing and synchronization are guaranteed.	CPRI RUs can be reused. Existing Ethernet network can be used.	Variable/lower bitrate on FH link. Existing Ethernet network can be used.
Cons	Constant high bitrate on FH link increasing by number of antennas.	High Bitrate. Delay can occur. Requires a gateway from CPRI to CPRI over Ethernet.	Delay can occur. Requires new RUs with higher complexity.

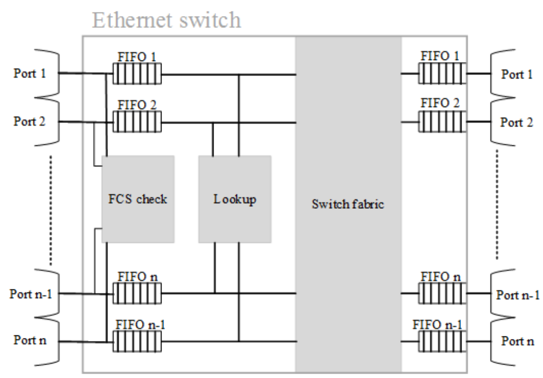


Figure 12. The construction of an Ethernet switch

B. *An Ethernet fronthaul energy consumption model*

In an Ethernet FH network, each switch consumes energy related to the amount of incoming traffic. This is expressed in (18), where P_{FH} is the total power in W consumed when transmitting data over the FH network between the RU and CU. P_{SW} is the total power consumed by one switch, and that is multiplied by the number of switches N_{SW} [1].

$$P_{FH} = P_{SW} \cdot N_{SW} \ \ , P_{FH} \in \mathbb{R} \tag{18}$$

Equation (19) determines the power consumed in one switch. $P_{standby}$ is the power always consumed in the switch to keep it running. P_{pk} is the power consumed by the switch when forwarding one packet. P_{bit} is the power consumed by the switch when forwarding one bit. These numbers are multiplied by the number of forwarded bits, N_{bit}, and the number of forwarded packets, N_{pk}. These numbers are dependent of the FH bitrate, which can be found in Fig. 2 [1].

$$P_{sw} = P_{standby} + P_{pk} \cdot N_{pk} + P_{bit} \cdot N_{bit} \ \ , P_{sw} \in \mathbb{R} \tag{19}$$

Determining the power consumed by the switch when forwarding one packet, requires the power consumed by the process only used once per packet, namely the MAC address lookup (P_{MAC}). This function's power consumption is divided by the maximal number of packets forwarded per second [1].

$$P_{pk} = \frac{P_{MAC}}{N_{pk}(\max)}, \ P_{pk} \in \mathbb{R} \tag{20}$$

$N_{pk}(\max)$, the maximal number of packets forwarded per second, is calculated by dividing the switch's maximum line bitrate by the minimum packet size.

Determining the power consumed by the switch when forwarding one bit, requires the power consumed by the processes where each bit is handled, namely the reception (P_{RX}), the FCS check (P_{FCS}), two FIFOs (P_{FIFO}) and the transmission (P_{TX}). These functions power consumption is divided by the maximal number of bits forwarded per second [1].

$$P_{bit} = \frac{P_{RX}+P_{FCS}+P_{FIFO}\cdot 2+P_{TX}}{N_{bit}(\max)} \ , P_{bit} \in \mathbb{R} \tag{21}$$

$N_{bit}(\max)$, the maximal number of bits forwarded per second, is the switch's maximum line bitrate. The given model is used for further investigation of the energy consumption in an Ethernet FH network.

C. *Results*

Based on the bitrate numbers provided in Fig. 2 and the Ethernet FH energy consumption model, are the following results obtained, illustrated in Figs. 13-17.

