

LTE Cat-M

A Cellular Standard for IoT

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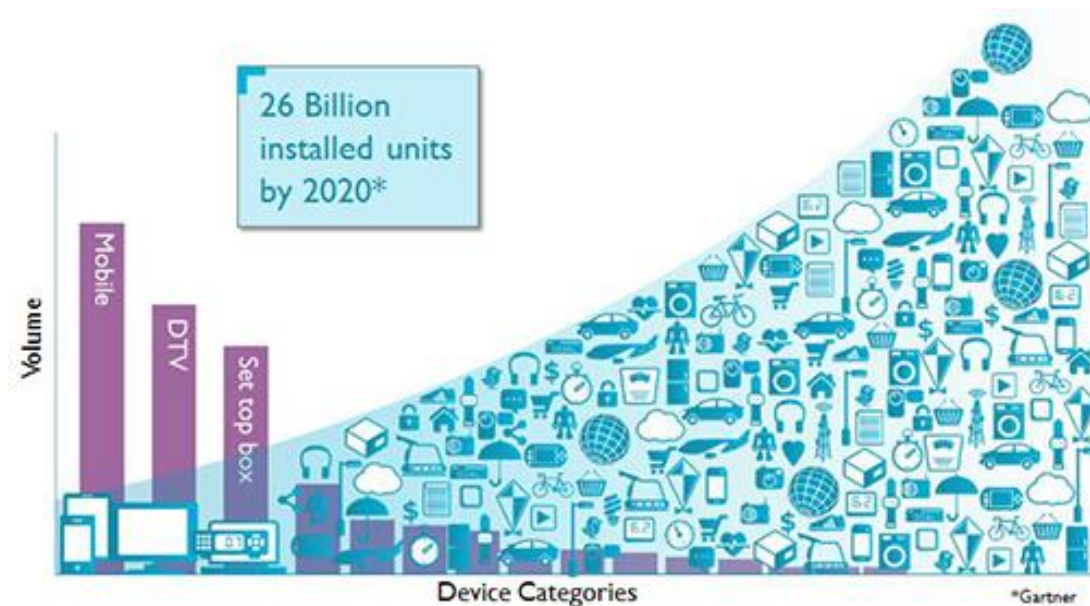
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Introduction

Mobile communications has been the foundation for the explosion in smartphones. Enormous consumer demand for mobile wireless broadband services has driven the last decade of telecom standards resulting in the LTE-Advanced 4G multi-mode devices that we take for granted today.

This market focus on mobile broadband has resulted in the standards bodies mostly focusing on how to deliver faster and faster data speeds to the consumer as well as how to help mobile operators deliver ever increasing network capacity. Today we see the very latest smartphone devices offering connection speeds in excess of 300Mbps with roadmaps through to Gigabit and beyond being discussed in the context of next generation 5G networks.

Beyond serving the needs of smartphones, mobile operators are increasingly thinking about what role they can play in delivering the Internet Of Things or so called IoT. The IoT market is still considered to be in its infancy, but according to industry analyst firm Gartner by 2020 we can expect over 26 billion 'things' or devices to be connected to the internet, the majority of those likely to be served via wireless connections.



