Smart Energy Consumption of IoT with Millimeter-Wave Cognitive Radio for 5G Cellular Network

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Abstract—Millimeter-wave technology is rising as a crucial component for 5G radio access and other emerging ancillary wireless networks including Gb/s device-to-device communication and mobile backhaul. This paper envisions that millimeter-wave cognitive radio in 5G network is a proposed smart energy consumption solution of Internet of Things (IoT) devices. Improving resource efficiency and enhancing data rates, resource sharing is a proposed advantage over millimeter wave cognitive radio in 5G IoT network. IoT Fog collaboration is proposed to apply artificial intelligence techniques to offer important energy-saving services allowing integrated systems to perceive, reason, learn, and act intelligently in intelligent gateway control. Smart energy meters are the current energy-saving utility in the flexible deployment of IoT architecture. NarrowBand IoT (NB-IoT) delivers Low Power Wide Area access (LPWA) to a new generation of connected things in the race to 5G IoT network, reducing energy computation and achieving promising network capacity. The renewable energy strategy is a proposed energy-efficiency solution in IoT network, maximizing the power supply while minimizing power consumption. A novel kind of visible light communications (VLC) is proposed to enable mmWave cognitive radio receiver in 5G IoT network. Simulation results show the proposed solution can reap the benefits of higher data rates, more IoT device connectivity, and lower energy consumption.

Index Terms—Millimeter wave, cognitive radio, Internet of Things, Smart Energy Consumption, smart meters, 5G networks.

I. INTRODUCTION

Limitless power and ubiquitous network can provide instant access to cloud services. Devices are becoming smarter, more connected, and central to all this transformation. The Internet of things (IoT) creates a platform for device manufacturers to transform their businesses by innovating new device types, new revenue streams through services.

Microsoft has unique approach to harness the power of IoT. Windows 10 IoT makes it possible to

create universal applications and drivers that can be used on any windows 10 devices from IoT gateways to point-of-service sensor devices. IoT devices incorporate APIs for GPIO, I2C, SPI, USB, HID and custom buses as well as system settings such as power, transceiver control, Bluetooth, and WiFi. Microsoft IoT solutions are designed to simplify implementation by working with legacy hardware while allowing next-generation sensor (e.g. cognitive radio), communications, and other technologies to be seamlessly incorporated.

To keep pace with the rising importance of cyber security, Microsoft windows 10 IoT employs a security model to protect devices from unauthorized access, and a unified development and management approach for developing next-generation components and devices. It supports Platform as a Service (PaaS), System as a Service (SaaS) as well as Infrastructure as a Service (IaaS) for creating scalable applications, services and supports such as OS X, iOS, and Android. IoT combines exceptionally high performance computing and data storage in the cloud as well as data management analytics, real-time report generation, increased visibility, improved efficiency, shared data and insights, many levels of messaging, global content delivery of any type of data, networking (including VPNs), domain hosting and express routing and load-balancing.

5G is developed and implemented towards much greater spectrum allocations at untapped mm-wave frequency bands, highly directional beaming antennas at both the mobile device and base station, longer battery life, lower outage probability, much higher bit rates in larger portions of coverage area, lower infrastructure costs, and higher aggregate capacity for many simultaneous users in both licensed and unlicensed spectrum (e.g. the convergence of WiFi and cellular). The backbone networks of 5G will move from copper and fiber to mm-wave wireless connections [1], allowing rapid deployment and mesh-like connectivity with cooperation between base stations. Mm-wave frequencies could be used to augment the currently saturated 700MHz to 2.6 GHz radio spectrum bands for wireless communications. Further, mm-wave carrier frequencies allow for larger bandwidth allocations, which translate directly to higher data transfer rates.

LoRaWAN is a Low Power Wide Area Network (LPWAN) specification intended for wireless battery operated things in regional, national or global networks. LoRaWAN targets IoT requirements such as secure full duplex communication, mobility and localization. LoRa is well accepted for its long range, excellent sensitivity, battery life and low cost.

Intel IoT provides a Bluetooth Low Energy (BLE) service. BLE is a low-power, short-range wireless communication technology for Internet of Things (IoT). BLE is designed for small and distant

data transfer, providing a fast connection between client and server and simple user interface, which makes it ideal for controlling and monitoring applications.

In this work, a novel millimeter wave cognitive radio combined with NB-IoT in LoRaWAN is proposed to save the energy consumption of IoT in 5G network. This paper focuses on the feature of smart metering, NB-IoT, millimeter-wave and visible light communications, which can maintain overall maximum energy efficiency. Performance evaluation of the proposed VLC system can obtain the optimum resource tradeoff between IoT devices.

The rest of the paper is organized as follows. In section II, the key technology of IoT architecture is elaborated. The analysis framework and functions of various core components are also shown. LPWA network is widely used in IoT applications. The virtual LPWAN is proposed for 5G IoT network. A new paradigm combined smart energy meter with millimeter wave cognitive radio for the optimization of overall energy efficiency is proposed in section III. Resource sharing scheme in mm-wave 5G cognitive radio is proposed to increase the data rates for IoT smart devices. NB-IoT is an ideal candidate solution for low-power wireless transmission in IoT applications. The advantage of fog collaboration regime is recapitulated in the energy-efficiency management. The impact on overall capacity towards overall energy efficiency in the proposed renewable energy mechanism is analyzed. New VLC system is designed to engage mm-wave cognitive radio receiver that applied in 5G IoT network. Finally, conclusions are reiterated in the last section IV.

II. FRONTIER TECHNOLOGY OF IoT

A. IOT ARCHITECTURE MODEL

Fig.1. IoT architecture model

Fig.2. IoT System

In Figure 1, IoT intelligent gateway can connect medical devices or mobile devices by sensors or

actuators. It interacts with traffic concerns, security alarm, and intelligent applications. Through communication network, infrastructure services are provided by device management, and data model, including big data and analytics service, integration service, event processing service, security service, identity management service, and user interface service. IoT application includes smart city, E-Health, home automation, industrial automation. Fog computing achieves the infrastructure device connectivity and services provider. In such application enablement platform, IoT can make data analytics and guarantee cyber and physical security by cloud computing. The relationship between fog computing and cloud computing is depicted in Figure 2.

B. KEY COMPONENT OF IOT

1) IOT INTELLIGENT GATEWAY

It offers industry-leading cellular machine-to-machine (M2M) technologies including industrial-grade embedded models with long life spans, cloud platforms, expert application development assistance. Data Agent gathers and formats data for the cloud from the different sensors and controls actuators based on commands from the cloud. Edge Analytics Agent learns actionable data in local context and near real time. Security Agent handles security primitives for gateways and sensors/actuators, including authentication keys and certificates. Management Agent handles manageability primitives for gateways and sensors/actuators, including provision, error handling, alerting, and eventing. The major software components and interfaces in Intel's IoT reference architecture for connecting devices without native Internet connectivity are shown in Figure 3. The components are grouped by on-premises and cloud.

Fig.3. Software Components and Interfaces for Intel's IoT Reference Architecture

2) FOG COMPUTING, CLOUD COMPUTING AND EDGE COMPUTING

“Fog computing” has been a shift from cloud-based analysis in the context of IoT. This takes a more holistic view of analytics in generated data at the sensor. A suitably equipped intelligent sensor’s internal compute engine and associated algorithm determine whether or not a byte of data is useful and what to do with it. It decides if that data can be analyzed locally for immediate response, or if it’s better to send data upstream to a high-level data-aggregation point or gateway. This follows its own context-sensitive decision path. Adding intelligence at more points at the operation technology (OT) level requires a cost analysis process with which embedded system designers and developers are very familiar. Fog computing is analogous to distributed computing techniques. The amount of computing or analysis to be done at each stage determines the cost, power consumption, processing power, flash, ROM, and communications requirements. The task of OT is to optimize at every node for cost, power consumption, memory, and connectivity, while ensuring scalability, manageability, security, and reliability. This is one of the more useful applications of the Intel IoT Platform. It identifies components of an end-to-end IoT solution. This adds power-monitoring capability at the outlet where the motors connect. This means power-consumption patterns can be analyzed at a local and macro level to help reduce overall consumption, and quite possibly save millions of dollars in energy costs over many plants.

