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APPLICATION OF 4G/5G COMMUNICATION IN EMBEDDED SYSTEMS

VYUŽITÍ 4G/5G KOMUNIKACE V EMBEDDED SYSTÉMECH

BACHELOR'S THESIS

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Bachelor's Thesis

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Application of 4G/5G Communication in Embedded Systems

INSTRUCTION:

Study and describe the basic principles of 4G/5G cellular networks with a focus on the use in the Internet of Things (IoT). Become familiar with the Quectel RM520N and Nordic Semiconductor nRF9160 chipsets, conduct research on available modules. Demonstrate the functionality of a device with 4G/5G connectivity using a selected development kit.

Propose scenarios and opportunities for 4G/5G communication and standards (URLLC, LTE-M, NB-IoT) for industrial IoT communication. Perform detailed parameter measurements. Process the obtained data and compare with theoretical assumptions and other currently existing communication systems.

RECOMMENDED LITERATURE:

- [1] SAUTER, Martin. From GSM to LTE-Advanced Pro and 5G an introduction to mobile networks and mobile broadband. Third edition. Hoboken, NJ, USA: Wiley, 2017. ISBN 978-1119346869.
- [2] STUBER, Gordon L. Principles of Mobile Communication. 4th ed. 2017. Imprint: Springer, 2017. ISBN 978-3319556147.

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ABSTRACT

This bachelor's 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 DECT-NR+ are mentioned. The selected chipset Nordic Semiconductor nRF9160/nRF9161 are described, together with their available development kits. Scenarios for industrial usage are outlined and demonstrated with the selected development kit !!!TODO!!!. These include a universal low-cost tracker with additional potential sensors and stationary low-power sensoric unit for remote reading, ((wireless version of experimental measuring for in-field usage)). In the frame of these demonstration applications relevant detailed measurements are made and elaborated in contrast to theoretical assumptions and expected results.

KEYWORDS

4G, 5G, IoT, LPWAN, NB-IoT, LTE-M, DECT-NR+, nRF9160, nRF9161

ABSTRAKT

!!!TODO!!!

KLÍČOVÁ SLOVA

4G, 5G, IoT, LPWAN, NB-IoT, LTE-M, DECT-NR+, nRF9160, nRF9161

ROZŠÍŘENÝ ABSTRAKT

!!! TODO !!!

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Author's Declaration

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Contents

Introduction	12
1 Communication standards for IoT devices in 4G/5G networks	13
1.1 Established communication standards for IoT devices	13
1.2 4G IoT networks (LPWAN)	13
1.2.1 NB-IoT	13
1.2.2 LTE-M	14
1.2.3 Comparison of 4G LPWAN with established technologies . . .	14
1.3 Cellular 5G IoT networks	14
1.3.1 URLLC requirements	15
1.3.2 Latency	16
1.3.3 Cellular URLLC reliability optimization	17
1.3.4 Shortcomings of cellular URLLC and time horizon	17
1.4 DECT NR+ standard for 5G IoT networks	17
1.4.1 Plain DECT	17
2 IoT communication modules for 4G/5G networks	18
2.1 Nordic Semiconductor nRF9160	18
2.1.1 Modules with nRF9160	19
2.2 Quectel RM520N	26
2.2.1 Modules with RM520N	27
3 Demonstration tacker and stationary smart sensor	30
3.1 Antenna	30
3.2 PCB	30
3.3 Case	30
3.4 End-result	30
4 Laboratory testing	31
4.1 Communication range	31
4.1.1 Antennas	31
4.2 Noise immunity - reliability	32
4.3 Power consumption	32
4.3.1 Nordic Power Profiler Kit II	32
4.4 Latency	32
4.5 Measurement	33
5 Field application testing of nRF9161-DK	36

6 Discussion	37
Bibliography	39
Symbols and abbreviations	44
List of appendices	46

List of Figures

1.1	NB-IoT modes	14
2.1	Nordic nRF9160 SiP	18
2.2	Nordic nRF9160DK	19
2.3	Nordic Thisgy:91	20
2.4	NimbeLink Nano Global LTE-M	21
2.5	LN60E	21
2.6	Pebble Tracker	22
2.7	Icarus SoM	22
2.8	Icarus Bee	23
2.9	Icarus IoT	23
2.10	nRF9160 Feather	24
2.11	SparkFun Thing Plus nRF9160	24
2.12	Connexio Stratus	25
2.13	Quectel RM520N	26
2.14	Waveshare dongle	27
2.15	Waveshare dongle	28
2.16	USB/Ethernet converter	28
2.17	Module for Jetson Nano	29

List of Tables

1.1	Performance requirements for URLLC	16
2.1	nRF9160 product options	19
2.2	Comparison of nRF9160 modules	26
4.1	NB-IoT / LTE-M measurements for message length = X B and added noise = X dBm	34
4.2	DECT-NR+ measurements for message length = X B and added noise = X dBm	35

Introduction

It is estimated that currently (2024/2025) 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.