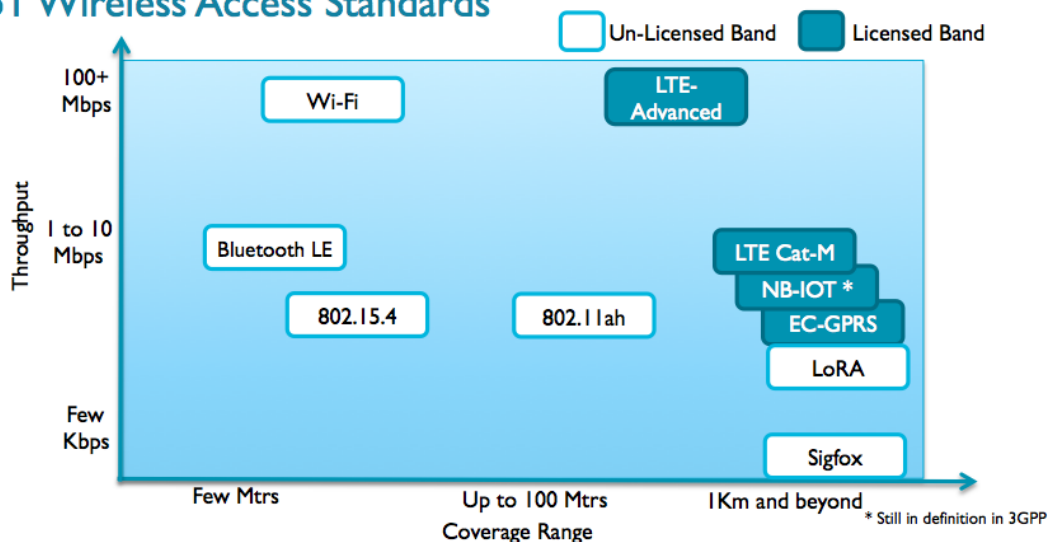
IoT is a broad category characterized by connecting physical objects to the internet and in-turn delivering intelligence through the data they collect. IoT capabilities can be added to just about any physical object including clothing, jewellery, thermostats, medical devices, household appliances, home automation, industrial controls, even light bulbs. The Internet of Things is already here and in use today. The present model started with specific sensors communicating with a single specific cloud application. The future will see an Internet of Things where billions of devices are connected to each other, all sharing data securely via the Internet

A plethora of access technologies exist or are emerging to enable the so called 'last mile' connectivity for the IoT connected objects. Wireless access broadly fits into two main areas: licensed band and unlicensed band. Unlicensed band technologies such as Bluetooth, Wi-Fi and 802.15.4 and the newly announced 802.11ah will all play an essential role in connecting devices.

Licensed band technologies have been somewhat slower to react to the IoT opportunity, in part because of the industry focus on mobile broadband services driven by the smartphone revolution. For decades we have seen so called machine to machine (M2M) services deployed on 2G systems such as GSM. These services are generally deployed in scenarios where there is a need to support wide area wireless networking coupled with mobility such as logistics and vehicle tracking. As the standards evolved through 3G and LTE the energy and complexity requirements of the technologies far outstretched the needs of IoT devices. As such 3G and LTE are only used in a few niche use cases that requires higher data rate connections, such as video surveillance.

The latest incarnation of 3GPP Release 13 has worked to re-address the balance and has introduced enhancements to the standards to focus more on IoT use cases and delivering energy efficient connections over licensed bands. LTE-MTC (Machine Type Communications) aims to deliver power efficient connections over existing LTE networks. With the inclusion of mobility, this technology promises to offer a long awaited upgrade path for the majority of 2G M2M connections today.

IoT Wireless Access Standards



Efficient implementation by designers and developers is key. With the need of IoT devices need to meet strict cost and power requirements the underlying SoC architecture is critical. In this whitepaper we examine the implementation of an LTE Cat-M physical layer on an ARM® based platform, taking the reader through the implementation and design considerations.

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Whether you are deploying the tiniest of ultra-efficient connected end nodes or a secure high-performance gateway or cloud platform, the scalable efficiency of ARM technology enables an optimized balance between performance, cost and power, and the quickest path to market.

This paper addresses the technical possibilities of the hardware and software architecture for terminals based on LTE Cat-M. We will provide comparisons that highlight the differences between LTE Cat-M and other categories. We will also describe the possible differences in architectures between categories and how we can benefit from the proposed changes in LTE Cat-M. We will also address the LTE-NB (LTE Narrow Band) proposals that exist in 3GPP and compare them with existing technologies. Other, competing technologies will also be compared to the LTE categories and proposed categories, highlighting pros and cons.

LTE Cat-M - a cellular standard for IoT

IoT devices will connect to the Internet through wired and wireless communication technologies. The wireless technologies could be both cellular and non-cellular. In the case of the local area unlicensed band standards, for example Bluetooth and WiFi, a router is needed to reach the Internet. The LTE Cat-M standard is a cellular standard and has a number of benefits compared to the non-cellular technologies. One obvious benefit is the existing infrastructure for LTE, where operators around the world have been rolling out this technology since 2009. According to GSA, there are now 480 LTE networks launched in 157 countries.

