

Energy Consumption of Nomadic 5G Systems

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Abstract—Nomadic 5G systems are often deployed to provide temporary coverage at large events, in agricultural settings, for constructions sites or for disaster response. Because such systems regularly rely on self-contained, limited power sources such as batteries, low energy consumption is crucial for sustainable operation. This paper examines the energy consumption of two transportable 5G campus network systems. The first one is equipped with O-RAN-based radio units, a 5G core and an edge GPU server and is fully instrumented with energy meters.

We analyze energy consumption under different workloads and test the power supply using batteries and a hydrogen fuel cell. We furthermore examine the energy consumption of a second, minimal system setup. Our results provide new insights into the energy footprint of nomadic 5G systems and highlight key challenges for energy-efficient, temporary network deployments. Furthermore, we provide first targeted optimization proposals.

Index Terms—Wireless networks, energy consumption, hydrogen fuel cell, nomadic, nomadic network, 5G, 6G

I. INTRODUCTION

5G campus networks provide reliable connectivity with low latency and guaranteed bandwidth within a confined but possibly large area. While the connected devices may be mobile, the network itself remains *stationary*, covering a fixed and well-defined area throughout its operational lifetime. In contrast, *nomadic 5G systems* allow the entire network—including core network and radio access network (RAN)—to relocate and establish temporary network coverage on demand. Nomadic 5G campus networks have been developed for a variety of domains, including agriculture [1]–[3], manufacturing [4], construction [3] or emergency/disaster response [5].

Nomadic networks typically operate off-grid, making energy efficiency a key design constraint. Their mobility necessitates the use of self-contained, limited power sources such as batteries. This reliance directly affects power capacity and heat dissipation design, ultimately shaping the system’s size, weight, and cost. However, no prior work has systematically analyzed the power consumption of nomadic 5G systems.

Our contribution is the first holistic study of component-level energy consumption across all elements of two nomadic 5G systems. The larger one was developed as part of the NoLa project for smart agriculture applications. The second system is small enough to be carried by one person and is designed for students’ hands-on projects and proof-of-concept studies with

industry partners. We cover the Radio Access Network (RAN) as well as core network and edge GPU server and provide the first analysis of energy usage in mmWave-based systems within such a deployment scenario and (to the best of our knowledge) the first hydrogen-powered 5G system. We also discuss how energy consumption can be optimized in future nomadic 5G systems.

This paper is structured as follows: Section II presents related work. Section III describes the NoLa system and its energy consumption while Section IV presents the highly-portable system and its energy needs. Section V discusses findings from the experiments and proposes optimizations. Section VI concludes the paper.

II. RELATED WORK

Due to their massive power demands and the corresponding cost, the energy usage of country-scale cellular networks is of high interest to operators: over 90 % of cellular network energy consumption is attributed to operation [6], [7]. In such networks, 50–73 % of the operational energy consumption is attributed to the radio access network (RAN) [8]. At the same time, present base stations show low load adaptivity: even under low utilization, they still consume about 70 % of the energy required during full-load operation [6], [7], [9], a number in line with our experimental results.

As a consequence, energy-efficient RAN design is increasingly in the focus of research and standardization, and a variety of technical approaches are discussed e.g. in 3GPP TR38.864 [10] for Release 18. A good overview of possible energy-saving measures in the RAN is provided in [8]. Although the energy consumption of mobile networks is so important, there remains a striking lack of actual measurement data from operational systems as noted by the 6G-IA [11].

Closest to our work is a recent study by Al-Tahmeesschi et al. [12] which investigates the energy consumption of ORAN-based radios for splits 7.2b and 8. In the split 7.2b configuration, the power consumption of the RU, CU, and DU is reported to remain nearly constant regardless of network load. While the reported RU power consumption of 29–46 W closely aligns with our results (37–53 W), the situation is different for the CU and DU consumption: while Tahmeesschi et al. report a nearly constant consumption of 187–194 W irrespective of load or up- or downlink direction, our study shows a load increase especially in the CU-Server depending on system load. Since our CU and DU have identical hardware

