Energy-Aware Design Considerations for Ethernet-Based 5G Mobile Fronthaul Networks

Larsen, Line Maria Pyndt; Berger, Michael Stübert; Christiansen, Henrik Lehrmann

Published in:
Proceedings of the Fourth International Conference on Green Communications, Computing and Technologies

Publication date:
2019

Document Version
Peer reviewed version

Citation (APA):
Larsen, L. M. P., Berger, M. S., & Christiansen, H. L. (2019). Energy-Aware Design Considerations for Ethernet-Based 5G Mobile Fronthaul Networks. In *Proceedings of the Fourth International Conference on Green Communications, Computing and Technologies* IARIA.

Energy-Aware Design Considerations for Ethernet-Based 5G Mobile Fronthaul Networks

Line M. P. Larsen, Michael S. Berger, Henrik L. Christiansen
Department of Photonics Engineering
Technical University of Denmark, DTU
Kgs. Lyngby, Denmark
e-mail: lmph@fotonik.dtu.dk

***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 in mobile networks. Hence, this work investigates how to lower the energy consumption in the Ethernet based fronthaul network by choosing the right C-RAN functional split. 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. This work presents a model for the fronthaul energy consumption, which takes the different steps of the Ethernet switch operations into account. The outcome of this model shows the extremely high importance of choosing the right functional split when mobile networks are entering the era of 5th Generation (5G). The impact of switch capacity and size of Ethernet packets is also considered. In a 5G worst case scenario, one switch will consume the same amount of energy as 199 households. The difference in energy consumption between the best and worst case scenario of this paper is 99.32% per switch.**

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

I. INTRODUCTION

The Information and Communications Technology (ICT) sector counts for over 2% of the world's carbon emissions nowadays [1]. 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 [1]. The ICT sector covers many areas and one of them is 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 [2]. 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.

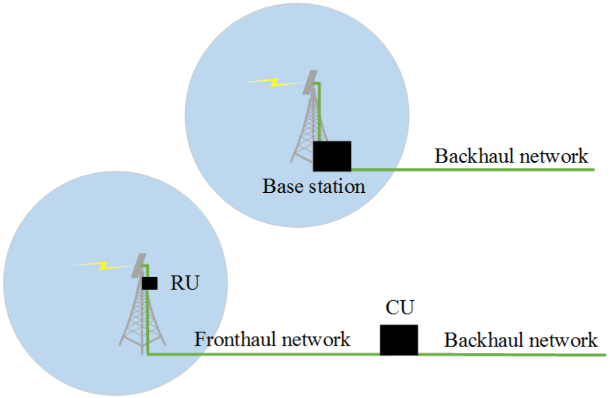
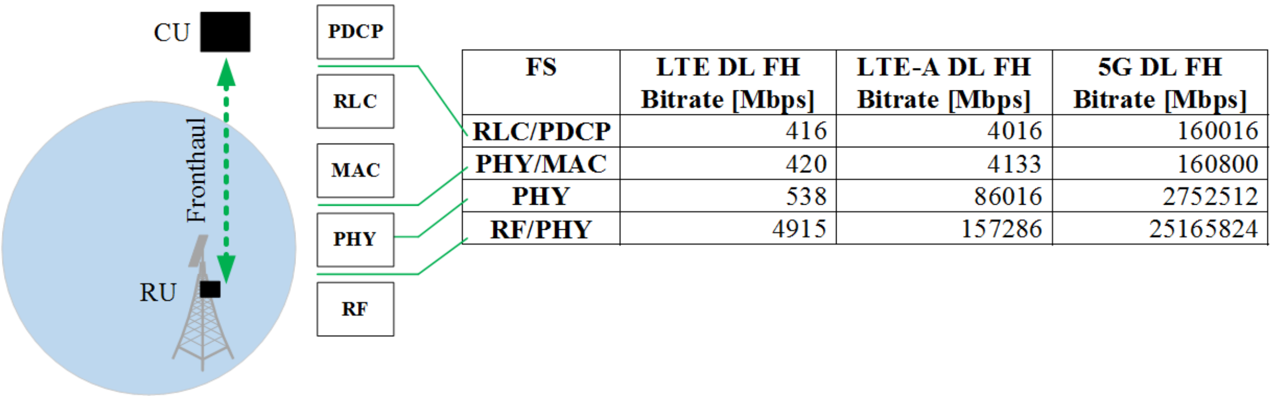


Figure 1. Comparison of traditional base station and C-RAN.

