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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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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 demonstруйте 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 srovnajte s teoretickými předpoklady a jinými v současnosti používanými komunikačními systémy.

DOPORUČENÁ LITERATURA:

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ABSTRACT

The growing number of interconnected Internet of Things (IoT) devices and their increasing complexity are placing new demands on range, reliability, and scalability of communication networks. 4G and 5G cellular networks offer a promising solution for wide-area low-power communication. This thesis explores the fundamental principles of 4G and 5G mobile networks with a focus on their architecture, communication protocols, and specific features relevant to IoT use cases. It further analyzes Low-Power Wide-Area Network (LPWAN) protocols, specifically NB-IoT and LTE-M, highlighting their advantages, limitations, and differences compared to traditional mobile networks. The work also provides an overview of the Nordic Semiconductor nRF9160 and nRF9161 chipsets, along with a review of commercially available development modules. To demonstrate practical usage, a universal low-cost tracking application is developed using the selected kit, aimed to simulate real-world scenarios such as remote monitoring, smart agriculture, smart cities, and asset tracking.

Laboratory experimental measurements are carried out, focusing on key communication parameters such as power consumption, signal strength, and data throughput. The collected data are analyzed and compared with theoretical expectations as well as other commonly used communication systems to evaluate performance and suitability for industrial IoT applications. Lastly in-field experimental measurements are carried out in the field to verify ability of suggested scenarios to communicate in mobile setting.

KEYWORDS

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

ABSTRAKT

Rostoucí počet propojených zařízení internetu věcí (IoT) a jejich narůstající složitost kladou nové požadavky na dosah, spolehlivost a škálovatelnost komunikačních sítí. Mobilní sítě 4G a 5G nabízejí slibné řešení pro komunikaci s nízkou spotřebou energie na velké vzdálenosti. Tato práce se zabývá základními principy mobilních sítí 4G a 5G se zaměřením na jejich architekturu, komunikační protokoly a specifické funkce relevantní pro případy užití v IoT. Dále analyzuje protokoly nízkoenergetických širokopásmových sítí (LPWAN), konkrétně NB-IoT a LTE-M, zdůrazňuje jejich výhody, omezení a rozdíly ve srovnání s tradičními mobilními sítěmi.

Práce také poskytuje přehled čipsetů Nordic Semiconductor nRF9160 a nRF9161, spolu s recenzí komerčně dostupných vývojových modulů. Pro demonstraci praktického využití pomocí vybraného kitu vytvořit univerzální nízkonákladovou trackovací aplikaci, zaměřenou na simulaci reálných scénářů, jako je vzdálené monitorování, chytré zemědělství, chytrá města a sledování majetku.

Byly provedeny laboratorní experimentální měření zaměřená na klíčové komunikační parametry, jako je spotřeba energie, síla signálu a propustnost dat. Shromážděná data byla analyzována a porovnána s teoretickými očekáváními, stejně jako s jinými běžně používanými komunikačními systémy, za účelem vyhodnocení vhodnosti pro průmyslové IoT aplikace. Na závěr byla provedena experimentální měření v terénu, aby se ověřila schopnost navržených scénářů komunikovat v mobilním prostředí.

KLÍČOVÁ SLOVA

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

ROZŠÍŘENÝ ABSTRAKT

Tato práce se detailně zabývá základními principy mobilních sítí 4G a nově nastupujících 5G se zaměřením na jejich základní architekturu, komunikační protokoly a specifické funkce, které jsou relevantní pro případy užití v IoT. Podrobně analyzuje protokoly nízkoenergetických širokopásmových sítí (LPWAN), konkrétně NB-IoT a LTE-M, a okrajově se dotýká i perspektivního DECT NR+. Zdůrazňuje jejich inherentní výhody, inherentní omezení a klíčové rozdíly ve srovnání s tradičními mobilními sítěmi, čímž poskytuje komplexní pohled na jejich vhodné uplatnění.

