BRNO UNIVERSITY OF TECHNOLOGY

VYSOKÉ UČENÍ TECHNICKÉ V BRNĚ

FACULTY OF ELECTRICAL ENGINEERING AND COMMUNICATION

FAKULTA ELEKTROTECHNIKY
A KOMUNIKAČNÍCH TECHNOLOGIÍ

DEPARTMENT OF RADIO ELECTRONICS

ÚSTAV RADIOELEKTRONIKY

USE OF 4G/5G COMMUNICATION IN EMBEDDED SYSTEMS

VYUŽITÍ 4G/5G KOMUNIKACE V EMBEDDED SYSTÉMECH

SEMESTRAL THESIS
SEMESTRÁLNÍ PRÁCE

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VEDOUCÍ PRÁCE

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VYSOKÉ UČENÍ TECHNICKÉ V BRNĚ
FAKULTA ELEKTROTECHNIKY A KOMUNIKAČNÍCH TECHNOLOGIÍ

Semestrální práce

bakalářský studijní program **Elektronika a komunikační technologie**

Ústav radioelektroniky

Student: Michal Hanus ***ID:*** 240621

Ročník: 3 ***Akademický rok:*** 2023/24

NÁZEV TÉMATU:

Využití 4G/5G komunikace v embedded systémech

POKYNY PRO VYPRACOVÁNÍ:

BP(K)C-SEP:

Prostudujte a popište základní principy 4G/5G mobilních sítí se zaměřením na využití v internetu věcí (IoT). Seznamte se s čipsety Quectel RM520N a Nordic Semiconductor nRF9160, zpracujte rešerši dostupných modulů. Pomocí vybraného vývojového kitu demonstrujte funkci zařízení s 4G/5G konektivitou.

BP(K)C-BAP:

Navrhněte scénáře a možnosti využití 4G/5G komunikace a využívaných standardů (URLLC, LTE-M, NB-IoT) pro průmyslovou IoT komunikaci. Proveďte detailní měření parametrů. Získané údaje zpracujte a srovnejte s teoretickými předpoklady a jinými v současnosti používanými komunikačními systémy.

DOPORUČENÁ LITERATURA:

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Vedoucí práce: Ing. Aleš Povalač, Ph.D.

Konzultant: Ing. Matěj Očenášek

doc. Ing. Lucie Hudcová, Ph.D.

předseda rady studijního programu

ABSTRACT

This semestral thesis provides an introduction to 4G/5G mobile networks for the Internet of Things (IoT) applications in the embedded electronic systems. Related communication protocols LPWAN (NB-IoT, LTE-M) and URLLC are mentioned. Two selected chipsets Quectel RM520N and Nordic Semiconductor nRF9160 are described, together with their available development kits. One of the development kits (nRF9160 DK) was used for practical demonstration of an IoT device with LPWAN connectivity on an example of a combined burglary and fire alarm system with 4 sensors, transferring data to a remote cloud server via MQTT protocol. Follow-up work for the bachelor thesis is outlined at the conclusion of this semestral thesis.

KEYWORDS

4G, 5G, IoT, LPWAN, NB-IoT, LTE-M, URLLC, RM520N, nRF9160

ABSTRAKT

Tato semestrální práce se zabývá úvodem do problematiky elektronických zařízení s 4G/5G mobilní konektivitou pro internet věcí (IoT). Práce popisuje související komunikační protokoly LPWAN (NB-IoT, LTE-M) a URLLC, spolu s parametry dvou vybraných komunikačních čipsetů Quectel RM520N a Nordic Semiconductor nRF9160 a dostupných vývojových modulů tyto čipsety využívajících. Jeden z těchto vývojových modulů (nRF9160 DK) byl použit k praktické ukázce IoT zařízení s LPWAN konektivitou na příkladu kombinovaného zabezpečovacího a požárního elektronického systému se 4 senzory a přenosem dat na vzdálený virtuální server pomocí MQTT protokolu. Závěrem této semestrální práce je přehled plánovaných prací v navazujícím bakalářském projektu.

KLÍČOVÁ SLOVA

4G, 5G, IoT, LPWAN, NB-IoT, LTE-M, URLLC, RM520N, nRF9160

Typeset by the `thesis` package, version 4.09; `https://latex.fekt.vut.cz/`

ROZŠÍŘENÝ ABSTRAKT

Tato semestrální práce provádí úvod do problematiky využití 4G a 5G mobilních sítí pro elektronická zařízení v oblasti internetu věcí (IoT).

