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

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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 insights 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 obtained results reveal that an 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 thus 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 future multi-RAT MMTC solutions.**

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 additional loading on the energy networks [4]. The concept of green IoT further 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 contemporary IoT vision. We envisage 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 sustainability 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 the key challenges are 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 convincingly confirm 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

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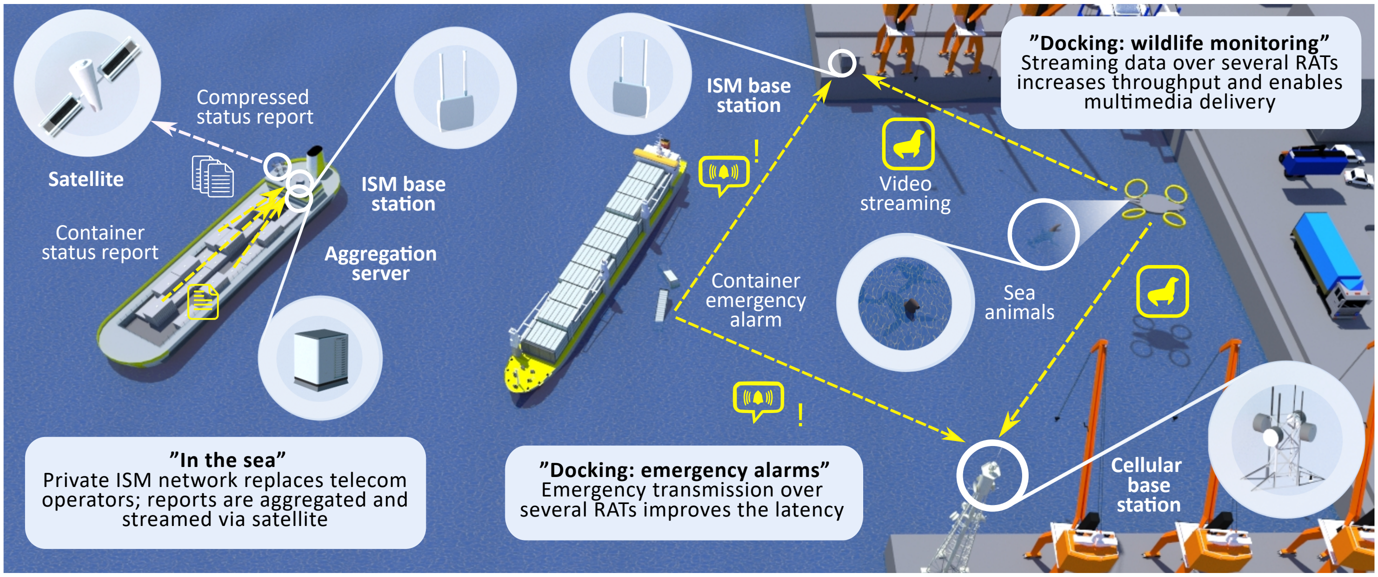
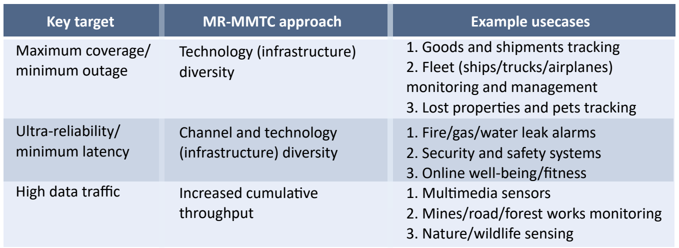


Fig. 1. Illustration of a motivating container shipment MMTC scenario.



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.

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 outlines 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.

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 levels, 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].