NB-IoT (Narrowband IoT) je specifická svou optimalizací pro maximální pokrytí a minimální spotřebu energie. Využívá velmi úzké pásmo v LTE spektru, což umožňuje mobilním operátorům nasadit ji ve frekvenčním ochranném pásmu (guard band) nebo ve vyhrazených frekvenčních blocích v rámci stávajících LTE úseků. Tímto přístupem mobilní operátor může efektivně zvětšit pokrytí a kapacitu své NB-IoT sítě bez jakéhokoli omezení stávající infrastruktury a služeb pro stávající LTE zákazníky, což minimalizuje investiční náklady a urychluje nasazení. Jejich síla spočívá v mimořádné schopnosti penetrace signálu a efektivní komunikace i za velmi nepříznivých podmínek.

DECT NR+ představuje zatím ještě poměrně nový protokol, který byl jako první uznán jako nebuňkový 5G protokol v rámci standardů 3GPP. To znamená, že pro svoje fungování, na rozdíl od klasických mobilních technologií, nevyužívá centrální vysílače mobilních operátorů. Místo toho si zařízení v síti sama koordinují komunikaci podle daného protokolu a shlukují se do takzvané mesh sítě. Tato decentralizovaná architektura nabízí flexibilitu a možnost budování privátních sítí bez závislosti na mobilním operátorovi, což je atraktivní pro průmyslové areály nebo specifické podnikové aplikace.

Práce také poskytuje detailní přehled vybraných čipsetů, konkrétně Nordic Semiconductor nRF9160 a jeho nástupce nRF9161. Součástí je i recenze komerčně dostupných vývojových modulů postavených na těchto čípech, což usnadňuje jejich praktické využití. Pro demonstraci praktického využití a ověření teoretických poznatků byl pomocí vybraného kitu vytvořen univerzální nízkonákladová trackovací destička. Tato aplikace byla zaměřena na simulaci reálných scénářů, jako je vzdálené monitorování zboží, chytré zemědělství (např. sledování a monitoring dobytku), aplikace v chytrých městech (např. monitorování úrovně naplnění kontejnerů) a sledování balíků v logistice. Pro další praktické testování byl vybrán modul Connexio Pro.

S cílem zhodnocení výkonu a vhodnosti jednotlivých technologií byly provedeny rozsáhlé laboratorní experimentální měření. Tato měření se zaměřila na klíčové komunikační parametry, jako je spotřeba energie za různých podmínek, síla přijímaného signálu a propustnost dat. Shromážděná data byla analyzována a porovnána

s teoretickými očekáváními, stejně jako s hodnotami získanými z jiných běžně používaných komunikačních systémů. Cílem bylo vyhodnotit jejich vhodnost pro specifické průmyslové IoT aplikace. Laboratorní měření ukázala, že LTE-M se jeví jako vhodnější protokol pro situace s normální až dobrou silou signálu, kde poskytuje vyšší datové rychlosti i lepší spotřebu energie. Naopak NB-IoT excelovalo ve svých schopnostech komunikace při velmi slabých signálech a v prostředí s vysokým útlumem, kde již LTE-M vůbec nefungoval, čímž potvrdilo svou optimalizaci pro hluboké pokrytí.

Kromě laboratorních testů byla provedena i experimentální měření v terénu, aby se ověřila schopnost navržených scénářů komunikovat v reálném, mobilním prostředí. Tato měření přinesla překvapivé výsledky vůči původnímu očekávání. Nevyvrátila totiž nevhodnost NB-IoT pro pohyblivé aplikace, ba naopak ukázala, že protokol ve valné většině případů bez problému fungoval i při rychlostech do 130 km/h. To naznačuje, že i přes svou optimalizaci pro stacionární použití, může mít NB-IoT potenciál i v některých mobilních aplikacích, kde je kladen důraz na větší dosah tuto hypotézu je však potřeba lépe prozkoumat.

Závěrem byly v diskuzi veškeré testované protokoly komplexně porovnány a na základě získaných dat byly navrženy konkrétní scénáře pro jejich nejvhodnější využití. Mezi těmito scénáři byly zmíněny i klíčová odvětví jako klasické IoT senzory pro monitoring prostředí, využití mobilních senzorů kombinovaných s trackery pro logistiku, vzdálená údržba pomocí přídavných senzorů zlepšujících diagnostiku strojů, masivní využití IoT v průmyslu pro monitorování výrobních procesů a kritické infrastruktury, a také v elektrické převodové soustavě pro chytré sítě. Kapitola byla zakončena fascinujícím zamyšlením nad potenciálním využitím NB-IoT v nanosatelitech.