První část práce se zaměřuje na přehled IoT protokolů pro 4G a 5G mobilní sítě (NB-IoT, LTE-M, URLLC), které jsou speciálně navrženy tak, aby splňovaly požadavky moderních IoT zařízení, jako jsou nízká spotřeba energie, vysoký datový tok, nízké komunikační zpoždění, vysoká spolehlivost a škálovatelnost.

Druhá část práce popisuje dva moderní čipsety použitelné pro konstrukci IoT zařízení s 4G/5G konektivitou - RM520N od firmy Quectel a nRF9160 od firmy Nordic Semiconductor, uvádí jejich základní parametry a přehled dostupných vývojových modulů z různých zdrojů.

Třetí část práce demonstruje praktický příklad využití vývojového modulu nRF9160 DK jako komunikační základny kombinovaného elektronického zabezpečovacího a požárního systému (EZS/EPS) s LPWAN konektivitou, využívajícího 4 senzory (pohybový senzor PIR HC-SR501, senzor hořlavých plynů MQ-2, teplotní senzor LM35, magnetický senzor otevření dveří/okna DRV5033), s lokální signalizací simulovanou 4 LED na vývojovém modulu, možností uživatelské lokální (de)aktivace jednotlivých senzorů pomocí 4 tlačítek a přepínačů na vývojovém modulu a s přenosem poplachových dat pomocí MQTT protokolu na virtuální server simulující pult centrální ochrany (PCO).

Závěrečnou částí semestrální práce je přehled náplně navazujícího bakalářského projektu, který se bude zabývat možnostmi využití 4G/5G mobilních sítí pro průmyslovou IoT komunikaci, s experimentálním měřením parametrů komunikace, jejich srovnáním s teoretickými předpoklady a jinými v současnosti používanými komunikačními systémy.

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Author's Declaration

Author:	Michal Hanus
Author's ID:	240621
Paper type:	Bachelor's Thesis
Academic year:	2023/24
Topic:	Use of 4G/5G communication in embedded systems

I declare that I have written this paper independently, under the guidance of the advisor and using exclusively the technical references and other sources of information cited in the paper and listed in the comprehensive bibliography at the end of the paper.

As the author, I furthermore declare that, with respect to the creation of this paper, I have not infringed any copyright or violated anyone's personal and/or ownership rights. In this context, I am fully aware of the consequences of breaking Regulation § 11 of the Copyright Act No. 121/2000 Coll. of the Czech Republic, as amended, and of any breach of rights related to intellectual property or introduced within amendments to relevant Acts such as the Intellectual Property Act or the Criminal Code, Act No. 40/2009 Coll. of the Czech Republic, Section 2, Head VI, Part 4.

Brno ....

author's signature*

*The author signs only in the printed version.

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Introduction

1 Communication protocols for IoT devices in 4G/5G mobile networks

1.1 Current situation

It is estimated that currently (2023/2024) there are two actively connected Internet-of-Things (IoT) devices per each person living on the planet Earth and the number will almost double furthermore until 2030, reaching nearly 30 billion connected IoT devices worldwide[41].

At the same time, complexity of the IoT devices rises every year and so is their requirements on the underlying network infrastructure and protocols, originally designed predominantly for completely different mobile applications (text messages and voice / video streaming). Need for new IoT-related protocols started to be prominent with wide-spreading and anticipated new use-cases of IoT devices, for which *Global System for Mobile communications* (GSM) and original *Long-Term Evolution* (LTE) networks were not originally intended and soon found unsuitable in terms of power efficiency, connection reliability and ability to accommodate billions of small devices with tiny average data rates.

IoT devices today are not only simple single-purpose meteo sensors, but more and more frequently this category includes very complex vehicles and machinery, such as autonomous cars with multiple RADAR/LIDAR sensors or cooperative industrial robots, needing to communicate with the central command & control facility and with each other in real time and with very high reliability. On the other hand large widespread of massive quantities of very low power devices in possibly critical application can also be expected. Related requirements on communication data volumes, response latency and network reliability far exceed capacity and technical possibilities of older mobile networks. Larger bandwidths, data speeds and lower latencies brought by 4G and especially 5G mobile networks are necessary for providing the appropriate working space for these new IoT devices.