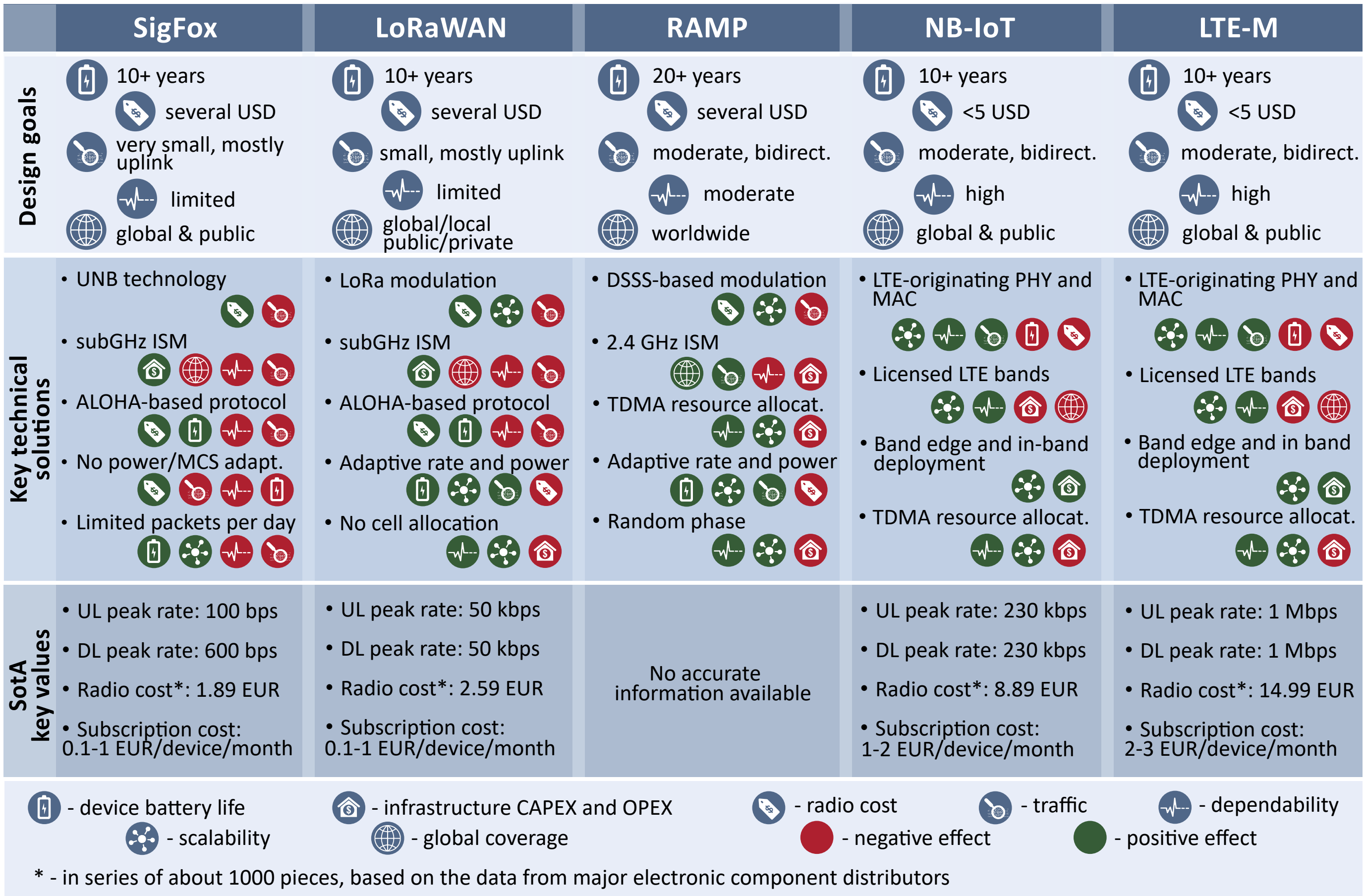
Let us consider how the envisioned MR-MMTC approach can benefit this use case – refer to Fig. 1. Assume that each container is equipped with an MR-MMTC transceiver. While in a depot or a container terminal – the locations with a private RAT infrastructure in place – the containers convey their traffic over this RAT. While traveling by land, the MR-MMTC device monitors the available networks around it and switches between them 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 connections via 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 threefold – refer to Fig. 2. First, MR-MMTC can improve coverage and reduce outage times, 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 augment the reliability of data delivery and reduce the delivery latency by avoiding retransmissions. It thus becomes beneficial for latency-critical accident and security alarms, or even Smart Grids. Third, splitting the data to be delivered between several RATs, which can be used in parallel, permits 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 MR-MMTC vision appears attractive, there are 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



