



# Article Multi-RAT Orchestration Method for Heterogeneous Wireless Networks

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### Featured Application: Future wireless heterogonous networks.

Abstract: Currently, energy efficiency (EE) of wireless communication is essential where many wireless networks with different Radio Access Technologies (RATs) coexist together. The RATs can be effectively selected and managed on a higher level to achieve maximum EE and save energy, e.g., save batteries. The approach to wireless traffic steering in mobile networks with a proof-of-concept solution is presented in this paper, owing to the developed high-level multi-RAT (multi-Radio Access Technology) heterogonous network orchestration approach. Based on the high-level network orchestrator, which traces network indicators, it is possible to decrease the user mobile terminal energy consumption, keeping traffic speed at an adequate level. The solution discussed was implemented in an experimental testbed with Software Defined Radio transmission systems. Downlink and uplink data links were toggled among different RATs according to the decisions that were taken by the end-to-end multi-RAT orchestrator based on the received proper network traffic-related indicators. The authors focused on finding an adequate algorithm that allowed for reduced power usage in the user terminal and made the attempt to verify how to reach the power reduction without introducing RAT-specific rules. The results showed that the proposed orchestration EE reduction was observed (from 11% to 42% for two different scenarios) in relation to the single LTE network deployment. The orchestration compared to the Wi-Fi network does not provide EE gain (-7% and 0%, respectively), but allows the user to achieve a higher data rate (23% and 39% gain, respectively), thus keeping the energy efficiency at almost the same level.

Keywords: wireless communication; network orchestration; multi-RAT; Software Defined Radio; 6G

## 1. Introduction

Currently, many wireless radio systems are being implemented around the world, which increase the number of deployed radio services with new possibilities [1,2]. However, the implementation of new 5G mobile networks in many countries is taking place gradually and slowly, and in the coming years it will not cover many areas, especially rural and distant from city centers—where other legacy radio services will still exist [3]. Depending on this mobile network deployment scenario, it may be not possible to deliver the expected service quality to these areas. In contrast, in vertical markets, such as industry and factories [4], green field network deployments need to be managed and coexist with various other legacy radio networks at the enterprise level. There are other currently deployed non-3GPP network solutions that offer wireless services in a way that is often more accessible from an investment perspective (e.g., from the spectrum fees point of view), more energy-efficient, or at the same level of required quality as the services provided in mobile networks, e.g., by Wi-Fi networks, ZigBee, LoRa, Bluetooth, and others. Research and work on so-called "beyond 5G" (6G) future wireless systems are currently being carried out worldwide. Those future networks would not necessarily use only single radio access and protocols technology (e.g., 3GPP 4G/5G), but would also use solutions based on heterogeneous



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**Copyright:** © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). integrated networks from the transmission medium point of view [5,6]. From a user point of view, usually only end-to-end (E2E) connection with a defined adequate quality based on defined KPIs (Key Performance Indicators) is needed—for example, expected throughput, delay, or others. In these future wireless networks, new requirements are expected that will also allow for the implementation of the E2E connections through various common managed radio interfaces via multi-RAT (multi-Radio Access Technologies) coexisting together. On top of this multi-network scenario, the E2E orchestrator placed outside a single RAN (Radio Access Network) may take the role of a data traffic controller, which will secure the proper indicator values (e.g., throughput), even including additional indicators that have not yet been defined for 5G networks (e.g., link-level energy savings, cost savings related to the spectrum fees or other factors, usage of unlicensed bands, or radio protocols with lower energy demand) [7]. Therefore, our work was undertaken to analyze the current directions of research in this field and to develop a practical prototype of the new type of wireless network orchestration. The main goal of our research was to develop a high-level solution to manage connectivity based on different indicators and to establish optimal decisions, for example-for user terminal power saving counters, taking into account the active monitoring of user throughput, as battery lifetime directly affects user experience—despite the fact that the performance matrices are good [8].