Fig. 13 illustrates the input parameters from the model in Section IV. The numbers are based on FS RF/PHY using 5G RAT for one switch. The energy consumption is illustrated on a logarithmic scale as a function of different packet sizes. The figure illustrates how different sizes of packets do not affect the total energy consumed by all bits (Pbit*Nbit) and neither the standby power (Pstandby) this is as expected as none of these parameters are affected by increasing packet sizes. However, the energy consumed for all packets (Ppk*Npk) is much affected by different packet sizes. The decrease in energy consumption between transmitting only the smallest possible Ethernet packets, and only the largest possible Ethernet packets is 95.78%.

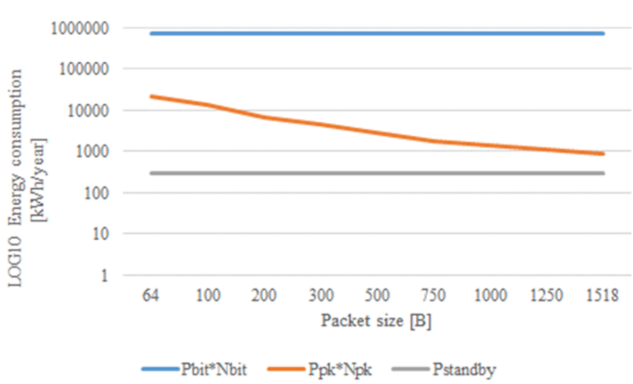


Figure 13. Energy consumption by packet size for the different elements in (3).

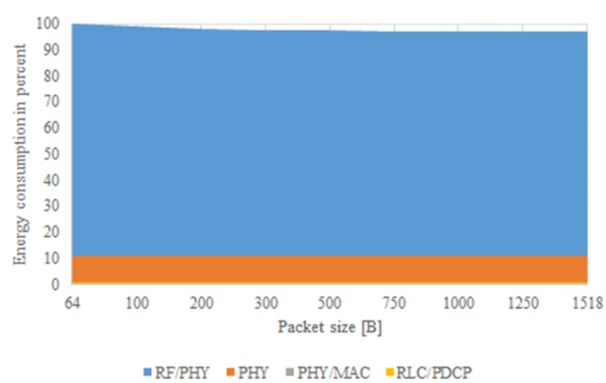


Figure 14. Percentage of energy consumption by increasing packet sizes using 5G RAT.

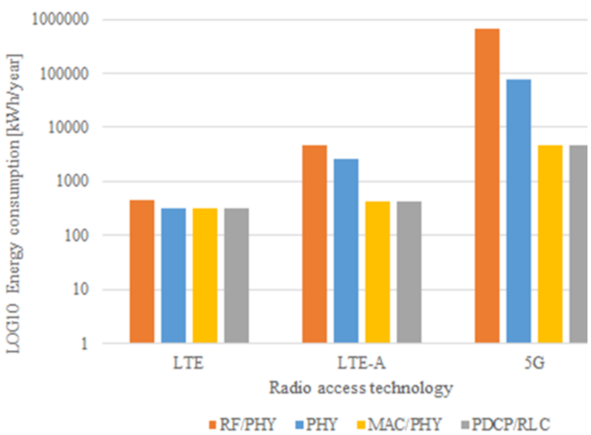


Figure 15. Ethernet energy consumption by radio access technology.

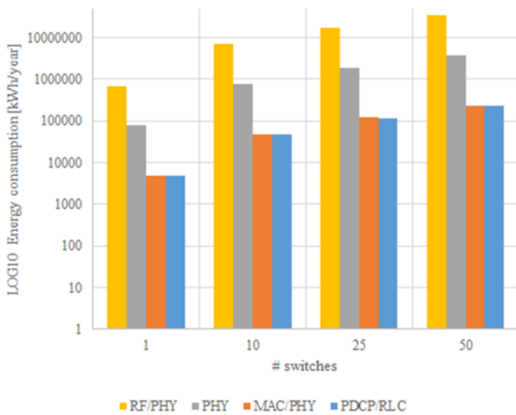


Figure 16. Energy consumption by increasing number of switches in 5G.

