Energy Efficiency of Multi-Radio Massive Machine-Type Communication (MR-MMTC): Applications, Challenges, and Solutions

Konstantin Mikhaylov[†], Vitaly Petrov, Rohit Gupta, Maria A. Lema, Olga Galinina,
Sergey Andreev, Yevgeni Koucheryavy, Mikko Valkama, Ari Pouttu, and Mischa Dohler

Abstract—**While the Internet of Things (IoT) has made significant progress along the lines of supporting its individual applications, there are many Massive Machine-Type Communication (MMTC) scenarios in which the performance offered by any single radio access technology (RAT) available today might be insufficient. To address these use cases, we introduce the concept of multi-radio MMTC (MR-MMTC), which implies the availability and utilization of several RATs within a single IoT device. We begin by offering insight into which use cases could benefit and what the key challenges for MR-MMTC implementation are. We continue by discussing the potential technical solutions and employing our own prototype of an MR-MMTC device capable of using LoRaWAN and NB-IoT RATs to characterize its energy-centric performance across the alternative feasible MR-MMTC implementation strategies. The results obtained reveal that the increased flexibility delivered by MR-MMTC permits the selection of more energy-efficient RAT options. The IoT devices capable of utilizing multiple radios simultaneously can, therefore, improve their energy utilization by leveraging the synergy between RATs. The novel vision of MR-MMTC outlined in this work could be beneficial across multiple fields, and calls for cross-community research efforts in order to adequately design, implement, and deploy the multi-RAT MMTC solutions in the interests of a greener and more sustainable IoT.**

I. INTRODUCTION

The past two decades have witnessed a remarkable transformation of the wireless connectivity landscape, which made a decisive leap in bringing the Internet of Things (IoT) vision closer to reality: starting with but a few wireless communication alternatives two decades ago and up to dozens of various radio access technologies (RATs) today [1]. The concerted effort of industry and academia brought dozens of new connectivity options to various markets – from medical to industrial and from military to smart home [2]. The unprecedented density and numbers of machine-type devices together with their increased autonomy levels spawned novel types of services, which can be referred to as Massive Machine Type Communication (MMTC) [3].

However, the roll-out of these MMTC applications requires substantial investments to produce the corresponding devices and the RAT infrastructure around them, as well as implies

K. Mikhaylov and A. Pouttu are with the Centre for Wireless Communications, University of Oulu, Oulu, Finland.

V. Petrov, O. Galinina, S. Andreev, Y. Koucheryavy, and M. Valkama are with the Laboratory of Electronics and Communications Engineering, Tampere University of Technology, Tampere, Finland.

R. Gupta is with Actility S.A., Paris, France

M. A. Lema and M. Dohler are with the Centre for Telecommunications Research, King's College London, London, United Kingdom

[†]K. Mikhaylov is the contact author: konstantin.mikhaylov@oulu.fi

additional loading on the energy networks [4]. The concept of green IoT therefore aimed at enabling the sustainable smart world through the effective and rational use of the available resources [5]. With green IoT, energy-efficient sensing, computing, and communication capabilities are all integrated into real-world applications, which is essential to make them sustainable [6]. Despite the immense past progress, there remain scenarios that feature more challenging requirements, especially when it comes to the desired levels of service quality, scalability, cost, and energy efficiency.

Development of a new dedicated communication technology to specifically target the "niche" use cases is unlikely, as it requires prohibitive resource investments and contradicts the vision of green IoT. We envision that a promising solution to overcome the limitations of a particular RAT is by combining several of them within a single multi-radio MMTC device. A similar approach has already proven its worth in human-type terminals, such as laptops, tablets, and smartphones [7] and we expect it to become useful for the MMTC domain as well. At the same time, the utilization of multiple RATs within a power-limited MMTC device may compromise its "greenness" and battery lifetime, thus motivating a closer look into the respective trade-offs.

In this article, we introduce the concept of multi-radio MMTC, which we term MR-MMTC, and explore its applicability. Accordingly, the contribution of our work is threefold. First, we define and illustrate which benefits the MR-MMTC may bring and what are the key challenges on the way to enable it. Second, we offer an investigation of the pros and cons behind MR-MMTC, together with its alternative architectures. Third, we report the results of our practical implementation of an MR-MMTC device prototype with its thorough energy consumption evaluation. These results illustratively show the feasibility of MR-MMTC and further suggest that there are practical scenarios where multi-RAT operation appears to be more energy efficient than the use of a single RAT.