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 [2]. Cloud-Radio Access Network (C-RAN) architectures have been introduced to lower these parameters. In C-RAN, the radio frequency and 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 network [3]. Originally, only the radio frequency functions were present in the RU, hence the fronthaul 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 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 fronthaul network, and gives the possibility of a bitrate varying with user load, but also a larger and more complex RU. Additional information regarding the functional splits is found in [3], which provides an in-depth analysis of the functional splits including latency and impact on fronthaul



FS	LTE DL FH Bitrate [Mbps]	LTE-A DL FH Bitrate [Mbps]	5G DL FH Bitrate [Mbps]
RLC/PDCP	416	4016	160016
PHY/MAC	420	4133	160800
PHY	538	86016	2752512
RF/PHY	4915	157286	25165824

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

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

network. Selected functional split (FS) options are illustrated in Fig. 2. Fig. 2 shows the RU and CU separated by the Fronthaul (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 functional splits 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 [3]. On the right side of the figure is a table stating the fronthaul bitrates for LTE, LTE-A and 5G considering different functional splits. These fronthaul bitrates are based on calculations in [4] and extended using the parameters stated in Table I, to also include LTE and 5G. The fronthaul bitrates are only considered for the Downlink (DL) direction.

This work investigates how different functional splits impact the energy consumption in the fronthaul network. The main goal is to investigate how much energy can be saved, when using different functional splits and thereby different bitrates on the fronthaul network. This paper is organized as follows: Section II provides and overview of research in this field. Section III introduces Ethernet fronthaul networks. Section IV outlines a model for energy consumption in the Ethernet fronthaul network. Section V introduces a small case study. Section VI presents the results of energy consumption in the fronthaul network. Section VII discusses the results provided, considering how to obtain an energy efficient fronthaul network for 5G. Section VIII concludes the paper.

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 [5]. In [6], Sun et al. investigate optimization algorithms to improve the user-centric energy efficiency by jointly allocating resources. Fathy et al. [7] present a power model for a RF/PHY split Passive Optical Network (PON) fronthaul considering sleep mode and active RUs. They find that the average network power consumption is lower using their "greedy selection" algorithm. The work in [8] investigates the energy consumption in the RU considering different functional splits, digital and analogue. In contrast to the previous mentioned papers, this work looks into the energy consumption in the fronthaul network specifically. In [9] Tan et al. analyse 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 fronthaul network. The work in [10] by Kondepu et al. investigate the energy efficiency for the fronthaul network for a flexible functional split, by switching on and off resources using Software Defined Networking (SDN). This work distinguishes from previous mentioned papers by considering the energy consumption for each of the functional splits and not the best option available. Further, it considers Ethernet for fronthaul transport. With regard to the arguments provided in this section, this work represents an uninvestigated area of looking into the fronthaul energy consumption while considering the different functional splits individually.

III. ETHERNET FRONTHAUL NETWORKS

Fronthaul transport can use many different types of technologies, one of them being Ethernet. The fronthaul

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

	Selected fronthaul 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 fronthaul link. Existing Ethernet network can be used.
Cons	Constant high bitrate on fronthaul 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.

network consists of different elements, depending on the type of network. In an Ethernet fronthaul network, the RU and CU are connected by fibers, transmitting Ethernet frames, and Ethernet switches, forwarding Ethernet frames in the right direction. The fibers alone do not consume any energy, they are just pipes, whereas the Ethernet switches require energy in order to function. Ethernet is a packet switched network technology, where it is possible to assign capacity depending on user load. As a fronthaul network, Ethernet benefits in being flexible and already widely used in other network segments. Table II summarizes three options for fronthaul transmission. The option of transmitting fronthaul data using CPRI; this option is most beneficial for functional splits located between the RF and the resource element mapper function, i.e., functional splits having a constant bitrate on the fronthaul link [3]. The same functional splits 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 fronthaul transmission over Ethernet. This solution is preferred for functional splits with a variable bitrate on the fronthaul link, i.e., those having the resource mapper 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 fronthaul network for 5G.