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Author's Declaration

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Topic: Use of 4G/5G communication in embedded systems

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Contents

Introduction	13
1 Communication standards for IoT devices in 4G/5G networks	14
1.1 Established communication standards for IoT devices	14
1.1.1 GSM (2G)	14
1.1.2 LoRa	14
1.1.3 Wi-Fi	15
1.1.4 Zigbee	15
1.2 4G IoT networks (LPWAN)	16
1.2.1 NB-IoT	16
1.2.2 LTE-M	17
1.2.3 Comparison of 4G LPWAN with established technologies . . .	17
1.3 Cellular 5G IoT networks	17
1.3.1 URLLC requirements	18
1.3.2 Latency	19
1.4 DECT NR+ standard for 5G IoT networks	20
1.4.1 Plain DECT	20
1.4.2 DECT NR+	20
2 IoT communication modules for 4G/5G networks	21
2.1 Nordic Semiconductor nRF9160	21
2.2 Nordic Semiconductor nRF9161	24
2.3 Nordic Semiconductor nRF9151	24
2.4 Modules with nRF91xx	25
3 Practical demonstration - tracker with meteo sensor	33
3.1 Hardware	33
3.2 Firmware tools	34
3.3 Firmware outline	35
3.3.1 LTE network connection	35
3.3.2 MQTT	35
3.3.3 Application loop	36
4 Laboratory testing	37
4.1 RF parameters - nRF modem	37
4.2 Power consumption - ampere meter	39
4.3 Cellular Results	42
4.3.1 Validity of attenuation and sensitivity	42

4.3.2	Power consumption analysis	44
4.3.3	Transmission speed and comparison to LoRa	45
4.4	DECT NR+	47
5	Field testing of mobile capabilities of NB-IoT and LTE-M	50
6	Discussion and usage scenarios	54
6.1	Comparison of discussed technology	54
6.1.1	NB-IoT	54
6.1.2	LTE-M	54
6.1.3	DECT NR+	54
6.2	Scenarios of IoT applications and recommended protocol	55
6.2.1	Classic stationary IoT	55
6.2.2	Mobile IoT	55
6.2.3	Remote tracking	55
6.2.4	Massive critical industrial IoT	55
6.2.5	Low Earth orbit satellites	56
6.3	Future work	56
	Conclusion	57
	Bibliography	58
	Symbols and abbreviations	63
	List of appendices	66
A	Result measurement - tables	67
B	Result of measurement - charts	74
B.1	nRF9161	78
B.2	nRF9160	94
C	Demonstrator electronic schemes	111

List of Figures

1.1	NB-IoT modes	17
2.1	Nordic nRF9160 SiP	21
2.2	Nordic nRF9160 SiP architecture	22
2.3	Nordic nRF9161 SiP	24
2.4	Nordic nRF9151 SiP	24
2.5	Nordic nRF9160DK	25
2.6	Nordic nRF9161DK	26
2.7	Nordic nRF9161DK	26
2.8	Nordic Thingy:91	27
2.9	Nordic Thingy:91X	27
2.10	NimbeLink Nano Global LTE-M	28
2.11	LN60E	28
2.12	Pebble Tracker	29
2.13	Icarus SoM	29
2.14	Icarus Bee	30
2.15	Icarus IoT	30
2.16	nRF9160 Feather	31
2.17	SparkFun Thing Plus nRF9160	31
2.18	Connexio Stratus	32
2.19	Connexio Stratus Pro	32
3.1	PCB of demonstrator tracker	33
3.2	Demonstrator tracker in 3D printed case	34
3.3	Demo MQTT communication	35
4.1	Nordic Power Profiler Kit II	39
4.2	Nordic PPK II measuring setup	40
4.3	Custom LTE antenna for bands around 800 MHz	41
4.4	PPK II current plot of NB-IoT	41
4.5	PPK II current plot of LTE-M	42
4.6	Reference Signal Received Power to attenuation	44
4.7	nRF9161 LTE-M and NB-IoT Charge per message to RSRP	45
4.8	Comparison of sensitivity and transmit speed of LTE to LoRa	46
4.9	DECT NR+ RSSI levels to to attenuation	48
4.10	DECT NR+ Power levels to to attenuation	49
5.1	Demonstrator secured in car for mobile measurement	51
5.2	Map RSRP reported by demonstrator operating using LTE-M	52
5.3	Map RSRP reported by demonstrator operating using NB-IoT	53
5.4	Map of LTE band used by demonstrator when using LTE-M	53

