OPTIMIZATION OF DRX POWER SAVING FOR LTE BASED IOT DEVICES

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List of Acronyms

3GPP	Third Generation Partnership Project
D2D	Devise to Devise
DRX	Discontinuous Reception
eDRX	Extended Discontinuous Reception
IoT	Internet Of Things
LPWA	Low Power Wide Area
LTE	Long Term Evolution
MTC	Machine-type Communications
M2M	Machine-to-Machine
MIMO	Multiple Input Multiple Output
NB-IoT	Narrowband IoT
PDCCH	Physical Downlink Control Channel
PSM	Power Saving Mode
RSMA	Resources speared multiple access
URLLC	Ultra Reliable and Low Latency Communication

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Abstract

The Third Generation Partnership Project (3GPP) has recognized machine-type communications (MTCs) as a vital medium to drive the Internet of Things (IoT). One of the key challenges in MTC is to reduce the energy consumption of the MTC user equipment (UE). Currently, the 3GPP Long Term Evolution (LTE)/LTE-advanced (LTE-A) standards incorporate discontinuous reception (DRX) mechanism for this purpose and the 3GPP extends the length of a DRX cycle. Therefore, how to configure the extended DRX (eDRX) cycle is a tradeoff between the delay in each session and the paging waste for a user equipment with a velocity, i.e. the extra cost of finding a user. In this paper, we analyze the tradeoffs and determine the optimal length for the eDRX cycle. The objective function is to minimize the total battery usage considering the tradeoff with the delays and the paging wastage. The analytical and simulation results demonstrate that the proposed mathematical model can mitigate the paging wastage and delay for the networks and the battery consumption of the user equipment.

Chapter 1

Introduction

The Machine-to-Machine (M2M) communication is gradually adding many devices to the wireless network. The explosive growth of the Internet of Things (IoT), an evolution of Machine-to-Machine (M2M) communication, is projected to reach multiple billions of devices in the next few years. The IoT is designed to integrate today’s rapidly expanding set of devices and machines, including but not limited to, sensors, alarms, meters, coffee-makers, and what not. At the same time, the unprecedented high adoption rate of long term evolution (LTE) is leading the industries to connect the majority of their devices to the Internet via LTE.

Connectivity is the foundation for IoT, and the type of access required will depend on the nature of the application. Many IoT devices will be served by radio technologies that operate on unlicensed spectrum and that are designed for short-range connectivity with limited QoS and security requirements typically applicable for a home or indoor environment. Currently, there are two alternative connectivity tracks for the many IoT applications that depend on wide-area coverage:

Cellular technologies: 3GPP technologies like GSM, WCDMA, LTE and future 5G. These WANs operate on licensed spectrum and historically have primarily targeted high-quality mobile voice and data services. Now, however, they are being rapidly evolved with new functionality and the new radio access technology narrowband IoT (NB-IoT) specifically tailored to form an attractive solution for emerging low power wide area (LPWA) applications. Unlicensed LPWA: new proprietary radio technologies, provided by, for example, SIGFOX and LoRa, have been developed and designed solely for machine-type communication (MTC) applications addressing the ultra-low-end sensor segment, with very limited demands on throughput, reliability or QoS.

1.1 Internet of Things (IoT)

In this vision of a totally interconnected world, cellular technologies will play a pivotal role – and they already have; 1G and 2G networks connected people to one another via voice, and 3G and 4G extended connectivity to the mobile Internet, delivering blazing fast mobile broadband services. Not only do cellular networks offer ubiquitous coverage, but they also bring unparalleled level of reliability, security, and performance required by the most demanding IoT applications. 3GPP technologies, such as 4G LTE, can provide wide-area IoT connectivity – LTE is established globally and the fastest growing wireless standard, already delivering over two billion connections worldwide. It will continue to gain momentum and proliferate even further in the decade to come. LTE is also backed by a common, global 3GPP standard with support of a strong, interoperable, end-to-end ecosystem. Altogether, LTE provides a solid foundation for the future growth of IoT, bringing significant benefits over non-3GPP/proprietary solutions. 3GPP has introduced a suite of two complementary narrowband technologies in Release 13, eMTC (enhanced machine-type communication) and NB-IoT (narrowband IoT), or collectively referred to as LTE IoT. Both eMTC and NB-IoT are optimized for lower complexity/power, deeper coverage, and higher device density, while seamlessly coexisting with other LTE services. Together, they expand the LTE technology portfolio beyond mobile broadband and are starting to connect the massive IoT today. Beyond 3GPP Release 13, there is a rich roadmap of LTE IoT technology inventions that are delivering many further enhancements to meet tomorrow’s massive IoT connectivity needs.

For example, 3GPP Release 14 will bring single-cell multicast for easy over-the-air firmware upgrades and device positioning for asset location tracking; in addition, 3GPP Release 15 will introduce TDD support for NB-IoT, as well as a new wake-up receiver design to allow for even better energy efficiency. LTE IoT will continue to evolve for many years to come, leveraging the scale, longevity and global coverage of LTE networks to not only seamlessly enable migration from 2G, but to also complement the initial 5G NR (New Radio) deployments that focus on enhanced mobile broadband and high-performance IoT. Eventually, there will be a 5G NR-based massive IoT solution, and it will bring advanced design techniques such as RSMA (resources speared multiple access) for grant-free transmissions and multihop mesh to further extend coverage. Furthermore, the MulteFire Alliance is adapting LTE IoT for the unlicensed spectrum to expand into new use cases such as private networks for the industrial IoT. All in all, the continued LTE IoT evolution and its expansion to new deployments are integral parts of the 5G Platform – a unified, more capable connectivity fabric for the next decade and beyond. [1]

All these connection between devices in IoT can be shown with a diagram below. Different color coding is used to represent different links.

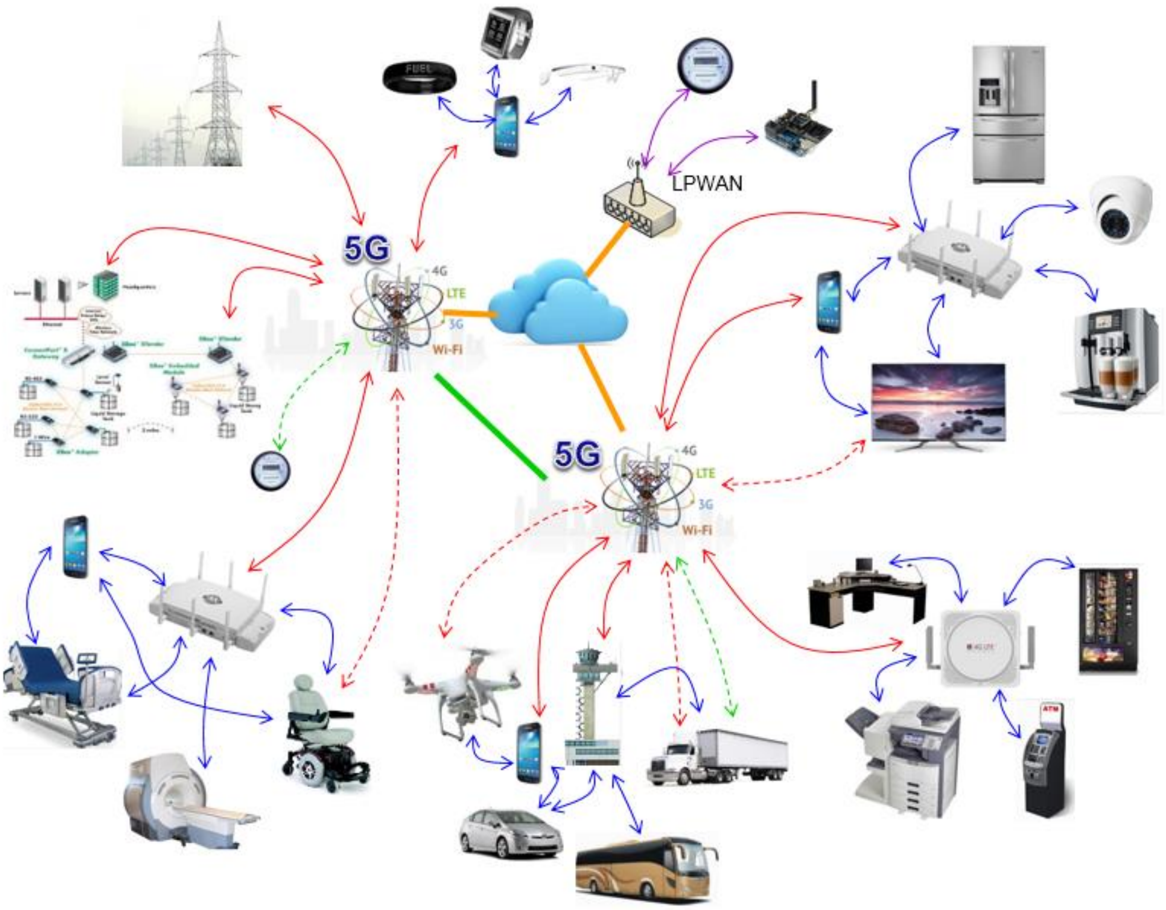

Figure 1 Connection between devices in IoT

- Dotted Red: This is cellular link (meaning communication between cellular network and the device). This link indicates what 5G people call 'eMBB' (Enhanced Mobile Broadband) and URLLC (Ultra Reliable and Low Latency Communication). We may not call this type of communication as a typical IoT, but some cases of this type of communication can be categorized as IoT. However, this link requires extremely short latency (remote control over cellular network) or extremely high throughput (downloading HD TV without compression). As of now (Oct 2015), this link would be difficult to be implemented. This link is one of the main target/motivation for 5G.
- Dotted Green: This link indicates a communication in which a lot of small end device (e.g., Water meter, power meter etc.) directly communicates with a cellular network

transmitting very low throughput data. This link will be the main target for LTE Cat 0, 1, LTE-M, MTC or NB-IoT (NB-LTE).