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].

Graf IoT zarizeni here

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

1.1 Established communication standards for IoT devices

dopl nit GSM, LoRa, Zigbee, Sigfox, Wifi, ESP32, 433 MHz

1.2 4G IoT networks (LPWAN)

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

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].

KajsiK zrcadlova λ krivka

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.

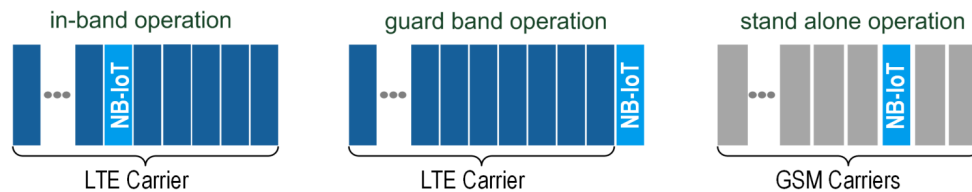


Fig. 1.1: NB-IoT modes of operation [6]

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].

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].

1.2.3 Comparison of 4G LPWAN with established technologies

1.3 Cellular 5G IoT networks

Kajsik 5G trojuhelnik

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

Zestručnit

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 HURLLC (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 scheduling timing mainly in Time Division Duplex (TDD).
- Flexible transmission duration This aspect is supported in 5G using larger subcarrier spacing. This shortens slot duration and gives bigger opportunity 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 completely. This is experimented in vehicle-to-vehicle (V2V) protocols and in non-IP based communication [12].

1.3.3 Cellular 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 exceeding 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].

1.3.4 Shortcomings of cellular URLLC and time horizon

1.4 DECT NR+ standard for 5G IoT networks

1.4.1 Plain DECT

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-](https://blog.nordicsemi.com/getconnected/could-dect-nr-democratize-massive-iot-in-5g)

[5g https://docs.nordicsemi.com/bundle/ps_nrf9161/page/dect.html#ariaid-title4](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-](https://devzone.nordicsemi.com/nordic/nordic-blog/b/blog/posts/dect-nr-a-technical-dive-into-non-cellular-5g)
[dive-into-non-cellular-5g https://blog.nordicsemi.com/getconnected/the-next-step-for-](https://blog.nordicsemi.com/getconnected/the-next-step-for-m2m-communications)
[m2m-communications](#)

2 IoT communication modules for 4G/5G networks

2.1 Nordic Semiconductor nRF9160



Fig. 2.1: Nordic nRF9160 SiP[13]

nRF9160, made by Nordic Semiconductor, is a System-in-Package (SiP) combining multiple integrated circuits into a single LGA package (10x16x1.04 mm in size), functioning as an entire computing system:

- Application Processor with Arm Cortex-M33 core at 64 MHz, 1 MB flash memory, 256 kB RAM and usual microcontroller peripherals - 4x SPI/UART/I2C, 4x PWM, PDM, I2S, 12-bit ADC @ 200 ksps, 3x timer, 2x RTC, WDT.
- LTE modem (700 – 2000 MHz) operating in the both LPWAN modes: LTE-M (300/375 kbps DL/UL) and NB-IoT (30/60 kbps DL/UL), supporting IPv4/IPv6 internet layer with optional security using TCP/TLS in transport layer and modem firmware upgrades via FOTA (firmware over the air).
- Radio-Frequency Front End (RFFE)
- GNSS receiver
- Power management integrated circuits.

nRF9160 is certified for global operations in multiple LTE bands, as shown in the figure below. For European operations, bands B1, B3, B8, B20 and B28 are available for both NB-IoT and LTE-M modes. Hardware security is strengthened with ARM TrustZone technology protecting against uploading unofficial or malicious firmware. TrustZone also protects from firmware attacks like memory and peripheral spoofing [16]. nRF9160 furthermore employs Arm CryptoCell solution optimized for high-performance cryptography for energy-constrained devices.