Historically, the most utilized cellular standard for IoT applications is GSM/GPRS. This 2G technology has been widely deployed for the last 20 years into applications such as transportation and asset tracking. We expect 2G technology will live on for some time until it is eventually replaced with other modern technologies such as LTE. The most recent release of 3GPP standards sees enhancements to GPRS to give existing coverage or so called EC-GPRS to support longer reach in IoT applications.

There are several different competing emerging wireless technologies to LTE, based on other specifications such as SigFox, LoRa and Weightless. They target extremely low-power low-throughput applications, most often in unlicensed spectrum. Although each solution has its own pros and cons, an advantage with LTE Cat-M and NB-IoT over these clean slate solutions is that LTE can leverage the existing network infrastructure. Indeed, base station providers claim that the LTE Cat-M and NB-IoT technologies will only mean a software upgrade to support the latest standards and therefore the network deployment cost will almost be zero.

IoT Verticals and Market

As previously stated, the IoT market will be enormous and will penetrate many existing market segments. These market verticals include automotive, agriculture, smart city, eHealth, smart home, smart meters, positioning and industrial. Many

different use cases with different demands on the IoT device will exist in these verticals. Some of them require long-range connection, some extremely low power and others, like eHealth, need high levels of reliability and security. Different technologies will address the different use cases, some will use a wired connection, some short range wireless and for some, a cellular connection is required. The cellular IoT technology will play an important role in many of these use cases.

As the GSM networks are being re-farmed to LTE, the standardization body 3GPP is specifying new standards to replace the legacy GSM networks. The most promising replacements for GSM are the new categories that are currently being specified in 3GPP for IoT applications. One category, LTE Cat-M, is an evolution of the existing LTE Cat-0 standard but where both control and data signals are allocated to 1.4MHz of spectrum. The other category that is being specified, NB-IoT, is designed to operate in a very narrow band 200kHz spectrum which can exactly replace 200kHz GSM bands. Both LTE Cat-M and NB-IoT can co-exist in already deployed LTE systems. They can also replace GSM spectrum and act as standalone systems.

Key requirements

Different verticals have different requirements with some more common than others. Cost and power consumption are common requirements seen in many use cases. Many use-cases assume battery-operated devices that should last for up to 10 years. The target for the new 3GPP categories for IoT is to be able to operate on 2AA batteries for more than 10 years. This will enable many new use cases in constrained environments, for example in the agricultural sector where it is costly to frequently replace batteries and where a power line is not present.

An important difference between fixed or short-range IoT technologies such as WiFi and Bluetooth is that cellular connections, such as LTE Cat-M, support mobility and much wider area coverage. Whilst mobility may not be a requirement for all use cases, it is an enabler for many IoT uses, such as positioning and within the automotive domain. The new categories in 3GPP aim to improve the existing coverage performance by 15-20dB. Electricity meters are often located in basements and an IoT connection to the meter would benefit from such an improvement, which is roughly equivalent to the loss in a wall or floor.

What's new in LTE Cat-M

There are several key additions to the Cat-M specification in 3GPP release 13 providing lower cost and power consumption.

Table 1 shows different key parameters for different LTE categories. The first LTE specification in release 8 specified 4 categories, with Cat-4 as the highest category supporting up to 150Mbps/s in the downlink. The modem complexity is derived from this category and normalized to it. Cat-0 was specified in release 12 as an intermediate step towards a competitive LTE specification for IoT applications. The complexity of LTE Cat-0 vs LTE Cat-4 is estimated to be reduced by 40% mainly due to lower data rates but also from the change in duplex mode, where half duplex mode eliminates the need of a duplexer and so saves cost. LTE Cat-M is an optimized IoT version of Cat-0 where the major

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change is the system bandwidth reduction from 20MHz to 1.4MHz. Another important change is the transmit power reduction to 20dBm. This reduction eliminates the need for an external power amplifier and enables a single chip solution, again reducing cost. Discussions about an even lower category, with a lower bandwidth, are ongoing in 3GPP, this will be called NB-IoT. In this category, even a lower system bandwidth, 200kHz, is planned.