- Solid Red: This is also cellular link (meaning communication between cellular network and the device). But some of the application might have already been seen being used even now (Oct 2015) and the type of cellular technology is covering the whole range from 2G (GSM, CDMA), 3G (WCDMA) through 4G (LTE). Relatively latest technology (as of Oct 2015) would be Category 3 LTE, but in most case this can be taken as too expensive solution. It starts moving towards Category 1 and Category 0. I think you would see many Category 1 devices from next year (2016) and Category 0 devices from late next year (2016) or early 2017 in the market. Currently, Category 0 activity is being done at mobile baseband chipset level.
- Solid Blue: This is a kind of short range communication being used between the device and a Gateway. Various communication technologies are used in this area. ZigBee or similar technology has been used in most cases, but recently there has been activities moving towards IEEE 802.15 based communication (e.g., 6 LoPAN). This type of communication would be more dominant in industrial IoT (e.g., Sensor network in a factory)
- Solid Green: This represents a backhaul line connecting cellular tower or core network data pipe. If IoT is realized as everybody says/hopes, the amount of traffic flowing through this line would be enormous and this path should be wide enough to handle all those traffics. Though may not be visible to most of cellular people, this part is one of the most actively working area recently (as of late 2015).
- Solid Violet: This represents Non-Cellular LPWAN like LoRa, SigFox etc.

1.2 IoT Specifications

Table 1 IoT Specifications

IoT		
Unlicensed	6LowPAN	IPv6 over Low Power Wireless Personal Area Network (RFC 4944)
	IEEE 802.15.4	Wireless PAN (IEEE 802.15.4)
	RPL	Routing Protocol for Low Power and Lossy Networks
	LoRa	LoRa Specification
	SigFox	SigFox Home
	ZigBee	ZigBee Smart Energy 2.0
	PLC	Power line Communication
Licensed	LTE	Category 1, Category 0, LTE-M (M1, M2)
	NB-IoT (NB-LTE)	3GPP TR 45.820 V13.1.0 (2015-11)
		3GPP 36.133 - Requirements for support of radio resource management (search 'NB' in the document)
		3GPP 36.211 - Physical channels and modulation, section 10.2.3, 10.2.5, 10.2.6,10.2.7,10.2.9
		3GPP 36.212 - Multiplexing and channel coding, section 6.4.3
		3GPP 36.213 - Physical layer procedures, chapter 16
		3GPP 36.306 - 4.1C UE Category NB
		3GPP 36.302 - Services provided by the physical layer (search 'NB' in the document)

		3GPP 36.321 - MAC Protocol, section 3.1,3.2,4.4,5.1,5.3,5.4,5.7
		3GPP 36.322 - RLC Protocol (Search 'NB' in the document. It is everywhere)
		3GPP 36.331 - RRC Protocol, section 4.2.1,4.4,5.1.3,5.2.2,5.2.3
		3GPP 36.401 - Architecture description, section 6.1,6.2.1,6.2.4,6.4, 7.2.5,7.2.7,7.2.11,7.2.12,9.1,9.2,11.2
Application	MQTT	MQ Telemetry Transport
	CoAP	RFC 7252
	WebSocket	RFC 6455
M2M		
	OneM2M	ETSI OneM2M, OneM2M Home
	ETSI TS 102.690	Machine-to-Machine communications (M2M); Functional Architecture
	ETSI TS 102.921	Machine-to-Machine communications (M2M); mla, dla and mld interface
MTC (Machine-Type Communications)		
	RP-141865	Further LTE Physical Layer Enhancements for MTC
	TR 36.888	Study on provision of low-cost MTC UEs
D2D (Device to Device)		
	TR 22.803	Feasibility study for Proximity Services(ProSe)
	TS 22.278	Service Requirements for the Evolved Packet System (EPS)
	TR 23.703	Study on Architecture Enhancements to support

		Proximity-based Services(ProSe)(Release 12)
	TS 23.303	Proximity-based services(ProSe); Stage 2(Release 12)
	TR 33.833	Study on Security Issues to support Proximity Services
	TR 36.843	Study on LTE Device to Device Proximity Services-Radio Aspects
	TS 24.333	Proximity-services Management Object(MO)
LTN (Low Throughput Network)		
	ETSI GS LTN 001	Low Throughput Network (LTN);Use Cases for Low Throughput Networks
	ETSI GS LTN 002	Low Throughput Network (LTN);Functional Architecture
	ETSI GS LTN 003	Low Throughput Network (LTN);Protocol and Interfaces

1.3 Key Requirements for IoT

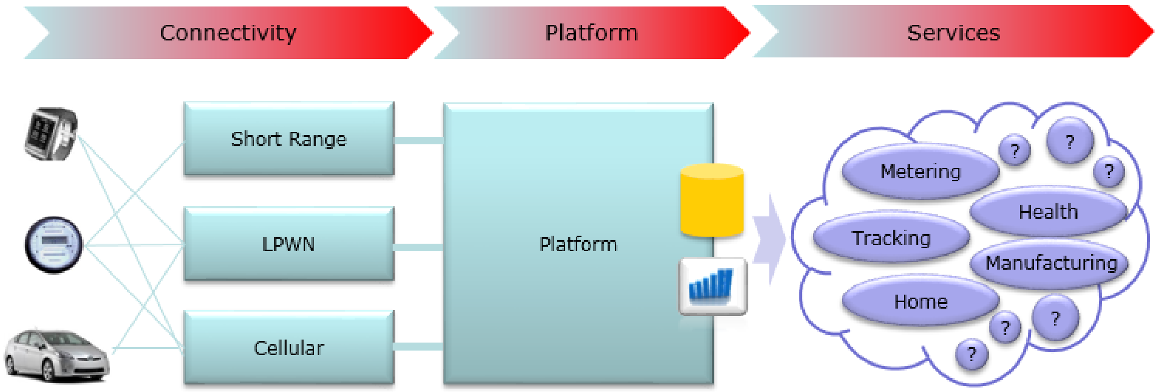

Figure 2 Requirements for IoT

IoT industry currently has following challenges to overcome.

- The critical point/requirement to trigger IoT industry is that 'the cost of the components in Connectivity sector (i.e., IoT chipset, module, connectivity cost)' should be lower than a certain critical point.
- There are many chipsets / modules that meets this criteria in Short Rage (e.g, Bluetooth module, Wi-Fi module) and LPWN (e.g., LoRa, SigFox).
- There are a lot of chipsets and modules that are available for developers at a very low cost (You can at least try out many things even with price of a fast food meal).
- Modules / Chipset in Cellular area hasn't reached this point yet.
- Cost for air charge (i.e., cost for connection) hasn't reach this point yet. (Especially the cost for cellular connectivity seems to be a little distant from the expectation).
- So the total cost for connectivity (from IoT module cost through air charge) might haven't reached the desired point yet.
- Eventually the cost for Air charge would reach the point of zero (almost free) eventually.

- Companies using IoT should make profit from Platform or Service sectors, but no clear idea on how to achieve this yet.
- The initial trigger for IoT industry would be 'Connectivity', but the most critical factors for the success of the industry is 'Service sector'.

The Internet of Things (IoT) broadly describes the concept of an interconnected network of physical objects, including machines, vehicles, buildings, and many other types of devices. And these connected “things” will deliver new services in the homes, businesses, cities, and across industries. The global IoT market is expected to grow aggressively over the next decade, and it is predicted that there will be 25 to 50 billion connected devices by 2020, fueling the multi-trillion dollars of economic growth across key markets. IoT will be much more than about connecting people to things, but extending existing networks to also bring machines and devices to work with one another, so they can deliver new levels of efficiency.

The Internet of Things encompasses a wide variety of applications across many different industries, with devices that can drive very diverse computing and connectivity requirements. In some use cases, devices may only require short-range communication to the network access point, such as ones deployed in connected homes, while many other applications need wider-area, ubiquitous coverage.

Connecting the Internet of Things will require heterogeneous connectivity technologies that offer different levels of optimization to address the varying needs. For example, smart lighting in an office building may be best served with a short-range wireless technology, such as Wi-Fi, as light fixtures are usually deployed in areas with reasonable Wi-Fi coverage (i.e., indoors). In contrast, parking meters deployed across a smart city will most likely leverage a wide-area network. Such deployments will require a technology that can provide ubiquitous coverage in both outdoor (e.g., street parking) and indoor (e.g., parking structure) locations.

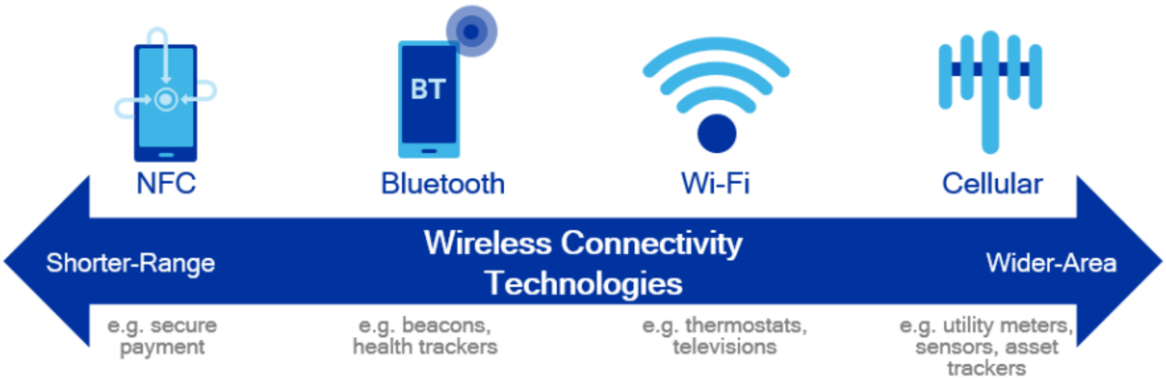

Figure 3 Examples of wireless connectivity technologies for the IoT

1.4 Cellular Technology as the platform for IoT

For the wide-area Internet of Things, cellular technology is evolving to become an attractive platform to address the growing connectivity needs. Already serving over 8 billion connections worldwide, cellular networks have proliferated in virtually all metropolitan cities, suburban, and rural areas across geographic regions. Not only do cellular-based solutions offer ubiquitous reach into both outdoor and indoor locations, they also bring many additional benefits to the table. The highly-available network design allows IoT devices to reliably access application services around the clock; moreover, the tried-and-true cellular deployments already deliver end-to-end security required by the most demanding users such as governments and financial institutions. And most importantly, the mature ecosystem is backed by global standards that ensure seamless interoperability across regions and devices.