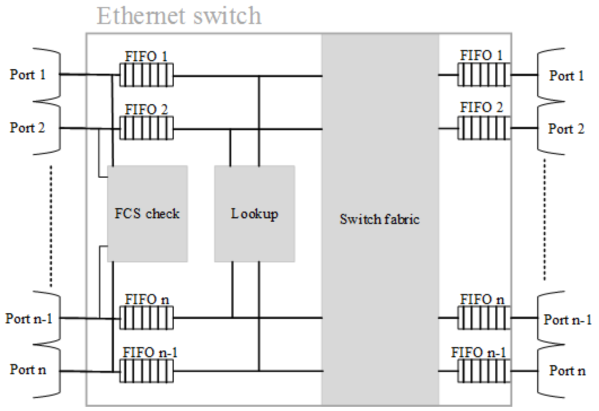


Figure 3. The construction of an Ethernet switch.

In the future 5G network, the RAN will be expanded with more antennas. This will increase the demands to the fronthaul 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. The following formula can be used for an estimate of the amount of RUs in an area covered by one CU assuming a circular coverage area:

$$N_{RU} = \frac{\pi \cdot D_{MAX}{}^{2}}{\pi \cdot D_{single}{}^{2}} \cdot RATs \tag{1}$$

D_{MAX} is the maximal distance between the CU and the RU due to fronthaul latency constraints. D_{single} is the maximal transmission distance for one single antenna. Radio Access Technologies (RATs) describe how many RUs are present at each antenna site. They describe whether 3rd Generation (3G), LTE, LTE-A etc. are present in the current area, as each RAT requires its own RU. 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 2 expresses the lowest number of switches N_{sw} to cover an area:

$$N_{SW} = \frac{N_{RU}}{N_{port}} \tag{2}$$

In (2), N_{port} is the number of ingoing ports in each switch.

In 5G networks, more capacity will be provided for the users. More capacity can be obtained e.g. by adding more bandwidth to the system or by adding more RUs for denser coverage and hotspot compliance. If more RUs are added to the system, more switches are necessary in the fronthaul network (as seen in (2)). If adding more bandwidth to increase the capacity, less RUs are necessary leading to less switches in the fronthaul network. The energy efficiency of the Ethernet fronthaul network depends on the number of RUs, the bandwidth available and the number of ports in each Ethernet switch.

IV. AN ETHERNET FRONTHAUL ENERGY CONSUMPTION MODEL

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 (First In First Out (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. Fig. 3 illustrates the composition of an Ethernet switch. All of these processes consumes energy depending on the fronthaul link bitrate.

In an Ethernet fronthaul network, each switch consumes energy related to the amount of incoming traffic. This is expressed in (3), where P_{FH} is the total power in W consumed when transmitting data over the fronthaul 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}.

$$P_{FH} = P_{SW} \cdot N_{SW} \tag{3}$$

Equation 4 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.

$$P_{SW} = P_{standby} + P_{pk} \cdot N_{pk} + P_{bit} \cdot N_{bit} \tag{4}$$

To Determine 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.

$$P_{pk} = \frac{P_{MAC}}{N\ MAX_{pk}} \tag{5}$$

N Max_{pk}, 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.

$$P_{bit} = \frac{P_{RX}+P_{FCS}+P_{FIFO} \cdot 2+P_{TX}}{N\ MAX_{bit}} \tag{6}$$

N Max_{bit}, 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 fronthaul network.

V. CASE STUDY

An Ethernet fronthaul limited by 20 km latency [5] using 3-sectorized antennas covering 13 km^2 per 3-sector, would need a total of 291 antennas/ RUs to cover the entire area. If the area is fully covered by four RATs (for example 3G, LTE, LTE-A and 5G) the total number of RUs in the area is 1164, considering (1). Using 24 port switches, this corresponds to 49 switches considering (2). These numbers only provide a rough estimate, but it gives the idea that 50 switches in the area covered by one CU-datacenter is not an unrealistic number.