Fog collaboration can conquer the challenge in the connectivity of smart devices. OpenFog Consortium is working to create a framework for efficient and reliable networks and intelligent endpoints combined with identifiable, secure, and privacy-friendly information flows between clouds, endpoints, and services. This includes a hierarchy of elements between the cloud and endpoint devices, and between devices and gateways that address the challenges at critical points. Intel is providing guidance on implementation such that the OpenFog model aligns with its system architecture specification (SAS) to make it easier to connect almost any type of device. Fog collaboration can reduce overall power consumption and optimize power-management function. It can fuse the power analysis information in gateway. IoT fog-collaboration is expected to apply artificial intelligence techniques to offer important energy-saving services allowing integrated systems to perceive, reason, learn, and act intelligently in intelligent gateway control.

Fog computing essentially moves processing resources closer to the edge, where data is produced but only modest processing power is available. Fog computing extends cloud capabilities to the edge in a fog or IoT gateway. It allows a single, powerful device to process data received from multiple end points and send information where needed. Latency is less than a cloud-only processing solution. Fog

computing can be more scalable than edge computing. The whole architecture of fog computing is depicted in Figure 4.

Fig.4. Fog computing

With edge computing, processing power and communication capability are moved to the edge rather than in a remote data center. It facilitates collecting and processing data from IoT devices rapidly where that data originates. Latency is reduced and response time is increased as only relevant data is moved to the cloud data server. Fog and edge computing are integral parts of the connectivity solution and will be used more often as IoT sophistication increases.

3) SMART ENERGY SENSORS

Capgemini Energy Control Service offers commercial customers integrated solutions, including demand management and demand response, and profitable Creating Value Roadmap (CVR) implementation. Allow customers to run their plant with higher throughput, and manage equipment in a way that minimizes downtime. With that in mind, Intel designed a highly accurate yet inexpensive energy sensor, which is integrated into Intel® Trend Analytics Software that provides high frequency samples of voltage and current and phase of key pieces of equipment. As they're switched on and off, the energy utility can capture what's happening on their grid as a result of those big loads and can suggest big savings for their clients.

IoT Cloud-Collaboration solution depends heavily on intricate layers of technologies, industry leaders, and pilot programs. The energy sensors used as crucial parts of plant incorporate Intel's reference design, Wind River operating systems, and McAfee security systems. Intel provides gateways and the edge-to-cloud infrastructure to manage those gateways, Windows 10 and Microsoft Azure

cloud service to host the data center, the promise of smart energy, efficiency and profit becomes reality.

Smart sensors are the integrated devices with IoT radio modules to transmit data wirelessly via LPWA network. Such appliances can be used in different IoT applications as part of distributed sensor network. Industrial solutions use a large number of different sensors, which required a reliable and robust connectivity. Pressure and atmosphere sensors, millimeter-wave cognitive radios, flow rate sensors and meters are paradigms for smart sensors.

LPWA technology allows connecting different type of IoT sensors in one wide area network for massive data aggregation. The customization program can bring efficient wireless IoT connectivity to the existing sensors.

4) ENERGY-EFFICIENT SMART METERING

At the cutting age, Intel and Capgemini deploy edge analytics to make energy grids more efficient.

Smart meters use two-way communication to reduce energy consumption and improve efficiency. By being smarter, the meters save money for both consumers and utilities. People use less energy when they see how much they are using: smart metering allows households to see the effect of turning off a couple of lights. This aspect alone has been shown to cut power bills by 5-10 percent.

In the connected smart home, every consumer will have a smart meter to control water, gas and electricity consumption in real-time. These meters will not only measure utility usage; they will be part of a holistic connected home platform in which appliances, lighting, and security systems are connected, provisioned, and optimized for efficiency. The benefits of smart meters are to leverage costs reduction and energy-efficient. Smart meters connected to IoT will enable service without onsite intervention.

Smart metering benefits utilities by improving customer satisfaction with fast interaction, while giving consumers more control of their energy usage to save money and reduce power consumption. With power visibility all the way to the meter, utilities can optimize energy distribution and even take action to shift demand loads. Smart metering helps utilities to reducing operating expenses by manual operations remotely. It can improve customer service through profiling and segmentation, reduce energy theft, and simplify micro-generation monitoring and track renewable power.

Smart meters can adopt new smart services to various kinds of customers to better manage their energy usage patterns, reduce overall power consumption and benefit from new infrastructure models. Cellular communications provide a reliable connectivity option for smart metering infrastructure, including full IP infrastructure and low latency in 4G LTE. With the ubiquitous reach of modern cellular networks, and the development of LTE-M (LTE for M2M) providing long-range low power

cost effective solutions, utilities can connect meters easily and inexpensively virtually anywhere. And they can benefit from a proven, highly reliable communications infrastructure without taking on the costs of deploying and maintaining it themselves. It offers industry-leading cellular machine-to-machine (M2M) technologies including industrial-grade embedded modules with long life spans, cloud platforms, expert application development assistance.

Smart Metering can be used as a service streamlines utilities' business processes. Combines leadership in managed services, ICT transformation experience and global service delivery organization to provide utilities with end-to-end smart metering. Smart meters offer a wide range of benefits to both utilities and their customers, including faster detection of outages, facilitation of more flexible billing plans, increased awareness of consumption and greater efficiency. To help electricity, gas and water utilities overcome these challenges, Ericsson is introducing Smart Metering as a Service, a complete, end-to-end, automatic smart metering and data management solution.

Fig.5. Characteristic of smart energy metering

Smart metering systems are assisting energy and utility companies meet the evolving demands and IoT smart home systems are providing homeowners with convenience, comfort and the ability to manage consumption. Smart energy solutions provide real time visibility into consumption and billing data helping consumers to conserve resources, while energy and utility companies are better able to balance production to meet actual demand reducing brown outs. These smart systems also enable operational efficiencies that require fewer service visits, reduced labor costs and improved cost efficiency for consumers and producers. The summary of benefits of smart energy metering is described in Figure 5.

Always-on, secure M2M connectivity transform smart meters into high speed smart home hubs enables new capabilities and services including Internet access, power-by-call and secure over-the-air updates and service changes when needed. M2M-enabled smart meters are continuously monitoring

and managing energy use so utility companies can react immediately to damaged equipment or service interruptions, even in remote, hard-to-reach locations.

C. KEY TECHNOLOGY LPWA

Low-Power Wide-Area (LPWA) technology is a brand new category of wireless that connect more objects to improve the safety, efficiency, and resource management by delivering on the 3C(Cost, Capacity, Coverage)'s demanded by many IoT applications. The cost savings are being driven by a significant reduction (more than 50%) in device complexity for LPWA compared to broadband LTE devices. More than 100x lower power than broadband LTE achieving 10+ years battery life. Coverage is 5-10x greater than broadband LTE. Cellular LPWA technologies meet the 3C's and bring best-in-class security, mobility, network quality, and voice capacity. There are two leading LPWA technologies NB-IoT and LTE-M. NB-IoT focused on very low data rates 20kbps. It has ability to use both 4G and 2G spectrum simultaneously. This is ideal for simpler static sensor applications. LTE-M occupies highest bandwidth among any LPWA technologies. It has ability to supply voice and roaming on 4G spectrum. This is ideal for real-time fixed or mobile applications. The maximum data rate of LPWA in IoT is 350 kbps. LTE is evolving to meet both the low-power needs of IoT and the high-speed, high-performance requirements of many critical communication IoT applications.

LPWA network has been designed with long range, low-price, and high-scalable which is especially for IoT and M2M applications which is architected as a star topology network depicted in Fig.6. Autonomous smart devices communicate with gateways on a wide-area. All data collected from gateways are processed on the servers and displayed in client IoT cloud platform.

LPWAN is low-power wide-area network also known as LPWA Network, which is a new type of radio technology used for wireless data communication in different Internet of Things applications and M2M solutions. Key features inherent in the technology are the long range of communication, low bit rate and small power budget of transmission. For the deployment of wireless sensor network, there are several wireless technologies suitable for different applications with regards to bandwidth and range. Most of IoT and M2M solutions require long-range communication link with low bandwidth and are not well covered with traditional technologies. That is right time and place for LPWAN technology, which is quite good for these emerging sensor applications. 5G is high bandwidth while LPWAN is low bandwidth. LPWAN has longer range than 5G and ZigBee. LPWAN is the best candidate for IoT and M2M. The benefits of low-power network include larger range, lower transmission latency. The range of LPWAN is varied from 5 to 50 km in different environment conditions. High autonomy of

smart devices with a lifetime is from 10 to 20 years. A small portion of data transmitted with low throughput which may vary from few bit/sec to 100s bit/sec. Less number of access points (base stations, gateways) cover wide area such as city or even country. Good penetration in case of sub-GHz ISM frequency used and better network coverage in the open district area. LPWAN is the engine of long-range Internet of Things. As more than 20 billions of IoT devices will be available by 2020, a large portion will be connected with LPWAN. There are several LPWAN technologies which differ from one another by frequency, bandwidth, RF modulation approach and spectrum utilization algorithms. As a result, some examples of IoT applications where LPWAN is perfect technology delivering a long-range and cost-effective connectivity. LPWAN is perfect to connect a high volume of low data-intensive sensors cost-effectively, rapidly and at a large area of a city or even country.