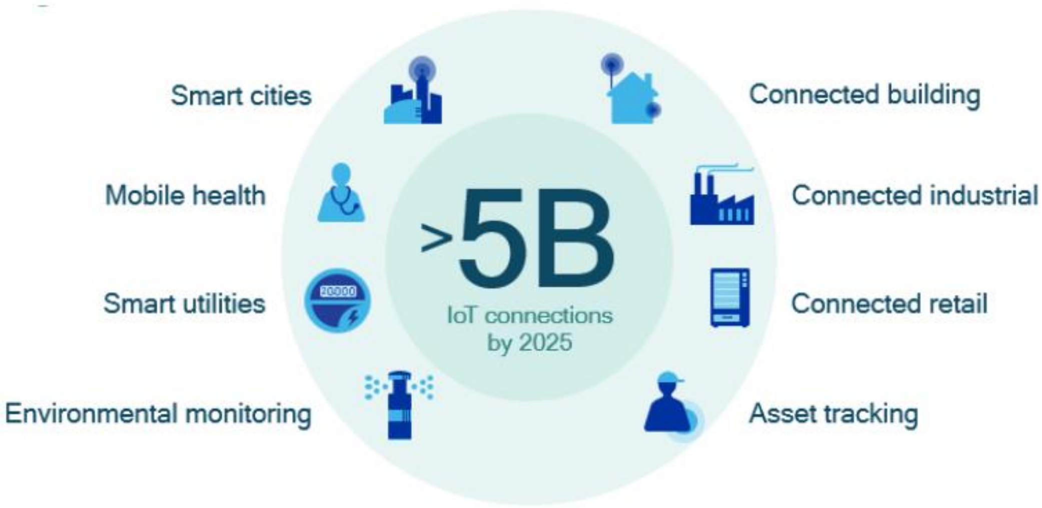

Figure 4 Cellular IoT enable a wide variety of services across many market verticals

LTE is globally established and the fastest growing wireless standard, expected to reach 80% world population coverage by 2022. LTE, originally introduced in release 8 of the 3GPP standard, was developed to provide faster mobile broadband access, offering a generational performance leap over 3G. The core LTE technology has evolved over time to adapt to the ever-changing market requirements, ensuring network longevity. LTE Advanced (3GPP release 10, 11, 12) evolved to optimize for better mobile broadband experience, enabling Gigabit-class throughput with the introduction of advanced techniques, such as carrier aggregation and higher-order MIMO. While high-performance IoT can benefit from the improvements introduced in LTE Advanced (e.g., HD security cameras), lower-complexity IoT devices (i.e., the massive IoT) require optimizations for a much-reduced set of functionalities. Release 13 of the 3GPP standard introduced a suite of two narrowband technologies optimizing for the Internet of Things. Collectively referred to as LTE IoT, it scales down LTE to more efficiently support lower data rate applications. LTE IoT is part of the unified LTE roadmap, providing a seamless path to deliver IoT service in existing network deployments; LTE can scale up to offer Gigabit-class data rates for high-performance IoT, or to scale down for applications requiring high power efficiency.

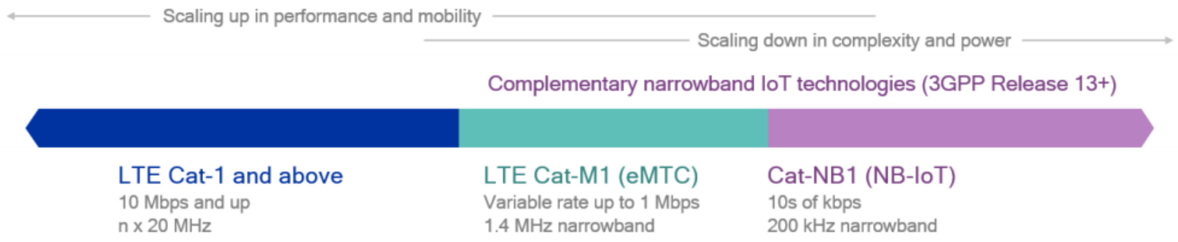

Figure 5 LTE is a scalable platform that can address a wide range of connectivity requirements

The Internet of Things (IoT) is expected to offer a wide array of applications and the energy requirements will vary widely among the huge range of IoT devices depending on their respective applications. The IoT devices may have either rechargeable or non-rechargeable power sources with widely varying capacities. Many IoT devices, which will function in stressful environments with low physical accessibility, will most likely be equipped with non-rechargeable power sources. Thus, a key requirement in many IoT scenarios is a very large battery replacement period, which can be even more than ten years [2]. The battery lifetime may even match the device lifetime. Thus, the energy consumption of many IoT devices must be minimized to maintain their desired battery lifetime without any loss of data.

In LTE, the key technique to saving power and prolonging battery life is to let the device or user equipment (UE) switch off its receiver circuitry periodically. This is referred to as discontinuous reception (DRX). The periodic cycle in DRX is called the DRX cycle. The DRX cycle consists of an active period at the beginning, called the on duration, and then a period during which the receiver circuitry is off, which is called the off duration [3]. In RRC_IDLE state, the DRX cycle is the same as the paging cycle for a UE. If a call or connection setup request arrives during an off duration, it cannot be set up until the off duration is over. This enhances the connection setup delay, which is the main drawback of a DRX operation. A longer DRX cycle allows better power saving but with a longer connection setup delay. Thus, the DRX cycle length involves a trade-off between power saving and connection setup delay.

For a wide range of IoT applications, the DRX cycle needs to be large enough to ensure considerable power saving in respective UEs. Consequently, Release 13 specifies extended DRX (eDRX) feature which increases the period of the DRX cycle. UEs operating under this feature are said to be in eDRX state, in which the UE attempts to receive signals every eDRX cycle as configured by the network.

In RRC_CONNECTED state, the eDRX cycle at its maximum can be extended up to 10.24s. However, for RRC_IDLE state, the maximum eDRX cycle can be extended up to 43.96 min for Category M1 and up to 2.91h for NB-IoT.

The communication pattern for different IoT scenarios involve extremely short RRC_CONNECTED period compared to ordinary smartphones. Hence, for IoT scenarios, power consumption during RRC_IDLE state tends to be more significant. Therefore, the operation of eDRX during RRC_IDLE state can have a greater power saving effect. Considering the paging requirements of the UE, appropriate eDRX cycle can be used to keep the power consumption and paging delay minimum.

Another way to save power for both Category M1 and Category NB1 specified in Release 13 is Power Save Mode (PSM), which eliminates page monitoring between data transmissions for device-originated or scheduled applications, e.g., smart metering, environmental monitoring. Thus, PSM allows the device to sleep for longer. However, the device becomes unreachable when PSM is active; therefore, it is best utilized by device-originated or scheduled applications, where the device initiates communication with the network.

The Mobility Management Entity (MME) sends a paging message to all eNodeBs which belong to the area covered by the current tracking area list (TAL). If the eDRX cycle is too long with respect to the mobility of UE, it is possible that the UE does not perform a tracking area update (TAU) although it moves to a location under a different TAL. Thus, the MME does not know the right location of the UE until the UE updates its location. Then the MME will not receive a paging response in the first round of paging operation. The MME will keep triggering additional paging operations, over larger areas under a higher number of eNodeBs, until the UE is found or the maximum number of paging operations is reached [4]. This leads to high signaling cost for paging. Thus, the DRX cycle length can also involve a trade-off between power saving and paging cost.

Since the battery replacement period can be many years for some IoT scenarios, the DRX cycle length, in some cases, should take into account how much the UE battery has drained out already. If the battery life is already endangered, a longer DRX cycle can be warranted. However, there is currently no way to take the battery status to consider in setting the DRX cycle length.

Unlike human-to-human (H2H) communication, the IoT scenarios vary widely in terms of connection setup request arrival profile, power saving constraints, battery capacities, mobility, and so forth. Thus, the appropriate DRX cycle length varies widely among IoT devices and the appropriate length can be estimated based on their types of applications. Consequently, optimization of power saving requires various DRX cycle lengths to be assigned to different IoT devices. Presently, there is no good provision for the assignment of various DRX cycle lengths.

The authors of [5] and [6] investigated the tradeoffs between power saving achieved and latency by DRX mechanism for active and background mobile traffic. The authors of [7] and [8] analyzed the impact of DRX cycles while reducing the RRC Connected-to-Idle transition tail time on power savings. The authors of [9] also propose an adaptive algorithm based DRX mechanism which reduces power consumption and also keeps the packet delay around a desired value. The authors of [4] investigated the trade-off relationship between TAU cost and paging cost in order to propose a DRX mechanism that is power saving for both the UE and the eNB. In [10] and [11], the authors investigated the tradeoff relationship between the power saving and wake-up delay performance using a semi-Markov process to model the system with bursty packet data traffic. The authors of [12] does an analysis of the power saving achieved by DRX using a mixture of short and long DRX cycles.

In this paper, we propose the introduction of different UE categories for IoT devices based on their requirement of DRX cycle lengths and there will be different default DRX cycle lengths for each of them. If any IoT device happens to require a special DRX cycle length, then the UE-specific DRX cycle, configured by upper layer dedicated signaling, will be used for the device. We also propose the occasional transmission of battery condition by the IoT device during periodic TAU procedure.

1.5 UE categories supporting IoT

In order to meet the requirements of low complexity, high battery life and low cost devices for IoT, 3gpp standardized new technologies and UE categories. Cat-1 introduced in Release 8, was well below the best 3G performance, but easily became an early alternative for IoT. Later, in Release 12, Cat-0 was introduced. It had a much reduced complexity resulting in a significant decrease in the device cost.

The 3GPP Release 13 standard then introduced two complementary User Equipment (UE) categories that scale down in functionalities to bring more efficiencies for connecting a wide variety of IoT devices. Category NB1 is designated for low-end IoT use cases, whereas Category M1 is designated for mid-range devices that require greater frequency and greater volume of data transfer.