Fig. 14 illustrates the percentage of total switch energy consumption as a function of the packet sizes. The figure illustrates different FSs using 5G RAT. It is clear that the RF/PHY split consumes the largest percentage of energy. The figure shows how large effect the packet size has, thus the energy consumption percentage decreases slightly when the packets are larger. It is not possible to see the FSs PHY/MAC and RLC/PCP in the figure as they consume much less energy. However, in those splits the decrease in energy consumption between transmitting only the smallest possible Ethernet packet, and only the largest possible Ethernet packet is 2.66% in both cases whereas for the RF/PHY split the difference is 2.84%.

Fig. 15 illustrates the energy consumption in the FH network when using different FSs and different RATs. Note that it is illustrated on a logarithmic scale. This calculation assumes that the packet size is 1518 B. The figure shows the energy consumption in the FH network using LTE, LTE-A and 5G RATs. The figure states huge differences in power consumption for the different FSs using LTE-A and 5G. In 5G, the energy saving by using split PDCP/RLC compared to

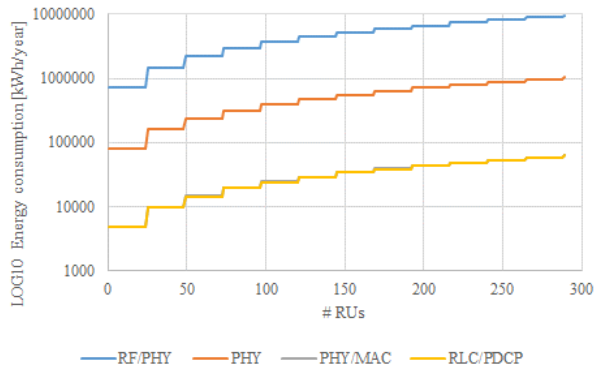


Figure 17. Energy consumption for 5G and different FS options compared to amount of RUs.

split RF/PHY is 99.32% per switch, compared to LTE where the energy saving is only 27.66% between the two splits. Or in other words if assuming one household consumes 3500 kWh per year, then the FH energy consumption in 5G using split RF/PHY covers 199 households per switch, where split PDCP/RLC covers less than 1.5 households per switch. In Fig. 15, the power consumption for LTE does not differ much when comparing the different FSs, meaning that significant energy consumption reductions or increases will not be present using this RAT.

Fig. 16 shows the yearly FH energy consumption in kWh using 5G RAT. This calculation assumes that the packet size is 1518 B. The energy consumption is illustrated by the increasing number of switches. As the figure shows, then the Energy consumption increases by number of switches in the network. The figure illustrates how much energy is required to run a FH network with many switches.

Fig. 17 illustrates on a logarithmic scale, how the FH energy consumption increases when more RUs are added to the network. In the figure, each switch is assumed to have 24 ingoing ports, and the indent behavior of the graph shows the capacity of each switch.

VI. FAIR INCLUSION OF LAYER PHY TECNOLOGIES

The section aims to make the most fair comparison of the different PHY layer technologies using Ethernet transport. In general the comparison is difficult as PtP/CWDM results consider a 10 Gbps capacity system where the PON technology is only represented by a 1 Gbps capacity. But as numbers for energy consumption are difficult to find, it has been chosen to use confirmed energy consumption values and not estimated ones. For PtP/CWDM the Ethernet switch energy consumption is just added to the layer PHY energy consumption. For MWR, the energy consumption of the Ethernet switch is not included, as the MWR system transports Ethernet frames, and in that regard, energy consumption of Ethernet is already included in the numbers provided. For PON the SFPs have already been included in the calculations for the PON energy consumption, therefore the SFP energy consumption of the Ethernet switch P_{RX} and P_{TX} has been excluded from the calculations. Further, for

PON, the number of Ethernet switches is equal to the number of linecards, N_{LC}.