The calculations in this paper uses a Cisco Catalyst 9200 switch for reference. This switch has a standby power of 35 W [11]. The switch has a power consumption of 42,27 W in case of full port traffic and 100% load [11]. The difference between standby and full load is thereby 7.27 W. Dividing this number into four switch processes, those mentioned in the model (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 Gb speed and transmitting/receiving via SFP+ modules consuming 1.5 W each [12].

VI. RESULTS

Based on the bitrate numbers provided in Fig. 2 and the model outlined in Section IV, combined with the switch energy consumption numbers provided in section V, the following results are obtained, illustrated in Fig. 4-8.

Fig. 4 illustrates the input parameters from the model in Section IV. The numbers are based on functional split 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

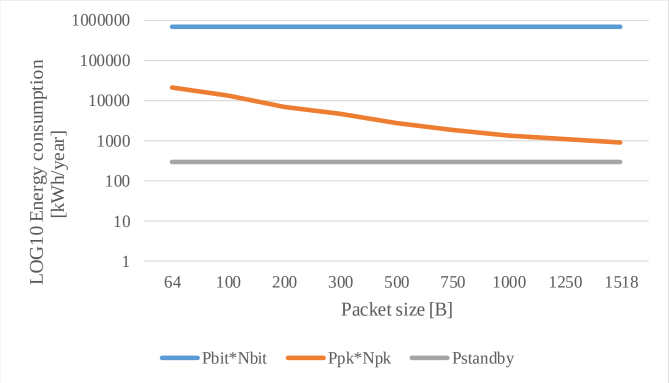


Figure 4. Energy consumption by packet size for the different elements in (3).

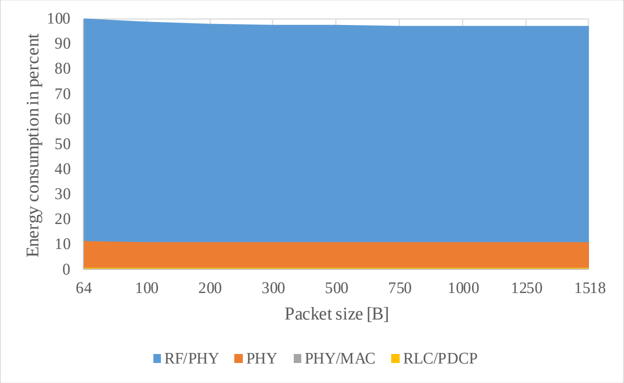


Figure 5. Percentage of energy consumption by increasing packet sizes using 5G RAT.

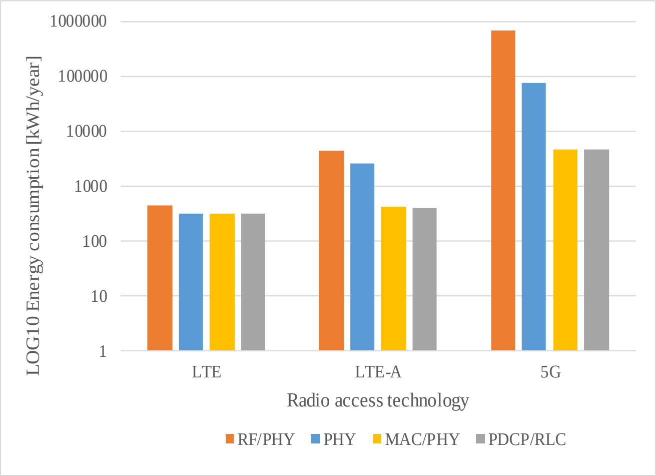


Figure 6. Energy consumption by radio access technology.