The paper is organized as follows. First, in Section 2, the current state-of-the-art is reviewed concerning heterogeneous wireless networks and SDR (Software Defined Radio) solutions, with particular emphasis on the solutions and practical tests that form the background of this work. Next, the energy efficiency aspects are presented. In Section 3, Materials and Methods, the concept and implementation of the proposed technical solution for the heterogeneous network orchestration are described. The measurement outcomes achieved in the testbed implementation are presented in Section 4. At the end, in Section 5, the results achieved are summarized and discussed. Finally, further possible development directions are indicated and concluded in Section 6.

#### 2. State-of-the-Art

Many types of services today (e.g., industry, healthcare, public sector, mass events, home automation, entertainment, media, etc.) require access to wireless networks as never before. While each vertical has its own specific needs, the demand for applications and services even within such a single market segment may vary significantly. An example of this is the production and industrial environment in factories, where there are various requirements for wireless communication types existing simultaneously. Needs in such environments range from low data rate and at the same time very low latency, closedloop communication between (parts of) machines, interaction over real-time based on requiring high throughput and reliability 3D video transmission, collaborative robots and people, downloading large amounts of data—which are not time-critical, to updating machine software. In many cases, different applications and services must share the same wireless infrastructure and compete for access to limited spectrum resources, which makes it difficult to meet the QoS (Quality of Service) demand requirements for different types of services in the same environment within one network radio. Radio resource management that are currently available in wireless technologies have to manage extremes (ultralow latency, very high throughput, and very high reliability) and with divergent needs (low and high data rates, time-critical communication needs), which becomes possible (sometimes partially and not all at the same time) only in the current 5G network solutions (3GPP rel. 16-17).

Therefore, the development of wireless networks is currently taking place at different levels, which enable the creation of many parallel network slices [9], each of which creates a separate data stream dedicated to specific applications. There are also many types of radio interfaces, including Wi-Fi, 4G/LTE, 5G/NR, LoRa, Zigbee, Sigfox, and others embracing a wide range of different Radio Access Technologies (RATs). In a given market segment (e.g., factory), dedicated radio interfaces for different applications are typically used. Often

it is a situation where the appropriate QoS quality and appropriate network parameters are available at a given location of the factory in one radio interface (RAT) and it is not possible in other RATs or some (noncritical) services may be performed with lower quality, e.g., in another radio interface, leaving adequate space for high QoS and Key Performance Indicators (KPIs) for critical services. Therefore, the concepts of using multiple different (from a technology point of view) radio networks (heterogeneous networks) are developed simultaneously by means of the so-called multi-RAT (multi-Radio Access Technology) networks [10].

In the concept of a multi-RAT heterogeneous network, service management is dedicated to ensuring the appropriate quality of services and its indicators for individual links (end-to-end E2E) without the need to use a defined one radio layer (RAT) at the start. The proposed network has a wireless architecture consisting of interfaces of many radio networks, ensuring tight integration of radio access through selected network interfaces and appropriate traffic control, data path selection, and aggregation of traffic flows from (and to) various sources, ensuring appropriate link parameters. This enables increased quality, a variety of network bandwidth variants, and increased network reliability with different QoS levels. In particular, it is possible to trace and control the traffic of users connected to several radio interfaces on a common higher layer control plane by means of an orchestrator managing these technologies and interfaces. This concept goes beyond the traditional 5G network solution, as the 5G network itself may be only one element of a wider multi-RAT network environment, characterized by specific features and various KPIs, which are not defined within the current 5G state-of-the-art solutions by ITU and/or 3GPP for the 5G NR. It refers to the development of the 5G network (beyond 5G) toward future 6G network solutions, where new KPIs will be introduced, not defined currently within the 5G framework (e.g., link energy efficiency, battery saving, and others), the implementation of which can be ensured by a properly managed multi-RAT network orchestrator.