The rest of this text is organized as follows. We begin in Section II with an example motivating and illustrating our further discussion. The key challenges on the way to enabling the MR-MMTC are presented in Section III. Section IV reviews the landscape of contemporary MMTC technologies and justifies the selection of RATs for our test implementation. Section V looks into the architectures for MR-MMTC. Our trial hardware implementation of MR-MMTC and the measurement results of its energy efficiency are reported in Section VI. The concluding remarks are offered in Section VII.
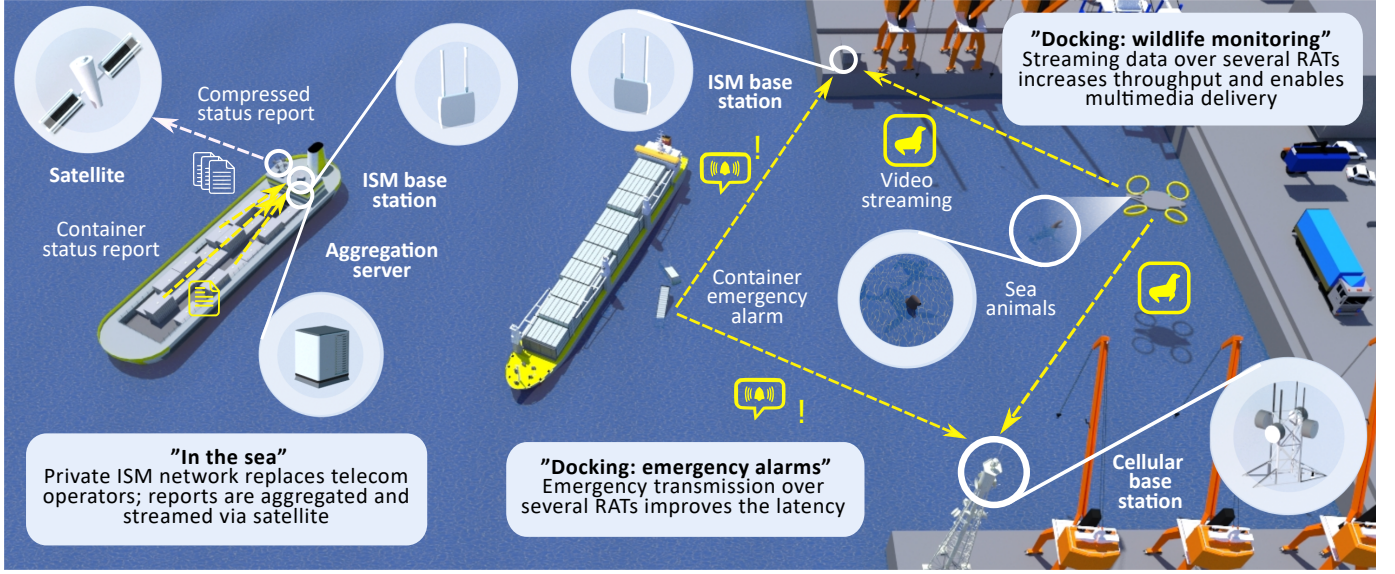
Fig. 1. Illustration of a motivating container shipment MMTC scenario

II. MOTIVATING EXAMPLE AND APPLICATIONS

To start with, we offer a motivating example and consider a container tracking use case. Today, inter-modal freight containers constitute one of the most common ways to move products between countries – by land or sea. However, no single-stop RAT can offer reliable and cost-effective means to track and report the current status (e.g., similar to [8]) of these ubiquitous containers. The satellite systems, albeit providing unprecedented connectivity, remain expensive in terms of costs. Satellite connection from inside a warehouse or ship's hold is also challenging. Conventional cellular technology, while covering the habitat of over 95% of the world's population [9], is not omnipresent and can hardly aid in the open sea. The ad-hoc solutions operating over license-exempt frequencies are low-cost but suffer from fragmentary coverage and a lack of spectrum harmonization [10].

Let us consider how the envisioned MR-MMTC approach can benefit this use case – refer to Fig. 1. Assume that each container is equipped with an MR-MMTC transceiver. While in a depot or a container terminal – a location with a private RAT infrastructure in place – the containers convey their traffic over this RAT. While traveling by land, the MR-MMTC device monitors the available networks around it and switches between the available RATs based on the signal availability and/or quality. While in the open sea, radio connectivity can be delivered by the RAT infrastructure deployed onboard the ship and by utilizing the vessel's satellite link for sending the aggregated and compressed data. The inclusion of the most common short-range technologies (e.g., WiFi) enables a container to opportunistically establish the connection through the public and private networks around it. Container breach or damage alarms can be sent over several RATs in parallel to improve reliability and minimize latency. Several RATs can also be employed should a need for bulky data transfers arise.

From the discussion above, one can conclude that the benefit of MR-MMTC approach is three-fold, refer to Fig. 2. First, MR-MMTC can improve coverage and reduce the outage time,

Key target	MR-MMTC approach	Example usecases
Maximum coverage/ minimum outage	Technology (infrastructure) diversity	1. Goods and shipments tracking 2. Fleet (ships/trucks/airplanes) monitoring and management 3. Lost properties and pets tracking
Ultra-reliability/ minimum latency	Channel and technology (infrastructure) diversity	1. Fire/gas/water leak alarms 2. Security and safety systems 3. Online well-being/fitness
High data traffic	Increased cumulative throughput	1. Multimedia sensors 2. Mines/road/forest works monitoring 3. Nature/wildlife sensing

Fig. 2. Potential benefits and applications of MR-MMTC.

which is especially beneficial for the use cases characterized by high mobility – versatile tracking and fleet management applications, to name a few. Second, parallel use of several RATs enables an MR-MMTC device to improve the reliability of data delivery and reduce the delivery latency by avoiding retransmissions and thus becomes beneficial for latency-critical accident and security alarms. Third, splitting the data to be delivered between several RATs, which can be used in parallel, enables an MR-MMTC device to achieve higher cumulative throughput, thus providing better support for advanced monitoring solutions, e.g., the ones involving audio or image transmission.