Both SIM and eSIM are supported for connection and authentication with mobile network operators [13]. nRF9160 can be powered from relatively large range

of voltages - from 3.0 to 5.5 V, allowing to directly connect Li-ion or Li-Po type batteries or USB-compatible power supplies.

nRF9160 is manufactured in 3 modifications, sharing the same 127-pin LGA package, but differing in LTE modem capabilities, as shown in table 2.1 below.

Name	RF features
nRF9160-SICA	Only LTE-M
nRF9160-SIBA	Only NB-IoT
nRF9160-SIAA	LTE-M, NB-IoT and GNSS

Table 2.1: nRF9160 LGA modules options and their limitations. [34]

2.1.1 Modules with nRF9160

There are several modules and development kits available with nRF9160 chipset, originating from Nordic Semiconductor, as well as from other vendors.

nRF9160 DK

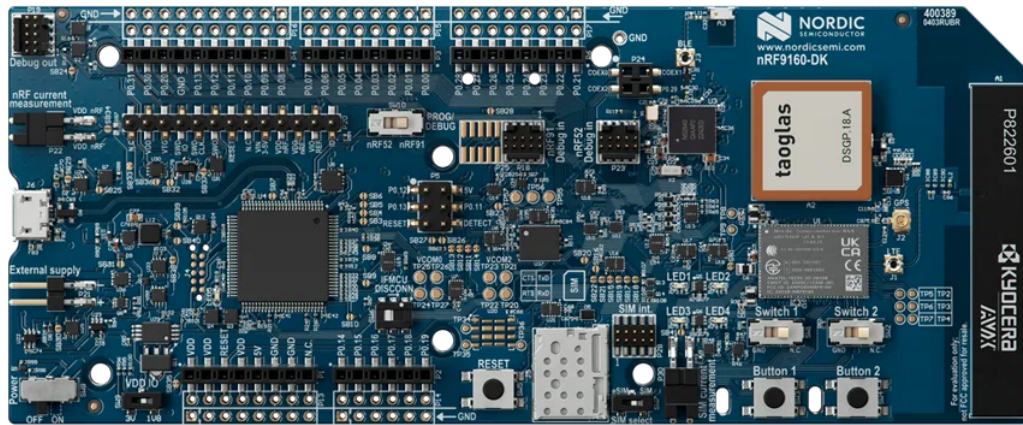


Fig. 2.2: Nordic nRF9160DK front view[17]

nRF9160 DK is an official pre-certified development kit for nRF9160 made and supported by Nordic Semiconductor. It is equipped with LTE-M/NB-IoT antenna, GNSS antenna, SIM connector, eSIM card from iBasis preloaded with 10 MB data. All peripheral GPIO pins of nRF9160 are available through connectors and headers compatible with Arduino Uno Rev3 form factor, there are also 4 on-board LEDs, 2 buttons and 2 switches connected to the application processor GPIO. The board also

includes nRF52840 board controller sharing the peripherals and allowing to build a Bluetooth Low Energy gateway. Powering and communication with PC are arranged via USB (virtual COM) port. Programming and debugging is enabled through the Segger J-Link OB. The nRF9160 DK is supported by a full suite of development software tools by Nordic Semiconductor, free to download and use commercially [17].

Nordic Thingy:91

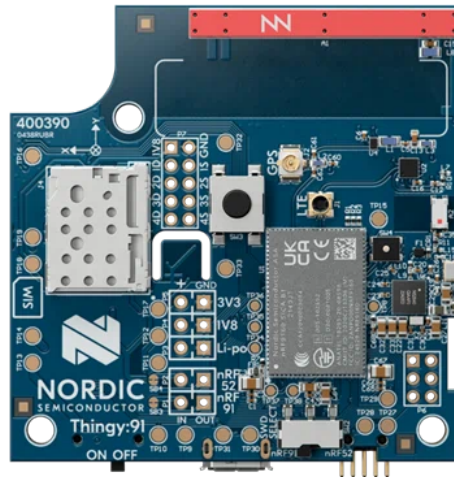


Fig. 2.3: Nordic nRF9160DK front view[18]

Nordic Thingy:91, also made by Nordic Semiconductor, is a compact small-factor module used as a rapid prototyping battery-operated platform, containing LTE-M/NB-IoT/GNSS, Bluetooth LE and NFC antennas, User-programmable button and RGB LEDs, environmental sensor for temperature, humidity, air quality and air pressure, plus a color and light sensor, low-power accelerometer and high-g accelerometer, rechargeable Li-Po battery with 1350 mAh capacity [18].