Fig.6. Long-range, low-cost, and high scalable in LPWAN

D. VIRTUAL LPWAN IN 5G IoT NETWORK

How virtualized LPWA network architecture achieves such decoupling, consider a three-tier network in which a IoT test user has a pico-BS as their closest IoT BS, then a micro-BS farther than the pico-BS, and then a macro-BS farther than the micro-BSs. Due to the downlink transmit power disparity, the macro-BS (pico-BS) provides the highest (lowest) downlink RSS. Instead of associating with the macro-BS only, which might be congested, the user can communicate in the downlink with the micro-BS for load balancing, and in the uplink with the pico-BS for transmit power reduction. To reduce the handovers caused by mobility, the user can receive control signaling from the macro-BS. Cognition, in this case, becomes important, since there is no single rule for association, as it depends on the underlying application and the network conditions. For example, if an application has tight rate constraint, an uplink connection to a less loaded, although much may require higher uplink transmit

power, BS may be more efficient than a congested nearby BS. Further, IoT users' association has to adapt to the traffic and spatial distributions in order to attain the desired 5 G network objective and application requirements.

Fig.7. 5G Network topologies for the same locations of BSs and UEs in which the triangles represent the IoT BSs and the dots represent smart meters, black dotted lines represent cell boundaries, blue dotted lines represent connectivity between smart meters and single IoT BS, red dotted lines represent connectivity between smart meters and multi-BS, and green dotted lines represent peer-to-peer D2D connectivity: a) context aware topology in which the connections are established based on the relative distance between nodes, application, SINR; and b) A two tier cellular networks with macro-BS (squares), small-cells (triangles), and a user's trajectory (highlighted in black). The figure shows the handover boundaries (in blue) for the conventional cellular network architecture and handover boundaries (in dotted red) for the virtualized LPWA network architecture.

III. CANDIDATE SOLUTION OF SMART ENERGY CONSUMPTION IN IOT

A. IOT ENABLES SMART METERS

The most important aspect of an efficient smart electricity grid is “Peak Load Management,” which refers to maintaining precise control of load management devices to offer superior demand response. Facilities that use distributed energy storage technologies to store clean and renewable energy created onsite can pump excess power back into the electric grid during off-peak periods.

Advanced Metering Infrastructure (AMI) is an electrical architecture that provides electrical grids with two-way communications for measurement, analysis, and optimization of energy usage down to the level of individual consumer devices. AMI allows end-user devices to communicate with local smart meters, which communicate with the central power company and substations to allow grid coordination and adjustment by meter data management systems. AMI plays a fundamental role in smart grid features like demand response, distribution automation, and other facets of electrical grid optimization, and the Industrial IoT makes smart meters and the smart grid even smarter. The whole IoT procedure includes lighting control, access control, video control, electrical distribution, energy

monitoring, critical power, and renewable energies. IOT platform is consisted of devices layer, communication layer, security layer, data sets, data integration layer, analytical layer, and user access layer.

B. RESOURCE SHARING

Resource sharing [2] represents a solution to better leverage the potential of mmWave technology [3]-[6] for cellular networks, where very large bandwidths and many antenna degrees of freedom are available. The desirability of a full spectrum and infrastructure sharing configuration leads to increase user rate for IoT service provider. Millimetric waves (30GHz ~ 300 GHz) [7-10] are poised as a great contributor towards phenomenal data rates.

We envision that the 5G network for IoT devices [11] should support: 1) global reachability: the devices need to be identified and located from any place in the network, 2) mobility support: the devices need to have seamless connection even in presence of high-speed device mobility, 3) richer communication patterns: the devices need communication patterns like query/response, pub/sub, anycast, etc., and 4) resource efficiency: a large proportion of IoT devices are severely constrained in energy, computation, or network capacity.

5G networks will offer data speeds 10 to 100 times faster than current 4G networks. In addition to increased speed, 5G networks will offer lower latency, increased reliability, better connectivity [12] from more places, and greater capacity, allowing more users and more devices to be connected at the same time. The resulting infrastructure will finally make the Internet of Things (IoT) scalable, with more than 20.8 billion things including buildings, cars, machines, appliances and wearable devices [13]. MmWave technology is rising as a crucial component for 5G radio access and other emerging ancillary wireless networks including Gb/s device-to-device communication and mobile backhaul.

C. NB-IoT

Intel is proud to have played a major role in creating NarrowBand IoT (NB-IoT) [14], the radio technology standardized by the 3GPP standards, which delivers Low Power Wide Area access (LPWA) [15] to a new generation of connected things in the race to 5G. NB-IoT offers important technical benefits that will accelerate 5G innovation. It is a core technology necessary to meet the cost, battery life and wide area coverage required of massive IoT. With spectrum in limited supply, 5G mobile networks must become more agile, delivering the right amount of data, at the right rate, over the right air interface, within the right area, to the right device, in the most efficient way possible. Supporting the

aggressive goals of 5G will require tapping into new licensed bands and exploring new ways to use new and existing unlicensed spectrum bands to meet data demands.

NB-IoT allows small form factor devices and sensors to connect efficiently to licensed spectrum of narrow bandwidth (180 kHz), mitigating growing network load in the valuable and scarce cellular bands, while also improving network capacity and spectrum efficiency. NB-IoT allows manufacturers and carriers to substantially reuse existing network and device technologies, deploying within a legacy LTE carrier [16], in the guard band, or stand-alone. NB-IoT also supports deep indoor and wide area coverage, a coverage extension of 10dB to 20dB over existing technologies with low device complexity and power consumption, which are important factors to consider when planning for rural as well as urban sensor-based applications. Smart devices accessing the network via NB-IoT are expected to launch in late 2016 or early 2017 with a battery life of more than ten years. NB-IoT eases entry for a variety of new products and use cases. Mobile operators can embrace emerging devices and technologies, creating new lines of revenue without stressing their network resources to the point of degrading the quality of traditional services. Manufacturers can develop solutions at massive scale for consumer, agricultural, industrial, metropolitan and governmental applications at affordable price points, speeding adoption. Equally importantly, NB-IoT provides insight on what the "things of the future" will be, what they will do and how they will shape our lives, while also helping us chart the path forward. And it gives the industry the time it needs to figure out the standards and technologies that will comprise the multi-faceted 5G" network of all networks. LTE, Wi-Fi, mmWave, NB-IoT, and the new 5G interface will work together seamlessly. Operate NB-IoT Network as a service, ARPC increased due to the opportunity to generate service revenue. It provides full NB-IoT network functionality in the cloud, supporting big data solution for enhancing user experience.

NB-IoT addresses LPWA use cases reusing existing cellular infrastructure. Covering new use cases means facing new challenges indicating extended coverage, low power consumption [17], and stability. Operators' acceptance includes 3GPP conformance test and certification. It uses integration of E7515A UXM Wireless Test Set and confidently runs RF & RRM conformance 3GPP test cases on a validated GCF/PTCRB test platform TP-195. It is designed as a pre-conformance and design verification (DV) tool. Extensive test coverage is served for major US operators acceptance test plans such as AT&T, Verizon, T-Mobile and Sprint. Scalable and compact solution is based on a common hardware set. It creates custom test campaigns with flexibility, and uses powerful debug tools for results analysis. It free-ups engineering resource by adopting test automation.