III. TOWARDS MR-MMTC: CHALLENGES

Albeit the presented vision is very attractive, there may be challenges on the way to its practical implementation, namely:

Technical – among which we consider the identification of the optimal level(s) of integration for an MR-MMTC transceiver as well as the development of the cost- and energy-efficient commercial integrated architectures to be the key ones. To this day, only several modules combining short-range and long-range technologies were announced. The design and optimization of such devices, their components (e.g., power subsystem and antennas), and engineering of the respective solutions are the key system design goals with respect to the practical utilization of the MR-MMTC technology.

	SigFox	LoRaWAN	RAMP	NB-IoT	LTE-M
Design goals	10+ years; several USD; very small, mostly uplink; limited; global & public	10+ years; several USD; small, mostly uplink; limited; global/local public/private	20+ years; several USD; moderate, bidirect.; moderate; worldwide	10+ years; <5 USD; moderate, bidirect.; high; global & public	10+ years; <5 USD; moderate, bidirect.; high; global & public
Key technical solutions	• UNB technology • subGHz ISM • ALOHA-based protocol • No power/MCS adapt. • Limited packets per day	• LoRa modulation • subGHz ISM • ALOHA-based protocol • Adaptive rate and power • No cell allocation	• DSSS-based modulation • 2.4 GHz ISM • TDMA resource allocat. • Adaptive rate and power • Random phase	• LTE-originating PHY and MAC • Licensed LTE bands • Band edge and in-band deployment • TDMA resource allocat.	• LTE-originating PHY and MAC • Licensed LTE bands • Band edge and in band deployment • TDMA resource allocat.
SotA key values	• UL peak rate : 50 kbps • DL peak rate : 50 kbps • Radio cost*: 1.89 EUR • Subscription cost: 0.1-1 EUR/device/month	• UL peak rate : 100 bps • DL peak rate : 600 bps • Radio cost*: 2.59 EUR • Subscription cost: 0.5-1 EUR/device/month	No accurate information available	• UL peak rate : 230 kbps • DL peak rate : 230 kbps • Radio cost*: 8.89 EUR • Subscription cost: 1-2 EUR/device/month	• UL peak rate: 1Mbps • DL peak rate: 1Mbps • Radio cost*: 14.99 EUR • Subscription cost: 2-3 EUR/device/month

Legend: 🔋 - device battery life | 🏠 - infrastructure CAPEX and OPEX | 🏷 - radio cost | ⏱ - traffic | 〰 - dependability | ❀ - scalability | 🌐 - global coverage | 🔴 - negative effect | 🟢 - positive effect

* - in series of about 1000 pieces, based on the data from major electronic component distributors

Fig. 3. Landscape of LPWAN technologies: development goals, technical approaches, and key numbers.

Research – including the development of appropriate device- and network-level algorithms, which specifically target multi-radio IoT devices as well as account for the practicalities of different RATs [11]. These algorithms must enable timely discovery and switching between RATs and multi-RAT modes. At the network level, another substantial gap is the development of joint decoding and data aggregation solutions, efficient device and service discovery mechanisms, together with robust security/privacy schemes to be used in conjunction with MR-MMTC solutions.

Business – addressing the identification of appropriate market domains for MR-MMTC and the optimization of today's business practices. First, there is a need to enable the acquisition and combination of data delivered over different RATs. Given that many of them already have an integrated Internet protocol (IP)-enabled database solution, while cellular IoT already provides IP-connectivity from the device level, the use of IP-based protocols is a viable option. However, harmonization of interfaces and facilitation of multi-source data acquisition remains to be addressed. Second, a valid business model either for a single service provider or for a collaboration of several providers offering MR-MMTC access under a single subscription is demanded.

Solving these challenges requires substantial efforts, which are hardly reasonable to invest before making certain that the MR-MMTC concept (a) is feasible and (b) brings benefits. Due to the resource-limited nature of many IoT applications, the energy aspect of the MR-MMTC devices is especially questionable. Therefore, in what follows, we provide insights into these issues by instrumenting a proof-of-concept prototype of an MR-MMTC device and studying its energy utility. In the course of this, we first discuss the alternatives and justify our selection for RATs and architecture for the test-bed, and then detail our experiment setup and present illustrative results.

IV. MMTC RAT LANDSCAPE: LPWAN

The landscape of today's IoT-grade RATs is excessively diverse composing hundreds of versatile technologies, which can be combined in myriads of ways. In what follows, we intentionally limit our focus to a single RAT class, which is often regarded as a key enabler for the MMTC applications – the Low Power Wide Area Network (LPWAN) technologies [12], [13]. Importantly, broader coverage of a single LPWAN base station and massive roll-out of the LPWAN infrastructure(s) have resulted today in the formation of a multi-RAT environment in many regions around the globe.