B.1	Charge per message to RSRP	74
B.2	Charge per message to RSRP	74
B.3	Data-rate to RSRP	75
B.4	Data-rate to RSRP	75
B.5	Maximal transmit current to RSRP	76
B.6	Maximal transmit current to RSRP	76
B.7	Average transmit current to RSRP	77
B.8	Average transmit current to RSRP	77
B.9	Signal-Noise Ratio to attenuation	78
B.10	Reference Signal Received Power to attenuation	78
B.11	Ready current to attenuation	79
B.12	nRF9161 LTE-M Average transmit time to attenuation	79
B.13	RF9161 NB-IoT Average transmit time to attenuation	80
B.14	nRF9161 LTE-M and NB-IoT Average transmit time to attenuation	80
B.15	nRF9161 LTE-M Max transmit time to attenuation	81
B.16	RF9161 NB-IoT Max transmit time to attenuation	81
B.17	nRF9161 LTE-M and NB-IoT Max transmit time to attenuation	82
B.18	nRF9161 LTE-M Charge per message to attenuation	82
B.19	RF9161 NB-IoT Charge per message to attenuation	83
B.20	nRF9161 LTE-M and NB-IoT Charge per message to attenuation	83
B.21	nRF9161 LTE-M Data-rate to attenuation	84
B.22	RF9161 NB-IoT Data-rate to attenuation	84
B.23	nRF9161 LTE-M and NB-IoT Data-rate to attenuation	85
B.24	nRF9161 LTE-M Transmit time to attenuation	85
B.25	RF9161 NB-IoT Transmit time to attenuation	86
B.26	nRF9161 LTE-M and NB-IoT Transmit time to attenuation	86
B.27	nRF9161 LTE-M Average trasmit current to attenuation	87
B.28	RF9161 NB-IoT Average trasmit current to attenuation	87
B.29	nRF9161 LTE-M and NB-IoT Average trasmit current to attenuation	88
B.30	nRF9161 LTE-M Charge per message to RSRP	88
B.31	RF9161 NB-IoT Charge per message to RSRP	89
B.32	nRF9161 LTE-M and NB-IoT Charge per message to RSRP	89
B.33	nRF9161 LTE-M Data-rate to RSRP	90
B.34	RF9161 NB-IoT Data-rate to RSRP	90
B.35	nRF9161 LTE-M and NB-IoT Data-rate to RSRP	91
B.36	nRF9161 LTE-M Maximal transmit current to RSRP	91
B.37	RF9161 NB-IoT Maximal transmit current to RSRP	92
B.38	nRF9161 LTE-M and NB-IoT Maximal transmit current to RSRP	92
B.39	nRF9161 LTE-M Average transmit current to RSRP	93