The latest trends in the use of software in the network, such as Software Defined Networking (SDN) and Network Function Virtualization (NFV), are opening new opportunities for operators, especially in deploying highly adaptive networks and offering defined specific requirements to end users. The centralized nature of SDN can directly help in obtaining network context information that can be used to optimize resources. The use of SDN allows for an even better implementation of the multi-RAT concept. For example, in [11], the authors proposed an SDN-based multi-RAT LTE and Wi-Fi data flow management system. In this case, a multi-RAT solution for automatic off-loading was proposed. Another paper [12] analyzes the multi-RAT solution in low-power, low-bitrate LPWAN networks (NB-IoT, Sigfox, and LoRaWAN) used to optimize the energy consumption and extend the life of battery transmitters.

It should be noted that various terms referring to "heterogeneous networks" exist. For some, even a single mobile network operator's environment, consisting of different 3GPP RATs (3G, 4G, 5G) or different cell types (macro, micro, pico), may be treated as a heterogeneous network. In other cases, it is also referred to as a cellular network, but with different radio band accesses, i.e., licensed, unlicensed LAAs, and/or shared LSAs). In this paper, we are using the broader concept of the heterogeneous wireless network term, which includes mobile networks (4G/LTE, 5G/NR, 6G) along with other non-3GPP RAT radio solutions (WLAN, LPWAN, RLAN), transmitting in licensed, unlicensed, and shared frequency bands—a new type of hybrid heterogeneous wireless network managed at the highest level while orchestrated on the hypernetwork layer setting.

At the radio level, there is the emergence of various multi-RAT radio network managers and the current development trend of software-defined radio solutions (SDR— Software Defined Radio) that can also be observed. SDR is a radio system in which transceiver components that are typically implemented in hardware (to name a few: implemented digital multiplexers, filters, equalizers, modulators/demodulators, multiple antenna techniques in an ASIC, i.e., application-specific integrated circuit) are instead implemented by computer software or an embedded system equipped with programmable hardware such as an ASIP (Application Specific Instruction Set Processor) or an FPGA (Field Programmable Gate Array). The combination of the multi-RAT technique with SDR solutions allows for modeling and predicting the emergence of new cases of its application, e.g., single radio systems (front-end) implementing many radio interfaces on one transmitting device (SDR/FPGA) or others. This may in the future further simplify the configuration and management of the radio interface, especially its analog radio part. Table 1 presents an overview of the currently available open source SDR software solutions dedicated for mobile system emulation and testing. The projects presented encompass both the Radio Access Network (RAN) and the core network (CN). RANs for the following solutions have a fully implemented Layer 1–3 radio protocol stack (i.e., PHY, MAC, RLC, PDCP, and RRC).

Software	eNB	gNB	EPC	5GC
OpenAirInterface [13]	Yes	Yes	Yes	Yes
srsRAN [14]	Yes	In development	Yes	No
Open5GS [15]	No	No	Yes	Yes
OMEC [16]	No	No	Yes	No
free5GC [17]	No	No	No	Yes

Table 1. Available open source solutions for mobile networks using SDR.

Programmable radio systems using the software solutions listed in Table 1 have been used in many research projects thus far, such as network coexistence analyzing using shared access to spectrum, smart metering in LTE networks [18], managing radio resources between Wi-Fi and LTE-U networks [19], developing a solution supporting the search for people after a disaster [20].

Analysis related to multiRAT related to traffic steering cannot ignore the proposed functional solutions developed by the 3GPP group, allowing for simultaneous data transmission via Wi-Fi and LTE networks, as well as only via LTE networks using both licensed and unlicensed bands, owing to aggregating all available bands. The use of wireless network deployment in unlicensed bands gives some freedom in network expansion by both operators and users. The former have the ability to increase the network capacity without the need to acquire new spectrum resources, while the latter may take measures to increase the coverage and/or capacity of the network regardless of mobile network operators. These rationales prompted work by 3GPP standardization organizations, which resulted in a series of technological solutions to enable the shared use of the bands.

