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

APPLICATION OF 4G/5G COMMUNICATION IN EMBEDDED SYSTEMS

VYUŽITÍ 4G/5G KOMUNIKACE V EMBEDDED SYSTÉMECH

BACHELOR'S THESIS

BAKALÁŘSKÁ PRÁCE

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VEDOUCÍ PRÁCE

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VYSOKÉ UČENÍ TECHNICKÉ V BRNĚ
FAKULTA ELEKTROTECHNIKY A KOMUNIKAČNÍCH TECHNOLOGIÍ

Bakalářská práce

bakalářský studijní program **Elektronika a komunikační technologie**

Ústav radioelektroniky

Student: Michal Hanus ***ID:*** 240621
Ročník: 3 ***Akademický rok:*** 2024/25

NÁZEV TÉMATU:

Využití 4G/5G komunikace v embedded systémech

POKYNY PRO VYPRACOVÁNÍ:

Prostudujte a popište základní principy 4G/5G mobilních sítí se zaměřením na jejich architekturu, komunikační protokoly a specifika využití v internetu věcí (IoT). Analyzujte klíčové vlastnosti technologií LTE-M a NB-IoT, jejich výhody, nevýhody a rozdíly oproti tradičním mobilním sítím. Seznamte se s čipovými sadami Nordic Semiconductor nRF9160 a nRF9161 a proveďte rešerši dostupných modulů. Na základě získaných poznatků vyberte vhodný vývojový kit a prakticky demonstrujte funkci zařízení s 4G/5G konektivitou.

Navrhněte reálné scénáře a možnosti využití 4G/5G komunikace v oblasti průmyslového IoT. Pro tyto scénáře zhotovte demonstrátor a otestujte je v předpokládaných podmínkách. Proveďte detailní měření komunikačních parametrů (latence, spotřeba energie, síla signálu, přenosová rychlost). Získané údaje zpracujte a srovnejte s teoretickými předpoklady a jinými v současnosti používanými komunikačními systémy.

DOPORUČENÁ LITERATURA:

[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.

Termín zadání: 10.2.2025 ***Termín odevzdání:*** 2.6.2025

Vedoucí práce: doc. Ing. Aleš Povalač, Ph.D.
Konzultant: Ing. Matěj Očenášek

doc. Ing. Lucie Hudcová, Ph.D.
předseda rady studijního programu

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 potentional sensors and staionary 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 contract 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

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.

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author's signature*

*The author signs only in the printed version.

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Contents

List of Figures

List of Tables

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[**statista**].

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 advancements in *Low-Power Wide-Area Network* (LPWAN) *Radio Frequency* (RF) technology in regards to power saving in weak signal decoding and subsequent longer range opens a door to vast filed of usage critical scenarios currently depended on more costly solutions with private networks. `Co to znamena???`

Graf IoT zarizeni here

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

1.1 Established communication standards for IoT devices

1.1.1 GSM (2G)

GSM represents most prominent ***2G!*** (**2G!**) standard of cellular network technology developed in the 1980s and adopted in . The most notable shift forward was the transition to digital form of communication. It was the first wildly adopted standard with *Short Message Service* (SMS). Initial deployment has began in 1990s with the peak of deployment in 2005. [2]

While superseded by 3G, 4G, and 5G, 2G remains essential in some regions for basic communication and ***M2M!*** (**M2M!**) applications. However, due to the advancement of technology, and the need for frequency space, many countries are planing shutting down their 2G networks in a controlled way. The outcome in some countries is shutdown of 3G before 2G and obligation from bureaus to mobile operators to keep 2G operational [3].

1.1.2 LoRa

Long-Range (LoRa) is a proprietary, spread-spectrum radio modulation technique developed by Semtech. It primarily operates within the sub-GHz unlicensed radio frequency bands, enabling long-range communication with minimal power consumption. LoRa can be [**semtech**]. LoRa less often operates in 2.4 GHz ISM band, amateur radio bands or on private private frequencies. LoRa physical layer modulation, based on *chirp spread spectrum* (CSS), allows for robust data transmission in noisy environments and over extended distances. This technology is particularly well-suited for applications requiring low data rates and long battery life, such as environmental monitoring, asset tracking, and smart agriculture.