	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: 100 bps • DL peak rate: 600 bps • Radio cost*: 1.89 EUR • Subscription cost: 0.1-1 EUR/device/month	• UL peak rate: 50 kbps • DL peak rate: 50 kbps • Radio cost*: 2.59 EUR • Subscription cost: 0.1-1 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: 1 Mbps • DL peak rate: 1 Mbps • Radio cost*: 14.99 EUR • Subscription cost: 2-3 EUR/device/month

- 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 figures.

transceiver as well as the development of cost- and energy-efficient commercial integrated architectures to be the key ones. To this day, only several modules combining short-range and long-range radio 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.

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 the 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 end-to-end IP-connectivity, 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 work, we first discuss the alternatives as well as justify our selection for RATs and architecture of the testbed, and then detail our experimental setup before presenting illustrative results.

IV. MMTC RAT LANDSCAPE: LPWANS

The landscape of today's IoT-grade RATs is excessively diverse and comprises hundreds of versatile technologies, which can be combined in multiple 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, broad coverage of a single LPWAN base station and massive roll-out of LPWANs have resulted today

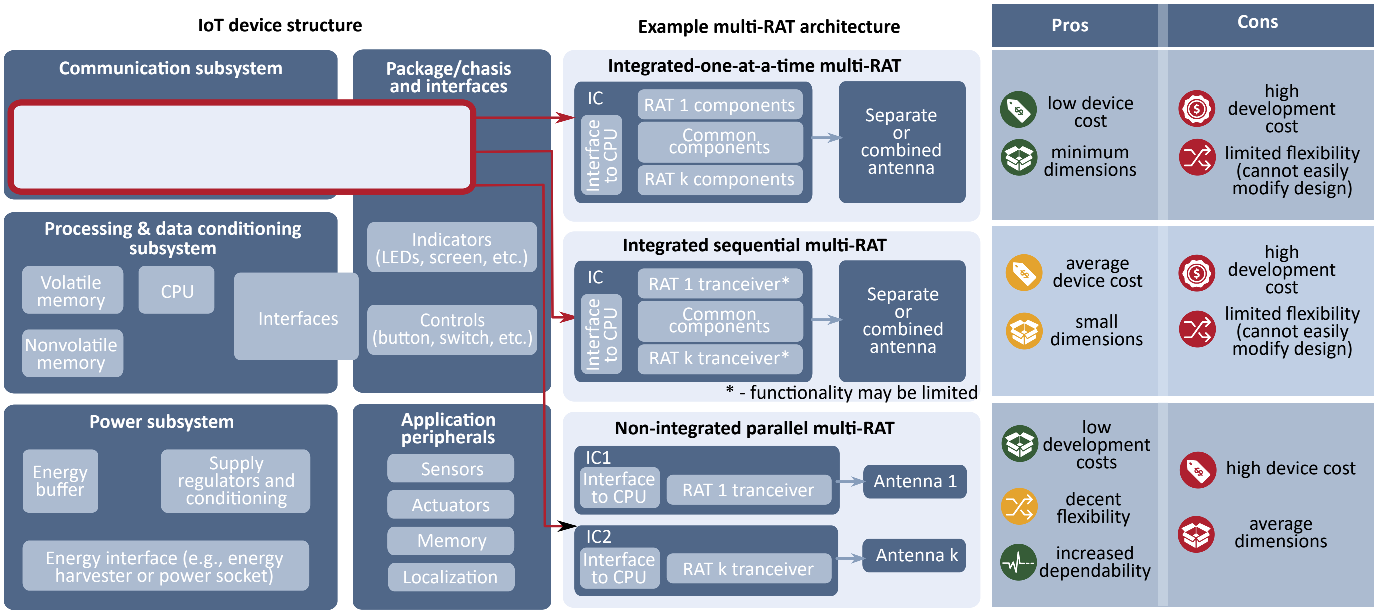


Fig. 4. Typical MMTC device structure and approaches to MR-MMTC implementation.