NimbeLink Nano Global



Fig. 2.4: NimbeLink Nano Global LTE-M[19]

NimbeLink Nano Global LTE-M (Skywire Nano Development Kit, NL-SWN-LTE-NRF9160), made by Airgain, is an add-on modem with nRF9160 and two U.FL antenna connectors, attached to a base board NL-SWNDK providing SIM holder, USB powering and distribution of GPIO pins to peripheral headers. The board has been originally certified only for Verizon networks [19].

LN60E

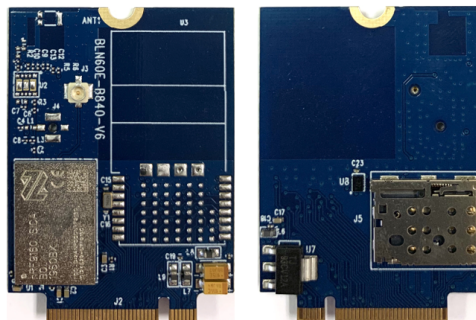


Fig. 2.5: LN60E[20]

LN60E is a simple modem provided by Fansel, having a U.FL antenna connector, SIM connector and M.2 card connector for nRF9160 peripherals [20].

Pebble Tracker

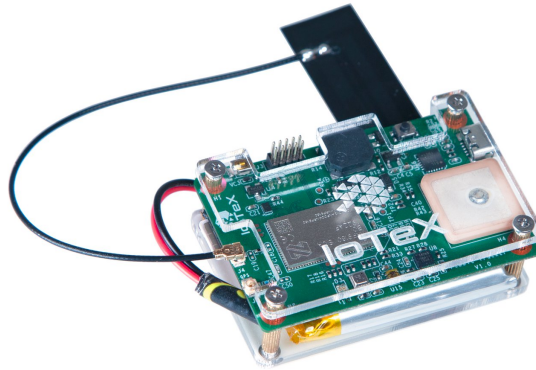


Fig. 2.6: Pebble Tracker[21]

Pebble Tracker, a crowdfunded module made by IoTeX, is a battery operated IoT prototyping platform based on a board with nRF9160, Bosch BME680 humidity/-pressure/temperature/air quality sensor, ICM-42605 3-axial gyroscope/accelerometer, AMS TSL2572 ambient light sensor, SIM slot, OLED display, in a compact plastic case [21]

Icarus SoM

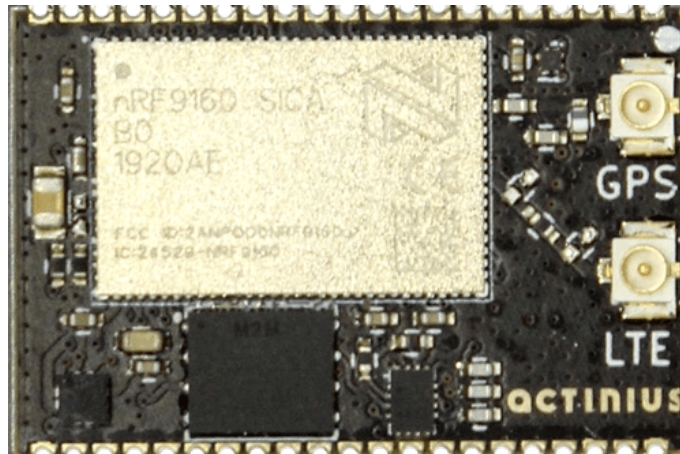


Fig. 2.7: Icarus SoM[22]

Icarus SoM, made by Actinius, is a simple module with U.FL antenna connectors for GNSS and LTE, eSIM and accelerometer, with spare GPIO pins headed to PCB edge connectors [22].

Icarus Bee

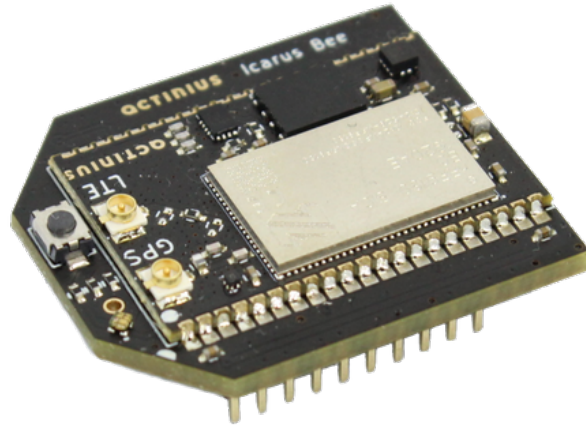


Fig. 2.8: Icarus Bee[23]

Icarus Bee, made by Actinius, expands the above-mentioned Icarus SoM module with a board connecting it to 64 Mbit flash memory, RGB LED, button, SIM connector and GPIO to pin headers [23].