LoRaWAN

Long-Range wide area network (LoRaWAN) represents a ***MAC!*** (**MAC!**) layer protocol built upon the LoRa physical layer. This protocol standardizes the communication architecture, network topology, and security mechanisms, enabling interoperability among diverse LoRa devices and infrastructure.

LoRaWAN effectively extends the capabilities of the LoRa physical layer by providing a comprehensive framework for network management and application development, thereby enabling the deployment of scalable and interoperable Low-Power Wide-Area Network solutions.

The deployment of LoRaWAN or LoRaWAN-like networks necessitates the implementation of dedicated gateway infrastructure, a characteristic that, conversely, affords enhanced control over network coverage compared to cellular technologies such as 4G and 5G which is dependent on mobile operators.

1.1.3 Wi-Fi

Wi-Fi, standardized under the IEEE 802.11, represents a most deployed *wireless local area network* (WLAN) technology with at least 19.5 billion Wi-Fi devices in use around the world. It played fundamental role in *Internet of Things* (IoT) implementation and innovations. Key characteristics are high data throughput, high bandwidth and usually short range [**wifi**].

Because of this higher data throughput it requires higher power consumption, longer communication establishment and worse spectrum utilization for smaller payloads. This makes it ideal for data hungry application such as video transition and high speed measurement.

Other key advantage of Wi-Fi is its ubiquity. This makes it valid option even in situations where usage of better suited protocol would require modification and/or investment in new infrastructure.

Although Wi-Fi technology is predominantly utilized for short-range wireless local area networks, there are notable exceptions involving long-range deployments, such as those employed by ISPs and for low-cost *point-to-point* (P2P) remote communication. Notable extreme example of this is 279 km long unamplified Wi-Fi link in Venezuela[4].

1.1.4 Zigbee

Zigbee is a open wireless communication protocol specification, operating within the IEEE 802.15.4 standard, designed for low-bandwidth, low-power, short-range *wireless personal area network* (WPAN). It is characterized by its mesh networking capabilities, which facilitate robust and scalable communication among numerous devices in close proximity. Its main application are smart home accessories and industrial sensors on sort range [**zigbee**].

Zigbee primarily operates on 2.4 GHz band (in usual gaps between Wi-Fi channels) but can also operate on sub-GHz bands. It is similar to Z-Wave protocol.

1.1.5 Sigfox

1.2 4G IoT networks (LPWAN)

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

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 [**gsmalpwan**].

Kajsik zrcadlova λ krivka

1.2.1 NB-IoT

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

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 [**rohdenbiot**].

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 ***SC-FDMA!*** (**SC-FDMA!**) for uplink communication.

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

- 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.

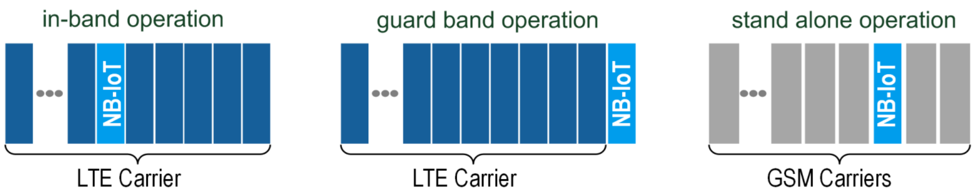

Fig. 1.1: NB-IoT modes of operation [**rohdenbiot**]

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 [**vodafonemap**], T-Mobile in selected larger cities and O2 only in Moravian-Silesian region [**narowbandcoverage**].

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 [**nordiccompare**].

As of writing this thesis (December 2023) LTE-M is covered in Czechia by O2 in 98.5 % [**o2catm**] and locally by Vodafone [**vodafonemap**].

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 [**5gnruk**]:

- 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 [**5gnruk**].