B.40 RF9161 NB-IoT Average transmit current to RSRP	93
B.41 nRF9161 LTE-M and NB-IoT Average transmit current to RSRP . .	94
B.42 Signal-Noise Ratio to attenuation	94
B.43 Reference Signal Received Power to attenuation	95
B.44 Ready current to attenuation	95
B.45 nRF9160 LTE-M Transmit time to attenuation	96
B.46 RF9160 NB-IoT Transmit time to attenuation	96
B.47 nRF9160 LTE-M and NB-IoT Transmit time to attenuation	97
B.48 nRF9160 LTE-M Transmit time to attenuation	97
B.49 RF9160 NB-IoT Transmit time to attenuation	98
B.50 nRF9160 LTE-M and NB-IoT Transmit time to attenuation	98
B.51 nRF9160 LTE-M Charge per message to attenuation	99
B.52 RF9160 NB-IoT Charge per message to attenuation	99
B.53 nRF9160 LTE-M and NB-IoT Charge per message to attenuation . .	100
B.54 nRF9160 LTE-M Data-rate to attenuation	100
B.55 RF9160 NB-IoT Data-rate to attenuation	101
B.56 nRF9160 LTE-M and NB-IoT Data-rate to attenuation	101
B.57 nRF9160 LTE-M Transmit time to attenuation	102
B.58 RF9160 NB-IoT Transmit time to attenuation	102
B.59 nRF9160 LTE-M and NB-IoT Transmit time to attenuation	103
B.60 nRF9160 LTE-M Average trasmit current to attenuation	103
B.61 RF9160 NB-IoT Average trasmit current to attenuation	104
B.62 nRF9160 LTE-M and NB-IoT Average trasmit current to attenuation	104
B.63 nRF9160 LTE-M Charge per message to RSRP	105
B.64 RF9160 NB-IoT Charge per message to RSRP	105
B.65 nRF9160 LTE-M and NB-IoT Charge per message to RSRP	106
B.66 nRF9160 LTE-M Data-rate to RSRP	106
B.67 RF9160 NB-IoT Data-rate to RSRP	107
B.68 nRF9160 LTE-M and NB-IoT Data-rate to RSRP	107
B.69 nRF9160 LTE-M Maximal transmit current to RSRP	108
B.70 RF9160 NB-IoT Maximal transmit current to RSRP	108
B.71 nRF9160 LTE-M and NB-IoT Maximal transmit current to RSRP . .	109
B.72 nRF9160 LTE-M Average transmit current to RSRP	109
B.73 RF9160 NB-IoT Average transmit current to RSRP	110
B.74 nRF9160 LTE-M and NB-IoT Average transmit current to RSRP . .	110
C.1 Demonstrator electronic schema	111
C.2 Demonstrator PCB 3D model render	111
C.3 Demonstrator PCB schema	112

List of Tables

1.1	Performance requirements for URLLC	18
2.1	nRF9160 product options	23
2.2	Comparison of nRF9160 modules	23
4.1	NB-IoT nRF9161 measurements with payload size 1024 B	43
4.2	Result table of DECT NR+ measurements	48
A.1	NB-IoT nRF9160 measurements with payload size 0 B	67
A.2	NB-IoT nRF9160 measurements with payload size 64 B	67
A.3	NB-IoT nRF9160 measurements with payload size 1024 B	68
A.4	LTE-M nRF9160 measurements with payload size 0 B	68
A.5	LTE-M nRF9160 measurements with payload size 64 B	69
A.6	LTE-M nRF9160 measurements with payload size 1024 B	69
A.7	NB-IoT nRF9161 measurements with payload size 0 B	70
A.8	NB-IoT nRF9161 measurements with payload size 64 B	71
A.9	NB-IoT nRF9161 measurements with payload size 1024 B	72
A.10	LTE-M nRF9161 measurements with payload size 0 B	72
A.11	LTE-M nRF9161 measurements with payload size 64 B	73
A.12	LTE-M nRF9161 measurements with payload size 1024 B	73

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[48].

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 field of usage critical scenarios currently depended on more costly solutions with private networks.

The goal of this thesis is to describe these gradually more and more adapted protocols. Than to practically demonstrate these capabilities with current communication modules. Both in laboratory setting with detailed measurement of their radio capabilities and power consumption and in real field scenarios. And finally use these finding to recommend in which scenario use what technology.

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 *2nd generation of cellular networks* (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 widely 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 *Machine-to-Machine* (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 [5]. 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 *Medium Access Control* (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 [4].

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[7].

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 [6].

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.

1.2 4G IoT networks (LPWAN)

IoT has become a large part of every day life and is now crucial to many both critical and non-critical applications. With planned shutdown of 2G and 3G networks [3] it is important to look on protocols that are supposed to replace them and enhance their capabilities.

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 [49].

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 [13].

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 [12].

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 [12]:

- 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 [15], T-Mobile in selected larger cities and O2 only in Moravian-Silesian region [16].

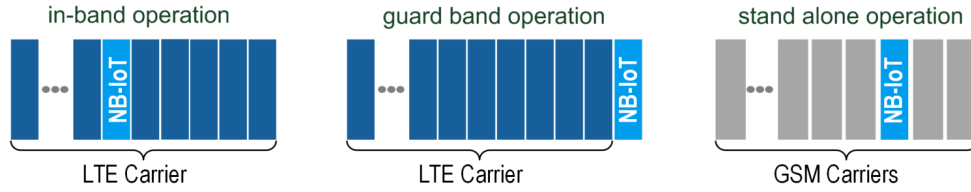


Fig. 1.1: NB-IoT modes of operation [12]

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 [50].