Icarus IoT Board v2

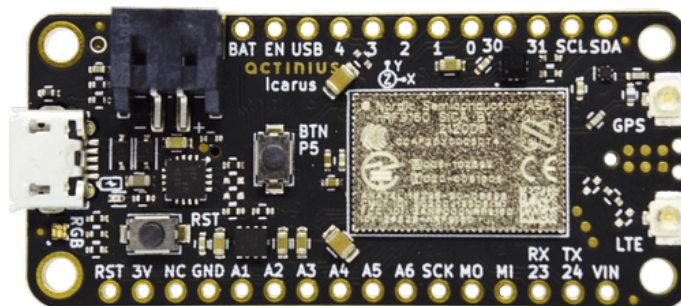


Fig. 2.9: Icarus IoT Board v2[24]

Icarus IoT Board v2, made by Actinius, contains nRF9160 chipset on a board with USB connector, U.FL antenna connectors for LTE and GNSS, LiPo charger, eSIM and nano SIM connector, accelerometer and SPI flash memory, with pin headers compatible with Adafruit Feather footprint [24].

nRF9160 Feather

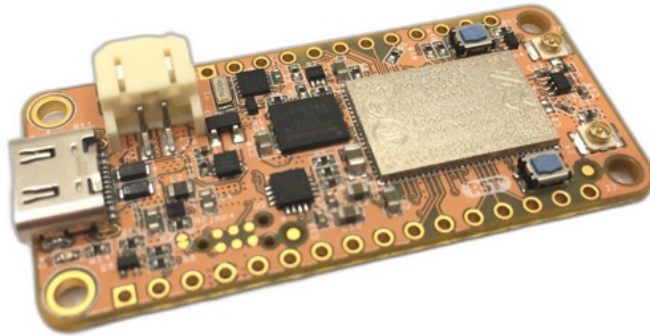


Fig. 2.10: nRF9160 Feather[25]

nRF9160 Feather, made by CircuitDojo, is a design with pin headers compatible with Adafruit Feather footprint and a functionality similar to the Icarus IoT Board v2 [25].

SparkFun Thing Plus nRF9160

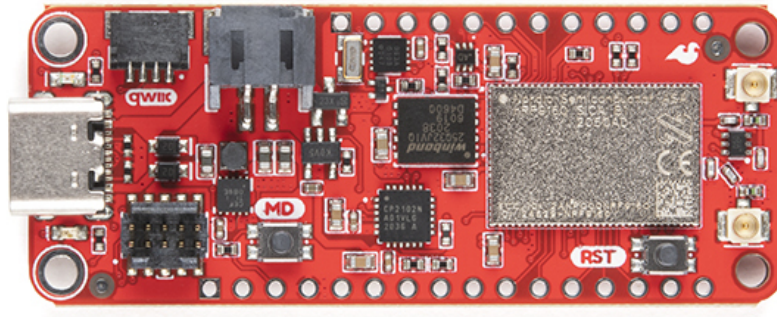


Fig. 2.11: SparkFun Thing Plus nRF9160[26]

SparkFun Thing Plus nRF9160, made by SparkFun, is another board with Adafruit Feather footprint and similar to Icarus IoT Board v2 described above, however with USB-C connector and providing 4 MB SPI flash memory, LiPo charger, low power RTC, a button, a LED, two U.FL antennas for LTE and GNSS [26].

Connexio Stratus

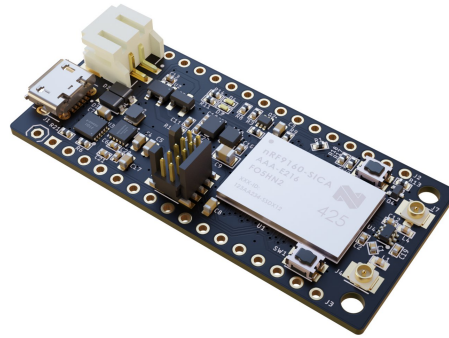


Fig. 2.12: Connexio Stratus[27]

Connexio Stratus, a crowd-funded development board, has a similar design to the SparkFun board above, adding SIM with 500 MB of mobile data, energy harvesting integrated circuit for Li-ion and NiMH battery charging, LiPo battery connection and charging, 2 push-buttons, 1 LED, SHT4x temperature and humidity sensor, LIS2DH 3-axial accelerometer [27].