The necessary communication protocols for 4G and 5G mobile networks are being standardized under an umbrella of *3rd Generation Partnership Project* (3GPP) - an association of national telecommunication standardization agencies and commercial partners. 3GPP has agreed upon and released several communication protocols (so-called „releases“) for the new generations of mobile networks, unfortunately with some ambiguities in their numbering and labeling. For example, Long-term evolution (LTE) was first introduced as a 3G technology standard but it later become a 4G standard. LTE was followed by LTE-Advanced labeled as „true 4G“ or 4.5G and LTE-Advanced Pro (LTE-A Pro) that is considered 5G but sometimes it is labeled as 4.9G [3].

1.2 4G IoT networks (LPWAN)

Low-power wide-area network (LPWAN) protocols are 4G LTE wireless communication technologies that enable long-range transmission among IoT devices. LPWAN protocols are designed to meet the diverse requirements of IoT applications, mainly low power consumption, wide coverage range, capacity for large number of devices, and high reliability [42].

1.2.1 NB-IoT

NB-IoT (Narrowband Internet of Things) is a cellular LPWAN standard that was developed by 3GPP for IoT devices and services in 2016 under 3GPP Release 13 and updated in 2017 with 3GPP Release 14 [7].

NB-IoT focuses on providing extended coverage, enhanced capacity, reduced complexity, and increased battery life for IoT devices that transmit small amounts of data infrequently [6].

NB-IoT operates on the licensed spectrum and uses a subset of the LTE bands with peak data rate of 26 kb/s for downlink and 16.9 - 66 kb/s for uplink using Cat NB1. Newer standard of Cat NB2 allows maximum peak rate of 127 kb/s for downlink and 159 kb/s for uplink. NB-IoT uses orthogonal frequency division multiplexing (OFDM) modulation for downlink communication and single carrier frequency division multiple access (SC-FDMA) for uplink communication.

Single NB-IoT communication channel corresponds to a single 180 kHz LTE frequency block [1]. This enables the following operation modes [6]:

- In-band operation - NB-IoT operates on standard LTE frequencies among other types of LTE communication
- Guard band operation - Communication takes place in LTE guard-band without any other LTE communication
- Stand alone operation - A theoretically possible scenario when mass adaption of technology will occur. This mode plans to utilize frequency allocation of current GSM networks.

As of writing this thesis (December 2023) NB-IoT is supported in Czechia by all three national mobile operators. Vodafone is declaring universal coverage across the whole country [9], T-Mobile in selected larger cities and O2 only in Moravian-Silesian region [10].

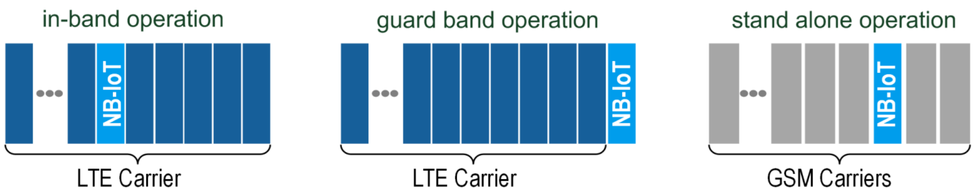

Fig. 1.1: NB-IoT modes of operation [6]

1.2.2 LTE-M

LTE-M or LTE-MTC (Long-Term Evolution Machine Type Communication) is a second LPWAN protocol specified in 3GPP Release 12, with improved specification in Releases 13 and 14. Unlike NB-IoT, LTE-M uses more bandwidth (1.4 - 5 MHz) and is capable of higher communication speeds (1 - 4 Mbit/s for downlink and 1 – 7 Mbit/s for uplink). Another advantage of LTE-M over NB-IoT is an ability to function with movable objects (such as cars or drones). Higher bandwidths however lead to greater circuit complexity and possible higher energy consumption related to it [43].

As of writing this thesis (December 2023) LTE-M is covered in Czechia by O2 in 98.5 % [8] and locally by Vodafone [9].

1.3 5G IoT networks

5G implementation into the mobile networks can be achieved via two methods [4]:

- NSA (non-stand alone) - 5G features are achieved by adding new RAN (Radio Access Network) to existing 4G LTE core. This approach implements dynamic spectrum sharing and enables rapid deployment of enhanced mobile broadband in customer market without larger changes in existing infrastructure.
- SA (stand alone) - LTE core and RAN are completely replaced with 5G ones. RAN can however still switch back to LTE air interface to ensure backward compatibility with non-5G devices.