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

- 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

Zestrucnit

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 [**5gamericasurllc**]. 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:

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

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 [**5gamericasurllc**]

latency, intensive optimization of air data delivery is necessary.

There are several possible approaches that can lead to reduced communication time and latency [**5gamericasurllc**]:

- 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 [**3gppurllc**].

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 [**5gamericav2v**].

1.3.3 Cellular URLLC reliability optimization

In 3GPP Release 16, redundant transmission for high-reliability communication was introduced [**5gamericasurllc**]. 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 [**3gppurllc**].

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-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

2 IoT communication modules for 4G/5G networks

2.1 Nordic Semiconductor nRF9160

Fig. 2.1: Nordic nRF9160 SiP[**nrf91desc**]

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 peripherials - 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 [**armtrustzone**]. 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 [**nrf91desc**]. 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. [**nrf91datasheet**]

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

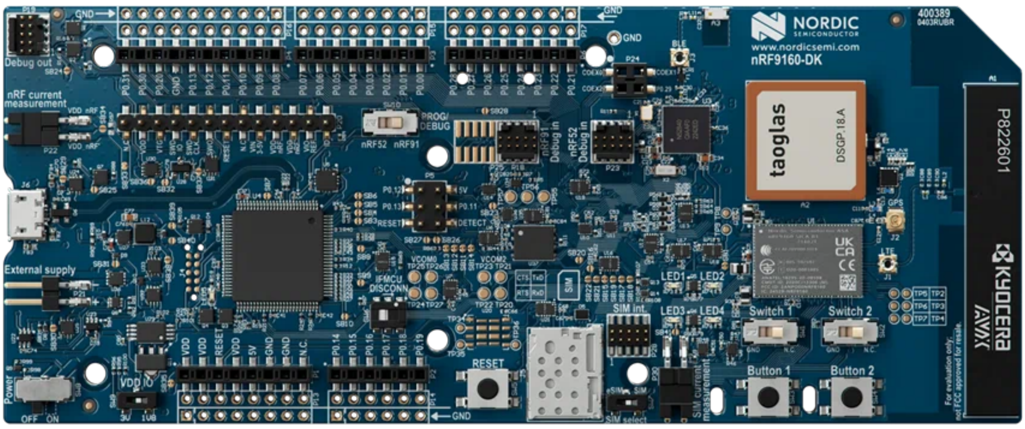

Fig. 2.2: Nordic nRF9160DK front view[**nrf91dkdesc**]

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 peripherial 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 peripherials 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 [**nrf91dkdesc**].

Nordic Thingy:91

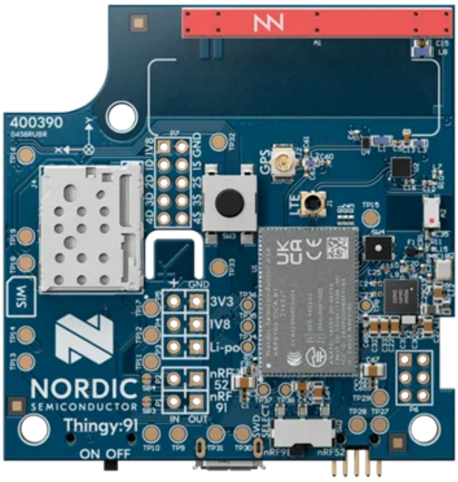

Fig. 2.3: Nordic nRF9160DK front view[**thingydesc**]

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 [**thingydesc**].

NimbeLink Nano Global

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

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 distributition of GPIO pins to peripherial headers. The board has been originally certified only for Verizon networks [**nimbelinkdesc**].

LN60E

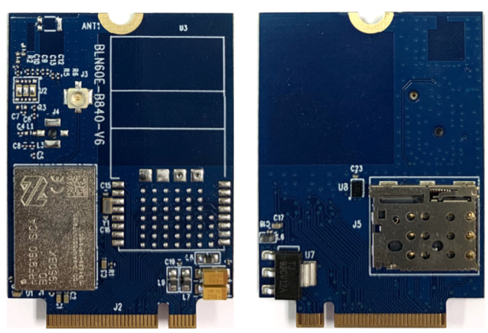

Fig. 2.5: LN60E[**ln60desc**]

LN60E is a simple modem provided by Fansel, having a U.FL antenna connector, SIM connector and M.2 card connector for nRF9160 peripherials [**ln60desc**].