The LPWAN RATs aim to provide cost- and energy-efficient communication in massive deployments of autonomous transducers and have lately experienced tremendous growth. Millions of MMTC devices that employ LoRaWAN, SIGFOX, LTE-M, and NB-IoT are already deployed widely, while others are on their way. Despite having much in common, various LPWAN solutions are considerably different (see Fig. 3), which

IoT device structure

Communication subsystem

Package/chasis and interfaces

Indicators (LEDs, screen, etc.)

Controls (button, switch, etc.)

Processing & data conditioning subsystem

Volatile memory

CPU

Nonvolatile memory

Interfaces

Power subsystem

Energy buffer

Supply regulators and conditioning

Energy interface (e.g., energy harvester or power socket)

Application peripherals

Sensors

Actuators

Memory

Localization

Example multi-RAT architecture

Integrated-one-at-a-time multi-RAT

IC — Interface to CPU — RAT 1 components — Common components — RAT k components — Separate or combined antenna

Integrated sequential multi-RAT

IC — Interface to CPU — RAT 1 tranceiver* — Common components — RAT k tranceiver* — Separate or combined antenna

* - functionality may be limited

Non-integrated parallel multi-RAT

IC1 — Interface to CPU — RAT 1 tranceiver — Antenna 1

IC2 — Interface to CPU — RAT k tranceiver — Antenna k

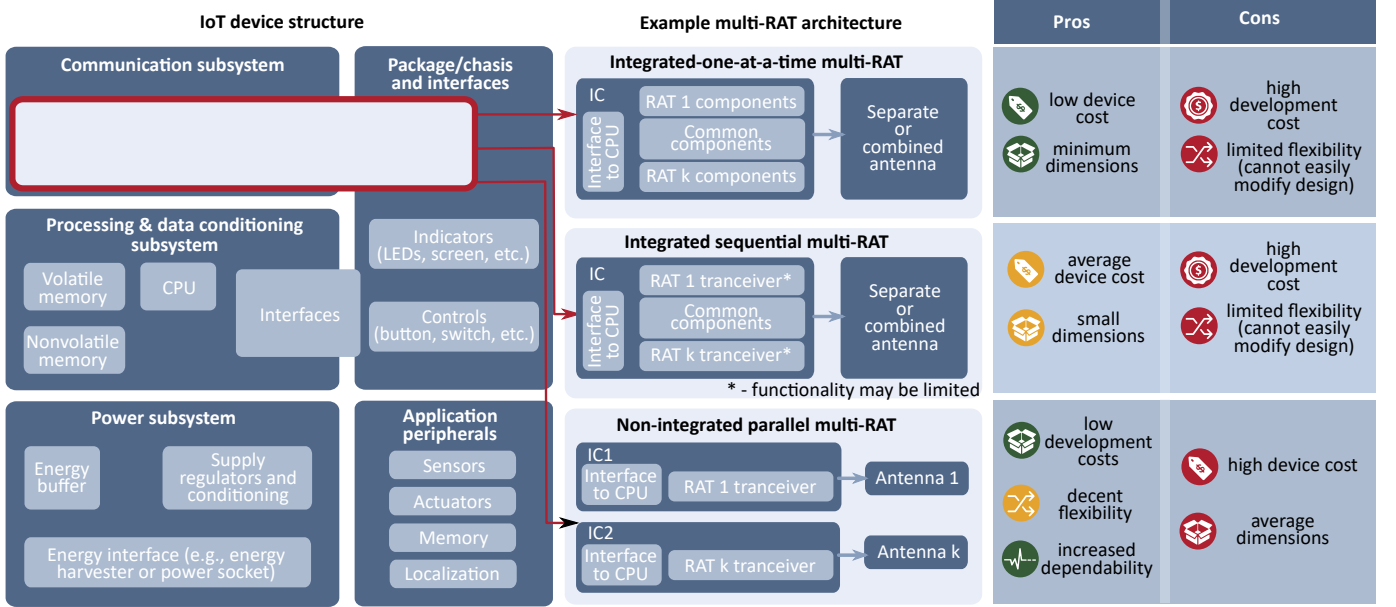| Pros	Cons
low device cost; minimum dimensions	high development cost; limited flexibility (cannot easily modify design)
average device cost; small dimensions	high development cost; limited flexibility (cannot easily modify design)
low development costs; decent flexibility; increased dependability	high device cost; average dimensions

Fig. 4. Typical MMTC device structure and approaches to MR-MMTC implementation.

includes their initial design goals, details of the underlying technical approach, and selected performance indicators.

Specifically, the SIGFOX technology utilizes sub-kHz-wide ultra-narrowband wireless channels. The LoRaWAN solution features frequency shift keying or LoRa modulation-based physical layer spread over a few-hundred-kHz-broad band. Both of these operate in license-free bands and utilize ALOHA-like channel access mechanisms. The counterpart 3GPP solutions, named LTE-M and NB-IoT, operate in licensed spectrum, thus enabling more predictable quality of service guarantees. Due to this reason and to facilitate the efficient use of frequency resources, these cellular RATs incorporate more advanced channel access schemes. The downside of this is communication overheads, which also lead to additional energy consumption.