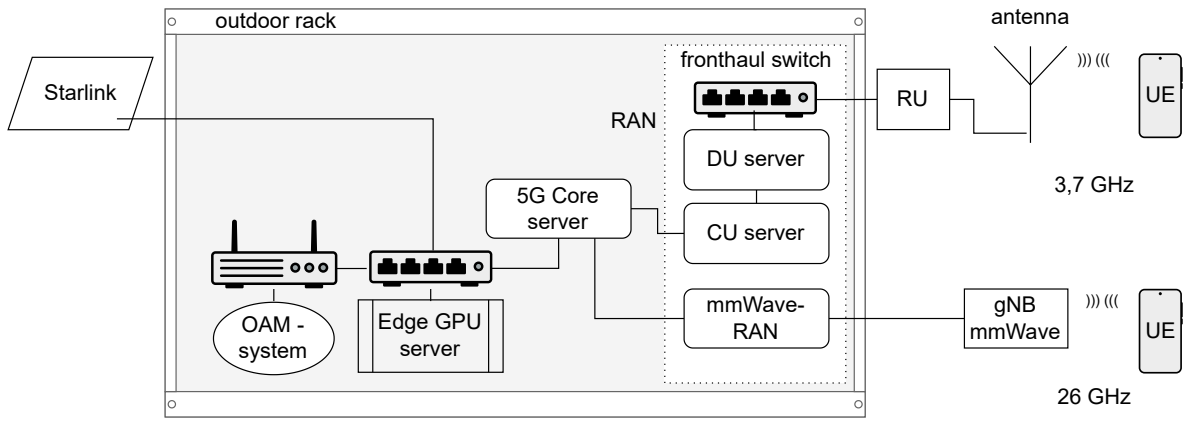


Fig. 1. Architecture of the nomadic 5G system from the NoLa project.

and special power meters are installed on all relevant hardware components, the difference can be attributed to the different measurement methodology, as [12] only takes estimates of the software components into account.

In contrast to these previous works, we provide a holistic view of energy consumption in nomadic 5G systems, covering the RAN as well as all other major network components. To the best of our knowledge, no prior studies have reported comprehensive energy consumption data for 5G campus networks as a whole—particularly for nomadic 5G network systems.

III. NOLa 5G SYSTEM

The NoLa 5G system is a nomadic, multi-purpose experimental 5G system designed within the NoLa project. The system has been built to support a range of applications with a focus on viticulture. Its development was motivated by the need for reliable, high-bandwidth connectivity in environments where public 5G coverage is unavailable or insufficient—such as the steep-slope vineyards of the Moselle region in western Germany. Besides connectivity, the system provides an edge GPU server for AI workloads. Its primary application is a closed-loop control process in which the 5G system operates as an integral component of a larger system. In this loop, the robotic platform acquires raw sensor data and transmits it via 5G to the edge GPU server, where the data is processed and control commands are generated. These commands are then sent back over the same wireless interface to the robot, enabling the execution of autonomous agricultural tasks such as mulching, defoliation, and crop treatment. Beyond smart farming, the NoLa system has also demonstrated its versatility in the areas of connecting machines for road construction and disaster management.

A. Architecture

The NoLa 5G system consists of a core network and two 5G gNBs for 3.7 GHz and 26 GHz (mmWave). The main components are supplied by CampusGenius, Airpuls and Microamp and are ORAN-enabled (Split 7.2a) following 5G

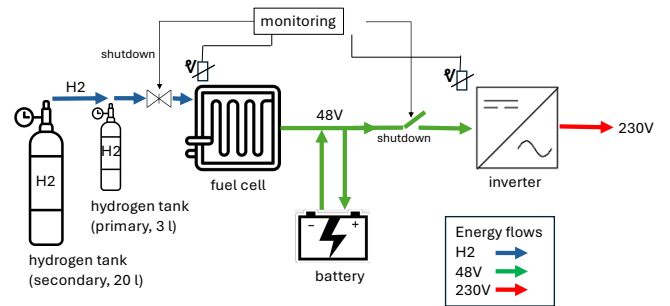


Fig. 2. Architecture and energy flows of the NoLa 5G system fuel cell.