During simultaneous transmission via Wi-Fi [21] and LTE, in such a way where the LTE RAN network does not need to know about parallel data transmission in Wi-Fi, there are limitations in maintaining IP mobility between networks. Moreover, difficulties arise from the need to select a particular WLAN network and to determine the conditions on which WLAN networks should be selected. For these needs, 3GPP has specified the Access Network Discovery and Selection Function (ANDSF), where a dedicated server in the operator's network controls and manages the connection [22,23]. Another approach is to implement functionality at the RAN level through LTE-WLAN aggregation (referred to as LWA). The data stream splitting with subsequent aggregation then occurs in the LTE PDCP layer, thus the data are transmitted via LTE and Wi-Fi. LAA (Licensed-Assisted Access) is a certain standardization approach close to LWA in the unlicensed 5 GHz band where transmission is carried out via the LTE with dedicated mechanisms to avoid collisions with Wi-Fi networks. It should be emphasized, however, that the LAA does not allow transmission in stand-alone mode, i.e., a primary cell (Pcell) working in the licensed band is always required, a cell in the unlicensed band is configured as the second (Scell-secondary cell) and is used only in conjunction with Carrier Aggregation (CA). The cell serves the user and aggregates the bandwidth of divided packets at the MAC layer level. A 4G/LTE network that can operate without the need to cooperate with cells in the licensed band is

the product solution developed by MulteFire Alliance [24]. Moreover, in 5G/NR-U, no aggregation with the cell in the licensed band is required. Details are presented in Table 2.

**Table 2.** List of 3GPP products and functional solutions enabling data transmission in unlicensed bands.

Radio Interface	Solution	<b>3GPP Release</b>	Standalone Operations
4G/LTE	LAA	Rel-13	No
4G/LTE	eLAA	Rel-14	No
4G/LTE	feLAA	Rel-15	No
4G/LTE	MulteFire	-	Yes
5G/NR	NR-U	Rel-16	Yes

Figure 1 shows schematically the places of the so-called data split. It can be seen that the mechanisms described above perform splitting at the Access Network (RAN) layer. In the case of E2E network orchestration, decisions about switching (or dividing) the data path may occur outside the decision space embedded in the architecture of a given system. Listed short summary of data transmission in the unlicensed band (both in the single-RAT and multi-RAT models), at least two basic goals should be noted: using the maximum needed throughput from the perspective of the end-user device and releasing resources in the licensed band (so-called offloading). These solutions, referring to the developments undertaken within the 3GPP, are used in places where it is necessary to achieve the goals mentioned above. However, they require a connection to the LTE network and they should be under the control of the LTE network (operator). Thus, in the case of bottlenecks and lack of free radio resources, it may be impossible to serve users, especially those who do not have an appropriate profile determining a higher priority in access to resources or are not within the coverage of LTE networks.

As part of the work on the LTE standard, 3GPP has developed the possibility of cooperation with WLAN networks by integrating them directly into the EPC backbone network (so-called non-3GPP Access). At this level, the EPS allows the non-3GPP network to be connected to the EPC. This applies to WLAN networks, WiMAX, and fixed cable networks. Non-3GPP is divided into trusted and untrusted access. The operator defines the group to which the given network belongs. Trusted non-3GPP networks can obtain a direct connection to the EPC. In contrast, untrusted non-3GPP networks can connect to the EPC through a dedicated node called ePDG (Evolved Packet Data Gateway), whose role is to provide security mechanisms (Figure 2). As part of access to the LTE network through non-3GPP networks, a mechanism related to the so-called IP Mobility is implemented [25,26]. Among others, owing to the IFOM solution (Mobility with IP address preservation for selected IP flows), the user terminal supporting this functionality has the ability to route different IP routes to the same PDN (through different access networks). It should be emphasized that packet route choices cannot be made in remote data centers due to delays that would be unacceptable for the adopted solutions. These solutions are not intended for choosing a radio interface that could completely replace the cellular network (here LTE), which is treated as the basic RAT from the user service point of view.