Table 2 Reducing complexity for LTE IoT devices

	LTE Cat-1 (Rel-8)	**eMTC Cat-M1 (Rel-13)**	**NB-IoT Cat-NB1 (Rel-13)**
Peak data rate	Up to 10 Mbps	Up to 1 Mbps	<100 kbps
Bandwidth	Up to 20 MHz	1.4 MHz	200 kHz
Rx antenna	Dual Rx	Single Rx	Single Rx
Duplex mode	Full duplex FDD/TDD	Full or Half duplex FDD/TDD	Half duplex FDD
Mobility	Full mobility	Limited-to-full mobility	Cell reselection only
Voice	VoLTE	VoLTE	No voice support
Transmit power	23 dBm	23, 20 dBm	23, 20 dBm

IoT is designed to deliver to a diverse set of industries and applications. While many IoT devices will bring about revenues similar to that of mobile broadband services (e.g., smartphones, tablets), most devices will bring about relatively smaller revenues and so they will need to be considerably low-cost to justify mass deployment.

For this reason, both Category M1 and Category NB1 devices are designed to be less complex to enable low cost while still meeting the application criteria. They are also designed for lower power, deeper coverage, and higher device density, while coexisting with other LTE services. This means Category M1 and Category NB1 are subjected to several limitations without downgrading their performance.

Both Category M1 and Category NB1 devices have reduced peak data rates compared to regular LTE devices. Cat-M1 has limited throughput of up to 1 MBps in both downlink and uplink directions, while Cat-NB1 further reduces peak data rate down to 10’s of kbps. This reduced data rate causes savings in both processing and memory. Bandwidth will be similarly reduced to match the data rate: 1.4MHz for Category M1 and 200 kHz for Category NB1. For both Cat-M1 and Cat-NB1, the receive RF is reduced to a single antenna. And due to the less frequent and latency-tolerant nature of IoT data transmissions, in Release 13, Cat-NB1 devices have reduced their complexity by only supporting half-duplex communications, where only the transmit or receive path is active at a given time. And Cat-M1 devices can support half-duplex FDD in addition to TDD.

On the mobility issue, Cat-NB1 devices support cell reselection only, which is optimized for both static and nomadic IoT devices. But Cat-M1 devices are allowed limited-to-full mobility, due to the non-stationary nature of some of their applications, such as asset tracking. For both the Categories M1 and NB1, uplink transmission power is reduced to 20 dBm compared to 23 dBm for LTE.

Both Cat-M1 and Cat-NB1 can be deployed in existing LTE Advanced infrastructure and spectrum, efficiently coexist with today's mobile broadband services. Cat-M1 utilizes 1.4 MHz bandwidth, leveraging existing LTE numerology (versus NB-IoT's new channel bandwidth of 200 kHz), and can be deployed to operate within a regular LTE carrier (up to 20 MHz). Cat-M1 devices will leverage legacy LTE synchronization signals (e.g., PSS8, SSS9), while introducing new control and data channels that are more efficient for low bandwidth operations. LTE network supporting Cat-M1 can utilize multiple narrowband regions with frequency retuning to enable scalable resource allocation, and frequency hopping for diversity across the entire LTE band.

Cat-NB1 devices can be deployed in LTE guard-bands or as a standalone carrier in addition to LTE inband. Nevertheless, the new 200 kHz device numerology (utilizing a single LTE resource block, or RB of 180 kHz) requires a new set of narrowband control and data channels. Unlike Cat-M1 in-band, Cat-NB1 does not allow for frequency retuning or hopping and occupies a fixed spectrum location. For guard-band deployment, NB-IoT leverages unused resource blocks without interfering with neighboring carriers. In standalone mode, Cat-NB1 devices can be deployed in re-farmed 2G/3G bands.

1.6 Periodic TAU procedure

Tracking Area is a logical concept of an area where a UE can move around without updating the MME. The network allocates a list with one or more TAs to the user. In certain operation modes, the UE may move freely in all TAs of the list without updating the MME. We can think of 'Tracking Area' as 'Routing Area' in UMTS.

Each eNodeB broadcasts a special tracking area code (TAC) to indicate to which Tracking Area the eNodeB belong to and the TAC is unique within a PLMN. (Since PLMN is a unique number allocated to each of the system operator and TAC is a unique in a PLMN, if we combine these two numbers you would have a globally unique number. This number (PLMN + TAC) is called Tracking Area Identity (TAI).

UE stores a group of TAC and this group of TAC maintained in a UE is called Tracking Area List. UE does not need to go through Tracking Area Update procedure when it moves along this TAI.

In RRC_IDLE state, the UE performs TAU procedure periodically in order to notify the network about its availability. For this purpose, the UE maintains Periodic Tracking Area Update Timer known as T3412. Every time T3412 expires, the UE performs TAU procedure and T3412 is restarted. However, if the UE is attached for emergency bearer services when T3412 expires, the UE performs detach procedure with the network instead of TAU procedure.

The network can assign and update the value of T3412 during the attach procedure and the tracking area update procedure using T3412 Value IE in ATTACH ACCEPT message and TRACKING AREA UPDATE ACCEPT message respectively. Its default duration is 54 minutes. The network may set the value of T3412 to zero or indicate deactivation of T3412. In these cases, the UE does not perform periodic tracking area updating procedure.

If the UE moves out of coverage, it can no longer perform periodic TAU procedure. So, if the UE does not perform periodic TAU procedure at its due time, the MME starts a timer called Mobile Reachable Timer. When the Mobile Reachable Timer expires without any communication with the UE, the MME infers that the UE has moved out of coverage. The default value of Mobile Reachable Timer is 4 minutes greater than T3412. But if the UE is attached for emergency bearer services, the value of this timer is set equal to T3412. When the Mobile Reachable Timer expires without any periodic tracking area update, the MME starts another timer called Implicit Detach Timer. This is because the MME wants to ensure that the UE has been out of coverage for enough duration before it detaches the UE. At this moment, the MME does not page the UE if downlink data arrives for the UE. The MME rather sends Downlink Data Notification Reject message to the Serving GW if it receives a Downlink Data Notification message from the Serving GW. If the Implicit Detach Timer expires and the UE does communicate with the network, then the MME infers that the UE has been out of coverage for a long period and so, it performs implicit detach with the UE.

The signaling in TAU procedure consumes resources. In order to reduce this consumption, Release 10 introduces assigning a longer value of T3412 by including T3412 Extended Value IE in both ATTACH ACCEPT message and TRACKING AREA UPDATE

ACCEPT message. It may be noted that this increases the duration of both Periodic Tracking Area Update Timer and Mobile Reachable Timer. If a network failure occurs or the UE moves out of coverage, the longer value of T3412 may increase the delay to detect them.

Chapter 2

Overview of the Proposed Model

Many IoT devices are battery-operated, and it is highly desirable for them to last for as long as possible on a single charge. The associated cost for field maintenance can be quite daunting, especially in massive deployments. Not only would the planning of scheduled maintenance be an operational overhead, but physically locating these mobile devices (e.g., asset trackers sprinkled all over the world) can also become a nightmare. Thus, maximizing battery life has become one of the most important improvement vectors in LTE IoT. In addition to the power savings realized through reduced device complexity, two new low-power enhancements have been introduced: power save mode (PSM) and extended discontinuous receive (eDRX) – both are applicable to Cat-M1 and Cat-NB1 devices.

2.1 Introduction

2.1.1 Power save Mode (PSM):

PSM is a new low-power mode that allows the device to skip the periodic page monitoring cycles between active data transmissions, allowing the device to sleep for longer. However, the device becomes unreachable when PSM is active; therefore, it is best utilized by device-originated or scheduled applications, where the device initiates communication with the network. Moreover, it enables more efficient low-power mode entry/exit, as the device remains registered with the network during PSM, without having the need to spend additional cycles to setup registration/connection after each PSM exit event. It is a special kind of UE status that can minimize the energy consumption that is supposed to be even lower than normal idle mode energy consumption. This is newly added feature in Release 12 and is specified in 3GPP 24.301-5.3.11 Power saving mode and 23.682-4.5.4 UE Power Saving Mode. Example applications that can take advantage of PSM include smart meters, sensors, and any IoT devices that periodically push data up to the network.

Based on 23.682-4.5.4 UE Power Saving Mode, PSM is defined as follows:

- Similar to power-off, but the UE remains registered with the network
- No need to re-attach or re-establish PDN connections.
- A UE in PSM is not immediately reachable for mobile terminating services.
- A UE using PSM is available for mobile terminating services only for the period of an Active Time after a mobile originated event like data transfer or signaling, e.g. after a periodic TAU/RAU procedure.
- Intended for UEs that are expecting only infrequent mobile originating and terminating services and that can accept a corresponding latency in the mobile terminating communication.
- No support in the CS domain on the network side.
- Should only be used by UEs using the PS domain, SMS and mobile originated IMS or CS services.
- A UE that uses mobile terminated IMS or CS services other than SMS should not use PSM as neither IMS nor the CS domain provide support for mobile terminated CS voice or IMS services to UEs that are in PSM.

As the term 'Power Saving' implies, the main purpose of this feature is to minimize energy consumption while the device is not transmitting or receiving anything. The target is to keep the energy consumption is almost as if the device is OFF and lower than the energy consumption of idle mode. Overall mechanism of PSM goes as follows and this would be a critical feature of MTC devices using LTE (like Category 0 device). The two timers are involved in this process. Based on 23.682-4.5.4 UE Power Saving Mode, UE and Network does as follows.

- When the UE wants to use the PSM it shall request an Active Time value during every Attach and TAU/RAU procedures.
- If the network supports PSM and accepts that the UE uses PSM, the network confirms usage of PSM by allocating an Active Time value to the UE. The network takes the UE requested value and any local MME/SGSN configuration into account for determining the Active Time value that is allocated to the UE.
- If the UE wants to change the Active Time value, e.g. when conditions are changed in the UE, the UE consequently requests the value it wants in the TAU/RAU procedure.