	Release/Category			
	Release 8	Release 12	Release 13	Release 13
	Cat-4	Cat-M	Cat-M	NB-IoT
Max. system bandwidth	20MHz	20MHz	1.4MHz	200kHz
Downlink peak rate	150 Mbit/s	1 Mbit/s	1 Mbit/s	~200kbit/s
Uplink peak rate	50 Mbit/s	1 Mbit/s	1 Mbit/s	~200kbit/s
Duplex	Full duplex	Half duplex	Half duplex	Half duplex
Number of antennas	2	1	1	1
Transmit power (UE)	23dBm	23dBm	20dBm	23dBm
Estimated modem complexity	100%	40%	20%	<15%

Table 1: Comparison between different LTE categories (3GPP)

ARM Cortex-M for Signal Processing

Cortex-M Instruction Set

A key feature of the ARM® Cortex®-M4 and Cortex-M7 processors is the addition of DSP extensions to the Thumb-2 instruction set, as defined in ARM's architecture ARMv7-M. These instructions accelerate numerical algorithms and provide the opportunity to perform signal processing operations directly on a microcontroller without the need for an external digital signal processor.

Traditionally, a separate Digital Signal Processor has been chosen to execute algorithms such as transforms and filters, which require particularly intensive mathematical calculations. The architecture of a DSP is designed to provide highly optimised implementations of the mathematical operations found in these algorithms. Conversely, this means that they are not particularly well-suited for the control tasks typically performed by standard microcontrollers.

Microcontrollers, on the other hand, are general purpose and are normally optimised for basic data and arithmetic processing, interfacing to standard peripherals, handling user interfaces, and providing connectivity via a network interface. Microcontrollers, however, are not usually good at performing intensely mathematical algorithms because they lack the required number of registers and a dedicated set of instructions that support these computations.

The DSP extensions to the Thumb Instruction Set found in Cortex-M processors provide a range of SIMD operations which allow multiple operations to be applied to 32-bit registers in parallel, either as 2x16-bit operations or 4x8-bit operations, thus speeding up calculations involving Q15 and Q7 data. Additionally these operations can be performed in a signed or unsigned manner and the results of the operations can be saturated to a given bit-position. The Cortex-M4 and Cortex-M7 processors also offer a large variety of MAC instructions each of which executes in a single cycle, thus speeding up traditional DSP algorithms. All of these instructions are available to an optimizing compiler to generate from standard C/C++ code, or they can be used directly via compiler intrinsics or inline assembler instructions if required in critical performance kernels.

32-bit			
16-bit		16-bit	
8-bit	8-bit	8-bit	8-bit

ADD R0, R0, R1
ADD16 R0, R0, R1
ADD8 R0, R0, R1

CMSIS DSP Library for Cortex-M4 and Cortex-M7

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The ARM Cortex Microcontroller Software Interface Standard (CMSIS) is a vendor-independent hardware abstraction layer for the Cortex-M processor series. The CMSIS defines consistent and simple software interfaces to the processor and the peripherals, simplifying software re-use, reducing the learning curve for new microcontroller developers and reducing the time to market for new devices.

Within the CMSIS package (which is available for free download), there is a library written entirely in C which implements a number of optimised functions using the SIMD, saturating arithmetic and single-cycle MAC instructions of the Cortex-M4 and Cortex-M7. This library contains optimized functions for transforms such as FFT, and filters such as Biquad, FIR, and IIR, as well as a wide range of other mathematical functions optimized for the ARMv7-M instruction set. The software for performing the analysis contained in this white paper was written using this CMSIS DSP Library.

Physical Baseband Architecture

Background

There has been a tremendous evolution of the cellular technologies the past 30 years. From the first generation, based on only analog components, going to the second generation, where digital processing was introduced. In the third and fourth generation even more digital processing was introduced as CMOS evolution enabled higher density, lower power and higher frequency. The modems currently used in smartphones consist of extremely complex hardware and software systems that support several standards such as GSM, HSDPA and LTE. The complexity is mainly driven by the increased data rates that reach 800Mbps today and will exceed 1Gbps in the near future.