Further, the discussed approaches differ in their underlying architectures. Specifically, while 3GPP solutions support IP-based communication from the end-device level, LoRaWAN and SIGFOX radios utilize a proprietary protocol between a device and its serving gateway, where IP features only from the gateway upwards – towards the network server [14]. For the two latter RATs, the network server is the key component that provides with an interface for various applications to collect the uplink data from end-devices or inject the downlink data into them. In cellular IoT, direct communication between the end-devices themselves or with an application server is allowed by means of well-established but not exactly energy consumption friendly IP-based protocols.

The dissimilar features of various LPWAN RATs make them more suitable for particular applications and justify our motivation to equip a single MMTC device with several alternative RATs. For our test implementation, we selected the two LPWAN RATs with maximum chipset production ([15]), namely, LoRaWAN and NB-IoT. These technologies also differ with respect to the used spectrum band (i.e., licensed vs. unlicensed) and the underlying business model

(LoRaWAN supports private networks, thus enabling interested parties to deploy their own infrastructure), which makes their combination especially attractive for research.

V. ENERGY EFFICIENT MR-MMTC CONSIDERATIONS: ARCHITECTURE

Contemporary IoT devices, such as sensor network nodes and other electronic systems, are composed of five major functional components, which are: power subsystem, data conditioning and processing subsystem, set of application-specific peripherals (e.g., sensors, actuators, memory, localization), communication subsystem, and a casing or chassis, which may serve as the user interface (LEDs, buttons, switches, screens, etc.). Out of these, the implementation of MR-MMTC functionality directly affects the communication subsystem and casing, but may also require modifications in power and processing subsystems.

The basic structure of a multi-radio IoT device together with several communication system design alternatives are captured in Fig. 4. Based on their support of MR-MMTC operation, IoT devices can be decomposed into three major groups.

The "parallel" MR-MMTC devices are capable of communicating over multiple RATs simultaneously. This resembles the mode of operation in today's smartphones (e.g., cellular-WiFi aggregation) and can improve throughput or connection reliability. A major downside of this approach is increased energy consumption, both average and (especially) peak. Further, this architecture imposes more stringent requirements on processing resources and interfaces to enable simultaneous control of multiple RAT transceivers, which also yields higher costs. The transceivers for parallel multi-radio operation can either be part of a single integrated circuit ("integrated") or remain separate ("non-integrated").

The "selective" MR-MMTC devices albeit supporting multiple RATs, employ only one of them at a time. For such equipment, multi-radio support offers higher connection versatility stemming from the difference in spatial coverage areas

of the respective RATs. In the regions where connectivity over several concurrent radios is available, MR-MMTC devices may perform RAT selection with the goal to optimize their energy consumption, communication latency, loss rate, or data delivery overheads. Compared to the parallel multi-RAT operation, this MR-MMTC option can be cheaper to implement owing to more relaxed requirements on power and processing capabilities as well as due to a possibility of re-using radio system components for integrated design.

The "sequential" MR-MMTC devices are the hybrids of the former two groups and support certain parallel operations but do not leverage all of the available RATs to their full extent. For instance, a device maintaining network synchronization over all RATs but sending its data over only one of them at a time belongs to this group. With respect to energy consumption and costs, sequential multi-RAT operation resides in-between the two previously discussed options. This approach can be applied for IoT devices, which require particular quality-of-service levels but are constrained in their cost and/or energy consumption.

As one can observe, the "parallel" MR-MMTC design is the most versatile; thus, we base our implementation on, albeit also enabling our device to operate in "selective" mode.

VI. Live MR-MMTC Prototype and Evaluation

A. Testbed Design Summary

A prototype MR-MMTC device was implemented on top of our in-house hardware platform built around ARM®Cortex®-M3 32-bit high-end RISC microcontroller. Two radio modules based on the commercial LoRaWAN and the dual-mode cellular (NB-IoT/LTE-M) chipsets were designed and then integrated with the processing module. The firmware to control the device operation comprised an industrial-grade embedded operating system, drivers for the interfaces and radio modules, and the test application. The test device was utilized in the 5GTN test network environment of the University of Oulu (https://5gtn.fi/), which comprises a private LoRaWAN network and a fully functional cellular cell featuring NB-IoT, LTE-M and broadband connectivity.

Once powered up, the MR-MMTC device connects to the available radio networks and periodically reports a block of application data. It can be configured to send the data to the two radio modules, either simultaneously (*parallel MR-MMTC*) or *sequentially* – first over LoRaWAN and then over cellular IoT – as well as to either one of the modules (*selective MR-MMTC*). The LoRaWAN packets were received by a commercial LoRaWAN gateway listening on seven LoRaWAN channels with the data rates (DRs) of 0 to 5 and operating over 868 MHz ISM band. The adaptive data rate was disabled during tests for clarity of exposition. The LoRaWAN gateway hosted a local network server (NS), which forwards the received data over the Message Queuing Telemetry Transport (MQTT) protocol link to an external MQTT broker.