2.1.2 Discontinuous Reception (DRX):

Even while there is no traffic between the network and UE, UE has to keep listening to Network. At least it should be ready to decode PDCCH. It means UE has to be "ON" all the time even when there is no traffic. But being ON all the time would drain the battery. One of the solution for this is let UE get into sleeping mode for a certain period of time and wake up again checking if there is any data coming from the network and getting into sleeping mode again if there is no data and wake up again... repeating this cycles. This kind of periodic repetition of "sleep mode and wake up mode" is called DRX (Discontinuous Reception)".

In reality implementing DRX may not be as simple because there should be well designed synchronization between UE and Network. In worst case, network tries to send some data while UE is in sleep mode and UE tries to wake up when there is no data to be received. To prevent this kind of worst case scenario, UE and Network has a well-defined agreement about when UE has to be in sleep mode and when UE has to wake up. This agreement is defined in 3GPP TS36.321 Section 5.7 for connected mode, and TS36.304 Section 7.1 for idle mode.

The following table shows the meaning of each DRX parameters.

Table 3 DRX Parameters

DRX Parameter	**Description**
DRX Cycle	The duration of one 'ON time' + one 'OFF time'. (This value does not explicitly specified in RRC messages. This is calculated by the sub frame time and longdrx-CycleStartOffset)
onDurationTimer	The duration of 'ON time' within one DRX cycle
drx-Inactivity timer	Specify how long UE should remain 'ON' after the reception of a PDCCH. When this timer is on UE remains in 'ON state' which may extend UE ON period into the period which is 'OFF' period otherwise. (See the figure for < case 2 > below)
drx-Retransmission timer	Specifies the maximum number of consecutive PDCCH sub frames the UE should remain active to wait an incoming retransmission after the first available retransmission time
shortDRX-Cycle	DRX cycle which can be implemented within the 'OFF' period of a long DRX Cycle.(See the figure for < case 4 > below)
drxShortCycleTimer	The consecutive number of sub frames the UE shall follow the short DRX cycle after the DRX Inactivity Timer has expired(See the figure for < case 4 > below)

The DRX cycle can be explained for different cases below:

Case 1: Only Long DRX Cycle is configured and No PDCCH is received during the cycle.

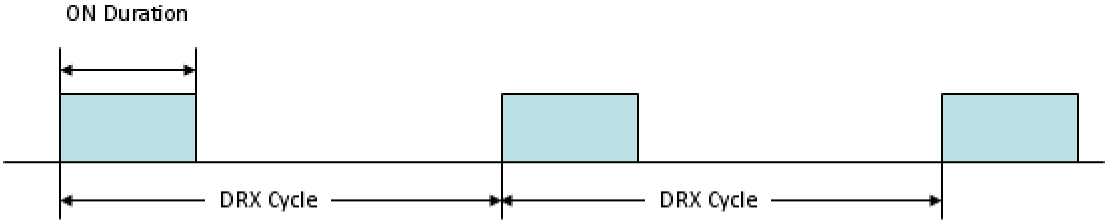

Figure 6 DRX Cycle with No PDCCH

Case 2: Only Long DRX Cycle is configured and a PDCCH is received during a cycle (Notice that the real 'ON time' May get extended depending on DRX Inactivity Timer and when the PDCCH is received as shown in thick Blue line).

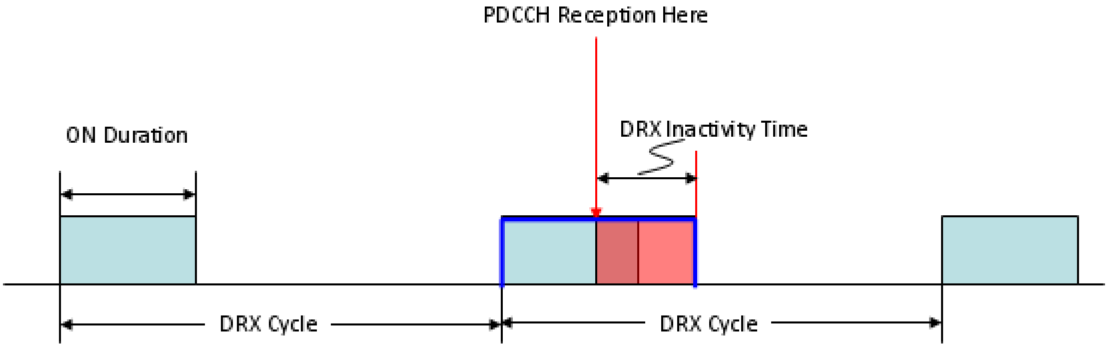

Figure 7 DRX Cycle with PDCCH

Case 3: Only Long DRX Cycle is configured and a PDCCH and DRX Command MAC CE are received during a cycle (Notice that the real 'ON time' MAY get shorter depending on exactly when DRX Command MAC CE is received as shown in thick Blue line).

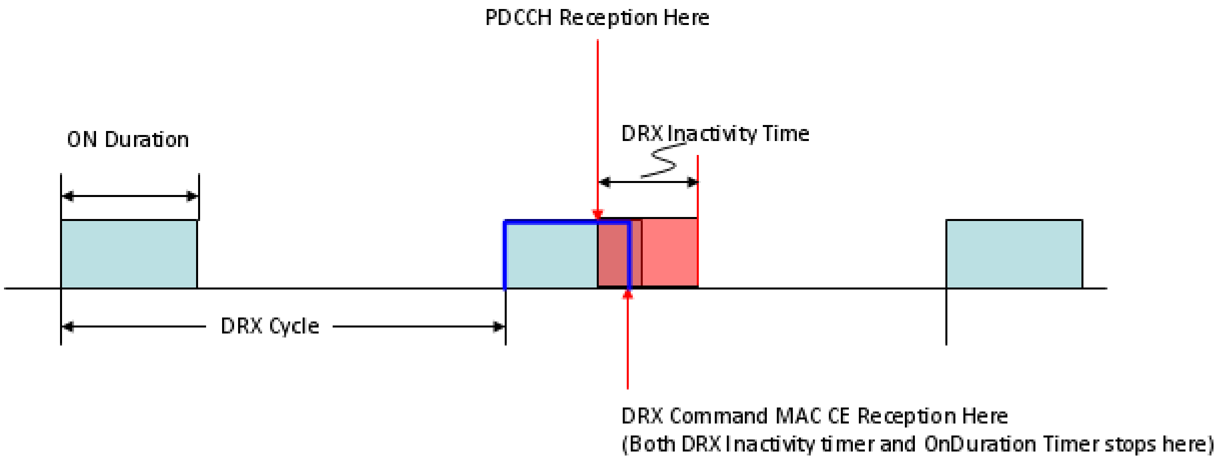

Figure 8 DRX Cycle with PDCCH & DRX Command MAC CE

Case 4: Both Long DRX Cycle and Short DRX Cycle are configured and No PDCCH is received during the cycle. This may be the most complicated case related to DRX cycle. Overall logic goes like this

i) When DRX is configured and the last DCI (PDCCH) arrived

ii) drx-inactivityTimer starts and 'Wake-up status' continues until the drx-inactivityTimer expires.

iii) After drx-inactivityTimer expired and the shortDrxCycle condition meet, the shortDrxCycle starts and drxShortCycleTimer starts.

iv) If there is no DCI (no PDCCH) until drxShortCycleTimer expires, Long Drx Cycle starts.

v) If any DCI (PDCCH) arrives during the wake-up period of any DRX cycle, go to step ii).

2.1.3 Extended Discontinuous Reception (eDRX):

eDRX optimizes battery life by extending the maximum time between data reception from the network in connected mode to 10.24s, and time between page monitoring and tracking area update in idle mode to 40+ minutes. It allows the network and device to synchronize sleep periods, so that the device can check for network messages less frequently. This; however, increases latency, so eDRX is optimized for device-terminated applications. Use cases such as asset tracking and smart grid can benefit from the lower power consumption realized through the longer eDRX cycles. eDRX would be mostly used in the application of IoT (Internet of Things) operating in energy saving mode. The concept of eDRX can be illustrated as shown below.

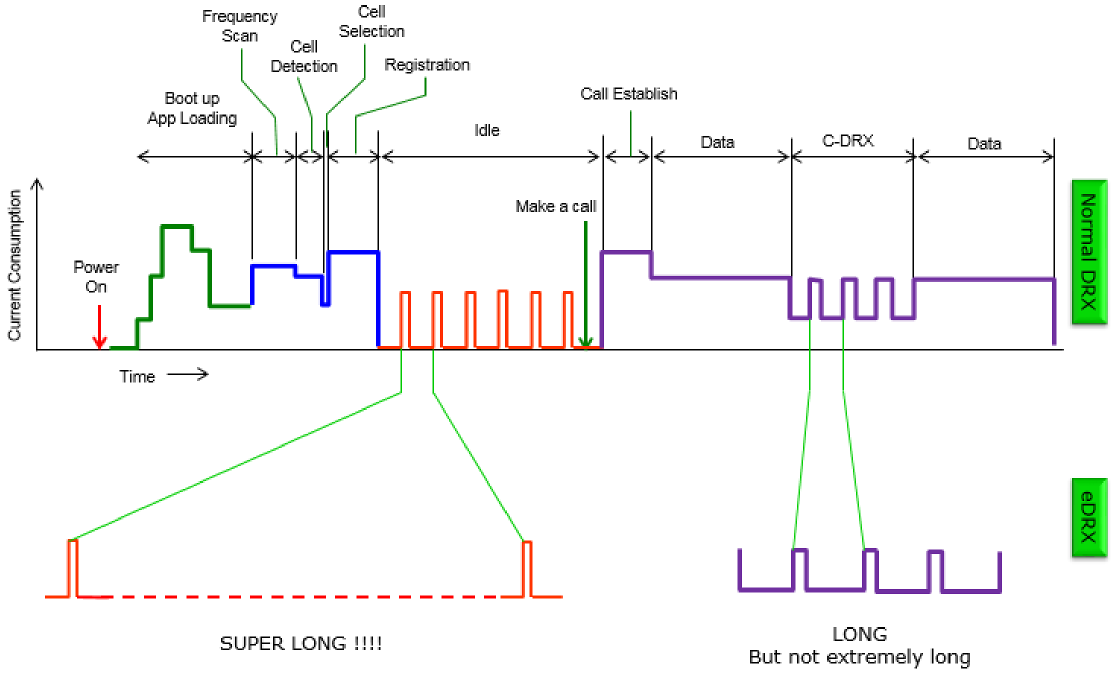

Figure 9 eDRX Cycle

2.2 Proposed Model

The eDRX can be as long as 43.96 minutes. The longer the DRX length, the more should be the power saving. But there are several tradeoffs involving longer DRX lengths. If the DRX is too long, it increases the bearer setup latency for the UE and also increases the tracking area update (TAU) cost and paging cost for the core network. [8]

It is important to note that IoT devices will have a wide range of applications and they may be deployed in just about any physical environment with limited battery support. If their application demands frequent communication between the eNB and the IoT device, then expected session setup request arrival rate, λ, will be high, in which case, length of DRX cycle must be small to avoid latency.