1. NB-IoT uplink power control

Uplink power control controls the transmit power of the different uplink physical channels. The setting of the UE transmission power for a Narrowband physical uplink shared channel (NPUSCH) is defined [15] as follows. The UE transmit power $P_{NPUSCH,c}(i)$ for NPUSCH transmission in NB-IoT UL slot i for the serving cell c is given by the below scenario. If the number of repetitions of the allocated NPUSCH RUs is greater than 2, $P_{NPUSCH,c}(i) = P_{CMAX,c}(i)[dBm]$ otherwise

$$P_{NPUSCH,c}(i) = \min \left\{ P_{CMAX,c}(i), 10 \log_{10}(M_{NPUSCH,c}(i)) + P_{O_NPUSCH,c}(j) + \alpha_c(j) PL_c \right\} [dBm] \quad (1)$$

where $P_{CMAX,c}(i)$ is the configured UE maximum transmit power in NB-IoT UL slot i for serving cell c . $M_{NPUSCH,c}$ is $\{1/4\}$ for 3.75 kHz subcarrier spacing and $\{1,3,6,12\}$ for 15 kHz subcarrier spacing which depends on bandwidth of the selected RU and subcarrier spacing. $P_{O_NPUSCH,c}(j)$ is a parameter composed of the sum of a component $P_{O_NOMINAL_NPUSCH,c}(j)$ provided from higher layers and a component $P_{O_UE_NPUSCH,c}(j)$ provided by higher layers for $j=1$ and for serving cell c where $j \in \{1,2\}$. For NPUSCH transmissions corresponding to a dynamic scheduled grant then $j=1$ and for NPUSCH transmissions corresponding to the random access response grant then $j=2$. $P_{O_UE_NPUSCH,c}(2) = 0$ and $P_{O_NOMINAL_NPUSCH,c}(2) = P_{O_PRE} + \Delta_{PREAMBLE_Msg3}$, where the parameter *preambleInitialReceivedTargetPower* P_{O_PRE} and $\Delta_{PREAMBLE_Msg3}$ are signaled from higher layers for serving cell c . When $j=1$, for NPUSCH format 2, $\alpha_c(j) = 1$; For NPUSCH format 1, $\alpha_c(j)$ is provided by higher layers for serving cell c . When $j=2$, $\alpha_c(j) = 1$. PL_c is the downlink path loss estimate calculated in the UE for serving cell c in dB. This factor is weighted by $\alpha_c(j)$. $PL_c = nrs - Power - NRSRP$ where *nrs-Power* is provided by higher layers and NRSRP is the higher layer filter configuration for serving cell c . Uplink modulation is QPSK, while sub-carrier spacing is 15 kHz.

If the UE transmits NPUSCH in NB-IoT UL slot i for serving cell c , power headroom is computed using $PH_c(i) = P_{CMAX,c}(i) - \{P_{O_NPUSCH,c}(1) + \alpha_c(1) PL_c\} [dB]$. The power headroom should round down to the closest value in the set [PH1, PH2, PH3, PH4] dB, which is delivered by the physical layer to higher layers.

2. NB-IoT downlink power allocation

The eNodeB determines the downlink transmit energy per resource element. For an NB-IoT cell the UE may assume NRS EPRE is constant across the downlink NB-IoT system bandwidth and constant across all subframes that contain NRS, until different NRS power information is received. Downlink

transmission power refers to NRS transmission power. Its value is indicated to the UE in order to estimate the path loss. It is constant for all resource elements carrying the NRS and all SFs. The downlink NRS EPRE can be derived from the downlink narrowband reference-signal transmit power given by the parameter *nrs-Power* provided by higher layers. The downlink narrowband reference-signal transmit power is defined as the linear average over the power contributions (in [W]) of all resource elements that carry narrowband reference signals within the operating NB-IoT system bandwidth.

For the NPBCH, NPDCCH and NPDSCH, the transmit power depends on the transmission scheme. If only one antenna port is applied, the power is the same as for the NRS, otherwise it is reduced by 3 dB. A UE may assume the ratio of NPDSCH EPRE to NRS EPRE among NPDSCH REs is 0 dB for an NB-IoT cell with one NRS antenna port and -3 dB for an NB-IoT cell with two NRS antenna ports. A UE may assume the ratio of NPBCH EPRE to NRS EPRE among NPBCH REs is 0 dB for an NB-IoT cell with one NRS antenna port and -3 dB for an NB-IoT cell with two NRS antenna ports. A UE may assume the ratio of NPDCCH EPRE to NRS EPRE among NPDCCH REs is 0 dB for an NB-IoT cell with one NRS antenna port and -3 dB for an NB-IoT cell with two NRS antenna ports. A special case occurs if the in-band operation mode is used and the *samePCI* value is set to true. Then the eNB may additionally signal the ratio of the NRS power to the CRS power, enabling the UE to use the CRS for channel estimation as well. For an NB-IoT cell with the parameter *samePCI* set to *TRUE*, the ratio of NRS EPRE to CRS EPRE is given by the parameter *nrs-CRS-PowerOffset* if the parameter *nrs-CRS-EPRE-Radio* is provided by higher layers, and the ratio of NRS EPRE to CRS EPRE may be assumed to be 0 dB if the parameter *nrs-CRS-EPRE-Radio* is not provided by higher layers.

3. NB-IoT design objectives

High density is approaching 10,000 devices/cell. Data rates of NB-IoT is 10 s/kbps. NB-IoT supports low frequency of connections. Low cost is its advantage. The cost of modules is less than 5 dollars. It is highly reliable and stable. The key design goal is superior battery life up to 10 years with enhanced sleep mode. Extreme coverage arrives +20 dB compared to GPRS. It can upgrade directly from existing RAN infrastructure. Uplink report latency is less than 10 seconds. NB-IoT creates innovation solution towards lower cost, lower power, extreme larger coverage, higher density, higher data rates, enhanced higher mobility, more accurate positioning, further power reduction.

4. NB-IoT Frame Structure

In the downlink frame, NB-IoT has same numerology as LTE and coexistence with LTE. 180 kHz bandwidth is consisted of 12 subcarriers each separated 15 kHz, which is equivalent to 1 LTE PRB. One frame duration includes 10 subframes 1024 SFN. One subframe occupies 2 slots in 1 ms. One slot assigns 7 OFDM symbols in 0.5 ms. One hyperframe comprises 1024*1024 radio frames for 3 hours. One radio frame lasts 10 ms. One OFDM symbol lasts 2208 Ts for symbol #0 or 2192 Ts for symbol #1 to symbol #6. Coexisting with LTE, it lasts 8448 Ts total available.

In the uplink frame, single-tone, as mandatory setting, has 1 subcarrier to provide capacity in signal-strength-limited scenarios and more dense capacity. Subcarrier spacing is 15 kHz or 3.75 kHz via random access and slot duration is 0.5 ms or 2 ms separately. Multi-Tone, as optional capacity, has 3, 6 or 12 signaled subcarriers via DCI to provide higher data rates for devices in normal coverage. Subcarrier spacing is 15 kHz and slot duration is 0.5 ms.

5. NB-IoT physical layer channel

NPRACH is designed as NB-IoT physical layer uplink random access channel. Dedicated channel specifies physical uplink shared channel NPUSCH. Downlink channels [18] include physical downlink broadcast channel NPBCH, dedicated channel that is divided into physical downlink shared channel NPDSCH and physical downlink control channel NPDCCH. Narrowband physical broadcast channel NPBBCH is transmitted in every downlink subframe #0. It has 8 independently decodable sub-blocks of 80 ms duration and 640 ms period consisting of 8 sub-blocks for each 80 ms. It carries the MasterInformationBlock-NB (MIB-NB) with part of system frame number and part of hypersubframe number. Others rest in SIB1-NB. SIB1-NB scheduling information indicates the number of repetitions. It has SystemInfoValue tag and supports standalone, in-band, guard-band operation modes. Each MIB-NB sub-block is repeated 8 times.

NB-IoT controls SIBs over Narrowband physical downlink shared channel NPDSCH. SystemInformationBlockType1-NB (SIB1-NB) uses a fixed schedule and periodicity derived from PCID and MIB-NB. It has periodicity of 2560 ms with 4, 8 or 16 repetitions within that period. It is transmitted in subframe #4 in every even frame during 16 consecutive frames. NPDSCH handles cell access and cell selection. Remaining SIB information, SIB2-NB has radio resource configuration common to all UEs. SIB3-NB has cell re-selection common. SIB4-NB accomplishes neighbor cells intra-frequency interaction. SIB5-NB realizes neighbor cells inter-frequency interaction. SIB14-NB provides access barring service. SIB16-NB has GPS and UTC functions.

NPSS and NSSS represent narrowband primary and secondary synchronization signals. It is used to estimate frequency and timing as well as derive the cell ID. NPSS is transmitted in subframe #5 in all frames. NSSS is transmitted in subframe #9 but only in even frames. Given before acquiring sync signals and operation mode is unknown, first 3 OFDM symbols are skipped and LTE CRS are also skipped in all modes. NRS denotes narrowband cell reference downlink signals. It used to estimate the channel. It is transmitted in every 'valid' downlink subframe except in NPSS/NSSS. For uplink, it has demodulation reference signals DMRS.