RAN 3GPP Release 16. Fig. 1 shows the internal structure of the system. It consists of five servers to support 5G core, CU, DU, mmWave RAN, and edge GPU functionality. Since it is used nomadically, all servers are hosted in a single server cabinet and the antennas are mounted on a telescopic mast. The core network's N6 interface is connected to a satellite ISP to provide Internet access to the system and the attached UEs. System administration and data logging are performed by a self-created OAM system (Operations, Administration, and Maintenance) installed on a RevolutionPi. This is connected to the switch via an additional router and enables network access. A fan cools the control cabinet. The nomadic 5G network platform can be powered by a) battery, b) a gasoline generator or c) hydrogen fuel cell.

The hydrogen fuel cell can provide a continuous output of 2 kW and a peak output of 3 kW for up to 30 min, delivered via two 230 V sockets. For operational monitoring, multiple sensors for parameters such as temperature and pressure are integrated. Mechanically, the system is integrated into a compact 19-inch rack to enable efficient use with the nomadic 5G system. The overall architecture is depicted in Fig. 2.

The system with the hydrogen fuel cell as power supply is shown in Fig. 3, with the following components: 1) 5G core server, 2) CU server and DU server, 3) fronthaul switch

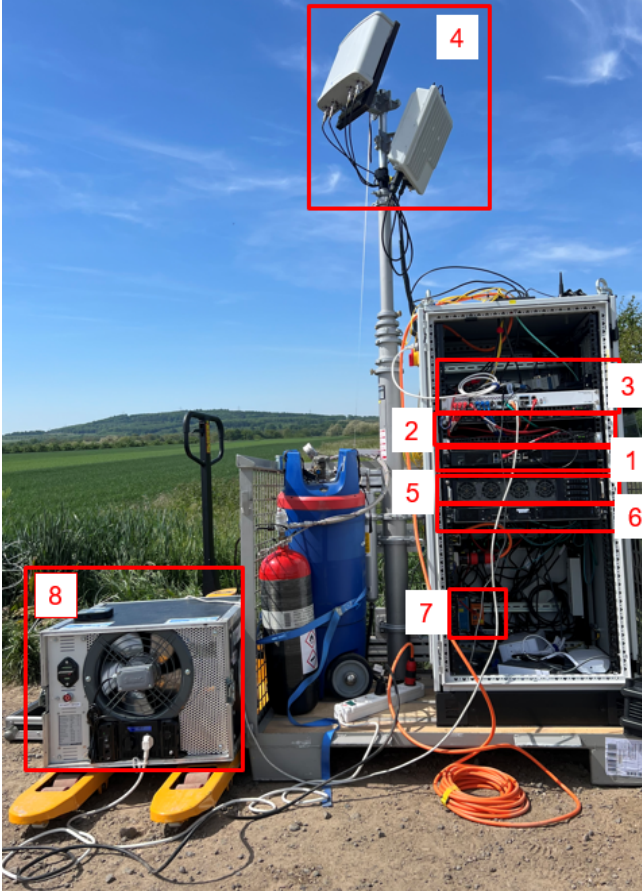


Fig. 3. Nomadic 5G network platform with hydrogen fuel cell.

(yFalcon-RX), 4) RU (Benetel RAN650) and antenna, 5) edge GPU server (Intel single-CPU RI1204-AIXSG with Intel Xeon Gold 5317), 6) mmWave RAN server, 7) OAM system (RevolutionPi Connect 4), 8) hydrogen fuel cell with buffer battery.

Note that the system design does not optimize for low energy consumption; instead it targets application requirements alongside administrative, legal, and organizational constraints. The O-RAN-based architecture increases the number of system components compared to a monolithic gNB, but in return provides broad access to system parameters – resulting in an open, highly capable and still transportable experimental system.

B. Power Measurement Setup

To quantify the power consumption of the NoLa 5G system, we measure the total system power at the central power supply and additionally monitor the energy consumption of selected individual components. Component-level measurements are performed for the antenna, the five servers in operation, and the OAM system. Elements assumed to consume power at a constant rate, such as the fan, WiFi router, and switches, were not measured individually but are included in the overall system load. Any fluctuations in performance during the

measurement series are attributed to measurement inaccuracies and to the temperature-controlled regulation of server rack and switch fans (consuming in the off state 0 W, and in on state a total of ca. 30 W). These effects are not examined in detail in this paper. We use Shelly Plus Plug S smart plugs as energy meters, as they are cost-effective and can be easily installed in the power supply lines of the components mentioned above. The measurement error of these smart plugs is 5 % at 60 W and decreases to 0.9 % at 1500 W [13]. Since the total energy consumption of the NoLa system does not exceed about 1000 W, assuming a linear behavior of the measurement error, the absolute error is expected to be around 10 W. The experiments have been executed without specific energy-saving functionality like micro-sleep [10] on hardware or software side and the transmission power of the antennas is set to 10 W.