But if their application requires relatively less frequent communication between eNB and the IoT device, then expected session setup request arrival rate, λ, will be low, in which case, length of DRX cycle can be increased to a certain extent without causing much latency.

The expected session setup request arrival rate,λ, is also affected by the IoT device's intended place of use and amount of battery backup. Devices placed in areas that are difficult to physically access or employed in "off-line" applications that are power consuming, will be designed to have low session setup request arrival rate, λ, in order to maintain energy efficiency. However, if DRX cycle is not increased as well, low session setup request arrival rate, λ, alone, will not be able to achieve desired energy efficiency.

Hence an IoT device will behave energy efficiently only when its DRX cycle has a suitable length that aligns with the expected session setup request arrival rate, λ. As λ will vary depending on the device, length of DRX cycle should also vary from device to device to ensure maximum efficiency.

Our proposal is to find suitable DRX lengths for different session setup request arrival rate, which would ensure a minimal battery consumption of UE and minimal TAU cost and paging cost of eNB with minimum bearer setup latency. These DRX lengths will then be used to suggest a UE categorization based on device requirements. There are already three UE categories present for machine type communications, namely Cat 0, Cat M1, and Cat NB1. For both Machine-to-machine communication and Network-to-machine communication, we want to suggest an expansion of UE categories based on these optimum DRX lengths. However, some IoT devices may act like “stand-outs” if their optimum DRX length differs widely from that of any UE category. Initially, they will be assigned to the closest UE category, but after a substantial amount of time has transpired and a significantly long history between the UE and eNB has been recorded by the eNB, the information from this history will be analyzed by the eNB in order to assign a specific DRX cycle length to that particular UE, which will not match that of any established UE category.

The direction for changing to a particular DRX cycle length (dedicated for the UE) will be given during TAU procedure. In order to record and analyze the history between UE and eNB, a new message named “battery status” can be introduced during each Tracking Area Update (TAU). The eNB will compare the battery status of consecutive TAUs in order to calculate the rate of power consumption by the UE. If the UE is consuming too much power, the eNB will opt for longer DRX cycles to ensure the UE does not run out of battery.

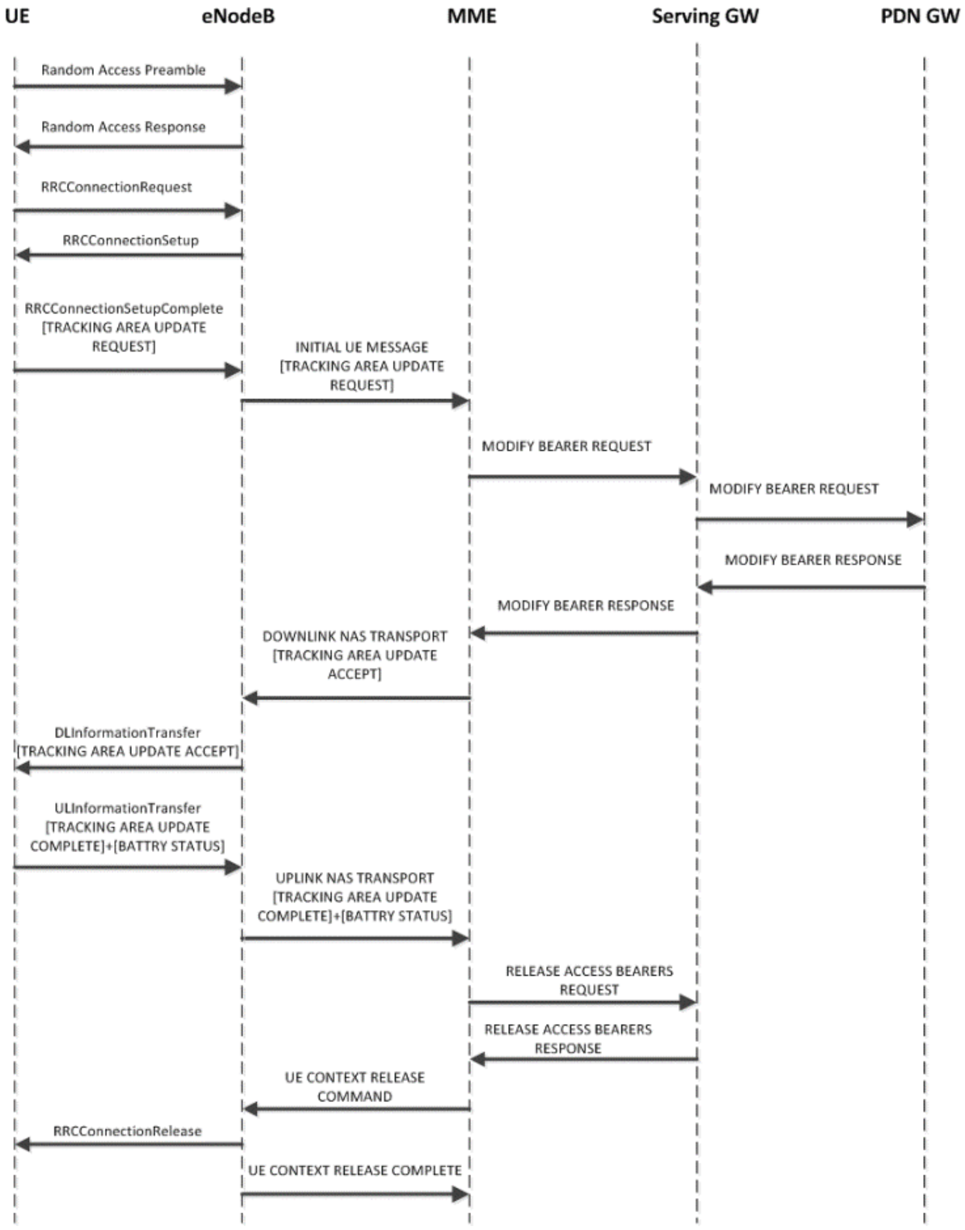

Figure 10 Battery Status Message

Chapter 3

Analytical Model

3.1 Analysis of Delay with respect to Session setup request arrival rate, λ

To evaluate the proposed and existing schemes, in this section, we present analytical models using the approach presented in [13] and [14]. We assume an M/G/1 system queue. Thus, the session setup request arrival follows a Poisson process and the inter-arrival times are distributed exponentially. We assume that the session setup request arrival rate is λ and that the service or transmission rate of the session setup requests is μ. Thus, the mean transmission time of a session setup request is $E[S] = 1/\mu$. The traffic intensity can be expressed as $\rho = \lambda/\mu$. We assume that the system is stable with $\mu > \lambda$. The probability of session setup request arrival in t_1 duration is $\int_0^{t_1} \lambda e^{-\lambda t} dt = 1 - e^{-\lambda t_1}$. Thus, the probability of no session setup request arrival in duration t_1 is $1 - \int_0^{t_1} \lambda e^{-\lambda t} dt = e^{-\lambda t_1}$.

We assume that the probability of session setup request arrival on the ith cycle is X_i. Since the session setup request arrival follows a Poisson process, X_i can be expressed as

$$X_i = (e^{-\lambda t_1})^{i-1}(1 - e^{-\lambda t_1}) \qquad (1)$$

Thus, the expected number of session setup request arrival, denoted as $E[N_C]$, can be expressed as

$$E[N_C] = \sum_{i=1}^{\infty} i \, X_i \qquad (2)$$

$$= (1 - \mathrm{e}^{-\lambda t_C}) \sum_{i=1}^{\infty} (\mathrm{e}^{-\lambda t_C})^{i-1}$$

$$= (1 - \mathrm{e}^{-\lambda t_C}) \frac{1}{(1 - \mathrm{e}^{-\lambda t_C})^2}$$

$$= \frac{1}{(1-\mathrm{e}^{-\lambda t_C})} \qquad (3)$$

Thus, the session setup request arrival delay, $E[Delay\_SSR]$, can be expressed as

$$E[Delay\_SSR] = \frac{T_C}{(1-\mathrm{e}^{-\lambda t_C})} \qquad (4)$$

The delay analysis differs between ON and OFF period of a DRX cycle. Let us assume that N_Q represents the number of session setup requests in the queue, excluding those for whom the transmission is ongoing, and that W_Q represents the waiting time of a session setup request from the moment it arrives until its transmission commences. Little's formula then provides the following relationship:

$$E[N_Q] = \lambda\, E[W_Q] \qquad (5)$$

The mean residual service time $E[R]$ represents the mean service or transmission time of session setup requests currently in transmission when a session setup request arrives. Because $\frac{E[N_Q]}{\mu}$ represents the service time of all session setup requests ahead in the queue waiting for service, according to the Pollaczek Khintchine formula, the mean wait time in the queue is given by

$$E[W_Q] = E[R] + \frac{E[N_Q]}{\mu} \qquad (6)$$

Using Little’s formula, we obtain

$$E[W_Q] = E[R] + \rho E[W_Q]$$

$$= \frac{E[R]}{1-\rho} \qquad (7)$$

When the transmission rate is very high compared to the session setup request arrival rate, making μ >> λ, the session setup requests ahead in the queue can be quickly transmitted resulting in $E[W_Q] \approx E[R]$. Here, $E[R]$ has the following relationship [15]:

$$E[R] = \frac{\lambda E[S^2]}{2} \qquad (8)$$

Using (40), we obtain

$$E[W_Q] = \frac{\lambda E[S^2]}{2(1-\rho)} \qquad (9)$$

.