For cellular IoT technologies, after connecting to the cellular network, the transceiver creates a Transmission Control Protocol(TCP)/IP connection, opens a socket connection to the MQTT broker, and utilizes an MQTT publish message to
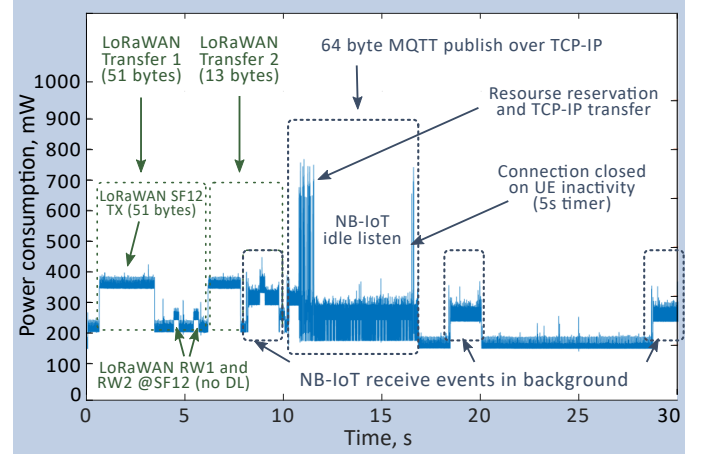

Fig. 5. Illustrative consumption profile for sequential MR-MMTC operation

deliver its data to the broker. The use of MQTT is motivated by the fact that both hardware platforms, as well as the IoT platform used for visualizing the data, support it. The use of 5GTN environment offers us full control over the system parameters and permits to monitor both user- and control-plane network traffic. The network operates in LTE band 28 and comprises one cell with two sectors. The NB-IoT RAT is deployed in-band with LTE-M and the conventional LTE.

B. Energy Consumption Dynamics

The energy consumption of the designed MR-MMTC device was characterized under 3.5 V supply using N6705B power analyzer for a device located 50 meters away from LoRaWAN GW and NB-IoT base station. The consumption profile sampled at 10000 samples per second rate was recorded and post-processed. The illustrative energy consumption profile for the MR-MMTC device sequentially transmitting 64 bytes of application data is depicted in Fig. 5. Initially, the device starts in low-power mode. After waking up, the processor exploits a serial interface to request the status information from both radio transceivers.

Making sure that both radios are ready, the microcontroller utilizes the serial interface and forwards the data to the LoRaWAN transceiver. Due to the limited throughput of the universal asynchronous receiver-transmitter interface and the need for representing the data bytes as text (i.e., ASCII) symbols, the transfer of a 51-byte data packet over the serial interface alone requires 15 ms of time. Once the data is acquired, the LoRaWAN transceiver starts transmitting over a random frequency channel. The duration of transmission and the respective current consumption depend on the amount of data and the used spreading factor (SF) as well as on the transmit power index, respectively.

The two receive windows (RW1 and RW2) are opened 1 and 2 seconds after the transmission, correspondingly. During RW1, the transceiver waits for a preamble on the channel where it had sent its data; if nothing received, the RW2 is opened in a pre-configured channel. In the illustrated case, no downlink transmission has been detected during either of the windows. After RW2, the LoRaWAN transceiver reports to the microcontroller that the transmission has been completed.
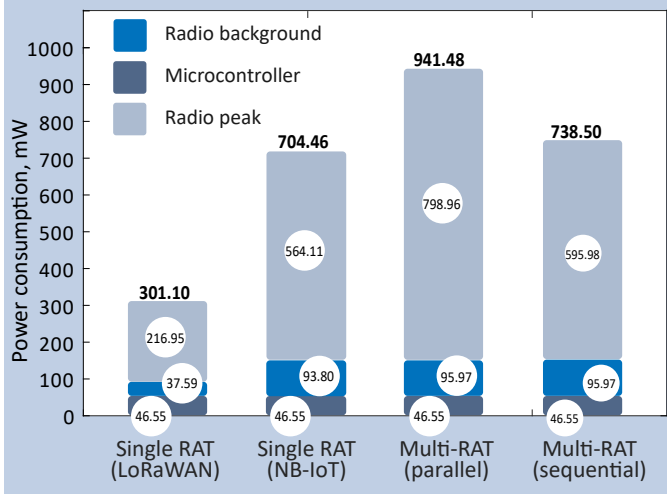
Fig. 6. Components of MR-MMTC device consumption

Since the payload for SF12 LoRaWAN frame is limited to 51 bytes, the microcontroller handles fragmentation and sends the remaining 13 bytes in the second frame.

Once finished with LoRaWAN, the microcontroller forwards the data to the NB-IoT transceiver over the serial interface. The MQTT publication does not imply acknowledgments from the server: the NB-IoT transceiver thus reports microcontroller on the transmission shortly after receiving the data, and the latter enters the sleep mode. Meanwhile, the NB-IoT transceiver requests resources from the network and injects an MQTT publish message into a TCP packet. Once the transmission is complete, the NB-IoT transceiver remains in a receive-ready mode to process downlink or convey more data from the microcontroller; it is disconnected upon an inactivity timeout. Note that apart from the operations triggered by the microcontroller, the NB-IoT switches to the receive mode every 10.2 seconds and monitors the network.

In the case of parallel MR-MMTC, the microcontroller sends the commands and data for uplink transmission to both radio transceivers at the same time. This makes the consumption profile more complex due to an overlay of the radio operations, but similar phases can be identified clearly.