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 across massive deployments of autonomous transducers and have lately experienced tremendous growth. Millions of MMTC devices that employ LoRaWAN, SIGFOX, LTE-M, and NB-IoT technologies 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 includes their initial design goals, details of the underlying technical approach, and selected key performance indicators.

Specifically, the SIGFOX technology utilizes sub-kHz ultra-narrowband wireless channels. The LoRaWAN solution features frequency shift keying or LoRa modulation-based physical layer spread over a few-hundred-kHz band. Both of these operate in license-free bands and utilize ALOHA-like channel access mechanisms. The counterpart 3GPP solutions, known as LTE-M and NB-IoT, operate in licensed spectrum, thus enabling more predictable quality of service operation. For 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. While 3GPP solutions support IP-based communication from the end-device level, LoRaWAN and SIGFOX radios utilize proprietary protocols 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 a key component that provides an interface for various applications to collect uplink data from the end-devices or inject downlink data into them. In cellular IoT, direct communication between the end-devices themselves or with a remote application server is allowed by means of well-established but not exactly energy consumption friendly IP-based protocols.

The dissimilar features of various LPWANs 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 prevalent chipset production [15], namely, LoRaWAN and NB-IoT. These technologies also differ with respect to the utilized spectrum band (i.e., licensed vs. unlicensed) and the underlying business model, where LoRaWAN supports private networks, thus enabling interested parties to deploy their own infrastructures. All of this makes their combination especially attractive for our 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 that 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 classified 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, such 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 the IoT devices, which require particular quality-of-service levels but are constrained in their target cost and/or energy consumption.

As one can observe, the “parallel” MR-MMTC design is the most versatile; thus, we base our implementation on it, albeit also enabling our device to operate in the “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 a 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 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 better 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.

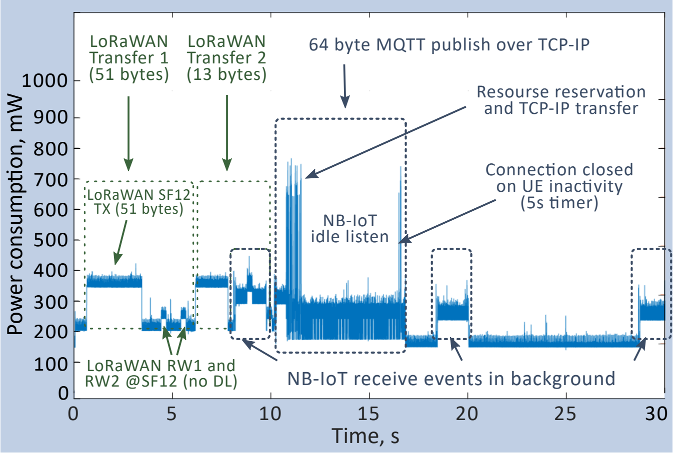


Fig. 5. Illustrative consumption profile for sequential MR-MMTC operation

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 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 features one cell with two sectors. The NB-IoT RAT is deployed in-band with LTE-M and the conventional LTE.

B. *Energy Consumption Dynamics*

In our initial tests, we validated the fact that in the parallel MR-MMTC mode our developed prototype outperforms the single-RAT solutions with respect to coverage, latency, and the peak traffic capabilities, as it was pointed out in Section II. Further, we focused on the energy consumption evaluation.

The energy consumption of the designed MR-MMTC device was characterized under 3.5 V supply using N6705B power analyzer and a prototype device located 50 meters away from the LoRaWAN GW and the NB-IoT base station. The consumption profile sampled at 10,000 samples per second was recorded and post-processed. An 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 the low-power mode. After waking up, the processor exploits a serial interface to request the status information of both radio transceivers.