LTE channels are time and frequency multiplexed supporting multiple channels per subframe. NB-IoT each physical channel occupies the whole PRB supporting only one channel per subframe. In NB-IoT random access procedure, it uses pseudo random hopping scheme during second repetition. In first higher layer protocol interaction, NB-IoT device transmits random access preamble to NB-IoT eNodeB. Preambles can be repeated up to 128 times. Then eNodeB sends back random access response to device. Scheduled transmission information is notified eNodeB by device. Contention resolution notification is delivered to NB-IoT device.

There are 3 different coverage levels signaled via SIB2-NB: Normal, Robust, and Extreme. The coverage level selected determines the NPRACH resources to use subset of subcarriers, PRACH repetitions, and max number of attempts. UE derives the coverage level based on NRSRP measured NPRACH resources. NB-IoT repetition technique is consisting on repeating the same transmission several times to achieve extra coverage up to 20 dB compared to GPRS. Each repetition is self-decodable. Scrambling code is changed for each transmission to help combination. Repetitions are just ACK message once. All channels of NB-IoT can use repetitions to extend coverage.

Narrowband physical downlink control channel NPDCCH carries Downlink Control Information (DCI). Three DCI types are defined that N0 is used to schedule uplink transmissions, N1 is used to schedule downlink transmissions, and N2 is used to schedule paging or direct indication. It fully occupies one downlink subframe where repetitions may be used to improve coverage. Resource elements are mapped around NRS. In the case of in-band, it is also around LTE CRS and starting at 1 symbol to skip LTE PDCCH as signaled by higher layers $l_{NPDCCHStart}$. There are two Control Channel Elements (NCCE) in every NPDCCH. Aggregation Level 1 uses only one NCCE. Aggregation Level 2 uses both NCCE for more robust transmissions.

Narrowband physical downlink shared channel NPDSCH carries user data and broadcast information instead of transmitting on NPBCH. NPBCH generally processes SIBs-NB, paging or

dedicated RRC information. For user data, it supports QPSK only and single HARQ process. TBS is less than 680 bits. A single TBS can be mapped to multiple consecutive downlink subframes (N_{SF}) signaled in DCI N1. It requires at least 3 subframes when TBS equals to 680 bits. Up to 2048 repetitions are used to reach larger coverage. Downlink scheduling signaled via DCI Format N1 indicates the modulation and coding scheme, scheduling delay, DCI repetition number, NPDSCH repetition, resource assignment, and HARQ-ACK resource index.

Narrowband physical uplink shared channel NPUSCH format 1 is used to transport user data via BPSK or QPSK. TBS is less than 1000 bits. Smallest mapping unit is the Resource Unit (RU) defined as the combination of number of subcarriers via DCI and number of slots fixed. Uplink Grant signaled via DCI Format N0 in the NPDCCH provides subcarrier indication, resource assignment, and modulation and coding scheme, scheduling delay, redundancy version, repetition number, DCI repetition number. LTE mapping unit is 1 PRB consisting of 2 slots for each 12 seconds while NB-IoT mapping unit is 1 RU with N slots for N seconds. A single NPUSCH instance can last more than 1 ms. NPUSCH format 2 is used to uplink control information (UCI). It has downlink HARQ feedback. It is transmitted ($k_0 - 1$) subframes after the last NPDSCH transmission via BPSK only and single tone only.

6. Table 1: Reference channel for category NB1

Parameter	Value
Sub-carrier spacing (kHz)	15
Number of tone	1
Modulation	$\Pi/4$ QPSK
Number of NPUSCH repetition	1
IMCS/ITBS	3/3
Payload size (bits)	40
Allocated resource unit	1
Code rate	1/3
Transport block CRC (bits)	24
Code block CRC size (bits)	0
Number of code block	1
Total number of bits per resource unit	192
Total symbols per resource unit	96
Tx time (ms)	8

7. Table 2: NB-IoT key parameters

Frequency range	NB-IoT (LTE) FDD Bands: 1, 2, 3, 5, 8, 11, 12, 13, 17, 18, 19, 20, 25, 26, 28, 66, 70
Duplex Mode	FDD Half Duplex type B
MIMO	No MIMO support
Bandwidth	180 kHz
Multiple Access	Downlink: OFDMA, 15 kHz tone spacing, TBCC, 1Rx. Uplink: single tone: 15 kHz and 3.75 kHz spacing, SC-FDMA: 15 kHz tone spacing, Turbocode
Modulation Schemes	Downlink: QPSK Uplink: Single Tone: $\Pi/4$ QPSK, $\Pi/2$ QPSK Multi Tone: QPSK

Coverage	164 dB (+20dB GPRS)
Data Rate	25 kbps in DL and 64 kbps in UL (multi tone UE)
Latency	< 10 seconds
Low Power	eDRX, Power Saving Mode
MTU size	1500 B
TBS	Maximum transmission block size 680 bits in DL, 1000 bits in UL, min.16 bits
Repetitions	Up to 2048 repetitions in DL and 128 repetitions in UL data channels
Power saving	PSM, extended idle mode DRX with up to 3 h cycle, connected mode DRX with up to 10.24 s cycle
Maximum transmit power	23 dBm or 20 dBm

8. NB-IoT deployment scenarios

Figure 8 depicts that NB-IoT has three deployment modes [19] including stand-alone, guard band and in-band. Stand-alone can replace a GSM carrier with an NB-IoT cell. Guard band can utilize the unused resource blocks within a LTE carrier's guard-band with guaranteed co-existence. Through flexible use of part of an LTE carrier with a self-contained NB-IoT cell using 1PRB in-band. Processing along with wideband LTE carriers implying OFDM secured orthogonally and common resource utilization. Maximum user rates are downlink 30 kbps and uplink 60 kbps. The capacity of NB-IoT carrier is shared by all devices. Capacity is scalable by adding additional NB-IoT carriers.

NB-IoT is a self-contained carrier that can be deployed with a system bandwidth of only 200 kHz, and is specifically tailored for ultra-low-end IoT applications. NB-IoT provides lean setup procedures, and a capacity evaluation indicates that each 200 kHz NB-IoT carrier can support more than 200,000 subscribers. The solution can easily be scaled up by adding multiple NB-IoT carriers when needed. NB-IoT also comes with an extended coverage of up to 20 dB, and battery saving features, power saving mode and eDRX for more than 10 years of battery life.

NB-IoT is designed to be tightly integrated and interwork with LTE, which provides great deployment flexibility. The NB-IoT carrier can be deployed in the LTE guard band, embedded within a normal LTE carrier, or as a standalone carrier in, for example, GSM bands.

Standalone deployment in a GSM low band: this is an option when LTE is deployed in higher band and GSM is still in use, providing coverage for basic services. Highest modulation scheme is QPSK. It supports half-duplex FDD operation mode with 60 kbps peak rate in uplink and 30 kbps peak rate in downlink. Narrow band physical downlink channels transmit over 180 kHz (1 PRB). Preamble based random access operates on 3.75 kHz. Narrow band physical uplink channel transmits on single-tone (15 kHz or 3.75 kHz) or multi-tone ($n \times 15$ kHz, $n=[3,6,12]$). Maximum transport block size (TBS) is 680 bits in downlink, 1000 bits in uplink. Use repetitions for coverage enhancements, up to 2048 reps

in downlink, 128 reps in uplink data channels. Maximum coupling loss 164 dB which has been reached with assumptions given in the table 3, shows the link budget for uplink.

Guard band deployment, typically next to an LTE carrier: NB-IoT is designed to enable deployment in the guard band immediately adjacent to an LTE carrier, without affecting the capacity of LTE carrier. This is particularly suitable for spectrum allocations that do not match the set of LTE system bandwidths, leaving gaps of unused spectrum next to the LTE carrier. It is single-process, adaptive and asynchronous HARQ for both uplink and downlink. In NB-IoT, data is transferred over Non-Access Stratum (NAS), or over user plane with RRC suspend/resume. NAS is a set of protocols used to convey non-radio signaling between the UE and the core network, passing transparently through radio network. The responsibilities of NAS include authentication, security control, mobility management and bearer management. Access stratum (AS) is the functional layer below NAS, working between the UE and radio network. It is responsible for transporting data over wireless connection and managing radio resources. AS optimization called RRC suspend/resume can be used to minimize the signaling needed to suspend/resume user plane connection. MTU size is 1500 bytes for both NAS and AS solutions. Extended idle mode DRX with up to 3 hours cycle, connected mode DRX with up to 9.216 second cycle. It supports multi-physical resource block (PRB)/carrier. It can enable error correction through ARQ, concatenation, segmentation to the SDUs from PDCP into the transmission block sizes for physical layer, and reassembly in RLC acknowledged mode. It authenticates between UE and core network, provides encryption and integrity protection of both AS and NAS signaling, encryption of user plane data between the UE and radio network, key management mechanisms to effectively support mobility and UE connectivity mode changes.