C. Energy Efficiency of MR-MMTC Architectures

Finally, Fig. 6 provides useful insights into the nature of power consumption for four MR-MMTC architectures: two selective options, one sequential, and one parallel. The figure illustrates the distribution of consumed power between the background operations, further subdivided into the processing system's consumption and the background consumption of the radio transceivers, as well as the peak radio consumption. The peak consumption is defined primarily by the consumption of the radio system in transmit.

As can be observed, the selective MR-MMTC with Lo-RaWAN radio features the lowest background and peak consumption. This is due to the absence of network synchronization, the lower maximum transmit power (14 vs. 23 dBm), and simpler radio transceiver architecture as compared to the cellular IoT radios. Parallel MR-MMTC is characterized by 30% and higher peak consumption than that for sequential

MR-MMTC, which was 5% on top of the IoT device using only NB-IoT. This is caused by an overlap of the transmission phases for LoRaWAN and NB-IoT. Since the processing resources are shared in case of MR-MMTC operation, the MR-MMTC device consumption is substantially lower than a sum of respective figures for two single-RAT devices.

Our further analysis of the energy-per-bit for the cases of different payloads provides useful results. In case of payloads of below 64 bytes and of over 512 bytes, single-RAT operation with LoRaWAN and NB-IoT, respectively, results in the most efficient use of energy. For the packets of 64 to 512 bytes, the per-bit energy efficiency of the MR-MMTC device becomes even slightly higher (up to 25%) than that for the single-RAT operation.

In summary, the dual-RAT operation is a compromise between the two RATs: for the extreme cases, favorable efficiency of one technology is compromised by poor efficiency of another. In the middle region, where both RATs display comparable efficiencies, the MR-MMTC device outperforms any of the single-RAT solutions, since the processing system's energy overhead for controlling the second radio transceiver is marginal with respect to the energy required for operating any single radio. Our performance comparison of the two MR-MMTC architectures highlights that both of them consume similar amounts of energy, but parallel MR-MMTC has substantially higher peak consumption.

VII. CONCLUSIONS AND FUTURE WORK

In this article, we introduce and motivate the concept of MR-MMTC, discuss the challenges and demonstrate the feasibility of its practical implementation, paying particular attention to the energy consumption profile. Our results suggest that MR-MMTC is feasible with the technology level of today, and may not only improve performance metrics such as reliability, coverage, latency, and throughput but also result in increased energy efficiency. We support our conclusions experimentally in settings selected based on a typical scenario.

To bring the MR-MMTC closer to everyday use, extensive further work is required; however, we are confident that flexibility of such systems will enable them to secure a niche and help instrument new exciting applications and use cases. Importantly, in the multi-RAT environment, the MR-MMTC devices can also surpass the performance limits of the underlying RATs. This may reduce the current push towards the development of niche communication technologies as well as roll-outs of isolated infrastructures, thus contributing to the green IoT vision.

On this way, accurate modeling of the discussed architectures, analysis of the fundamental performance limits, understanding of the involved trade-offs and effects of the key parameters in the context of various MMTC RATs are vital. Optimization of the enabling architectures and development of efficient algorithms is another crucial challenge. Finally, engineering of efficient MR-MMTC platforms and seamless integration of MR-MMTC devices with the business processes is an important matter to be addressed. All of these represent possible future work.

References

[1] A. Al-Fuqaha et al., "Internet of Things: A Survey on Enabling Technologies, Protocols, and Applications," IEEE Commun. Surveys Tuts., vol. 17, no. 4, 2015, pp. 2347–2376.

[2] M. R. Palattella et al., "Internet of Things in the 5G Era: Enablers, Architecture, and Business Models" IEEE J. Selected Areas Commun., vol. 34, no. 3, Mar. 2016, pp. 510–527.

[3] Z. Dawy et al., "Toward Massive Machine Type Cellular Communications" IEEE Wireless Commun., vol. 24, no. 1, Feb. 2017, pp. 120–128.

[4] W. Ejaz et al., "Efficient Energy Management for the Internet of Things in Smart Cities" IEEE Commun. Mag., vol. 55, no. 1, Jan. 2017, pp. 84–91.

[5] C. Zhu et al., "Green Internet of Things for Smart World," IEEE Access, vol. 3, 2015, pp. 2151 – 2162.

[6] K. Lin et al., "Balancing energy consumption with mobile agents in wireless sensor networks", Future Gener. Comp. Syst., vol. 28, no. 2, Feb 2012, pp. 446–456.

[7] O. Galinina et al., "5G Multi-RAT LTE-WiFi Ultra-Dense Small Cells: Performance Dynamics, Architecture, and Trends," IEEE J. on Sel. Areas in Commun., vol. 33, no. 6, June 2015, pp. 1224–1240.

[8] E. Hidalgo Fort et al., "Intelligent Containers Based on a Low-Power Sensor Network and a Non-Invasive Acquisition System for Management and Tracking of Goods" IEEE Trans. Intelligent Transportation Syst., vol. 19, no. 8, Aug. 2018, pp. 2734–2738.

[9] "Ericsson Mobility Report," Ericsson AB, June 2017.

[10] S. Andreev et al., "Understanding the IoT connectivity landscape: A contemporary M2M radio technology roadmap," IEEE Commun. Mag., vol. 53, no. 9, Sept. 2015, pp. 32–40.