**Figure 1.** The architecture of LTE networks with locations (marked in color), in which a decision to split the data stream can be made to/from the user terminal (UE).



**Figure 2.** The architecture of LTE networks with locations in which a decision to split to 3GPP and non-3GPP access can be made to/from the user terminal (UE).

In 5G/NR networks, cooperation with non-3GPP networks is also provided and is supported by the non-3GPP Interworking Function (N3IWF) component, where it acts as a gateway to the 5G network. It is worth emphasizing that the use and integration of a specific network (e.g., WLAN) as a non-3GPP network requires cooperation with the operator. Thus, in this study, the management of access to the network from the E2E level is considered where the decision-making processes are taken both beyond the access network and the backbone.

Orchestration at a higher level (over 3GPP networks) allows, in particular, management of traffic in places where the 3GPP network is unavailable (especially in case of lack of coverage) or its parameters do not allow implementation of a specific KPI defined by the user for a given end-to-end links (such as energy efficiency). Such orchestration requires the use of specific policy rules, which may relate generally to both technical parameters (QoS, KPI) and business indicators (link cost, selection of specific equipment suppliers), or others (selection of licensed/unlicensed bandwidth, energy consumption on a given path, and others). The possibility of using multiple RAT networks allows for a broader definition of orchestration parameters and is not limited to only qualitative criteria. Decision rules can be freely defined and changed at the programming level, without the need to violate solutions of radio interfaces. The scope and type of networks will depend on the manager ordering the multi-RAT networks.

According to the development of new telecommunication standards and introduction of new services, there is an expectation and strong pressure to improve mobile terminal power consumption. It is necessary to gain user experience, which means ensuring a long battery lifetime, owing to the reduction of power consumption. From the 5G standardization perspective, ITU in [27] put the energy efficiency aspect as one of the minimum basic technical performance requirements for 5G networks. This requirement encompasses both:

- (a) Efficient data transmission in a loaded case;
- (b) Low energy consumption when there are no data.

It is worth distinguishing that the total device energy savings can be achieved through the reduction of power consumption by either hardware solutions (e.g., proper CPU, screens) or adequate radio interface solutions, and their implementation. Referring to [27] below, a list of basic features, which are strictly dedicated to power saving aspects, may be indicated:

- Power consumption reduction during the network access;
- Dynamic adaptation to traffic in different dimensions (carrier, bandwidth, and beamforming);
- Improvement of RRM measurements for low mobility UE.

Furthermore, currently, mobile networks, both 4G/LTE and 5G/NR, widely use DRX (Discontinuous Reception) techniques, which allow for partial monitoring of the physical DL channels only in repetitive time slots defined by so-called time profiles. DRX capable UE receives RRC messages with the proper configuration, which allows for full synchronization with the base station. These solutions can reduce the total energy consumption in a macro timescale. Besides the RAT specific approach, mobile network deployments also impact directly on the UE energy consumption, what is caused by radiated power, distance to base station, indoor/outdoor reception, and network densification.

In our research scenario, we implemented a new network element, i.e., a high-level E2E orchestrator placed outside radio access networks. The main goal is toggling transmission across different RATs based on instantaneous energy efficiency metrics, which depend directly on the proposed solution. This solution monitors the continuously changing radio network environment and makes decisions on current links usages depending on the present best energy efficiency of terminals during communication.

#### 3. Materials and Methods

The motivation of our work coincides with the discussion concerning the Inter-RAT inter-system energy saving solution, which is addressed also by the 3GPP Release 16 [28,29] (however, RAT here means a 3GPP related RAT, not a generic one) and in [30]. Addressing the topic of a multi-RAT heterogeneous wireless network and managing them at the hypernetwork level (orchestration of various radio networks) together with the possibility of its practical implementation in the SDR environment (Software Defined Radio) is part of the current global research trend in the field of wireless networks and allows for obtaining results that are convergent or even beyond the current state of the art in this field. Such an approach is presented in Figure 3, where the mobile network coverage is overlaid by another RAT, which energy efficiency is higher or the instantaneous UE energy consumption is lower.