In 2018, 3GPP Release number 15 laid down 5G specification named 5G NR (New Radio). Unlike LTE-A Pro that has just added more features to 4G LTE and operated in LTE standards and channels, 5G NR introduced a new physical layer in air interface [4].

5G NR tries to solve three key aspects of wireless technology [4]:

- eMBB (Enhanced Mobile Broadband): Data-intensive applications needing large bandwidth for primarily traditional end-user demand, like video streaming. This should be achieved by Gigabit LTE, massive MIMO, mmWave technologies, spectrum sharing techniques and advanced channel coding.

- mMTC (Massive Machine Type Communications): Low-power and low-cost applications with small data volumes but potentially large number of these devices in a small footprint. It is built on LTE LPWAN protocols like LTE-M and NB-IoT, making them potentially a core part of 5G.
- URLLC (Ultra-reliable and Low-latency Communication): Mission-critical applications traditionally possible only by direct wire connection, necessary for real-time control of autonomous vehicles and industrial machinery.

As of December 2023, 5G IoT networks are not yet commercially available in Czechia.

1.3.1 URLLC requirements

URLLC (Ultra-Reliable and Low-Latency Communication) is a new requirement for 5G networks for providing real-time communication protocols with very low delays and very high levels of reliability. First attempts to address this were introduced in 4G LTE HRLLC (Higher-Reliability and Low-Latency Communication) in 3GPP release 15 [11]. Until this point, aspects of latency and reliability were dealt in separately and sometimes were in direct contradiction to each other (reliability was achieved with repeated data redundancy, which multiplied latency). Combination of these two aspects is however essential for several critical applications with different requirements, as shown in table 1.1:

Scenario	E2E latency [ms]	Reliability [%]	Data rate [Mbps]
Discrete automation	10	99.99	10
Process automation – remote control	60	99.9999	100
Process automation – monitoring	60	99.9	1
Process automation – monitoring	40	99.9	10
Electricity distribution – high voltage	5	99.9999	10
Intelligent transport systems	30	99.9999	10

Table 1.1: Performance Requirements for Low-Latency and High-Reliability Scenarios [11]

1.3.2 Latency

With such strict latency requirements, as low as 5 ms end-to-end latency, it is necessary to minimize air interface delay (to 1 ms or less). To achieve such low latency, intensive optimization of air data delivery is necessary.

There are several possible approaches that can lead to reduced communication time and latency [11]:

- Frequent transmission opportunities Downlink control channel used to carry scheduling information for data transmission is not usually monitored by end device for power saving reasons. However to reduce the waiting time for delivering the control information, the end device could do this. For device to start uplink transmission, it needs to send a scheduling request (SR) that allocates a specific transmission slot. To minimize the waiting time, the periodicity of the SR resource configuration should reflect latency requirements. This can be further emphasized by flexible schedulling timing mainly in Time Division Dulex (TDD).
- Flexible transmission duration This aspect is supported in 5G using larger subcarier spacing. This shortens slot duration and gives bigger oportunity for quicker communication establishment.
- Grant-free (or configured grant) uplink transmission In cases with very low latency demand, grant-free uplink transition, specific periodic uplink resource for device can be arranged. End device in this scenario does not need to wait for scheduling request and at any time it has data it can transmit in this arranged slot without a need for dynamic grant.

Air interface is only partially responsible for total end-to-end latency. Remaining latency is caused by core network, internet network and particular server with which the device is communicating. This is to be solved by new concept of Edge computing. Edge computing is a possibility for a mobile operator or another entity to move services from a remote server closer to the device and to execute necessary task right in 5G core network [2].

Another method of lowering transport network latency is to avoid transport network completly. This is experimented in vehicle-to-vehicle (V2V) protocols and in non-IP based communication [12].

1.3.3 URLLC reliability optimization

In 3GPP Release 16, redundant transmission for high-reliability communication was introduced [11]. With this method, user packets are duplicated and simultaneously transferred to the receiver via two disjoint user plane paths. The redundant packets are then eliminated at the receiver side. This further avoids occasional fails in one path propagation and slims probability of exceding the delay requirements. Other changes can be made in 5G core parameters settings, like QoS Monitoring, dynamic division of Packet Delay Budget and enhancements of session continuity [2].