Comparisons of the main parameters of the most common nRF9160 boards is provided in the following table 2.2 taken from [27]:

	Stratus	Thingy:91	Icarus	Feather	Pebble Tracker	Thing Plus
Manufacturer	Conexio	Nordic Semi	Actinius	CircuitDojo	IoTex	Sparkfun
Total Pins	33	8	28	28	None	28
I/O Pins	26	8	21	20	None	20
Energy Harvester	Yes	No	No	No	No	No
Accelerometer	Yes	Yes	Yes	Yes	Yes	Yes
Environmental Sensors	Yes	Yes	No	No	Yes	No
Onboard LEDS	2	1 RGB	1 RGB	2	1 RGB	2
Sensor power gating	Yes	No	No	No	No	No
Power switch	Yes	Yes	No	No	Yes	No
Lipo battery charger	Yes	No	Yes	Yes	No	Yes
USB interface	Yes	Yes	Yes	Yes	Yes	Yes
Debugging connector	Yes	Yes	No	No	Yes	No
Prepaid Cellular data	500 MB	10 MB	10 MB	10 MB	No	10 MB
Cellular data validity	10 years	N/A	N/A	N/A	N/A	N/A
SMS Data	250	No	No	No	No	No
Dedicated sensor shield	Yes	No	No	No	No	No
VS Code dev. extension	Yes	Yes	No	No	No	No
Breadboard compatible	Yes	No	Yes	Yes	No	Yes
Edge Impulse ready	Yes	Yes	No	No	No	No
Memfault ready	Yes	No	No	No	No	No
Golioth ready	Yes	No	No	Yes	No	No
Open-source	HW+SW	HW+SW	No	HW+SW	No	HW+SW
Dimension [mm]	50.8x22.8	58.8x58.5	50.8x22.8	50.8x22.8	53x35	58.42x22.86
Weight	5 g	61 g	5 g	5 g	10 g	5 g
Price (USD)	\$159	\$126.25	\$115	\$99	\$215	\$129.95

Table 2.2: Comparison of nRF9160 main modules

2.2 Quectel RM520N



Fig. 2.13: Quectel RM520N series front view[14]

RM520N is a 5G Sub-6GHz IoT module, made by Chinese company Quectel, optimized for IoT and eMBB applications with worldwide spectrum coverage, but capable of also 3G/4G multi-mode operation. The module is made in an M.2 form factor (30 x 52 x 2.3 mm) with 4 antenna connectors and is compatible with 3GPP Release 16 specification, supporting both 5G NSA (data rates: 3.4 Gbps DL / 550 Mbps UL) and SA modes (data rates: 2.4 Gbps DL / 900 Mbps UL).

The RM520N is an industrial-grade module for industrial and commercial applications. It should cover nearly all the mainstream carriers worldwide and support Qualcomm® IZat location technology Gen9C Lite (GPS, GLONASS, BDS and Galileo). The integrated GNSS receiver simplifies the product design.

It communicates using USB and PCIe drivers provided by Quectel for Windows 7 or higher, Linux, and Android. Main anticipated usage are industrial routers, home gateways, laptops / tablet PCs as well as IoT applications [14].

The module comes in two variants: RM520N-GL with global coverage and RM520N-EU with EU frequency regulatory spectrum.

2.2.1 Modules with RM520N

Development support for RM520N modules is provided by a Chinese company Waveshare [28][29] making several hardware kits for rapid development and implementation with RM520N and having a distribution network across EU (e.g. <https://rlx.sk/sk/vyhladavanie?controller=search&s=RM520N>)

Dongle

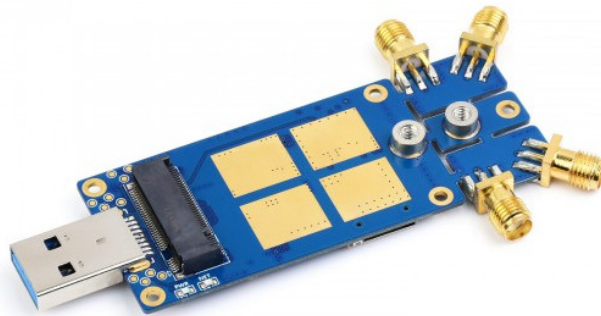


Fig. 2.14: Waveshare dongle[30]

5G DONGLE module [30] providing simple expansion board with 4 SMA antenna connectors, nano SIM card holder, M2 connector for RM520N, heatsink and USB3.1 port for connecting to PC or Raspberry Pi.