A prototype proposed solution for testing is composed of two different radio networks (RATs): Wi-Fi and LTE, established using software defined radio technology with the orchestrator set on the top of both RATs and continuously monitoring network parameters and making a decision on switching transmission between the two RATs. Basic mobile terminal (MT) power consumption metrics for different RATs are stored in the E2E orchestrator, which allows for traffic steering with the goal to decrease terminal power consumption. Our approach can allow tracing of power-saving and throughput for terminal oriented indicators. This approach is sufficiently flexible for traffic steering among generic RATs, including those not defined directly by 3GPP. Based on the E2E managing approach, it is still possible to keep flexible data reconnection toward 5G, 6G, and future Wi-Fi (Wi-Fi6 and next), or if other KPI-oriented services need to be maintain.



**Figure 3.** Sample visualization of cellular network coverage (e.g., 4G/LTE, which coverage is overlaid by another RAT, e.g., Wi-Fi).

The testbed configuration is depicted in Figure 4. Two different RATs were connected to the public network via eNB and the access point. The throughput KPIs for both were reported to the nonreal time E2E orchestrator, which is delay sensitive and treated as a new network element. Network context DB stores the latest reported data. UE took the role of DUT. Multi-RAT consists of LTE and Wi-Fi networks, which are accessible via an external modem (UE). The network traffic was artificially steered to simulate different data rate values affected by traffic load and congestion. The decreasing data rate was also treated as a simulation of transmission on a cell edge where lower order modulations are used to maintain stable connectivity.



Figure 4. Testbed network architecture.

Energy efficiency is estimated in the orchestrator, as presented in Equation (1). The metric defined is widely known in the literature, e.g., [31].

$$EE = \frac{R}{P} \left[ \frac{b}{J} \right] \tag{1}$$

Throughput here is denoted as R (b/s), and current power consumption as P (W). It is not obvious how to measure power consumption as it is not agreed what exactly should be measured (total device energy consumption, RAN energy usage, or even if estimation should be done based on physical layer operation).

In our scenario, power *P* is treated as the total power consumption of a device-undertest (i.e., LTE modem, Wi-Fi dongle). Current mobile networks do not support the reporting of current power consumption in a standardized way. Thus, for the testbed configuration, premeasurements were conducted and outcomes were grouped into classes dependent on throughput.

According to Equation (1), two factors in our scenario are needed to make a proper decision by the orchestrator:

(a) Current network throughput (*R*) from UE perspective;

(b) Total UE power consumption (*P*) for a specific data rate grouped into classes, called PC.Based on premeasurements, the power classes were grouped as listed in Table 3.

 Modem
 Throughput [Mbit/s]
 Power Consumption

 <2</td>
 0.6 W

 LTE
 2-10
 0.9 W

 ≥10
 1.2 W

 Wi-Fi
 ≤1
 0.3 W

 >1
 0.6 W

Table 3. Power consumption classes according to the measured network throughput.

Current network throughput is reported as the maximum data rate based on active network measurement to the orchestrator from the mobile terminal. Power classes were hardcoded in the orchestrator. In the production environment, the estimation of instantaneous UE throughput would be done by RAN-related network element measurements. Equation (2) is proposed for the solution, which defines how the energy efficiency is estimated based on the two factors *R* and *P*. Measurements are done in a constant time frame; loop and stamps are averaged (here t = 10 s, and N = 3). The goal of constant loop is to eliminate too frequent links toggling, which may bring additional delay for receiving/sending the user data packet. Such an approach allows calculation of the instantaneous *EEMT* (Energy Efficient Maximum Throughput) values in the orchestrator, which is able to assess in the current radio network conditions.

$$\overline{EEMT_{\text{inst.}}}\left[\frac{Mb}{J}\right] = \frac{\sum_{n=1}^{N} \frac{R_n}{P_n}}{N}$$
(2)

There are many factors that impact UE throughput. At least two can be listed: base station–user terminal distance, interference levels, and current network load (number of users and user activity). We modeled these two scenarios and examined in our testbed to verify how E2E orchestration improved total energy consumption. The impact on total data volume was also evaluated.