Making sure that both radios are ready, the microcontroller utilizes a 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 are 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 is received, the RW2 is opened on 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. Since the payload of 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 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, the sequential option, and the parallel option. The figure illustrates a distribution of the consumed power between the background operations, further subdivided into the processing system's consumption and the background consumption of the radio transceivers, to reveal the peak radio consumption. The latter is defined primarily by the consumption of the radio system in transmit.

As can be observed, the selective MR-MMTC mode with LoRaWAN 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. The parallel MR-MMTC option is characterized by 30% higher peak consumption than that for the sequential MR-MMTC case, which is in turn 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 during MR-MMTC operations, the MR-MMTC device consumption is substantially lower than a sum of respective figures for two single-RAT devices.

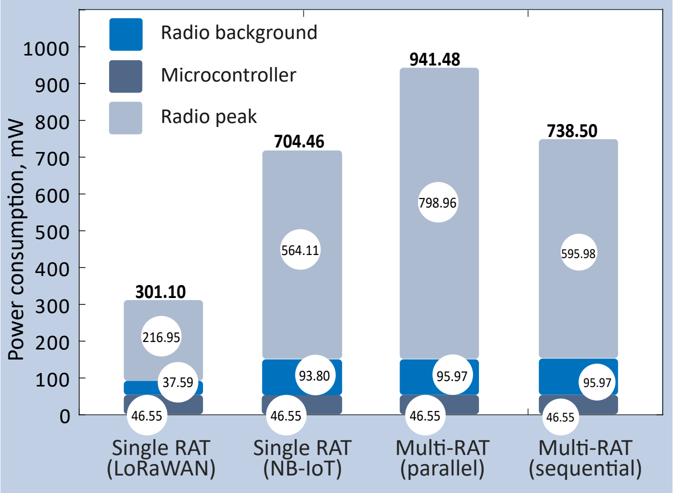


Fig. 6. Components of MR-MMTC device consumption

Our further studies revealed that for very low and very high data volumes, respectively, the transmission of these over the LoRaWAN and NB-IoT radios in the single-RAT mode is the most energy-efficient strategy. In case of medium payloads of several hundreds of bytes, the MR-MMTC operation is preferred. This is because dual-RAT mode 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 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 as compared to the energy required for operating any particular 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 associated challenges, and demonstrate the feasibility of its practical implementation by paying particular attention to the energy consumption profile. Our results suggest that MR-MMTC is feasible with today's technology and may not only improve the performance metrics such as reliability, coverage, latency, and throughput but also result in increased energy efficiency. We support our conclusions experimentally for the settings based on a typical scenario.

To bring 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, we expect that in a 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 radio infrastructures, thus contributing to the green IoT vision.

Along this way, accurate modeling of the discussed architectures, analysis of fundamental performance limits, understanding of the involved trade-offs and effects of the key parameters in the context of various MMTC RATs are essential. Optimization of the enabling architectures and development of efficient algorithms are further crucial challenges. Finally, engineering of suitable MR-MMTC platforms and seamless integration of MR-MMTC devices with the contemporary business processes are important matters to be addressed. All of these constitute possible future work.