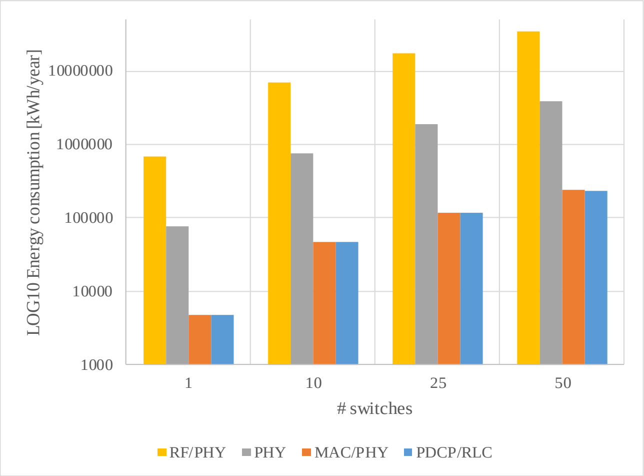


Figure 7. Energy consumption by increasing number of switches in 5G.

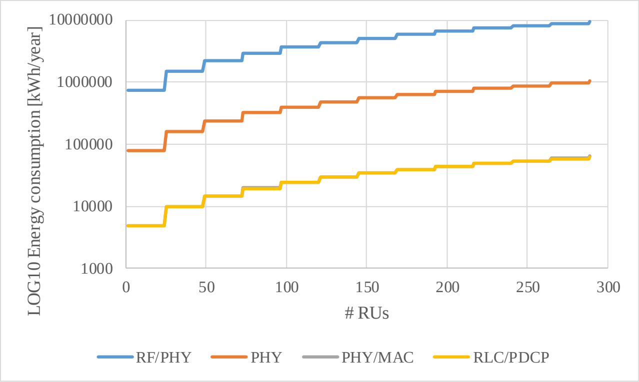


Figure 8. Energy consumption for 5G and different functional split options compared to amount of RUs.

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%.

Fig. 5 illustrates the percentage of total switch energy consumption as a function of the packet sizes. The figure illustrates different functional splits 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 functional splits 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. 6 illustrates the energy consumption in the fronthaul network when using different functional splits 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 fronthaul network using LTE, LTE-A and 5G RATs. The figure states huge differences in power consumption for the different functional splits using LTE-A and 5G. In 5G, the energy saving by using split PDCP/RLC compared to 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 fronthaul 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. 6, the power consumption for LTE does not differ much when comparing the different functional splits, meaning that significant energy consumption reductions or increases will not be present using this RAT.

Fig. 7 shows the yearly fronthaul energy consumption in kWh using 5G RAT This calculation assumes that the packet size is 1518 B. The energy consumption is illustrated by 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 fronthaul network with many switches, as illustrated in the case study in Section V, where 50 switches did not seem unrealistic in the area covered by one CU-pool.

Fig. 8 illustrates on a logarithmic scale, how the fronthaul 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.

VII. DISCUSSION

The energy consumption is an important matter considering all areas of the ICT sector. The fronthaul network must never be a bottleneck for the expensive RAN capacity, but neither should it consume more energy than necessary. In that regard, the fronthaul network must be carefully aligned. From the results, it seems like there is a large gap in the bitrates and energy consumption between the PHY split and the MAC/PHY split. The MAC/PHY split has the physical processing in the RU and handles all baseband processing in the CU. This means a relatively simple RU and a significantly lower energy consumption.

Results in this work show how the choice of a functional split, the number of RUs and the number of ingoing ports per Ethernet switch has huge impact on the energy consumption in an Ethernet fronthaul network. The energy consumption does not differ much between the different functional splits when considering LTE, but when entering the era of 5G, the fronthaul networks will suffer from large energy consumption. To lower the energy consumption in the fronthaul network, the choice of a functional split 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 this 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 [13]. In a time critical transmission, the packet might need to be sent before it is filled, leading to smaller packets and more overhead transmission.

Fig. 7 shows the energy consumed by up to 50 switches in a network. According to the roughly estimated calculation of the number of switches in Section III, then 50 switches in the coverage area of one CU is not unrealistic. It depends on several factors, for example, if the area is covered only by three RATs, then the number of switches required is reduced to 37. These assumptions are though not completely realistic. In reality the area might be fully covered by 3G and LTE RATs, and then LTE-A and 5G will be used to cover hotspots. Different cell sizes are not considered. Considering the energy consumption of 25 switches this corresponds to the energy consumption of 4975 households when using split RF/PHY in 5G and split PDCP/RLC covers less than 38 households.