C. Experiment I - 3.7 GHz Setup in Idle State

Fig. 4 shows the required base load of the system. After switching on the power supply, the servers boot up and go into standby mode. None of the software components of the 5G system (CU, DU, core network software) are running, thus experiment I exposes the energy consumption of the running servers, without additional software. At the beginning, there are power consumption peaks caused by the servers booting up, etc. After this settling phase, the system stabilizes. The components require a relatively constant amount of power in this state. The entire system consumes approximately 755 W in the constant state shown here, the per-component values can be found in the first column of Table I. Note that the mmWave server - while unused here as well as during experiment II and III - was not in operation and was therefore in standby mode, yet it still consumed a constant power of 26 W. This is attributable to the IPMI/BMC for out-of-band access, although this was not investigated in detail.

The rise in antenna power consumption after about 750 s may occur because, after a period without connection to the 5G core, it switches to transmit/receive mode to signal that the core is unreachable. This was not investigated further.

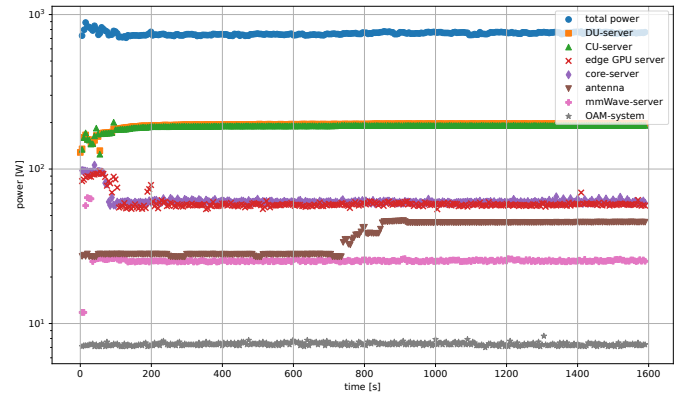


Fig. 4. Power consumption when all servers are running, but 5G software is not yet running (experiment I).

D. Experiment II - 3.7 GHz Setup Control Plane Only

In the second experiment, the system is operated with the software for the 5G core/O-RAN/antenna switched on. A connection to the end devices has already been established; however, only control plane data required for connection setup (N1 and N2, as defined in 3GPP TS 23.501 [14]) has been transmitted. No user plane data via N3 is being exchanged. As shown in Table I, the system's overall power consumption raises by (only) 81 W to 836 W due to this.

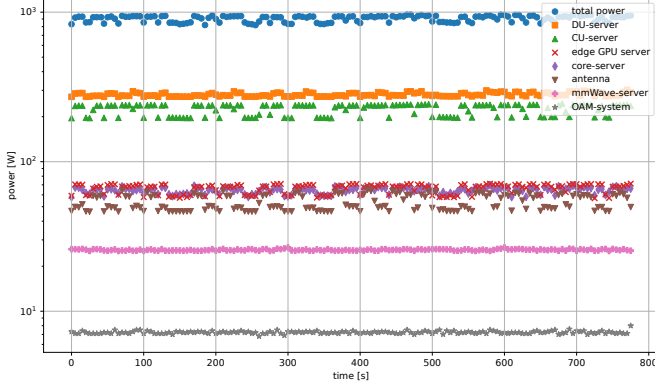


Fig. 5. Power consumption of the NoLa 5G system when transmitting user plane traffic with maximum throughput (experiment III).