In scenario A, a good Wi-Fi connection condition exists. It represents a situation where a terminal is in an area with good Wi-Fi coverage (e.g., closer distance to the Wi-Fi access point) or very limited interference in the Wi-Fi band exists, which may correspond, for example, to the situation where the mobile user moves among different locations, from outdoor to indoor.

In Scenario B, a good LTE connection is available and much worse conditions are through Wi-Fi networks in many instances. This scenario represents a very congested environment of Wi-Fi networks or Wi-Fi access points that are far away in distance.

In this work, for our research, the srsRAN solution was used, which is well proven and tested in the LTE testbed network environment. The core network (EPC) in this case consists of the Mobility Management Entity (MME), Home Subscription Server (HSS), Service Gateway (SGW), and Packet Gateway (PGW) modules. MME here is mainly responsible for establishing a connection with the UE, implementation of procedures related to mobility, and the tunnel (bearer management) between the EU and PGW. HSS is responsible for authenticating users, SGW and PGW, carrying user and signaling plane data and communication with the IP network.

The architecture presented was deployed in the laboratory and all measurements were conducted in the anechoic chamber, where eNB and Wi-Fi access points were seated (see Figure 5). Detail setup configuration follows:

- 4G Core Network + eNB deployed with USRP B210 and srsLTE;
- Wi-Fi access point MikroTik mAP lite;
- LTE USB modem Huawei E3372;
- Wi-Fi USB dongle TP-Link TL-WN725N;
- Log-period antenna Kent Electronic LP8565.



**Figure 5.** Testbed hardware: 1—AP Wi-Fi, 2—EPC Server, 3—USRP B210 (eNB), 4 and 5—set of antennas, and 6—USRP B210 as spectrum analyzer for spectrum observation.

#### 4. Results

Figures 6 and 7, respectively, present the results for the two simulated scenarios A and B. In the scenario A, we observe that in the first period of time, LTE transmission has higher throughput and also higher energy efficiency. The network condition was then changed and as the Wi-Fi available data rate increased, the orchestrator toggled the active network from LTE to Wi-Fi. Such a scenario may represent coming with a terminal in an area with better Wi-Fi coverage (e.g., closer distance to the Wi-Fi access point) or less interference in the Wi-Fi unlicensed band.

Scenario B reflects very congested Wi-Fi networks, which in standalone operation have better measured energy efficiency; however, is unable to deliver continuously adequate high data rate to the end user. In this case, to achieve the required minimum performance (i.e., throughput) the multi-RAT orchestrator more frequently switches transmission to the LTE network.

The orchestrator analyzes the current network conditions and, based on EE rules (defined in Equation (2)), switches the transmission from one RAN network to the other. Results of the energy efficiency and throughput measurements are shown in Figures 6 and 7.



**Figure 6.** Scenario A—(**Top**) Instantaneous throughput from UE perspective. (**Bottom**) Energy efficiency from UE perspective for different RAT with the indication of which network is selected by the orchestrator to maintain user data transfer.



**Figure 7.** Scenario B—(**Top**) Instantaneous throughput from UE perspective. (**Bottom**) Energy efficiency from UE perspective for different RAT with the indication which network is selected by the orchestrator to maintain user data transfer.

The aggregated outcomes for the presented charts are shown in Tables 4 and 5. In scenario A, the orchestrated approach allows for higher data volume transfer than in the case of a single RAT (27% better than LTE and 23% better than Wi-Fi). Total energy efficiency is 42% better compared to the single LTE case. Wi-Fi network in standalone mode of operation would get 7% better EE; however, then only lower data rates can be achieved, not fulfilling the requirements.