Efficient in-band deployment, allowing flexible assignment of resources between LTE and NB-IoT: it will be possible for an NB-IoT carrier to time-share a resource with an existing LTE carrier. The in-band deployment also allows for highly flexible migration scenarios. For example, if the NB-IoT service is first deployed as a standalone deployment in a GSM band, it can subsequently be migrated to an in-band deployment if the GSM spectrum is refarmed to LTE, thereby avoiding any fragmentation of the LTE carrier.

The standalone deployment is a good option for WCDMA or LTE networks running in parallel with GSM. By steering some GSM/GPRS traffic to the WCDMA or LTE network, one or more of the GSM carriers can be used to carry IoT traffic. As GSM operates mainly in the 900MHz and 1800 MHz bands, this approach maximizes the benefits of a global-scale infrastructure.

In-band deployment is best option for LTE. An NB-IoT carrier is a self-contained network element that uses a single physical resource block (PRB). The base station scheduler multiplexes NB-IoT and LTE traffic onto the same spectrum, which minimizes the total cost of operation for MTC, which essentially scales with the volume of MTC traffic. The capacity of a single NB-IoT carrier is quite significant. Evaluations have shown that a standard deployment can support a deployment density of 200,000 NB-IoT devices within a cell for an activity level corresponding to common use cases.

A third alternative is to deploy NB-IoT in a guard band, the focus is on the use of such bands in LTE. To operate in a guard band without causing interference, NB-IoT and LTE need to coexist. Like LTE, NB-IoT uses OFDMA in the downlink and SC-FDMA in the uplink. The design of NB-IoT has fully adopted LTE using 15 kHz subcarriers in the uplink and downlink, with an additional option for 3.75 kHz subcarriers in the uplink to provide capacity in signal-strength-limited scenarios.

Long range and long battery life. Not only can NB-IoT reuse the GSM, WCDMA, or LTE bands, the improved link budget enables it to reach IoT devices in signal-challenges locations such as basements, tunnels, and remote rural areas where cannot be reached using the network's voice and MBB services. The battery life of an MTC device depends to some extent on the technology used in the physical layer for transmitting and receiving data. However, longevity depends on a greater extent on how efficiently a device can utilize various idle and sleep modes that allow large parts of the device to be powered down for extended periods. The NB-IoT specification addresses both the physical-layer technology and idling aspects of system. Like LTE, NB-IoT uses two main RRC protocol states: RRC_idle and RRC_connected. In RRC_idle, devices save power, and resources that would be used to send measurement reports and uplink reference signals are freed up. In RRC_connected, devices can receive or send data directly. Discontinuous reception (DRX) is the process through which networks and devices negotiate when devices can sleep and can be applied in both RRC_idle and RRC_connected. For RRC_connected, the application of DRX reduces the number of measurement report devices send and the number of times downlink control channels, leading to battery savings. In RRC_idle, devices track area updates and listen to paging messages. To set up a connection with an idle device, the network pages it. Power consumption is much lower for idle devices than for connected ones, as listening for pages does not need to be performed as often as monitoring the downlink control channel.

When PSM was introduced in release 12, it enabled devices in RRC_idle to enter a deep sleep in which pages are neither listened for, nor mobility-related measurements perform. Devices in PSM

perform tracking area updates after which they directly listen for pages before sleeping again. PSM and eDRX complement each other and can support battery lifetimes in excess of 10 years for different reachability requirements, transmission frequencies of different applications and mobility.

Fig.8. NB-IoT deployment scenario

Figure 9. Good Coverage

The range of solutions designed to extend battery lifetimes need to be balanced against requirements for reachability, transmission frequency of different applications, and mobility. These relations are illustrated in Figure 9.

NB-IoT reduces device complexity below that of LTE-M with the potential to rival module costs of unlicensed LPWA technologies, and it will be ideal for addressing ultra-low-end applications in markets with a mature LTE installed base.

9. Maximum throughput in Inband

The downlink channels consume total 26 ms. The max TBS in Inband transmits 680 bits. The throughput should be computed as $680/26 = 26.15$ kbps. For uplink channels, single-tone UE total costs 60 ms. Max TBS in Inband transmits 1000 bits. The uplink throughput should be obtained by $1000/60 = 16.67$ kbps. In practice throughput does not fulfill these ideal cases because both NPDSCH &

NPDCCH are affected by collisions with NPSS and NSSS, collisions with broadcast as well as NPDCCH occasions periodicity. Real average throughput is approximately 22 kbps for downlink and 15 kbps for uplink.

10. NB-IoT system architecture

Figure 10 depicts that network architecture is based on evolved packet core (EPC) used by LTE, cellular IoT user equipment (CIoT UE) is the mobile terminal. CIoT Radio Access Network (CIoT RAN) handles the radio communications between the UE and the EPC, and consists of the evolved base stations called eNodeB or eNB. It can provide authentication and core network signaling security as in normal LTE. Security supporting optimized transmission of user data. Encrypted and integrity protected user data can be sent within NAS signaling. Minimized signaling can resume cached user plane security context in the radio network.

Figure 10. Network architecture for the NB-IoT data transmission and reception. In red, the Control Plane CIoT EPS optimization is indicated, in blue the User Plane CIoT EPS optimization is indicated.

On the control plane CIoT EPS optimization, UL data are transferred from the eNB (CIoT RAN) to the MME. From there, they may either be transferred via the Serving Gateway (SGW) to the Packet data Network Gateway (PGW), or to the Serving Capability Exposure Function (SCEF) which is only possible for non-IP data packets. From these nodes they are finally forwarded to the application server (CIoT Services). DL data is transmitted over the same paths in the reverse direction. In this solution, there is no data radio bearer set up, data packets are sent on the signaling radio bearer instead. Consequently, this solution is most appropriate for the transmission of infrequent and small data packets. The SCEF is a new node designed especially for machine type data. It is used for delivery of non-IP data over control plane and provides an abstract interface for the network services (authentication and authorization, discovery and access network capabilities). With the User Plane CIoT EPS optimization, data is transferred in the same way as the conventional data traffic, i.e. over radio bearers via the SGW and the PGW to the application server. Thus it creates some overhead on

building up the connection, however it facilitates a sequence of data packets to be sent. This path supports both IP and non-IP data delivery.

11. NB-IoT Power Saving Mode (PSM) and enhanced DRX (eDRX)

T3324 determines for how long the UE will monitor paging before entering in PSM shown in Figure 11 (a). While in PSM, UE is not reachable by the network and all circuitry is turned off. UE exits PSM when T3412 expires (TAU) or with a Mobile Originated transfer. DRX cycles extended from 2.56 seconds to 9.22 seconds in NB-IoT CONNECTED eDRX mode indicated in Figure 11 (b). For idle eDRX mode depicted in Figure 11 (c), new paging time window allows longer paging cycles about 3 hours in NB-IoT.

Figure 11. (a) Rel-12 Power Saving Mode (PSM) (b) Rel-13 Enhanced DRX (eDRX) CONNECTED eDRX (c) IDLE eDRX

The UE in the RRC_IDLE state only monitors some of the SFs with respect to paging, the paging occasions (PO) within a subset of radio frames, the paging frames (PF). If coverage enhancement repetitions are applied, the PO refers to the first transmission within the repetitions. The PFs and POs are determined from the DRX cycle provided in SIB2-NB, and the IMSI provided by the USIM card. DRX is the discontinuous reception of DL control channel used to save battery lifetime. Cycles of 128, 256, 512 and 1024 radio frames are supported, corresponding to a time interval between 1.28s and 10.24s.

12. NB-IoT power consumption & efficiency optimization

There exists some design challenges for power consumption and efficiency. It is expected to setting the device in different operating modes realistically, including IDLE, CONNECTED, PSM and eDRX. Power consumption impact of every consuming activity on repetitions, data transmissions or OTA updates should be carefully designed.