E. Experiment III - 3.7 GHz With User Plane Traffic

In the third experiment, we add user plane traffic via N3 [14]. Load is generated by continuously measuring the throughput between edge GPU server and UE, alternating between downlink and uplink directions. To this end, we installed the open-source speed test application openSpeedtest on the edge GPU server. The tool determines maximum throughput and saturates the available bandwidth. Typical throughput ranged from 340–450 Mbps for downlink and 120–139 Mbps for uplink, depending on the distance between UE and antenna. As shown in Fig. 5, user plane traffic causes a notable increase in power consumption, with expected fluctuations across CU, DU, 5G core, and edge GPU server. The CU server alternates between 195–200 W and 235–245 W, while the antenna alternates between 46–52 W and 58–64 W. As visible in Fig. 6, this results in a clearly bimodal power distribution, reflecting the alternating downlink and uplink transmission phases.

Table I shows the average consumption in the individual operating states. As expected, power consumption increases with increasing network availability and data exchange activity. Interestingly, the overall power consumption of the system increases by only about 150 W (or 20%) from the lowest to the highest operational state, and the major contribution to this is the higher power consumption in CU and DU that together increase their consumption by 123 W. To verify the influence of constant data throughput, we also performed measurements with fixed data rates of 5 Mbit/s, 8 Mbit/s, and 15 Mbit/s. The deviation of the components is 0.46% and can therefore be

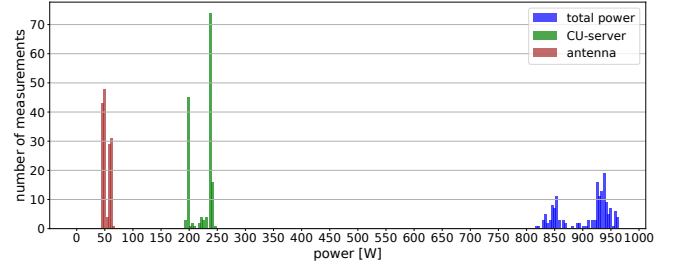


Fig. 6. Power distribution, counted in bins of width 4 W (experiment III).

TABLE I
NoLa 5G SYSTEM 3.7 GHz

device	no application running [W]	control plane running [W]	control and user plane running [W]
core-server	62	61	64
CU-server (3.7 GHz)	189	193	224
DU-server (3.7 GHz)	193	271	281
RU/antenna (3.7 GHz)	37	43	53
mmWave-server	26	26	26
edge GPU server	61	59	66
OAM-system	7	7	7
Switches/Starlink/cooling	180	176	186
total power	755	836	907

neglected as a major factor influencing energy consumption. At the time of measurement, only a load-testing server was running on the edge GPU server. Therefore, the application layer workload is low.

F. Experiment IV - mmWave

The experiment with the mmWave radio is conducted in the same way as the previous experiment. A higher sampling rate of 1 Hz was used, as a shorter overall measurement duration was considered due to the previous almost constant consumption results. The CU and DU servers, which start automatically when power is supplied, were switched off manually again after booting because they are not required for mmWave. The startup process results in higher power consumption in the “no application running” column. Interestingly, after shutdown, the power consumption for the CU and DU servers remains at approximately 16 W each. It is suspected that this is due to IPMI/BMC for out-of-band access and losses in the servers’ power supplies.

The results of this experiment are shown in Table II. Due to the different server structure in the mmWave setup (CU- and DU-server are switched off), its overall power consumption is lower. Furthermore, core-server, edge GPU server and OAM-system consume about the same amount of power as during the 3.7 GHz experiments. The consumption of the mmWave server indicates that this has a better power profile when in low use, as it only consumes 27 W in the ‘no application running’ state. Note that the power consumption of ‘Switches/Starlink/cooling’ is about 50 W higher than in the previous experiments. As experiment IV has been conducted

TABLE II
NoLa 5G SYSTEM, 26 GHz

device	no application running [W]	control plane running [W]	control and user plane running [W]
core-server	63	61	71
CU-server (3.7 GHz)	47	16	16
DU-server (3.7 GHz)	45	16	16
mmWave RU	112	109	113
mmWave-server	27	216	227
edge GPU server	67	61	71
OAM-system	7	7	7
Switches/Star-link/cooling	194	216	226
total power	562	702	747

outside on a sunny day, this might be a result of the necessary higher cooling fan speeds. Despite these differences, the two measurement series at 3.7 and 26 GHz show the same moderate increase in power consumption under full load.