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AUTHORS' BIOGRAPHIES

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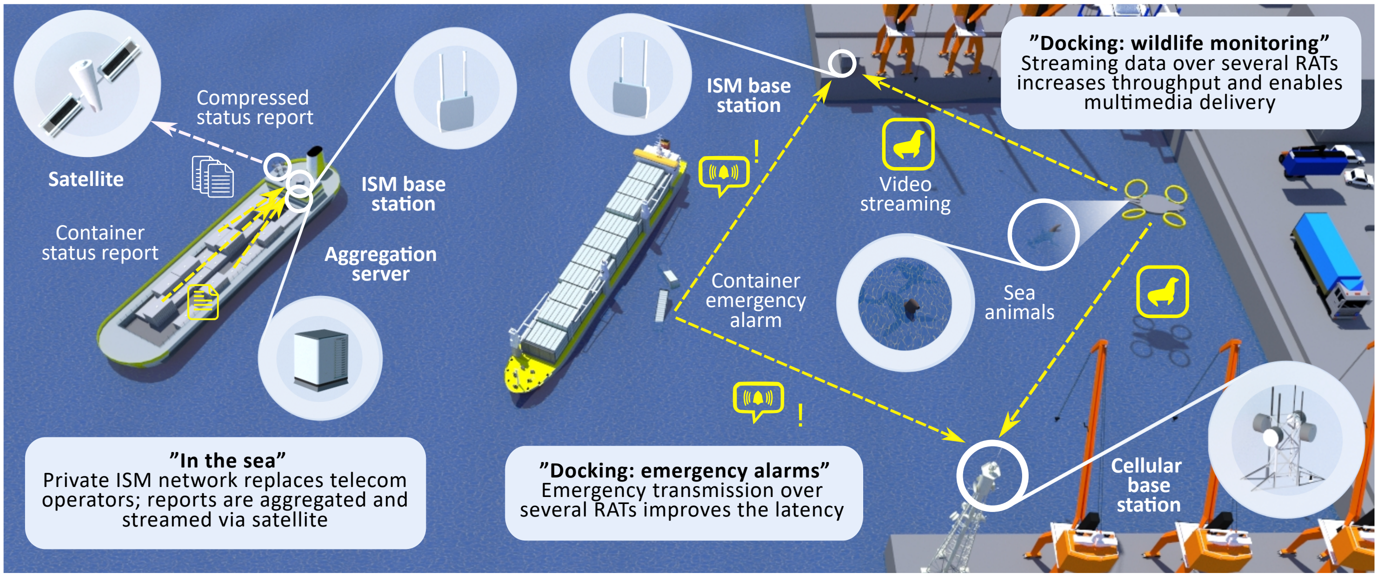
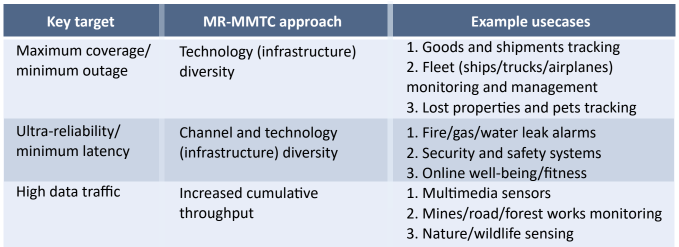
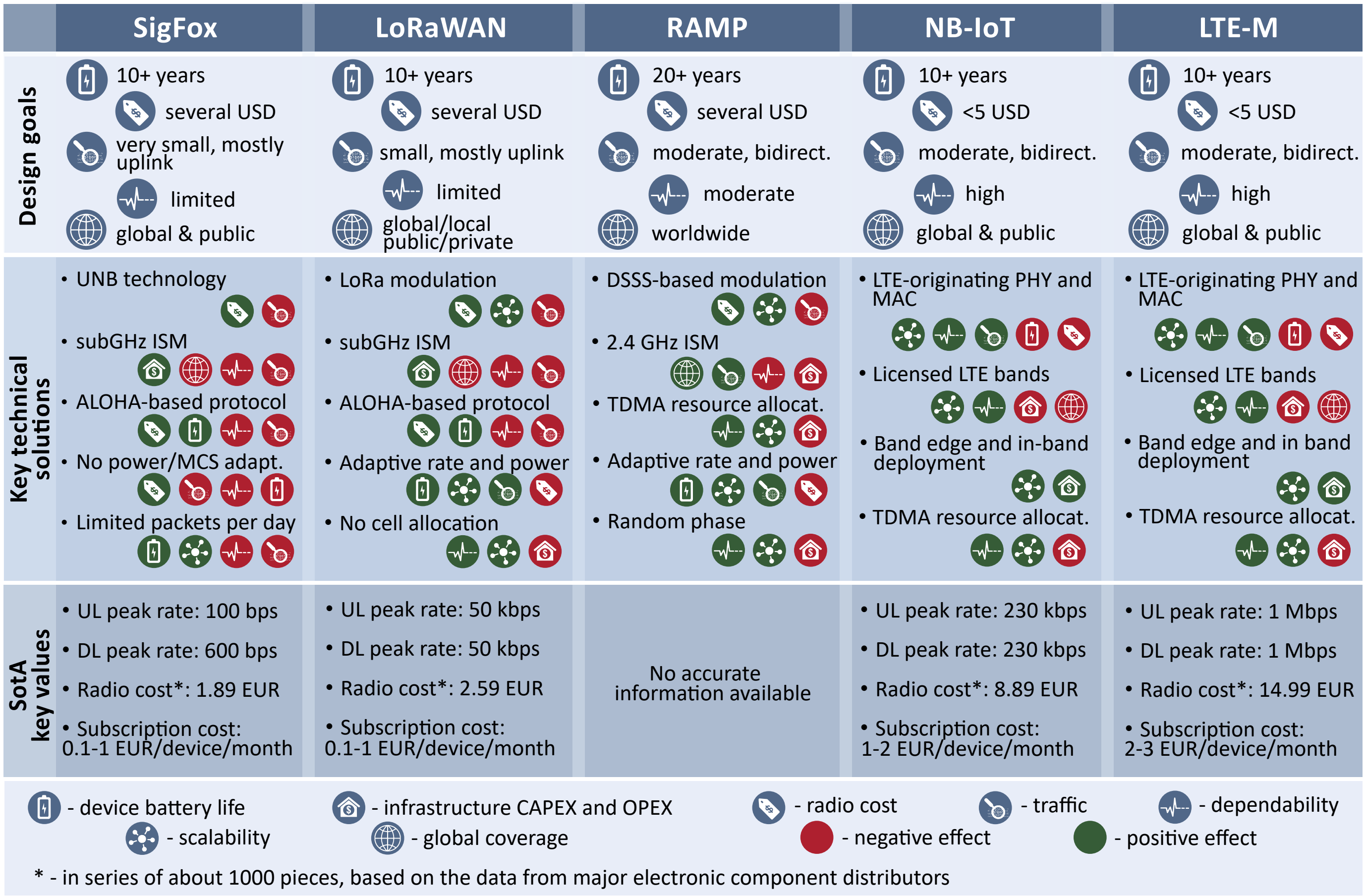