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 Ethernet-based fronthaul networks for current and future mobile networks. The fronthaul network connects the RU at the antenna site and the CU located in a datacenter. A model for the fronthaul energy consumption was presented, taking the different steps of the switching process into account. The outcome of this work shows the extremely high importance of choosing the right functional split, when mobile networks are entering the era of 5G, 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 now compared to 5G mobile networks, and predicts that in a worst case scenario one switch will consume the same amount of energy as 199 households. Suggestions provided in this paper to lower the energy consumption in the fronthaul network includes: choosing a functional split with lower fronthaul bitrates, development of low energy consuming Ethernet switches with many ports, and attempt to fill up Ethernet packets in order to transmit as large packets as possible and utilize the already used resources to a higher degree.

REFERENCES

[1] N. Jones, “How to stop data centres from gobbling up the world’s electricity,” https://www.nature.com/articles/d41586-018-06610-y Accessed: June, 2019. .

[2] N. Piovesan, A. Fernandez Gambin, M. Miozzo, M. Rossi, and P. Dini, “Energy sustainable paradigms and methods for future mobile networks: A survey,” Comput. Commun., vol. 119, pp. 101–117, Apr. 2018.

[3] L. M. P. Larsen, A. Checko, and H. L. Christiansen, “A Survey of the Functional Splits Proposed for 5G Mobile Crosshaul Networks,” IEEE Commun. Surv. Tutorials, vol. 21, no. 1, pp. 146–172, 2019.

[4] NTT DOCOMO, “R3-162102: CU-DU split: Refinement for Annex A.” 3GPP.

[5] A. Checko et al., “Cloud RAN for Mobile Networks - A Technology Overview,” IEEE Commun. Surv. Tutorials, 2015.

[6] Y. Sun, S. Li, and L. Yang, “Green fronthaul allocation and power management in Cloud-RAN,” EURASIP J. Wirel. Commun. Netw., vol. 2018, no. 1, p. 188, Dec. 2018.

[7] M. Fathy, B. Mokhtar, M. A. Abdou, and M. R. M. Rizk, “Extended study towards performance improvement of Cloud-RAN,” in 2017 13th International Wireless Communications and Mobile Computing Conference (IWCMC), 2017, pp. 1061–1066.

[8] Y. Alfadhli, M. Xu, S. Liu, F. Lu, P.-C. Peng, and G.-K. Chang, “Real-Time Demonstration of Adaptive Functional Split in 5G Flexible Mobile Fronthaul Networks,” in Optical Fiber Communication Conference, 2018, vol. 2018, p. Th2A.48.

[9] Z. Tan, C. Yang, J. Song, Y. Liu, and Z. Wang, “Energy consumption analysis of C-RAN architecture based on 10G EPON front-haul with daily user behaviour,” in 2015 14th International Conference on Optical Communications and Networks (ICOCN), 2015, pp. 1–3.

[10] K. Kondepu, “Performance Evaluation of SDN-Controlled Green Mobile Fronthaul Using a Federation of Experimental Network,” Photonic Netw. Commun., vol. 37, no. 3, pp. 399–408, 2019.

[11] Cisco, “Cisco Catalyst 9200 Series Switches Data Sheet,” Accessed: May 2019. [Online]. Available: https://www.cisco.com/c/en/us/products/collateral/switches/catalyst-9200-series-switches/nb-06-cat9200-ser-data-sheet-cte-en.html#Warranty.

[12] Cisco, “Cisco 10GBASE SFP+ Modules Data Sheet,” Accessed: May 2019. [Online]. Available: https://www.cisco.com/c/en/us/products/collateral/interfaces-modules/transceiver-modules/data_sheet_c78-455693.html.

[13] 3GPP, “TS 36.321 V15.6.0 (2019-06) Evolved Universal Terrestrial Radio Access (E-UTRA); Medium Access Control (MAC) protocol specification.”