G. Experiment V - Fuel Cell as Power Source

The next experiment focuses on powering the NoLa 5G system with the hydrogen fuel cell. The fuel cell here supplied both the NoLa 5G system and some further devices required for the test, such as laptops. Thus, the overall consumption is slightly higher than in the previous 3.7 GHz measurements.

Fig. 7 shows the hydrogen tank pressure and the power output of the fuel cell when the system is powered by hydrogen. At the beginning, the pressure rises because the measurement is taken at the outlet of the smaller 3-liter hydrogen tank, which is equipped with a pressure regulator, a safety device, and a pressure sensor. This tank was connected in series with a larger 20-liter hydrogen tank to ensure longer operating time. When both tanks are connected, an initial pressure equalization between the 20-liter (200 bar) storage tank and the 3-liter operating tank occurs (130 bar at first), which explains the observed rise at the beginning of the measurement. It can also be seen that consumption is approximately constant around 1000 W which means that the tank pressure also decreases at an approximately constant rate.

The battery is fully charged when the NoLa 5G system is started at the beginning of the experiment. This measurement proves that fuel cells are well suited as a power supply for nomadic 5G systems. Furthermore, it was possible to extrapolate that the selected hydrogen tank with 20-liter (200 bar) is sufficient for an 8-hour working day and thus represents a viable alternative to batteries.

IV. MINIMAL NOMADIC 5G SYSTEM - EXPERIMENT VI

In this section, we investigate whether a minimal configuration can be realized—one that deliberately limits transmit power, and thus coverage and data rate, in exchange for energy optimization. This minimal system retains only essential components and features a simple architecture, as illustrated in Fig. 8. Please note that also here, we use the devices in their standard configuration. The actual implementation is shown in Fig. 9. It consists of a small, fanless PC (HUNSN RJ17a) as

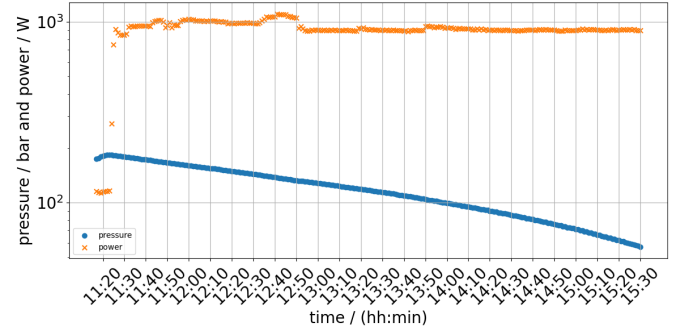


Fig. 7. Pressure of the primary 31 hydrogen tank and the power output of the hydrogen fuel cell (experiment V).

core server, running Open5GS version 2.7.6 as 5G Core and a Sercomm SCE5162-B78 small cell as 5G gNB.

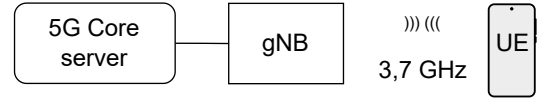


Fig. 8. Architecture of the minimal nomadic 5G system.



Fig. 9. Minimal nomadic 5G system.

It should be noted that this system exhibits markedly different performance characteristics compared to the one presented in the previous section: while the NoLa 5G system achieves a transmission range of up to 500 meters and download speeds in the range of 400 Mbps, the minimal nomadic 5G system reaches about 70 meters and speeds of 110 Mbps.

The same Shelly smart plugs were used to measure the energy consumption of the minimal nomadic 5G system. Similarly, no energy-saving functions are activated on either the hardware or software side, and the transmission power of the antennas is set to 1 W. Since the setup comprises only two components, two smart plugs are sufficient for monitoring. With this setup, the 3.7 GHz experiments I - III from the previous Section III have been repeated. The results are shown in Table III.

TABLE III
MINIMAL NOMADIC 5G SYSTEM, 3.7 GHz

device	no application running [W]	control plane running [W]	control and user plane running [W]
core-server	16	19	26
gNB	26	27	29
total power	42	46	55

In the idle state, the system consumes 42 W overall, increasing to 55 W when fully loaded. Interestingly, 10 W increase are contributed by the core network server, in contrast to only 3 W from the radio. This shows that a minimal and energy-optimized setup can work with a very low amount of energy, compared to a larger scale system.