The cellular platform companies are constantly challenged by new higher demands on new functionality that enable higher data rates. New faster general-purpose processors (GPP) are developed together with powerful digital signal processors (DSP) to keep up the pace with the new requirements. Figure 1 shows a typical system architecture for an LTE modem. Multi-core solutions for both GPPs and DSPs add another dimension to the complexity in these systems. Custom HW accelerators are also updated and developed to comply with new demanding specifications. Although these new requirements push technology to new limits, another development, the IoT development, is challenging system architecture in a different way. The focus is changed from high data rates to low cost and low power. The system architecture for IoT should be lightweight and simple to meet these requirements of low-cost and low-power. We will describe different approaches to system architecture for the new LTE specifications.

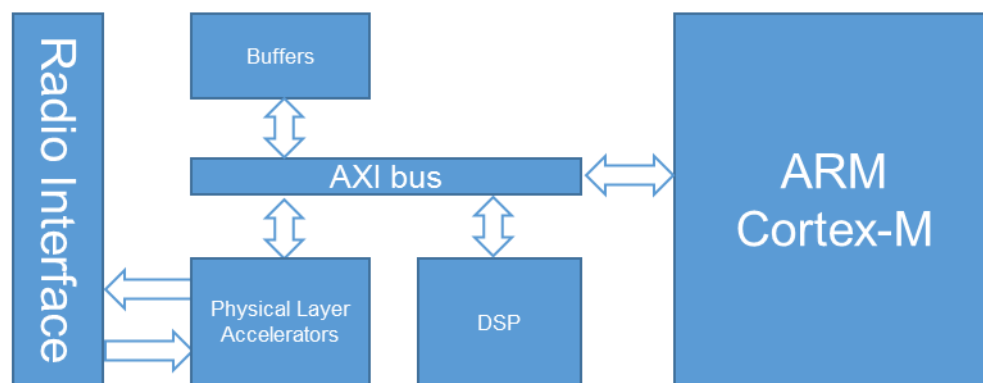


Figure 1: Typical LTE system architecture

Common design approach for IoT

A natural approach when designing a low-cost and low-power digital modem is to adopt previous existing architectures to the new low-complexity requirements. This approach results in a traditional architecture based on one or a number of GPPs, DSPs and accelerators, see Figure 1. This is an approach that is common among many modem design companies and also in the contribution documents for 3GPP specification.

There are a number of advantages using this approach but also some disadvantages. The most important advantage is the reuse aspect. Shrinking a full LTE modem to be able to only support Cat-M or even NB-IoT can reduce the total design effort. However, the final architecture, which is originally based on a full LTE architecture, might not be optimal in terms of cost and power consumption since the full LTE modem is fundamentally different than a Cat-M/NB-IoT modem. Reducing the number of GPP and DSP cores, using low complexity ARM and DSP cores, reducing clock frequency and memory are typical approaches when shrinking a full LTE modem towards a Cat-M/NB-IoT modem. To accomplish really low power and low cost a different method might be advantageous. A new approach to reduce complexity is the elimination of the dedicated DSP, see Figure 2.