On the other hand, while the UE is running a DRX (in state E), the session setup request may arrive at any time within the DRX cycle. There will then be an additional delay $E[W_D]$ because the session setup requests are not processed until the particular DRX cycle is over. The overall mean delay $E[D_{DRX}]$ can be given by

$$E[D_{DRX}] = E[W_Q] + E[W_D] \qquad (10)$$

. The Poisson process has time-homogeneity. Thus, a session setup request can arrive at any time during the DRX cycle with equal probability, and has to wait for the rest of the DRX cycle for any process to begin. The mean wait time can be computed as one-half of the average length of the DRX cycle, and is independent of the session setup request arrival rate. This mean wait time is equivalent to $E[R]$ which can be expressed as $\frac{T_{OFF}}{2}$.

Similarly, $E[W_D]$ can be estimated as

$$E[W_D] = \frac{T_{OFF}}{2(1-\rho)} \tag{11}$$

Denoting the probability of a session setup request arrival during OFF period and ON period are τ_{ON} andτ_{OFF}, respectively, they can be expressed as

$$\tau_{OFF} = \frac{T_{OFF}}{T_{OFF}+T_{ON}} \tag{12}$$

And

$$\tau_{ON} = \frac{T_{ON}}{T_{OFF}+T_{ON}}. \tag{13}$$

The overall paging delay can be expressed as,

$$E[\text{Delay}] = (1 - \tau_{OFF})\, E[W_Q] + \tau_{OFF}\left[E[W_Q] + \frac{T_{OFF}}{2(1-\rho)}\right] = E[W_Q] + \tau_{OFF}\frac{T_{OFF}}{2(1-\rho)} \tag{14}$$

3.2 Analysis of Paging Waste with respect to velocity

We assume that TAL change follows a Poisson process when the user equipment has a velocity, v. We denote the TAL change rate as γ and the diameter of a TAL as D. Thus the TAL change rate can be expressed as $\gamma = \frac{v}{D}$. The probability of TAL change in T_C duration is $\int_0^{T_C} \gamma e^{-\gamma t} dt = 1 - e^{-\gamma T_C}$. Thus the probability of no TAL change in duration T_C is $1 - \int_0^{T_C} \gamma \mathrm{e}^{-\gamma t} dt = e^{-\gamma T_C}$.

We assume that the probability of TAL change on the ith cycle is β_i. Since the TAL change follows a Poisson process, β_i can be expressed as

$$\beta_i = (1 - e^{-\gamma T_C})^{i-1}(e^{-\gamma T_C}) \qquad (15)$$

Thus, the e number of TAL change, denoted as $E[N_T]$, can be expressed as

$$\begin{aligned} E[N_T] &= \textstyle\sum_{i=1}^{\infty} i\,\beta_i \\ &= \frac{e^{-\gamma T_C}}{1 - e^{-\gamma T_C}} \sum_{i=1}^{\infty} i(1 - e^{-\gamma T_C})^i \\ &= \left(\frac{e^{-\gamma T_C}}{1-e^{-\gamma T_C}}\right)\left[\frac{1-e^{-\gamma T_C}}{\{1-(1-e^{-\gamma T_C})\}^2}\right] \\ &= \frac{1}{e^{-\gamma T_C}} \\ &= e^{\gamma T_C} \qquad (16) \end{aligned}$$

Thus, the paging cost, C_p, can be expressed as

$$C_p = N_e N_t N_p \, [ceil(e^{\gamma T_C}) - 1] \qquad (17)$$

Where $N_p$the number of is times to page a UE; $N_e$is the number of eNBs in a tracking area and N_t is the number of tracking areas in a tracking area list.

Chapter 4

Performance Evaluation

The analysis is validated by simulations using Matlab. We have used four different off duration values, to make the analysis more reliable. The values used for off duration, $\boldsymbol{T_{OFF}}$, are 100, 200, 500 and 800 seconds respectively. The on-duration, $\boldsymbol{T_{ON}}$, is taken as 0.1 second. Thus, the DRX cycle lengths are 1.67, 3.33, 8.33, 13.33 minutes respectively.

In the following sections, the simulation results for the delay with respect to session setup request arrival rate and the relative paging waste with respect to velocity is discussed. Finally, new UE categories are suggested using the data obtained from both the simulations. The parameters values used, are described in the respective sections.

4.1 Overall delay vs. Session setup request arrival rate

The service or transmission rate of the session setup requests, μ, is taken as 100. The range for session setup request arrival in sessions per second, λ, is taken from 0 to 90. Finally, we made the simulation using the equation,

$$E[\text{Delay}] = E\left[W_Q\right] + \tau_{OFF}\frac{T_{OFF}}{2(1-\rho)} \qquad (14)$$

From figure 11, we can observe that relationship between the expected delay, $E[\text{Delay}]$ and the session setup request arrival rate, λ. It can be seen that with the increase in session setup request arrival rate, the expected delay increases. From the λ value 60 to 90, the rate of increase is observed to be higher. This clearly validates our statement that, depending on the application, the delay will significantly vary as the session setup request arrival rate depends on the application.

The DRX cycle lengths are 1.67, 3.33, 8.33 and 13.33 minutes which are being represented by the blue, red, yellow and purple colors respectively. It is observed that the expected delay for the DRX cycle length, 1.67 minutes is significantly lower than that of the other larger DRX cycle lengths. The delay increases with the increase in DRX cycle lengths. The on-duration, T_{ON}, is constant. It means that the delay is related to the off-duration, T_{OFF}. The higher the value of T_{OFF}, the higher is the expected delay.

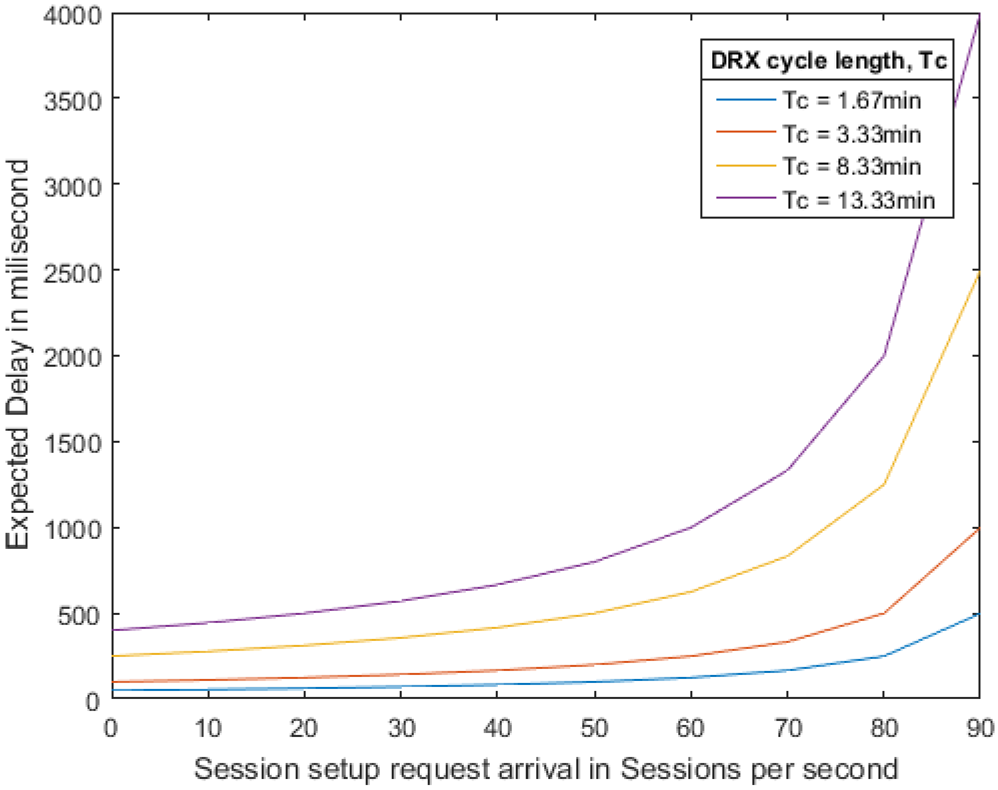

Figure 11 Expected Delay vs Session setup request arrival rate

Depending on the application of the device, a high delay may not be affordable. However, the battery life is also an important issue. The battery replacement time must be as long as the device lifetime. The battery lifetime may be required to be as long as 10 years. Therefore, to increase the battery lifetime, the off duration, T_{OFF}, must be longer. Thus, there must be a tradeoff between the delay and the battery lifetime.

4.2 Relative Paging Waste vs. Velocity

In the simulation for the relative paging waste vs. velocity the system parameters are set as follows: N_p, the number of times to page a UE = 2; N_e, the number of eNBs in a tracking area = 7 and N_t, the number of tracking areas in a tracking area list = 7. The average diameter of a tracking area list is also assumed to be 10 km. The range of velocity for the simulation is taken to be 0 to 200 kph. Finally, we did the simulation using the previously derived formula,

$$C_p = N_e N_t N_p \left[ceil(e^{\gamma T_C}) - 1\right] \qquad (17)$$

Figure 12 shows the relationship between the velocities in kph with the relative paging waste. The paging waste has no unit as it is a relative term which gives us an idea of how much paging is going to be wasted if the user equipment moves away from one tracking area list to another. With the given values for N_e, N_t, it can be said that there are 47 eNBs in each TAL. If the network fails to find a UE in a cell, it will page a maximum, N_p, times. And then, will move on to another cell to find the UE. With the increase in velocity, the UE will change the TAL more frequently and hence it will be more difficult for the eNB to find the UE. It can be observed that the relative paging waste increases with an increase in velocity of the user equipment.