V. RESULT DISCUSSION AND SYSTEM OPTIMIZATION

A number of learnings emerge from these experiments about the energy efficiency of nomadic 5G systems:

1) The fully loaded 5G systems consume only 20 - 33% more compared to the idle state, where, in fact, the 5G system software has not even been started. The difference becomes even smaller when comparing the "control plane functions running" states with the consumption at full user plane throughput: here, the increase is at most 8.5% for the larger NoLa 5G system (at 3.7 GHz) and 19.6% for the minimal system. These results indicate a generally low power-to-load adaptability of nomadic 5G systems, which is likely representative of 5G networks more broadly. Consequently, improving load-dependent energy scaling should be a key objective for future research and standardization efforts.

2) With higher system usage, energy consumption obviously increases: the main driver in the ORAN setups are the 'non-antenna components' of the RAN, i.e. CU and DU in the 3.7 GHz setup and the mmWave server at 26 GHz. The gNB in the minimal system setup which implements all RAN components in a single box also increases in power consumption, but just by about 10 W.

3) In the fully loaded state of experiment III, the NoLa 5G system exhibits an alternating energy consumption pattern, switching between two states (roughly 850 W and 930 W respectively) with a difference of about 80 W in between as visible in the distribution of total power in Fig. 6. We suspect this is a result of the system either transmitting or receiving, and our power meters recording the consumption in this instant.

4) The long-term measurements with hydrogen fuel cells show that such nomadic 5G systems hardly experience any power peaks, consumption remains virtually constant. This behavior is an excellent fit for fuel cells, and hydrogen therefore represents a viable alternative to battery-powered power supply. Even if future 5G systems would exhibit a better power-to-load adaptability, consumption peaks can be compensated by the battery that is part of the fuel cell design (see Fig. 2). As additional benefit, the two-bottle design utilized in this design enables longer unplanned operation. In the battery-powered configuration, the system has to be shut

down to replace the battery (or high losses would occur when charging the built-in battery with another battery). With the two-bottle design, it is easy to swap the larger bottle while the smaller one continues to supply the system.

5) The considered NoLa 5G system relies on standard industrial servers, which are not optimized for energy efficiency due to their high performance and active cooling requirements. Consequently, hardware selection itself has a substantial impact on overall energy consumption. The use of industrial-grade, energy-efficient computers with passive cooling (as in the minimal system) instead of standard 19-inch rack servers thus offers fundamental advantages, as it reduces both the baseline power consumption and the additional overhead caused by active cooling.

6) The overall energy consumption of the NoLa 5G system is primarily driven by the high power demand of individual servers and the architectural decision to deploy separate hardware for each functional component (CU, DU, core, edge, and mmWave server). Consolidating these components onto fewer physical servers, for example through containerized deployment using Docker, offers substantial potential for reducing energy consumption. This approach can be further enhanced by dynamically scaling resources, where additional servers are activated only under increased load and components are migrated accordingly. While eliminating redundant power supplies may reduce reliability, it can also contribute to improved energy efficiency in nomadic deployments. In addition, both cooling and standby operation significantly impact total power consumption, particularly as the servers in our setup consume up to 16 W even when switched off. Therefore, an energy-efficient system design should minimize the number of active hardware components, favor software consolidation on shared infrastructure, and incorporate load- and capacity-aware control mechanisms to optimize server utilization.

VI. CONCLUSIONS

Our work examines the power consumption of two nomadic 5G systems in the 3.7 GHz and 26 GHz bands. We show that a well equipped system requires 560-900 W of total power depending on operation state and that power consumption remains high even in idle mode.

The analyzed systems exhibit only limited load-dependent scaling, consuming a large fraction of their peak power even at low utilization. This indicates a lack of energy proportionality and highlights the need for future system designs that more effectively adapt power consumption to the actual load. Furthermore, our results demonstrate that hydrogen is a suitable power source for nomadic applications. We also identify optimization potential through the selection of alternative hardware components for both the core network and the RAN.

In future work, we plan to examine the optimization potential of virtualization of the system's software components and the influence of 3GPP-specified energy-saving functions on energy consumption. This should enable the operation of

nomadic campus networks with a more compact design and longer network-independent power supply.

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