As of writing this thesis (December 2023) LTE-M is covered in Czechia by O2 in 98.5 % [14] and locally by Vodafone [15].

1.2.3 Comparison of 4G LPWAN with established technologies

1.3 Cellular 5G IoT networks

5G implementation into the mobile networks can be achieved via two methods [10]:

- NSA (non-stand alone) - 5G features are achieved by adding new *Radio Access Network* (RAN) 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 [10].

5G NR tries to solve three key aspects of wireless technology [10]:

- 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 HURLLC (Higher-Reliability and Low-Latency Communication) in 3GPP release 15 [17]. 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 [17]

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 [17]:

- **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 [8].

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 [18].

1.4 DECT NR+ standard for 5G IoT networks

1.4.1 Plain DECT

Digital Enhanced Cordless Telecommunications (DECT) is a digital wireless technology standard primarily known for cordless telephones, though its applications have expanded to some not foreseen use-cases (professional wireless audio solutions such as walkie-talkies and wireless audio on music concerts).

DECT is an open standard that operates in a dedicated frequency range, typically 1880-1900 MHz in Europe, Asia, Australia, New Zealand, and South America, and 1920-1930 MHz in the US. This dedicated spectrum helps minimize interference from other wireless technologies like Wi-Fi and Bluetooth.

DECT uses a combination of *Time-Division Multiple Access* (TDMA), *Frequency-Division Multiple Access* (FDMA), and *Time-Division Duplex* (TDD). This means the radio spectrum is divided into frequency channels (10 frequency channels) and time slots (24 of 10 ms slots per one frame), allowing multiple conversations to occur simultaneously on the same frequency band without interference. A typical DECT system can support up to 12 duplex speech channels per base station frame. [39]

1.4.2 DECT NR+

Digital Enhanced Cordless Telecommunications: New Radio plus (DECT NR+) is an evolution of the DECT standard, developed by *European Telecommunications Standards Institute* (ETSI). It is designed to address the requirements of IoT in existing DECT bands. It meets the 5G requirements for *Massive Machine Type Communications* (mMTC) and *Ultra-reliable and Low-latency Communication* (URLLC) applications. DECT NR+ is recognized by *International Telecommunication Union* (ITU) as the world's first non-cellular 5G technology standard (however nonsensitive it may sound) [35].

DECT NR+ supports P2P, star, and mesh topologies. Devices are organized into individual cluster tree topologies, called clusters. [36]

The low latency and high reliability are done by combination of factors. The main is further division of 10 ms slots to 0.5 ms sub-slots and implementation of *Hybrid Automatic Repeat Request* (HARQ). The preservation of base 10 ms slots is done to ensure backward compatibility with older DECT devices [36].

2 IoT communication modules for 4G/5G networks

This chapter describes a *System-in-Package* (SiP) nRF9160 from Nordic Semiconductor and its successors nRF9161 and nRF9151. It is focused on its parameters and high level overview of its particular parts.

Later there the chapter continues in overview and comparison of available modules with these SiPs.

2.1 Nordic Semiconductor nRF9160



Fig. 2.1: Nordic nRF9160 SiP[19]

nRF9160, made by Nordic Semiconductor, is a 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 *Firmware Over The Air* (FOTA) (firmware over the air).
- *Radio Frequency Front End* (RFFE)
- *Global Navigation Satellite System* (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 [21]. 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 [19]. 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.

Architecture

The architecture of the SiP consist of two mostly independent parts. One is a application processor that can be imagined as ordinary ARM Cortex-M microcontroller. And the other is programmable modem. These two cores communicate between each other using AT commands. For visual representation see figure 2.2.