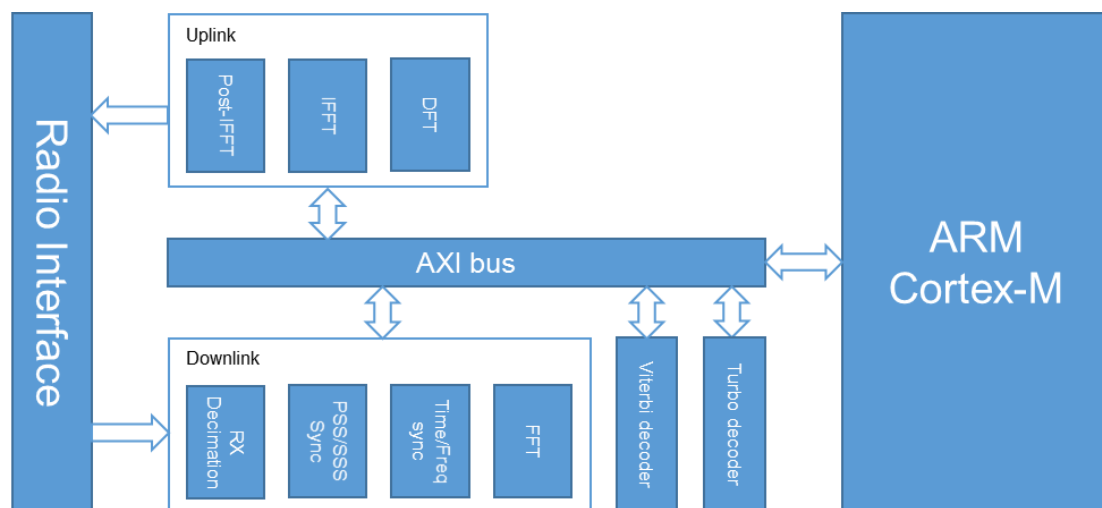


Figure 2: New system architecture

LTE IoT architecture

Due to the simplifications introduced in 3GPP for the upcoming LTE Cat-M standard, architectural simplifications are also possible. The traditional approach, which includes a GPP, a DSP and a number of accelerators, could be also be simplified. The ARM Cortex-M4 processor with its DSP instructions and pre-compiled optimized signal processing libraries can be utilised. Instead of using a dedicated DSP for the signal processing algorithms an ARM Cortex-M4 is able to run some of the algorithms that traditionally are run on DSPs, as in the system depicted in Figure 2. The heaviest algorithms, in terms of signal processing, are still run on dedicated accelerators in order to meet timing and reduce power. The identified potential algorithms that are candidates for the Cortex-M4 include: FFT, channel estimation, equalizer, modulation and demodulation. Algorithms that are mapped to dedicated HW are: decimation, initial filtering, synchronization and decoding.

DSP Performance

System partitioning (i.e. which algorithms should run in HW, on a GPP or on a DSP) is an important task when optimizing performance while limiting the cost and power consumption. The most demanding algorithms in LTE are in the downlink and include algorithm like FFT, channel estimation, equalization de-modulation, Turbo decoding and Viterbi decoding. The two last algorithms are typically not very well suited for implementation on either a GPP or DSP since they require extensive bit operations. GPPs and DSPs are not optimized for these types of operations.

The FFT algorithm, which transforms a signal in time domain to frequency domain, is a very heavy DSP algorithm that could be implemented in hardware, GPP software or DSP software. The channel estimator is another algorithm present in modern communication systems that could be implemented in these three ways. The main purpose of the channel estimator is to estimate the propagation between the base station and the terminal to be able to equalize. Equalization and de-modulation (where the received data is transformed into bits) are performed by separate algorithms that could also be mapped to dedicated hardware or implemented in software, either in GPP or DSP.

LTE systems have certain requirements on performance. For example, a terminal must be able to decode data and report back to the base station if the data was properly decoded within 4 milliseconds. Higher categories of LTE require more signal processing due to the higher data rates. Lower categories, such as Cat-M and below, have such low data rates that certain DSP algorithms could be implemented on a GPP. Figure 3 shows 3 algorithms, channel estimator, equalizer and de-modulation, across the different standards. The FFT algorithm is shown in Figure 4. The algorithms are run on an ARM Cortex-M4 processor running at 200MHz. The requirement line of 1ms is the LTE data rate, where data arrives in so-called sub-frames with duration of 1ms each. The conclusion is that LTE Cat-0 is far from reaching the requirement when implemented on this GPP. For LTE Cat-M the requirements can be met if we assume the FFT is managed by an offload accelerator or if it is mapped to another ARM core. Looking ahead at the newly emerging NB-IoT standard all algorithms can run and the requirements are met with a great margin. This means that an even lower frequency and/or processor family can be used.