2 Communication standards for IoT devices in 4G/5G networks

- převzít kapitolu 1.1
- doplnit grafy nárůstu IoT zařízení

2.1 Established communication standards for IoT devices

- doplnit GSM, LoRa, Zigbee, Sigfox, Wifi, ESP32, 433 MHz

2.2 4G IoT network standards (LPWAN)

- převzít kapitolu 1.2.
- doplnit kapitolu 1.2.3 Comparison of 4G LPWAN with established technologies
- zrcadlova lambda křivka

https://blog.nordicsemi.com/getconnected/what-is-cellular-iot https://www.nordicsemi.com/I
power-cellular-IoT/Development-tools?lang=en#infotabs

2.3 5G IoT network standards

- převzít kapitolu 1.3, doplnit 5G trojuhelník
- zestručnit kapitolu 1.3.1 URLLC, bez zbytečných detailů

2.4 DECT NR+ standard for 5G IoT networks

- Stary DECT a IP telefony, pasmo, HW vrstva, NR a teorie prenosovych rychlosti

https://www.nordicsemi.com/Products/Wireless/DECT-NR?lang=en#infotabs
https://www.nordicsemi.com/Products/Wireless/DECT-NR/Applications?lang=en#infotabs
https://www.nordicsemi.com/Products/Wireless/DECT-NR/Related-publications?lang=en#info
https://blog.nordicsemi.com/getconnected/could-dect-nr-democratize-massive-iot-in-5g https://docs.nordicsemi.com/bundle/ps_nrf9161/page/dect.html#ariaid-title4

https://devzone.nordicsemi.com/nordic/nordic-blog/b/blog/posts/dect-nr-a-technical-dive-into-non-cellular-5g https://blog.nordicsemi.com/getconnected/the-next-step-for-m2m-communications

3 Nordic Semiconductor nRF91 series SiP for 4G/5G IoT communication

- důvod, proč vybrán nRF9161

3.1 nRF9161 SiP

- popsat funkcionalitu a fíčury

3.2 nRF9160 and nRF9131

- pouze stručně – popsat odlišnosti od nRF9161

3.3 nRF9161 development kit

- podrobně popsat nRF9161-DK

3.4 nRF9160 modules and kits

- doplnit další kity z internetu, zestručnit do 2 tabulek (modules, kits), sloučit obrázky
  - https://blog.nordicsemi.com/getconnected/blog-plug-and-play-development-kits-make-cellular-iot-accessible-to-everyone
  - Ardesco

3.5 nRF Connect SDK

- popis funkcionalit

4 Laboratory testing

Každá section jak protokol, Co chci změřit, Fyzika - princip toho co měřím, čím to měřím, zapojení měřící techniky, tabulky, graf

4.1 Comunication range

One of main considaritation when choosing a IoT platfrom is communication range. Main source of attenuation of radio energy caused by electric field dispersion/diffusion of electric field. This effect if best desribed by *Free space path loss* (FSPL):

$$FSPL = \left(\frac{4\pi d}{\lambda}\right)^2 \tag{4.1}$$

Signal attenuation is also dependent on directivity of antennas and loss on connectors and **electrical wiring**. When antenna and transmition total **gain** is constant and can be added to equation like this:

$$A = D_{ANT} \cdot A_{RX} \cdot \left(\frac{4\pi d}{\lambda}\right)^2 \tag{4.2}$$

Where D_{ANT} is directivity of antenna and A_{RX} is total loss from *Radio Frequency* (RF) connector to LTE modem. These must be accounted to only when maasuring on directly on LTE modem.

This can be coverted to simplify calculation to decibel form:

$$A = D_{ANT}^{[dB]} + A_{RX}^{[dB]} + 10 \cdot \log_{10} \left(\frac{4\pi d}{\lambda}\right)^2 \tag{4.3}$$

From this a maximal range can be simulated using RF attenuators in laboratory enviroment by converting

$$d = A_{max} \tag{4.4}$$

Dosah zásvisí na vzdálenosti, v ideálních podmínkách line of sight Free-space path loss

Popis Free-space path loss, teorie, vzorečky

Technika - variable attenuator,

Tabulka utlum , km ve free-space , teoreticka sila signalu , signal na vstupu podle FW , packet drop / BER

4.2 Noise immunity - reliability

Noise makes signal bad, reciver much sad.