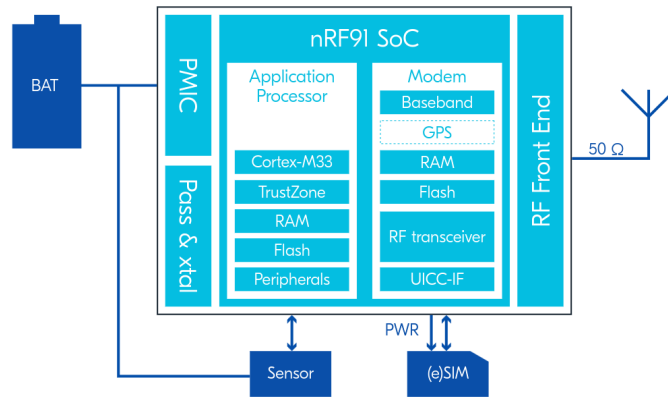


Fig. 2.2: Nordic nRF9160 SiP architecture[57]

Modem on nRF9160 can, without program memory change, operate with LTE-M, NB-IoT and GNSS but not simultaneously. Switching between the two LTE modes is done by AT commands to the modem and it can be set to one or the other at one moment. There is an option for automatic mode where the modem evaluates both options and the better one on it own discretion [40].

Modem can get a geolocation information from the GNSS satellite constellations but with following limitations [57]:

- Support only for *Global Positioning System* (GPS) layer 1 and *Quasi-Zenith Satellite System* (QZSS) layer 1
- Maximum limit of concurrent active satellites of 12

- Cellular communication interrupts geolocation service

Manufacturing variations

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. [37]

Comparisons of the main parameters of the most common nRF9160 boards is provided in the following table 2.2 taken from [33]:

	Stratus	Thingy:91	Icarus	Feather	Pebble Tracker	Thing Plus
Manufacturer	Connexio	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 Nordic Semiconductor nRF9161



Fig. 2.3: Nordic nRF9161 SiP[19]

nRF9161 is evolution of nRF9160 in same form-factor and it enables every function of its predecessor with additional and improved capabilities such as implementation of 3GPP Release 14 LTE-M/NB-IoT LTE stack and support for alternative modem firmware for DECT NR+ stack operating on 1.9 GHz band. Switching between LTE and DECT NR+ is done by loading given firmware to modem part of the ***SiC!*** (SiC!). [34]

This means that application such LTE and DECT NR+ gateway would by using only nRF9161 need two of them (even though technologically dubious not so much from financial sense considering €23 for single ***SiC!***).

Capabilities and description of DECT NR+ can be found in chapter 1.4.2.

2.3 Nordic Semiconductor nRF9151



Fig. 2.4: Nordic nRF9151 SiP[19]

nRF9151 is another evolution of nRF9151. Its main advantages are smaller footprint (reduction of 20 %), additional Power Class 5 (20 dBm) support for LTE stack and promise of eventual addition for *Non Terrestrial Network* (NTN) [42].

2.4 Modules with nRF91xx

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

nRF9160 DK

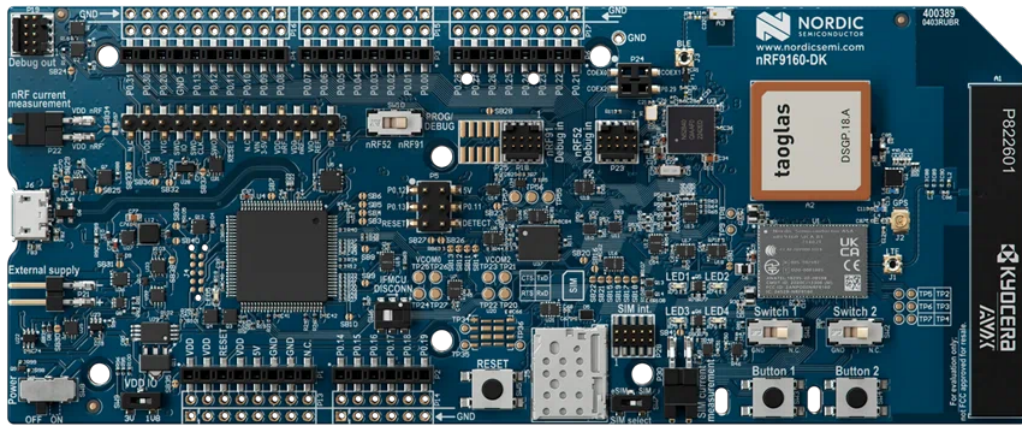


Fig. 2.5: Nordic nRF9160DK front view[22]