Figs. 18 and 19 illustrate the huge impact of the bitrate in these measurements, because the tendencies in the two figures are very different. The only difference between these two figures is the used FS and hereby the FH bitrate. According to Fig. 2, then the bitrate is more than 10 times larger for RF/PHY than for RLC/PDCP considering LTE. This difference is significant for PON. Because in the RLC/PDCP scenario the FH bitrate is smaller than maximum PON capacity, resulting in $ONT_{OLT} > 1$, meaning the capacity per OLT is shared among several ONTs. This results in PON having the lowest energy consumption in Fig. 19, whereas in Fig 18 $ONT_{pair} \leq 1$ and PON has the largest energy consumption. In this regard it would have been very interesting to compare with a 10 Gbps PON technology, but that must be a matter for future work.

VII. Discussion

The energy consumption is an important matter considering all areas of the ICT sector. The mobile networks are no exception and within mobile networks the FH network must never be a bottleneck for the expensive RAN capacity, but neither should it consume more energy than necessary. In that regard, the FH network must be carefully aligned. This work considers different layers of FH network transport. Different technologies in the physical layer and Ethernet in the data link layer. The total FH energy consumption will be the sum of the energy consumption in the physical layer and the energy consumption by the Ethernet overlay.

This work has looked into the energy consumption of different types of FH networks. In this regard, PtP fiber and CWDM definitely consume less energy compared to the other options. CWDM and PtP obtains very low results for energy consumption in this work, while it still have lots of capacity for the FH transmission. CWDM can be a solution to share resources in PtP scenarios because multiple links can be added to the same fiber. In reality CWDM will most likely be used to multiplex data from all RUs at the same base station onto the same fiber.

When comparing the different FH network types in Section VI, MWR consumes the largest amount of energy. At the same time, the MWR results are the only ones based on real life measurements, and not data sheet numbers. The MWR results depend on the bitrate and it is very clear to see how much the FS and the RAT influence the energy consumption. MWR might not be the most optimal solution energy-wise, but in some situations it is not possible to deploy fiber. Then MWR is an easy deployment solution.

PON as a FH network obtains in general higher energy consumption compared to the other wired solutions presented in this work, but not for lower bitrates as stated in Section VI, where the PON network is able to share the connections among several RUs. It should be noted that the energy consumption numbers provided in this work are only for GPON with a capacity of 1.2 Gbps, other PON solutions with higher bitrates, for example 10 Gbps or 40 Gbps, will most likely, according to Section VI, obtain much better results for energy consumption, because more resources can be shared among different users or more RUs. Unfortunately, it has only been possible to obtain energy consumption number for GPON for the examples in this paper. But, when having the power consumption for other PON solutions, the models in this work can still be used.

Considering the multiple RUs use case in Section IV.E, where an area covered by 290 RUs were used as an example. Here, changing from MWR FH to PtP/CWDM FH the energy consumption will be halved, regardless of the FS used. This is a significant difference from the one RU-CU pair examples presented in section IV.A,B,C,D. But in these examples lower decreases in energy consumption were provided using LTE RAT. More specifically, PtP and MWR had the same energy consumption for all FSs, MWR had a decrease between split RF/PHY and PHY/MAC of 60% whereas is PON the decrease between the same FSs were 37%.

Ethernet results in this work show how the choice of a FS, the number of RUs and the number of ingoing ports per Ethernet switch has huge impact on the energy consumption in an Ethernet FH network. The energy consumption does not differ much between the different FSs when considering LTE,

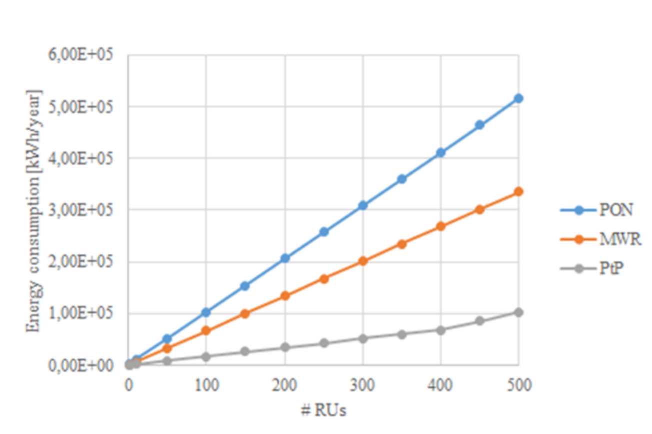


Figure 18. Ethernet energy consumption by increasing number of RU's .For FS RF/PHY and LTE RAT.