Raspberry Pi HAT

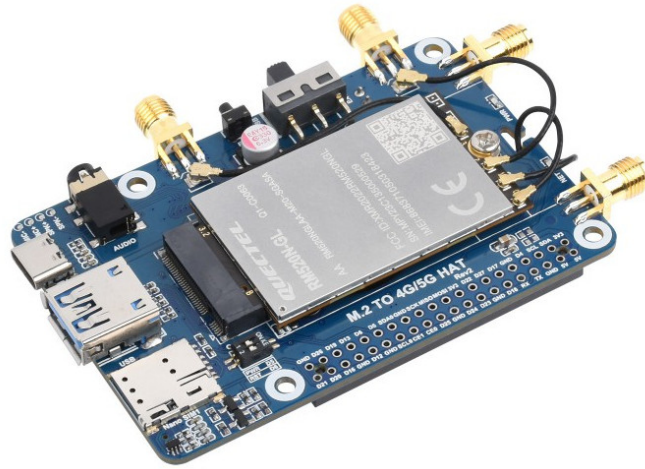


Fig. 2.15: Waveshare dongle[31]

5G HAT for Raspberry Pi [31] , with a case for Raspberry Pi 3B/4B, onboard USB3.1 and USB-C ports, 2x SIM card slot, 4 antennas, 3A power supply circuit.

USB/Ethernet converter



Fig. 2.16: USB3.1 / Gigabit Ethernet converter to 5G[32]

USB3.1 / Gigabit Ethernet converter to 5G [32] capable to connect RM520N module to its M2 connector header and acting as a 5G communication bridge to PC, industrial control hosts, Raspberry Pi, ethernet switch or router using their USB3.1 or Ethernet connections.

Module form Jetson Nano

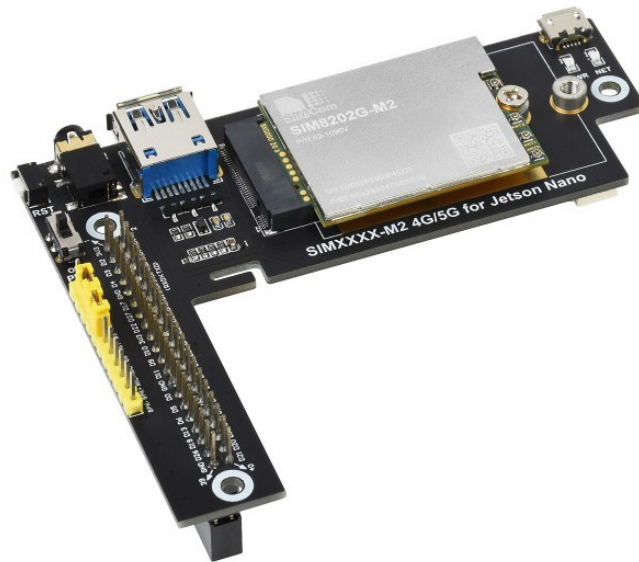


Fig. 2.17: Communication module for Jetson Nano[33]

Communication module for Jetson Nano [33] - interface with M2 connector, USB3.1 port, audio jack and decoder, SIM card slot, 40-pin GPIO extension header for direct connection to Jetson Nano, 4 antennas.

3 Demonstration tacker and stationary smart sensor

3.1 Antenna

3.2 PCB

3.3 Case

3.4 End-result

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 Communication range

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

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

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

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

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 measuring on directly on LTE modem.

This can be converted to simplify calculation to decibel form:

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

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

$$d = A_{max} \quad (4.4)$$

4.1.1 Antennas

For ability to add additional attenuators external antennas had to be made. For this a $\lambda/4$ monopole antenna design has been chosen.

O2 on 800 MHz

Dosah závisí 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 gaussian 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 consumption

Toto asi bude chujovina With wireless communication often comes an incentive for power source without need for external wires and power transmission network. Significant research has been made to alternative power sources for IoT devices from prevalent energy sources like light, vibration, temperature gradient and similar. Use of small solar panels with potential large capacitor seems to be the most viable out of these but there [tuzdroj].

Konec chujoviny

All power sources except the ones connected directly to energy power grid have some sort of limited capacity. In the case of primary batteries and rechargeable batteries this limit is absolute and usually has to be guaranteed in terms of

4.3.1 Nordic 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 merení - Náhradní modely prostředí. Degradace signálu.