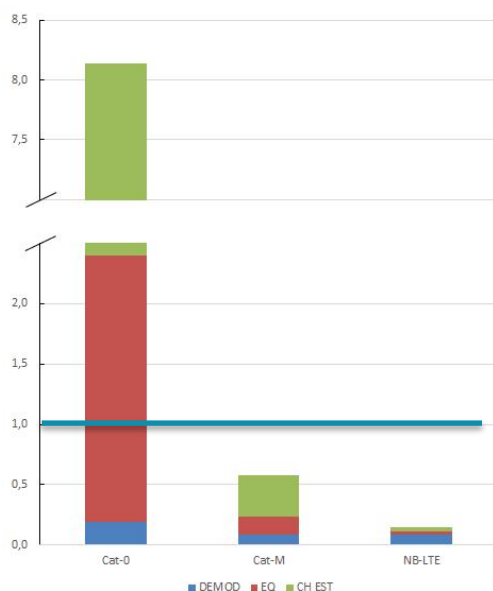


Figure 3 - DSP SW performance

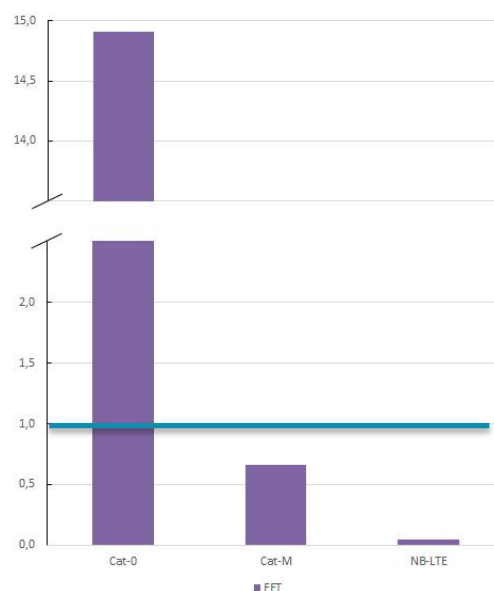


Figure 4 - FFT SW performance

Conclusions

In this paper we have looked at how crucial wireless connectivity is in enabling the IoT. There are a wide range of standards covering both local area as well as wide area networks. These wireless standards each have their own particular set of attributes that allow them to serve a set of end markets such as automotive, home, eHealth, etc.

Recent activity in 3GPP standards body has seen new licensed band cellular standards being developed to serve the IoT market, most notably the LTE Cat-M and NB-IoT standards. It is expected that both of these standards are likely to have wide adoption and in the most part replace a number of legacy 2G systems that are widely in use today.

When considering the requirements around the end devices we see low cost and low power as being key drivers to the successful adoption of the standards. Device vendors are challenged to deliver very low cost systems that achieve extremely long battery life to meet the needs of most IoT applications.

Traditional cellular modem designs are built for high throughput and as such cannot simply 'shrink' to meet the new standards, instead they require a redesign and a new approach. Standards such as LTE Cat-M and NB-IoT have significantly lower signal processing needs and in turn allow the selection of low power optimized architectures.

ARM Cortex-M family of processors is extremely well positioned to enable the emerging family of low power, always connected IoT devices. The ability to implement the protocol software as well as many elements of the lower level DSP code brings considerable benefits including cost reduction and power saving. In addition, this approach offers the benefit of a unified architecture for development and debug.

ARM's business model is based on licensing the core technology to different partners, allowing them to differentiate and add value. Multiple suppliers for each form factor ensures competition, competition spurs innovation and differentiation, which helps drive diversity in the Internet of Things. Together with its partners such as Mistbase, ARM is ready to deliver the next wave of smart connected devices.

Abbreviations

LTE	Long Term Evolution (So called '4G' wireless)
NB-IoT	Narrow Band IoT, a new 'clean slate' narrow band wireless standard in R13 3GPP
CMOS	Complimentary Metal Oxide Semiconductor
UE	User Equipment
MTC	Machine-Type Communication
DSP	Digital Signal Processing
GPP	General Purpose Processor
3GPP	3 rd Generation Partnerships Project, standards body overseeing wireless cellular standards