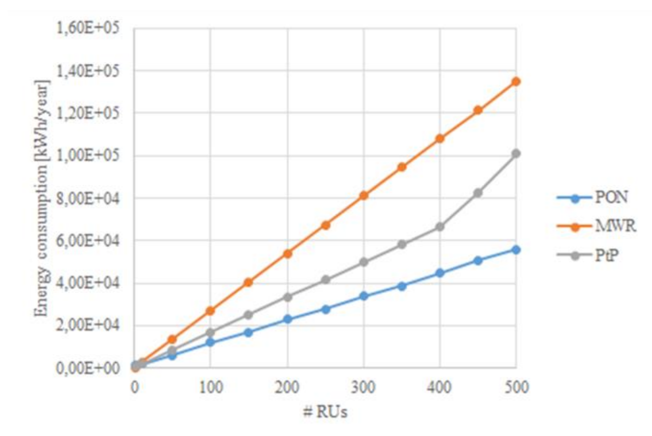


Figure 19. Ethernet energy consumption by increasing number of RU's. For FS PHY and LTE RAT.

but when entering the era of 5G, the FH networks will suffer from large energy consumption. To lower the energy consumption in the FH network, the choice of a FS becomes very important, together with high capacity Ethernet switches, and packet sizes. Slight decreases are obtained by transmitting larger sized packets even in splits PHY/MAC and PCP/RLC. In the Ethernet FH energy consumption model, a fixed packet size is used, which is very optimistic. In reality packets will be of different sizes, and the smaller packets, the more packets are necessary to transmit the same amount of data. At the same time, every packet carries a header, so more packets means more headers. Hence, using smaller packets, more bits have to be transmitted. In relation to that, it might not always be possible to fill up an entire Ethernet packet. Some functions in the protocol stack are time critical, e.g., the HARQ process [23]. In a time critical transmission, the packet might need to be sent before it is filled, leading to smaller packets and more overhead transmission.

This work provides an overview of the energy consumption of different network types. Products from different vendors or with higher capabilities may vary from these numbers provided. This work only considers the energy consumption, not the sustainability in using the resources already deployed. Or in other cases, one solution might be the only one possible, deployment-wise. Network operators can use the models provided in this work to estimate when it will be cheaper – energy-wise, to change already established equipment. Also for the case of green field deployment, the models provided can be used to evaluate the energy consumption of different solutions.

The results representing 5G and the extremely high bitrates and energy consumption related to that is only an extrapolation, but is found useful as a guideline for what can be expected.

VIII. CONCLUSION

This work investigated energy consumption in different types of FH networks for current and future mobile networks. The FH network connects the RU at the antenna site and the CU located in a datacenter. Different models for the FH energy consumption were presented, relating to different FH types. The outcome of this work shows the extremely high differences in energy consumption for different network types. Further, it is also important to choose the right FS, as significant reductions in energy consumption can be obtained. Many assumptions have been made due to lack of data but the paper gives an overview of the energy consumption in different network types and for the choice of different FSs. This makes the comparisons provided less accurate. But the models provided can be used for all vendors equipment and own numbers can easily be inserted. Results show that MWR consumes a lot of energy while CWDM consumes much less. If changing from MWR FH to PtP/CWDM FH the energy consumption will be halved, regardless of the FS used. For the Ethernet overlay alone, the difference in energy consumption between the, energy consumption wise, best and worst case scenario is 99.3 % per switch.

ACKNOWLEDGEMENT

The authors would like to thank the Danish network provider Norlys for providing information about products and energy consumption in their PON and PtP networks.

The authors would also like to thank master's student Keld Fernstrøm for providing information about the energy consumption of MWR connections.

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