Pebble Tracker

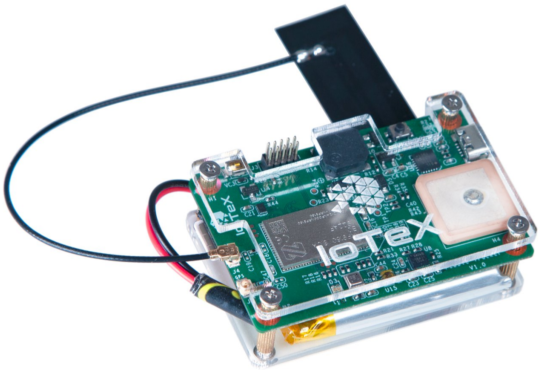

Fig. 2.6: Pebble Tracker[**pebbledesc**]

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 [**pebbledesc**]

Icarus SoM

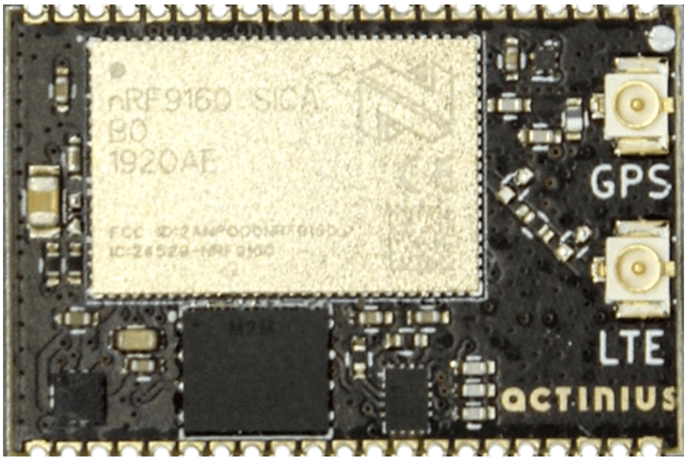

Fig. 2.7: Icarus SoM[**icarusdesc**]

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 [**icarusdesc**].

Icarus Bee

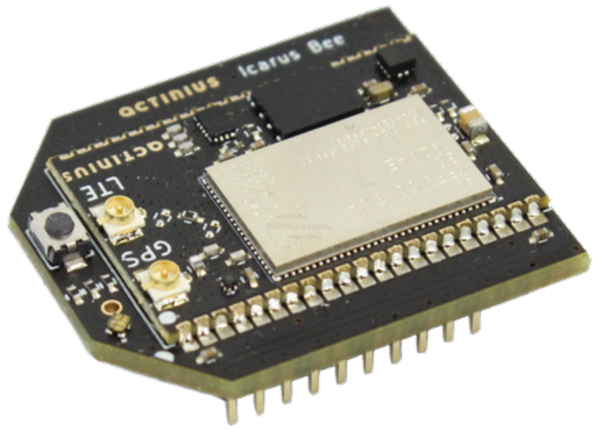

Fig. 2.8: Icarus Bee[**icarusbeedesc**]

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 [**icarusbeedesc**].