Teorie, vzorecky, Bit error rate, Added white gausian noise

Teoreticke vypocty pro NB-IoT, LTE-M, DECT NR+

Technika zdroj šumu, směšovač,

Pro jednotlivé AWGN a CNR carier noise ratio Tabulka utlum , km ve free-space , teoreticka sila signalu , signal na vstupu podle FW , packet drop / BER , spotřeba

4.3 Power consumtion

Globalni oteplovani bad, small battery good

Technika Power Profiler Kit II

4.4 Latency

Pro jednotlivé AWGN a CNR carier noise ratio Tabulka utlum , km ve free-space , teoreticka sila signalu , signal na vstupu podle FW , packet drop / BER , spotřeba , latence

Experimentální ověření NB-IoT, LTC-M, DECT NR+:

- dosah - popis cesty šíření ve volném prostoru, odkaz na teoretický výpočet útlumi vzdáleností ve volném prostředí ve vzduchu. Popis atenuátoru.
- spotřeba - variabilní snižování síly signálu, popis Power Profiler Kit II
- přenosová rychlost - primárně pro DECT, praktická superhurbá přenosová rychlost UDP Byty/(čas od konce do začátku sleep)
- odolnost vůči šumu - VF generátor šumu, teorie

Experimentální ověření DECT NR+ navíc:

- spolehlivost -
- latence -

Teorie mereni - Náhradní modely prostředí. Degradace signálu.

Popis experimentální instrumentace a sestav.

Spotřeba, packet drop, rychlost, latence závislá na útlumu (popř. intenzita bílého šumu) (vsechny protokoly)

5 Field application testing of nRF9161-DK

Externí interference: mikrovlnka...

- Urban environment (industrial plant, underground spaces, bunkers)
  - co testovat?
  - nějaká aplikační deska pro „průmysl“?
- Rural environment (open field, forest)
- Herd monitoring application (Temp+RH, Accel, Light, GPS)
  - GPS functionality
  - FOTA
  - ARM CryptoCell
  - ARM TrustZone

6 Discussion

- Scénáře použití IoT, vhodnost jednotlivých druhů komunikace pro ně Navrhněte scénáře a možnosti využití 4G/5G komunikace a využívaných standardů (URLLC, LTE-M, NB-IoT) pro průmyslovou IoT komunikaci.
- Srovnání experimentálnách výsledků protokolů s teoretickými předpoklady Proveďte detailní měření parametrů. Získané údaje zpracujte a srovnejte s teoretickými předpoklady a jinými v současnosti používanými komunikačními systémy.

7 Conclusion

Deadline: 31 May 2024 (2 + 4 + 5 + 4 + 5 weeks) max. 100 pages / 20 weeks = min. 5 pages weekly

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Symbols and abbreviations

3GPP 3rd Generation Partnership Project
4G, 5G 4th and 5th Generation mobile networks
ADC Analog-Digital Converter
DL Downlink
E2E End-to-End
eMBB Enhanced Mobile Broadband
eSIM embedded SIM card
GNSS Global Navigation Satellite System
GPIO General-Purpose Input/Output
HAL Hardware Abstraction Layer
HRLLC Higher-Reliability and Low-Latency Communication
I2C Inter-Integrated Circuit
IoT Internet of Things
IP Internet Protocol
LE Low Energy
LED Light Emitting Diode
LGA Land Grid Array
Li-ion Lithium-Ion
Li-Po Lithium-Polymer
LPWAN Low-Power Wide-Area Network
LTE-M Long-Term Evolution Machine Type Communication
LTE Long-Term Evolution
mMTC Massive Machine Type Communications
MQTT Message Queuing Telemetry Transport
NB-IoT Narrowband Internet of Things
NFC Near-Field Communication
NSA Non-Stand Alone
PC Personal Computer
PCB Printed Circuit Board
PCIe Peripheral Component Interconnect Express
PDM Pulse-Density Modulation
PIR Passive Infra Red
PWM Pulse-Width Modulation
RAN Radio Access Network
RGB Red Green Blue
RTC Real-Time Clock
SA Stand-alone

SDK Software development kit
SIM Subscriber Identity Module
SiP System-in-Package
SMA Subminiature Version A
SPI Serial Peripheral Interface
TCP Transmission Control Protocol
TLS Transport Layer Security
UART Universal Asynchronous Receiver-Transmitter
UL Uplink
URLLC Ultra-reliable and Low-latency Communication
USB Universal Serial Bus
WDT Watch Dog Timer
FSPL Free space path loss
RF Radio Frequency
GSM Global System for Mobile communications