Accurately measuring sleep modes in presence of large spikes, the upper limit in wide dynamic range is 100 mA. Single view logging provides complete analysis. Characterizing battery run-down including aging effect, it is promising feature to measure current and voltage simultaneously with enough accuracy. The design anticipation is emulation of series resistance of the power supply. Before deploying, the critical characteristics should guarantee efficiency of power saving modes (PSM or eDRX). The states shift transitions between connected, idle, sleep states. Data transfer in uplink,

downlink, or bi-directional. The repetitions performance is varied for different coverage levels. Negative testing scenarios should be taken into account such as IoT server down, no coverage. Software updates should adapt to different IoT applications when in the field.

Extreme Coverage controls remote location, basements and sewerages, hidden installation, and industrial environments. The characterization is extreme sensitivity, synchronization under low SNR, transmitted signal, blocking and intermodulation. It suffers slow fading profiles under propagation conditions. Different operation modes and antenna configurations lead to performance disparity.

Receiver sensitivity without and with repetitions, below -120 dBm requires very accurate signal generation. Soft-combination delivers expected gain in the receiver. NRSRP and NRSRQ properly measured and reported to higher layers. Performance characterization using low cost components considers that synchronization is difficult when poor signal to noise ratio due to low cost crystal oscillator. Impact of the transmitted signal is caused by removal of PAPR reduction circuitry. Nomadic devices with slow mobility are stemmed from SISO and transmission diversity. Complex test set-ups environment including multiple antennas, AWGN and Fading becomes an obstacle facing extreme coverage. The test equipment for extreme coverage consists of vector signal analyzer, interference generator and network emulator, and fader. Vector signal analyzer can measure power, EVM, carrier leakage, frequency error, OBW. Interference generator can emulate in WCDMA, GSM, LTE modes. Network emulator can call set-up, network settings, BLER. Fader can produce fading profiles.

13. Capacity design

To meet capacity requirement, NB-IoT needs to multiplex many devices simultaneously, and provide connectivity in an efficient manner for all of them irrespective of coverage quality. As a result, the design of NB-IoT supports a range of data rates. The achievable data rate depends on the channel quality (SNR), and the quantity of allocated resources (bandwidth). In the downlink, all devices share the same power budget and several receive base-station transmissions. In the uplink, each device has its own power budget, and this can be used to advantage by multiplexing the traffic generated by several devices, as their combined power is greater than that of a single device.

Data rate is a significant factor when trying to achieve the best design for NB-IoT, as it affects both latency and power consumption. Uplink latency values for a device to connect and transmit data. The data rates for worst-case coverage (+20 dB) are lower than those for MBB at the cell edge (0 dB), and latency increases from 1.6 to 7.6 seconds. The uplink data rate is the main cause of this degradation, NB-IoT uplink latency is still under the 10 second design target. When it comes to power consumption,

the dominating factor is the speed at which devices transmit data, which increases in line with accelerating data rates.

NB-IoT has been designed with good multiplexing and adaptable data rates and so it will be able to meet predicted capacity requirements supporting 200,000 devices per cell. NB-IoT devices support reduced peak physical layer data rates: in the range of 100-200 kbps or significantly lower for single-tone devices. To facilitate low-complexity decoding in devices, turbo codes are replaced with convolutional codes for downlink transmissions, and limits are placed on maximum transport block size which is 680 bits for DL and not greater than 1000 bits for UL. By operating NB-IoT devices half duplex so that they cannot be scheduled to send and receive data simultaneously, the duplex filter in the device can be replaced by a simple switch, and an only single local oscillator for frequency generation is required. These optimizations reduce cost and power consumption.

At 200 kHz, the bandwidth of NB-IoT is substantially narrower than other access technologies. LTE bandwidths, range from 1.4 MHz to 20 MHz. The benefit of a narrowband technology lies in the reduced complexity of analog-to-digital (A/D) and digital-to-analog (D/A) conversion, buffering, and channel estimation all of which bring benefits in terms of power consumption.

The design of NB-IoT radio access reuses a number of LTE design principles and has the backing of the traditional cellular network. NB-IoT employs the same design principles as LTE, although it uses a separate new carrier, new channels, and random access procedures to meet the target requirements of IoT use case such as improved coverage, lower battery consumption and operation in narrow spectrum.

The NB-IoT downlink is based on OFDMA and maintains the same subcarrier spacing, OFDM symbol duration, slot format, slot duration, and subframe duration as LTE. As a result, NB-IoT can provide both in-band and guard band deployment without causing interference between its carriers and those used by LTE for MBB, making NB-IoT a well integrated IoT solution for LTE-focused operators.

Use of same upper layers is another similarity between LTE and NB-IoT, with some optimizations to support operation with low-cost devices. For example, NB-IoT does not support dual connectivity and devices do not support switching between access technologies (GSM, WCDMA, or Wi-Fi) in active mode. The connection to EPC provides NB-IoT devices with support for roaming and flexible charging, meaning that devices can be installed anywhere and can function globally. The ambition is to enable certain classes of devices to be handled with priority to ensure that emergency situation data can

be prioritized if the network is congested. NB-IoT reduces operational costs in provisioning, monitoring, billing, and device management. It supports state-of-the-art 3GPP security, with authentication, signaling protection, and data encryption. NB-IoT could support existing LTE features and future functionality designed for the entire cellular ecosystem, including MBB as well as IoT use cases. NB-IoT promising features consist of the broadcast feature eMBMS enable a large number of devices to be updated simultaneously and the device-to-device communication feature that relays transmissions to devices in poor coverage [20].

Data rate is a significant factor when trying to achieve the best design for NB-IoT, as it affects both latency and power consumption. As NB-IoT can be deployed in GSM spectrum, within an LTE carrier, or in an LTE or WCDMA guard band, it provides excellent deployment flexibility related to spectrum allocation, which in turn facilitates migration. Operation in licensed spectrum ensures that capacity and coverage performance targets can be guaranteed for the lifetime of a device, in contrast to technologies that use unlicensed spectrum, which run the risk of uncontrolled interference emerging even years after deployment, potentially knocking out large populations of MTC devices.

D. Renewable energy

[21] formulates a renewable energy aware cluster formation (REAL) problem to minimize the energy consumption in electric grid, with the support of hybrid energy supply in each cell site. Due to the difficulties in solving the REAL problem, they propose to decompose it into two stages and design polynomial-time algorithms for the decomposed problems. The proposed solution can better utilize the harvested energy and effectively save the energy consumption in electric grid. This paper proposes CoMP transmission of IoT devices for energy saving with the incorporation of renewable energy.

In WSNs, the nodes are actually provided with small batteries and substituting or recharging the batteries is very difficult task, since the nodes are deployed in the uncongenial environments for various applications. The important elements in the sensor nodes are transceiver, micro controller, power resource and external memory and one or more sensors, whereas for transmitting and receiving the packets or messages would possible through the transceiver. Equation (1) represents the Energy Consumption (EC) model while transmitting the message with k -bits over certain distance (d) in same manner, when receiving the message with k -bits over certain distance (d) is estimated in the equation (2). In this model, renewable energy (RE) is utilized, while distance is smaller than a threshold value d_0 , multi-path (mp) pattern is utilized.

$$E_T(k, d) = \begin{cases} kE_{IoT} - k\epsilon_{RE}d^2 \\ kE_{IoT} + k\epsilon_{mp}d^4 \end{cases} \quad (2)$$

$$E_R(k) = kE_{IoT} \quad (3)$$

where E_{IoT} is the energy needed by IoT. ϵ_{mp} is the energy needed by the amplifier in multi-path. ϵ_{RE} is the energy needed by renewable process. The total computational cost of the sensor node based on the transceiver, is directly proportional to the distance between the smart meters and sensor nodes. The minimum distance between the sensor node and gateway must be exact characteristics of WSN for minimizing power utilization. It is well understood that the high-energy resources are required for the gateway node to perform significantly during data transmission of the messages to IoT cloud server.

For selection in the sensor nodes, it is very essential to choose the effective a. Let's consider that average sensor node (W) as functioning on the renewable energy process and PT_{SN} is the probability distribution that occurs in the intermediate computation outcome. It is assumes that E_{RN} , E_{SN} and E_{RE} are the energy consumption of receiver node, sender node and renewable node of single message packet. Remember that each sensor node has average λ neighbors and it can approximately calculate the additional energy preserving/saving because of the renewable process in the WSN.