Icarus IoT Board v2

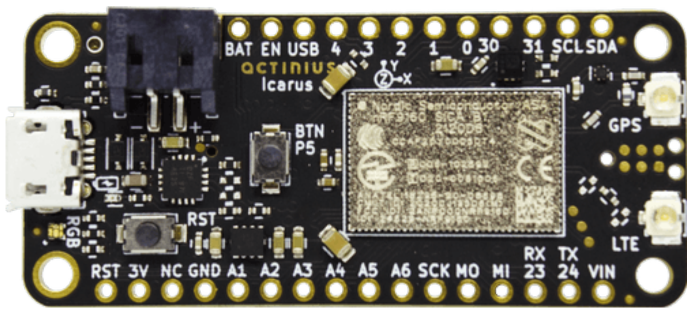

Fig. 2.9: Icarus IoT Board v2[**icarusiotdesc**]

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 [**icarusiotdesc**].

nRF9160 Feather

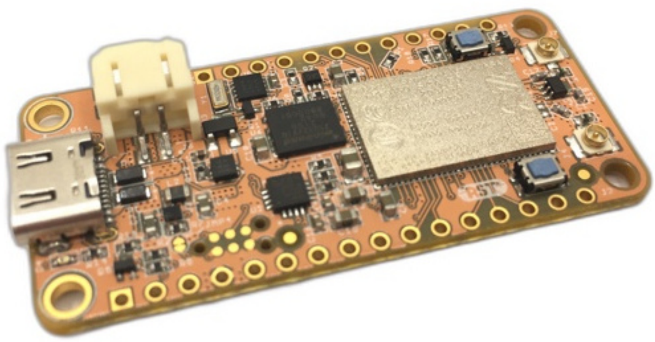

Fig. 2.10: nRF9160 Feather[**featherdesc**]

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 [**featherdesc**].

SparkFun Thing Plus nRF9160

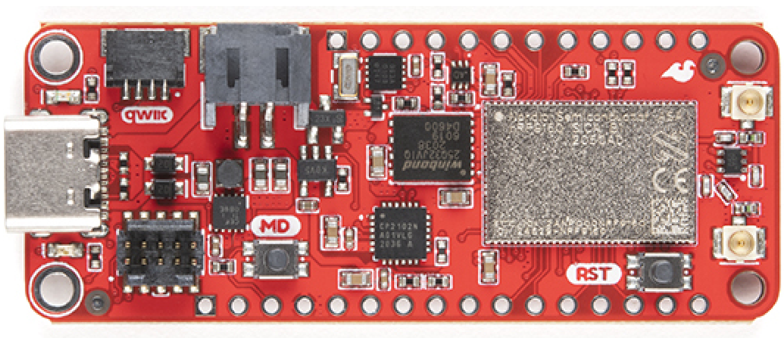

Fig. 2.11: SparkFun Thing Plus nRF9160[**sparkfundesc**]

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 [**sparkfundesc**].

Connexio Stratus (Pro)

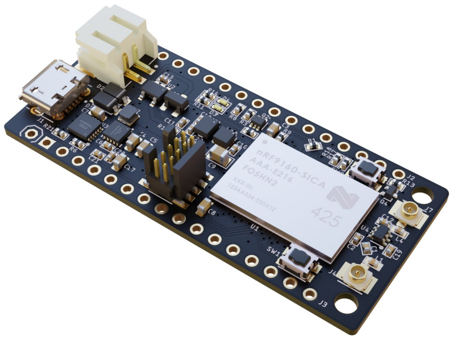

Fig. 2.12: Connexio Stratus[**connexiodesc**]

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 [**connexiodesc**].

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

	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	$\tilde{5}$ g	61 g	$\tilde{5}$ g	$\tilde{5}$ g	10 g	$\tilde{5}$ g
Price (USD)	$159	$126.25	$115	$99	$215	$129.95

Table 2.2: Comparation of nRF9160 main modules

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 if best described 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 transmission total **gain** is constant and can be added to equation like this:

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

Where D_{ANT} is directivity of antenna and A_{RX} is total loss from 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:

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

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

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

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 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 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 expect 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 guarantied 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 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)

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} [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
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 Field testing of mobile capabilities of nRF916X-DK

7 Future of Non-Terrestrial Network

8 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.

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

SMS Short Message Service

M2G Machine-to-Machine

LoRa Long-Range

LoRaWAN Long-Range wide area network

CSS chirp spread spectrum

WPAN wireless personal area network

WLAN wireless local area network

P2P point-to-point

List of appendices