In the second scenario (B), it may be observed that the total energy consumption by Wi-Fi standalone transmission would be 38% lower than the orchestrated approach. However, owing to the applied dynamic steering, the data path is switched toward LTE which has a higher data rate giving adequately defined throughput for the users. Finally, Energy Efficiency gain is higher (11% for LTE, 0% for Wi-Fi).

Table 4. Summary of aggregated KPIs for two different scenarios with indication of relative gains for Scenario A.

RAT	Data Volume [Mb]	Total Energy Consumption [mWh]	Total Energy Efficiency [Mb/mWh]
Wi-Fi	2640 (-23%)	55 (-22%)	48 (+7%)
LTE	2531 (-27%)	98 (+27%)	26 (-42%)
Multi-RAT orchestrated	3444	77	45

Table 5. Summary of aggregated KPIs for two different scenarios with indication of relative gains for Scenario B.

RAT	Data Volume [Mb]	Total Energy Consumption [mWh]	Total Energy Efficiency [Mb/mWh]
Wi-Fi	963 (-39%)	55 (-42%)	18 (+0%)
LTE	1687 (+7%)	106 (+19%)	16 (-11%)
Multi-RAT orchestrated	1576	89	18

## 5. Discussion

Orchestration of multi-RAT heterogeneous wireless networks is not a trivial task. Implementation of such a solution in real network situations requires the use of continuously monitored indicator values, which are measured and/or estimated in either the terminal or at a network element—due to continuously changing conditions in the existing wireless environment. This is possible only by continuous measurements reported to the orchestrator established above all involved RATs. The appropriate decision-making algorithm and process for solutions we proposed in the paper also need to be deployed. The use of algorithms that are too simple may lead to, e.g., frequent path switching or selecting an inappropriate RAN from an energy efficiency (or other) perspective. An interesting approach, also in terms of research, could be to add artificial intelligence algorithms and machine learning techniques to build a self-learning and self-organizing decision-making module in the orchestrator, based on historical data from a given geographical area and period of time. In some cases, however, it may also not provide an optimal solution, i.e., in cases where the radio environment changes without specific behavior. The proposed solution is adequate for testing and providing conclusions for its practical application.

The proposed solution, as a hardware–software prototype with proof-of-concept algorithm, indicates practical power consumption reduction at a very attractive level, i.e., 11–42%, depending on the scenario analyzed under working conditions with 4G/LTE and Wi-Fi wireless networks. We also assume that the terminals of 5G/NR would have similar efficiency conditions as measured in the testbed 4G/LTE, in the case of broadband communications related to high throughput data transfer, due to similar modulation and coding schemes and DRX mechanism. Therefore, a significant level of power reduction should also be achieved in the case of 5G–Wi-Fi orchestration, but this requires further measurements and confirmation.

# 6. Conclusions

The proposed solution presented, as a proof-of-concept hardware-software prototype, offering increased energy efficiency of communication links, would also support all other types of wireless network RATs solutions (e.g., LoRa, Sigfox, Zigbee, Bluetooth) and can also include other different decision rules (not only energy efficiency but also, e.g., spectrum efficiency and relaying time or others). As shown, the multi-RAT orchestration approach could be very effective from an energy efficiency point of view and allows for better wireless network management in a continuously changing wireless environment. It should be pointed out that the high-level multi-RAT end-to-end orchestrator may support future new operator-defined decision rules, also those based on specific business case settings, in contrast to the purely technically related QoS mentioned above. That approach would allow for the optimization of, e.g., operational costs, energy consumption, or setting time for operation of the network. Another aspect of this end-to-end multi-RAT orchestration deployment could be security-related applications where parallel orchestrated transmission (e.g., parts of encryption keys) in different types of RAT networks can increase the level of security, but this requires further study. Demonstrated practical testbed transmission in the paper with proof-of-concept showed that the solution can be applied to real-life scenarios and could achieve practical improvements in the energy consumption and user terminal battery savings. Other similar decision factors may also be implemented on this high multi-RAT level, and then the solution could also offer gains to the wireless network development on other practical network aspects.

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