1. SN_j sensors nodes would locally forward their intermediate calculation results including the energy consumption of $SN_j * E_{SN}$.
2. Approximately $SN_j \lambda / 2$ sensor nodes would receive the intermediate calculation results including energy consumption of $SN_j \lambda / 2 * E_{RN}$.
3. Approximately $SN_j \lambda / 2$ sensor nodes would speed up the renewable process utilizing the received intermediate calculation outcome with energy preservation of

$$SN_j \lambda / 2 * 2E_{RE} = \lambda SN_j * E_{RE}. \quad (4)$$

Hence, the total energy consumption would be

$$\sum_{SN_j=1}^W PT_{SN} (SN_j * E_{SN} + SN_j \lambda / 2 * E_{RN} - \lambda SN_j * E_{RE}) \quad (5)$$

E. Visible light communications (VLC)

The advantage of visible light communications [22][23] is high data rates up to 10 Gbits/s, low power, low cost, and optical and radio communications complement each other. WiFi spectrum relief can provide additional bandwidth in environments where licensed or unlicensed communication bands are congested. In smart home network, enabling smart domestic/industrial lighting supports home wireless communication including media streaming and internet access. At the office, smart LED lighting assists HD video streaming, PDA, laptop communication.

A new kind of visible light communications (VLC) is proposed to enable mmWave cognitive radio to control smart energy meters in 5G IoT network. VLC is designed to connect smart sensors by mmWave communication. VLC is expected to achieve the objective of minimizing the energy consumption and maximizing data rates, the number of UEs associated with IoT BSs and maximizing UE connection. Simulation environment setup: small cell radius is 20m, IoT UE randomly distributed, number of cellular UEs is 30, number of channel resources is 30, number of D2D pairs is 6 to 30, maximum UE Tx power is 200mW (23dBm), channel bandwidth is 180 kHz, circuit power consumption is 50 mW (17 dBm), battery capacity is 800 mA/h, operating voltage is 4V.

Figure 12 indicates the proposed solutions in system sum rate with different D2D pairs. VLC has highest data rates in IoT transmission. As the number of D2D pairs increases, the system sum rate roars significantly. Figure 13 highlights that VLC can minimize the system power consumption. Figure 14 presents the renewable energy solution has longest average UE battery lifetime since renewable energy can get constant maximum power supply. The longer communication distance leads to more power consumption, then it reduces battery lifetime. Figure 15 depicts eDRX has more expected data. The more UE connection, the more the number of channels occupied, the higher data volume has. Balancing the data rates, energy consumption, and battery lifetime, UE connectivity, consumed system resources, VLC can obtain superior performance than others.

Figure 12. System sum rate with number of D2D pairs.

Figure 13. System power consumption with number of D2D pairs.

Figure 14. Average UE battery lifetime for different maximum D2D communication distances.

Figure 15. Expected data per UE with number of channels (cellular UEs).

IV. CONCLUSION

Several promising solutions for energy saving in 5G IoT network are proposed in this paper. Millimeter wave cognitive radio is designed into 5G IoT platforms. NB-IoT and virtual LPWAN are poised as great contributors towards phenomenal data rates and lower power consumption. IoT Fog collaboration platform is gearing up to the application of artificial intelligence to achieve smart energy control management. Resource sharing is expected to improve resource efficiency. Renewable energy is proposed to achieve stringent energy supply requirement of 5G IoT network. The expectation 5G IoT objectives can be arrived by the combination of smart energy meters, VLC, and millimeter wave cognitive radio with NB-IoT and LPWAN.

References

- [1] C. Jeong, J. Park, and H. Yu, "Random access in millimeter-wave beamforming cellular networks: issues and approaches," *Communications Magazine, IEEE*, vol. 53, no. 1, pp. 180–185, January 2015.
- [2] Mattia Rebato, Marco Mezzavilla, Sundeep Rangan, Michele Zorzi. "Resource Sharing in 5G mmWave Cellular Networks", 8 March, 2016. arXiv:1603.02651v1 [cs.IT].
- [3] C. Barati, S. Hosseini, S. Rangan, P. Liu, T. Korakis, S. Panwar, and T. Rappaport, "Directional cell discovery in millimeter wave cellular networks," *Wireless Communications, IEEE Transactions on*, vol. 14, no. 12, pp. 6664–6678, Dec 2015.
- [4] G. Lee, Y. Sung, and J. Seo, "Randomly-directional beamforming in millimeter-wave multi-user miso downlink," *Wireless Communications, IEEE Transactions on*, 2015.
- [5] V. Raghavan, J. Cezanne, S. Subramanian, A. Sampath, and O. Koymen, "Beamforming tradeoffs for initial UE discovery in millimeter-wave MIMO systems," *Selected Topics in Signal Processing, IEEE Journal of*, 2016.
- [6] J. Kim and S.-N. Hong, "Dynamic two-stage beam training for energy-efficient millimeter-wave 5G cellular systems," *Telecommunication Systems*, vol. 59, no. 1, pp. 111–122, 2014. [Online]. Available: <http://link.springer.com/10.1007/s11235-014-9891-6>.
- [7] R. Pec, K. S. Kim, I. S. Kim, B. W. Ku, and Y. S. Cho, "Cell searching and DoA estimation for a mobile station with antenna array in mm-wave cellular communications," in *Vehicle Technology Conference (VTC Spring), 2014 IEEE 79th*, May 2014, pp. 1–5.
- [8] J. Choi, "Beam selection in mm-Wave multiuser MIMO systems using compressive sensing," *Communications, IEEE Transactions on*, vol. 63, no. 8, pp. 2936–2947, Aug 2015.
- [9] M. Akdeniz, Y. Liu, M. Samimi, S. Sun, S. Rangan, T. Rappaport, and E. Erkip, "Millimeter wave channel modeling and cellular capacity evaluation," *Selected Areas in Communications, IEEE Journal on*, vol. 32, no. 6, pp. 1164–1179, June 2014.
- [10] T. Bai and R. W. Heath, "Coverage and rate analysis for millimeter-wave cellular networks," *IEEE Transactions on Wireless Communications*, vol. 14, no. 2, pp. 1100–1114, Feb 2015.
- [11] Making the connection: How the internet of things engages consumers and benefits business. The Consumer Goods Forum, Capgemini and Intel, 2016.
- [12] Marco Giordani, Marco Mezzavilla, Sundeep Rangan, Michele Zorzi. "Multi-Connectivity in 5G mm Wave Cellular Networks", 30 April, 2016. arXiv:1605.00105v1 [cs.NI].
- [13] Connecting sensor networks and devices to the cloud in just minutes. Intel, May 2014.
- [14] Antti Ratilainen. NB-IoT presentation for IETF LPWAN.
- [15] J. Schlien, D. Raddino. Narrowband Internet of Things, Whitepaper.
- [16] Z. Zhou, M. Dong, K. Ota, G. Wang, and L. T. Yang, "Energy-efficient resource allocation for D2D communications underlying cloud-RAN-based LTE-A networks," *IEEE Internet of Things*, vol. 3, no. 3, pp. 428–438, June 2016.
- [17] J. Liu, H. Guo, Z. Md. Fadlullah, and N. Kato, "Energy consumption minimization for FiWi enhanced LTE-A HetNets with UE connection constraint," *IEEE Communications Magazine*, vol. 54, no. 11, pp. 56–62, Nov. 2016.
- [18] NB-IoT Enabling New Business Opportunities. Whitepaper, Huawei, 2015.
- [19] NB-IoT: A sustainable technology for connecting billions of devices, Ericsson technology review, Volume 93, #3, April 22, 2016.
- [20] Ericsson, White Paper: Cellular networks for massive IoT. Enabling low power wide area applications, January 2016.
- [21] Yi-Han Chiang and Wanjiun Liao, "Renewable Energy Aware Cluster Formation for CoMP Transmission in Green Cellular Networks," *IEEE GLOBECOM 2014*, Austin, Texas, USA, Dec. 2014.
- [22] Marcos Katz. Two Novel Technologies Enabling IoT: Mobile Clouds and Visible Light Communications.
- [23] Chia-Wei Chen ; Wei-Chung Wang ; Jhao-Ting Wu ; Hung-Yu Chen ; Kevin Liang, et al. "Visible light communications for the implementation of internet-of-things", *Opt. Eng.* 55(6), 060501 (Jun 28, 2016).

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