Fig. 1. Illustration of a motivating container shipment MMTC scenario



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.



	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: 100 bps • DL peak rate: 600 bps • Radio cost*: 1.89 EUR • Subscription cost: 0.1-1 EUR/device/month	• UL peak rate: 50 kbps • DL peak rate: 50 kbps • Radio cost*: 2.59 EUR • Subscription cost: 0.1-1 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: 1 Mbps • DL peak rate: 1 Mbps • Radio cost*: 14.99 EUR • Subscription cost: 2-3 EUR/device/month

🔋 - device battery life
✳ - scalability
🏠 - infrastructure CAPEX and OPEX
🌐 - global coverage
🏷 - radio cost
🔍 - traffic
💓 - dependability
🔴 - 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.

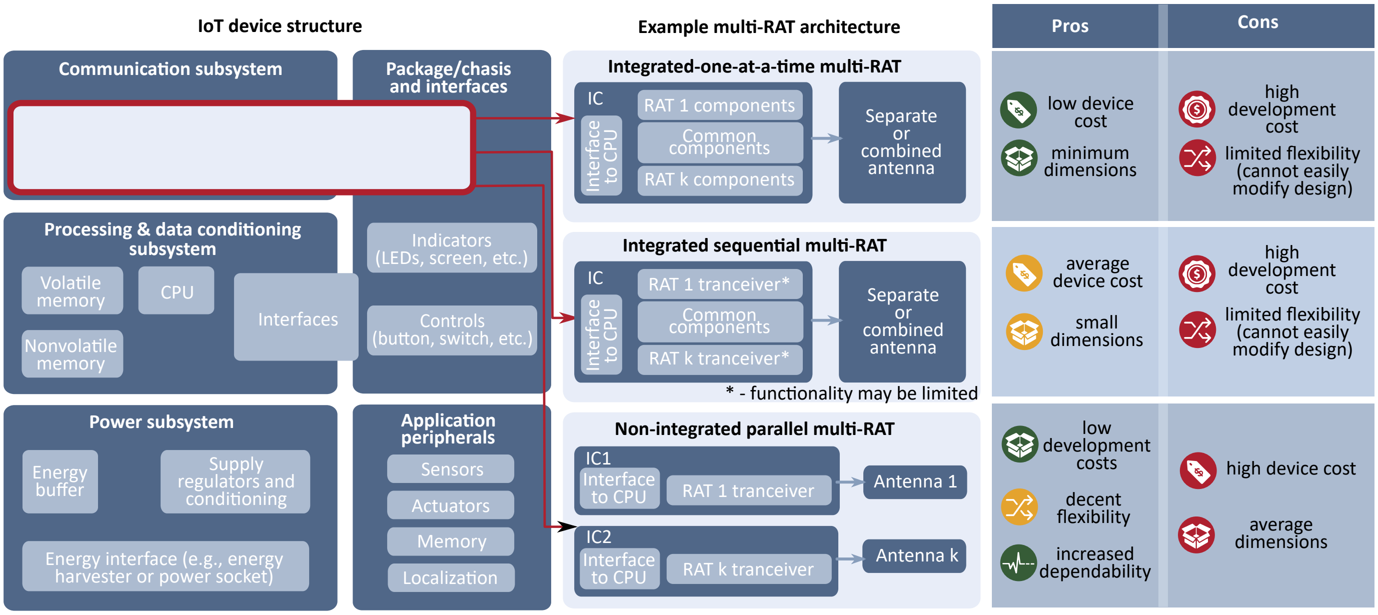


Fig. 4. Typical MMTC device structure and approaches to MR-MMTC implementation.

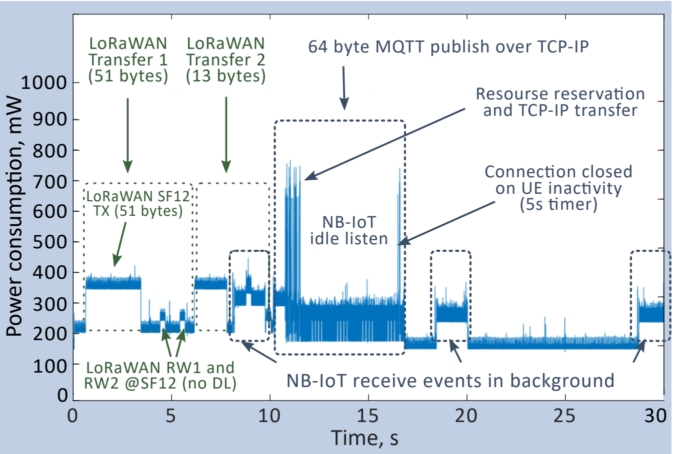


Fig. 5. Illustrative consumption profile for sequential MR-MMTC operation

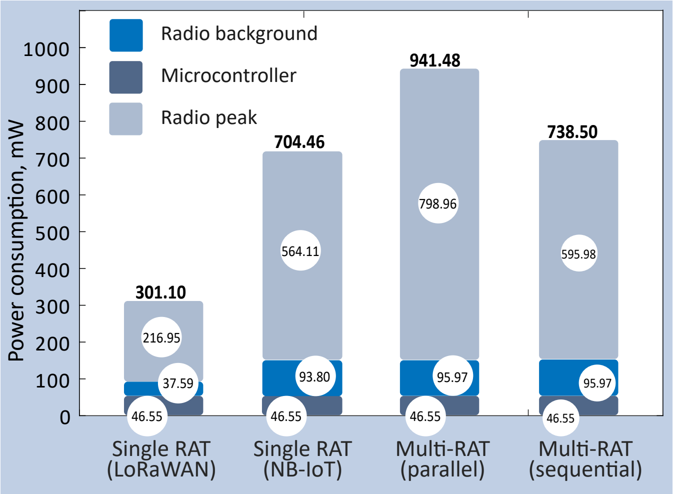


Fig. 6. Components of MR-MMTC device consumption