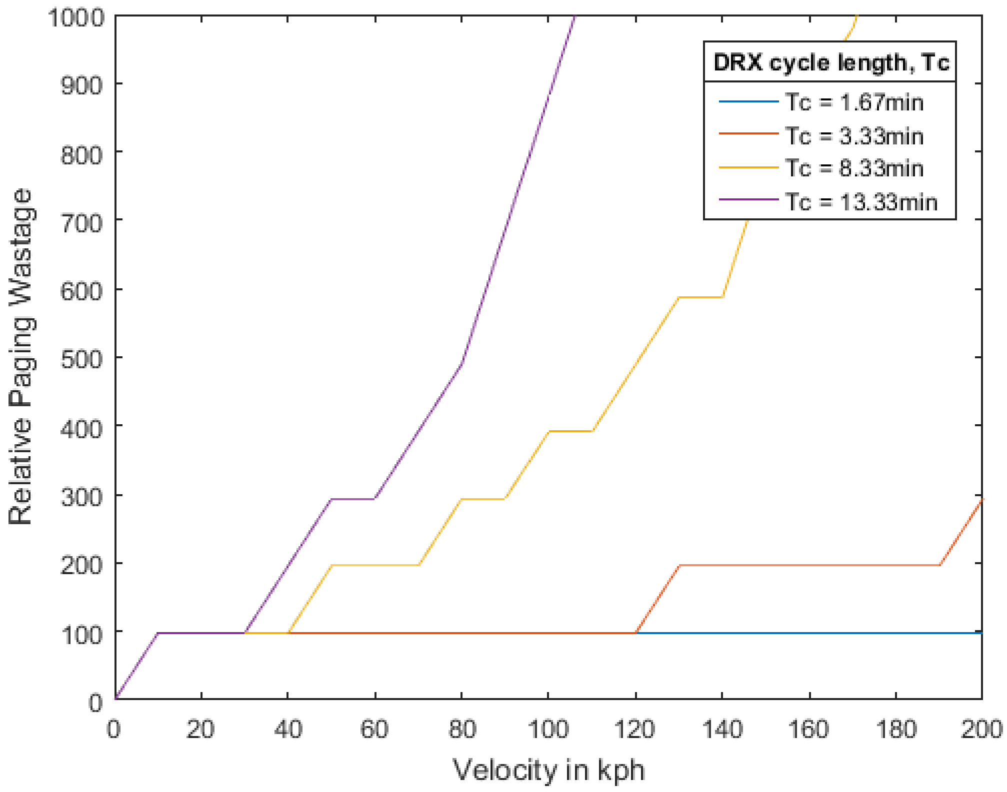

Figure 12 Relative Paging Wastage vs Velocity

The simulation was done for four different DRX cycle lengths. The DRX cycle lengths are 1.67, 3.33, 8.33 and 13.33 minutes which are being represented by the blue, red, yellow and purple colors respectively. It can be seen that the relative paging waste increases with the increase in DRX cycle length for the same velocity. And, the paging waste is minimum when the DRX cycle length is also minimum. The on-duration**,** T_{ON}, is constant. It means that the paging waste is related to the off-duration, T_{OFF}. The higher the value of T_{OFF}, the higher is the paging cost.

Depending on the velocity of the user equipment, a suitable value for DRX cycle length should be chosen. As it can be seen from the graph, that the paging waste is pretty low for the one with the minimum DRX cycle length. But, the paging waste for the 13.33 minute

DRX cycle length is very high. To minimize the paging waste, the lowest DRX cycle cannot be chosen. It is because, lowering the DRX cycle means lowering the value of T_{OFF}. A lower value of T_{OFF} means less battery saving. As previously mentioned, in order to reduce the paging waste, DRX cycle lengths cannot be decreased significantly. With lower DRX cycle lengths, there will be lesser battery saving.

It is interesting to note that, the graphs show same paging waste for two different DRX cycle lengths at the same velocity. It is obvious that the one with the larger DRX cycle length should be chosen for the UE. Therefore, it will have lower paging cost but with a higher DRX cycle length i.e. more battery saving.

Further discussions are done in the next section, where both the velocity and the session setup request arrival rate are considered to determine new UE categories where both the delay and the paging cost will be as minimum as possible all the while keeping the battery consumption as low as possible.

4.3 A New UE Categorization

From the observation of the graphs above, new UE categories can be assigned for different session setup request arrival rate and velocity using suitable DRX cycle lengths. For simplicity, only the DRX cycle lengths are being considered to create new UE categories. It is up to the network provider to assign suitable DRX cycle length and setting other parameters according to the requirement for the user equipment applications.

The expected delay vs. session setup request arrival graph from figure11 gives a very simple idea about the impact on delay by different DRX cycle lengths. The higher the DRX cycle lengths, the higher is the delay. The graphs do not intersect, and rises exponentially. The network provider must always keep a balance between the delay and session setup request arrival rate. To keep the battery usage minimum, the higher DRX cycle lengths should be chosen. It is quite a dilemma to choose between the delay and the session setup request arrivals. Therefore, the network must choose the suitable DRX cycle length only analyzing the UE, if it is delay tolerant or not.

If the user equipment turns out to be delay tolerant, the longer DRX cycle length, i.e. the one with the high delay can be used. Similarly, if the user equipment is a delay intolerant one, the shorter DRX cycle length, i.e. the one with the shorter delay can be used. And, also the decisions can be changed with respect to any change in the session setup request arrival rate.

From figure 12, we can observe the tradeoff between the paging waste and the velocity of the UE. Starting from the shorter DRX cycle lengths we can observe that the paging waste is minimum for the one with the lowest velocity. There comes significant changes when the DRX cycle lengths are varied. Interestingly, the relative paging waste for different DRX cycle lengths overlaps at certain velocities.

The DRX cycle length of 1.67 minutes provides the best solution regarding the relative paging waste. But, this is going to give the worst results for the battery saving purpose. On the other hand, the DRX cycle length of 3.33 minutes gives better power saving but with a tradeoff with relative paging waste. For velocity 10 to 120 kph (approx.) it is observed that the paging waste is same for both the DRX cycle length of 1.67 and 3.33 minutes. In such cases, the network provider will select the more suitable DRX cycle length i.e. the longer cycle.

In case of the longest DRX cycle length shown in the graph, i.e. the DRX cycle length of 13.33 minutes gives the most relative paging waste at velocities where other DRX cycle lengths provide relatively low paging waste. From velocities 40 to 80 kph, the relative paging waste for 8.33 and 13.33 minutes are quite comparable. Beyond 80 kph, the relative paging waste for 13.33 minutes becomes so high that it may not be affordable by the eNB – the paging waste by the network provider will outweigh the user equipment battery saving.

In such cases, the DRX cycle length should be such that it balances the paging waste and the battery saving. The DRX cycle length of 8.33 minutes may prove to be useful in this case. It is up to the network provider to select their own DRX cycle length for the devices. We are only comparing the four DRX cycle length as shown in our simulations.

The battery status message, as shown earlier, may prove to be of significant importance here. Using the battery status message, the eNBs will be notified about the battery status of the devices with each TAU. The eNBs will decide on which parameter should be prioritized. When the UE has a higher battery percentage, the eNB will prioritize on keeping the paging waste minimum as well as keeping the battery usage reasonable. But, when the UE has a lower battery percentage, the eNB will prioritize on keeping the battery alive. It will choose the most suitable DRX cycle length in order to keep the battery usage minimum and keep the paging waste reasonable as well.

In table 4, we have provided some example on creating new UE categories. Here, we have only considered the four DRX cycle length that we have used in our simulations. The network provider may choose any length of DRX cycle. It is not required to be as discrete as it is shown in our examples.

Table 4 A New UE Categorization

UE category	Session setup request arrival rate, λ, in sessions per second	Velocity, v in kph	eDRX cycle length, T_c, in minutes
Category 1a	2	10	1.67min (low paging cost/higher battery cost) 8.33min (higher paging cost/lower battery cost) 13.33min (highest paging cost/lowest battery cost)
Category 1b	4	20	1.67min (low paging cost/higher battery cost) 8.33min (higher paging cost/lower battery cost)
Category 1c	6	40	1.67min (low paging cost/higher battery cost) 8.33min (higher paging cost/lower battery cost)
Category 1d	8	50	1.67min (low paging cost/higher battery cost)

The UE categories shown above only considers the data obtained from the graphs shown before. In practical cases, there will be other factors present in the selection of suitable DRX cycle lengths. Some discrete of session setup request arrival rate is taken here. The dominating factor here is the velocity. In the first example, Category – 1a has a session setup request arrival rate of 2 sessions per second and a velocity of 10 kilometers per hour. From the graph and then from the table we can see the difference in outcome for using different DRX cycle lengths. In the first case, all the three are usable as the relative paging waste is not too high.

Progressing through the table it can be seen that, with the increase in velocity, the usable DRX cycle length choices become narrower. It is because the paging cost becomes extremely high at higher velocities. So, the DRX cycle length chosen should be the shorter one.

Chapter 5

Conclusion

To meet the requirements of Internet of Things, and creating the cellular technologies as the ideal platform for it, it is necessary to overcome the challenges that comes with it. The battery usage requirement is one of the major challenges. The battery must last as long as the device lifetime in order to make the IoT devices more usable. And, to achieve high battery lifetime, discontinuous reception (DRX) is one of the best solution.

The extended discontinuous reception (eDRX) can make it possible to overcome this challenge. But, as we have shown in our analytical model and simulations, the eDRX comes with some tradeoffs. We cannot blindly increase the eDRX cycle length in order to increase the battery lifetime.

The tradeoffs that come with eDRX include the delay in each session and the paging waster that occurs if the UE has a velocity. According to the simulations of delay and paging cost shown in the previous section, suitable T_{OFF} can be determined. So, that particular eDRX cycle length can be assigned for a particular UE category which will be suitable for a particular user equipment.

Each device can have its own suitable DRX cycle length which will ensure reduced paging cost and paging delay all the while keeping battery consumption as low as possible. The selection of a suitable DRX cycle length is strongly dependent on the type of application of the device. Considering the other practical factors along with the type of device, the network provider can develop algorithms in order to get the best possible results.

The battery status message can be of significant importance in determining the DRX cycle lengths. The eNBs will be able to adjust the DRX cycle lengths by using the data received from the battery status message.

Thus, one of the major challenges of implementing IoT can be overcome by using optimized DRX and keeping the tradeoffs that come with it as balanced as possible.

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