Popis experimentální instrumentace a sestav.

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

4.5 Measurement

Nominal		nRF modem			nRF FW		Power Kit II					
K_U [dB]	CL [dB]	P_I [dBm]	Q_I [dBm]	SNR [dB]	T_{lat} [ms]	PD [%]	P_{TX} [mW]	P_{RX} [mW]	W [J/msg]	T_{TX} [μs]	T_{RX} [μs]	R_B [kB/s]
0	-140	-80	10	40	0.5	0.1	98	10	0.1	400	400	1
3	-140	-80	10	40	0.5	0.1	98	10	0.1	400	400	1
6	-140	-80	10	40	0.5	0.1	98	10	0.1	400	400	1
10	-140	-80	10	40	0.5	0.1	98	10	0.1	400	400	1
13	-140	-80	10	40	0.5	0.1	98	10	0.1	400	400	1
16	-140	-80	10	40	0.5	0.1	98	10	0.1	400	400	1
20	-140	-80	10	40	0.5	0.1	98	10	0.1	400	400	1
23	-140	-80	10	40	0.5	0.1	98	10	0.1	400	400	1
26	-140	-80	10	40	0.5	0.1	98	10	0.1	400	400	1
30	-140	-80	10	40	0.5	0.1	98	10	0.1	400	400	1
33	-140	-80	10	40	0.5	0.1	98	10	0.1	400	400	1
36	-140	-80	10	40	0.5	0.1	98	10	0.1	400	400	1
40	-140	-80	10	40	0.5	0.1	98	10	0.1	400	400	1
43	-140	-80	10	40	0.5	0.1	98	10	0.1	400	400	1
46	-140	-80	10	40	0.5	0.1	98	10	0.1	400	400	1
50	-140	-80	10	40	0.5	0.1	98	10	0.1	400	400	1
53	-140	-80	10	40	0.5	0.1	98	10	0.1	400	400	1
56	-140	-80	10	40	0.5	0.1	98	10	0.1	400	400	1
60	-140	-80	10	40	0.5	0.1	98	10	0.1	400	400	1

Table 4.1: NB-IoT / LTE-M measurements for message length = X B and added noise = X dBm

Nominal		nRF modem					Power Kit II					
K_U [dB]	CL [dB]	$RSSI$ [dBm]	$RSSI - 2$ [dBm]	SNR [dB]	T_{lat} [ms]	PD [%]	P_{TX} [mA]	P_{RX} [mA]	W [J/msg]	T_{TX} [μ s]	T_{RX} [μ s]	R_B [kB/s]
0	-140	-80	10	40	0.5	0.1	98	10	0.1	400	400	1
3	-140	-80	10	40	0.5	0.1	98	10	0.1	400	400	1
6	-140	-80	10	40	0.5	0.1	98	10	0.1	400	400	1
10	-140	-80	10	40	0.5	0.1	98	10	0.1	400	400	1
13	-140	-80	10	40	0.5	0.1	98	10	0.1	400	400	1
16	-140	-80	10	40	0.5	0.1	98	10	0.1	400	400	1
20	-140	-80	10	40	0.5	0.1	98	10	0.1	400	400	1
23	-140	-80	10	40	0.5	0.1	98	10	0.1	400	400	1
26	-140	-80	10	40	0.5	0.1	98	10	0.1	400	400	1
30	-140	-80	10	40	0.5	0.1	98	10	0.1	400	400	1
33	-140	-80	10	40	0.5	0.1	98	10	0.1	400	400	1
36	-140	-80	10	40	0.5	0.1	98	10	0.1	400	400	1
40	-140	-80	10	40	0.5	0.1	98	10	0.1	400	400	1

Table 4.2: DECT-NR+ measurements for message length = X B and added noise = X dBm

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 experimentálních výsledků protokolů s teoretickými předpoklady Provedte detailní měření parametrů. Získané údaje zpracujte a srovnajte s teoretickými předpoklady a jinými v současnosti používanými komunikačními systémy.

Conclusion

This semestral thesis provided a brief introduction to 4G/5G mobile networks for the Internet of Things (IoT) applications in the embedded electronic systems. Related communication protocols for 4G IoT networks (LPWAN NB-IoT and LTE-M) and 5G IoT networks (5G NR - URLLC) were described and a survey of two selected chipsets for 4G networks (Nordic Semiconductor nRF9160) and 5G networks (Quectel RM520N) and their development modules and kits was made.

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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

List of appendices