[11] X. Zhai et al., "Optimization Algorithms for Multi-Access Green Communications in Internet of Things," IEEE Internet of Things J., vol. 5, no. 3, June 2018, pp. 1739–1748.

[12] W. Yang et al., "Narrowband Wireless Access for Low-Power Massive Internet of Things: A Bandwidth Perspective," IEEE Wireless Commun., vol. 24, no. 3, June 2017, pp. 138–145.

[13] W. Ayoub et al., "Internet of Mobile Things: Overview of LoRaWAN, DASH7, and NB-IoT in LPWANs standards and Supported Mobility," IEEE Commun. Surveys Tuts., in press.

[14] U. Raza, P. Kulkarni, and M. Sooriyabandara, "Low Power Wide Area Networks: An Overview," IEEE Commun. Surveys Tuts., vol. 19, no. 2, 2017, pp. 855–873.

[15] M. Chen et al., "Cognitive-LPWAN: Towards Intelligent Wireless Services in Hybrid Low Power Wide Area Networks," IEEE Trans. Green Commun. Netw., in press.

Authors' Biographies

Konstantin Mikhaylov (konstantin.mikhaylov@oulu.fi) is a post-doctoral research fellow at the Centre of Wireless Communications (CWC), University of Oulu (UO), Finland. He received his B.Sc. and M.Sc. degrees from St. Petersburg State Polytechnical University (SPbSPU), Russia, and Ph.D. degree from UO in 2018. His has (co-)authored more than 60 research papers on the energy efficient radio access technologies for massive IoT.

Vitaly Petrov (vitaly.petrov@tut.fi) is a PhD candidate at the Laboratory of Electronics and Communications Engineering (LECE) at Tampere University of Technology (TUT), Finland. He received the Specialist degree from St. Petersburg State University of Aerospace Instrumentation (SUAI) University, Russia, as well as the M.Sc. degree from TUT. Vitaly (co-)authored more than 30 research works on terahertz band communications, IoT, nanonetworks, cryptology, and network security.

Rohit Gupta (rohit.gupta@actility.com) is currently with Actility, France, as a senior wireless product manager for developing roadmaps for wireless related products for LoRa and 3GPP. He received the M.Sc. degree from Nanyang Technological University, Singapore, and the Ph.D. degree in wireless communication from the University of Washington, USA. His research interests include IoT, cloud RAN, virtualization, and the design of low-power soft eNB/UE using general-purpose processors (x86/ARM) and SDR.

Maria A. Lema (maria.lema_rosas@kcl.ac.uk) is the technical project manager and the lead researcher with the Centre for Telecommunications Research (CTR), King's College London (KCL), UK. She received the M.Sc. and Ph.D. degrees from the Universitat Politecnica de Catalunya, Spain. Most of her research in this area has been focused on designing end-to-end utra-reliable low latency 5G networks in the context of the Internet of Skills.

Olga Galinina (olga.galinina@tut.fi) is a research scientist in the LECE at TUT, Finland. She received her B.Sc. and M.Sc. degrees in applied mathematics from the Department of Applied Mathematics, SPbSPU, as well as her Ph.D. degree from TUT. Her research interests include applied mathematics and statistics, queueing theory and its applications; wireless networking and energy efficient systems, and M2M and D2D communication.

Sergey Andreev (sergey.andreev@tut.fi) is an assistant professor at TUT, Finland. He received the Specialist degree and the Cand.Sc. degree both from SUAI, as well as the Ph.D. degree from TUT. Sergey (co-)authored more than 150 research works on wireless communications, energy efficiency, and heterogeneous networking.

Yevgeni Koucheryavy (evgeni.kucheryavy@tut.fi) is a full professor at the LECE of TUT, Finland. He received his Ph.D. degree from TUT. He is the author of numerous publications in the field of advanced wired and wireless networking and communications. He is associate technical editor of IEEE Communications Magazine and Editor of IEEE Communications Surveys and Tutorials.

Mikko Valkama (mikko.e.valkama@tut.fi) is a full professor and the head of the LECE at TUT, Finland. He received his M.Sc. and D.Sc. degrees (both with honors) from TUT. Currently, his research interests include radio communications and systems with particular emphasis on 5G and beyond mobile communications.

Ari Pouttu (ari.pouttu@oulu.fi) is a professor with the CWC, UO, and is leading a research group targeting dependable wireless solutions including solutions for 5G and is acting as collaborative projects leader in national 6Genesis flagship targeting 6G solutions. He has published more than 50 conference or journal papers in the field of wireless communications and holds two patents.

Mischa Dohler (mischa.dohler@kcl.ac.uk) is a full professor in wireless communications at KCL, head of the CTR, co-founder and member of the Board of Directors of the smart city pioneer Worldsensing, Distinguished Lecturer of the IEEE, and Editor-in-Chief of Wiley Transactions on Emerging Telecommunications Technologies and EAI Transactions on the Internet of Things. He is a frequent keynote, panel, and tutorial speaker. He has pioneered several research fields, contributed to numerous wireless broadband, IoT/M2M, and cyber security standards, holds 12 patents, has organized and chaired numerous conferences, has more than 200 publications, and has authored several books.