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 [22].

nRF9161 DK

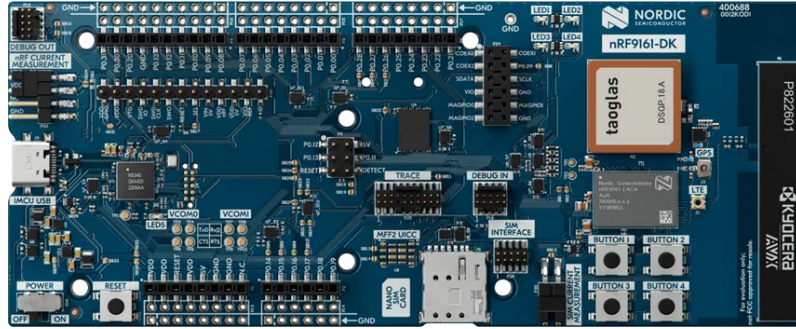


Fig. 2.6: Nordic nRF9161DK front view[22]

nRF9161 DK is nRF9160 but with nRF9161 instead of nRF9160 and USB-C.

nRF9151 DK

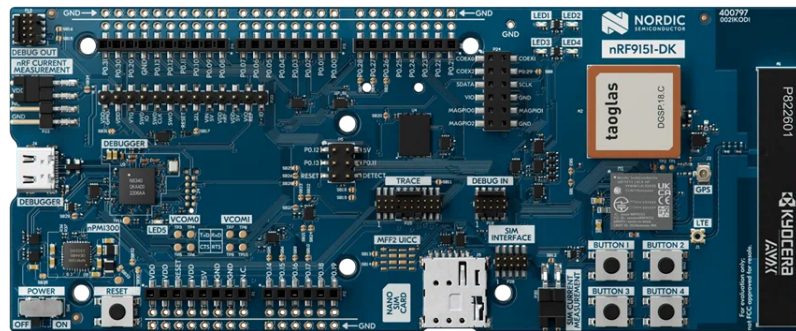


Fig. 2.7: Nordic nRF9161DK front view[22]

nRF9161 DK is nRF9161 DK but with nRF9151 instead of nRF9161.

Nordic Thingy:91

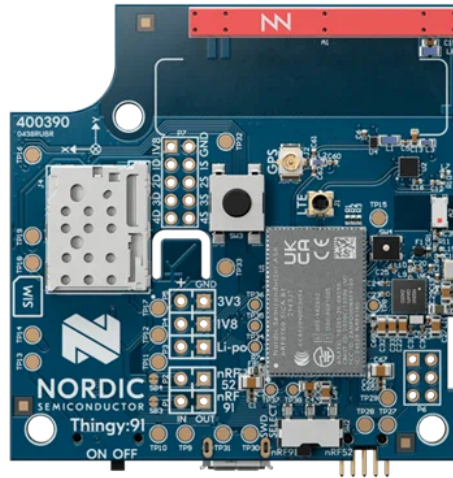


Fig. 2.8: Nordic nRF9160DK front view[23]

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 [23].

Nordic Thingy:91X

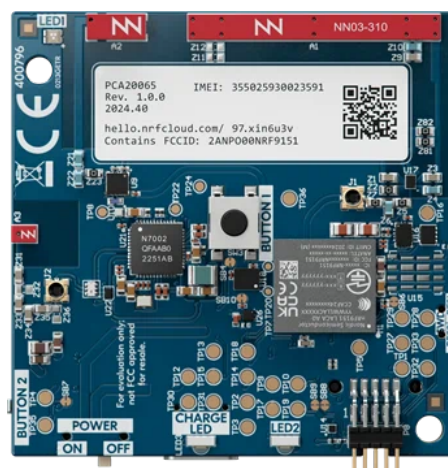


Fig. 2.9: Thingy:91X view[24]

Thingy:91X is Thingy:91 but with nRF9161 instead of nRF9160 and Wi-Fi chip nRF7001. [24].

NimbeLink Nano Global



Fig. 2.10: NimbeLink Nano Global LTE-M[25]

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 [25].

LN60E

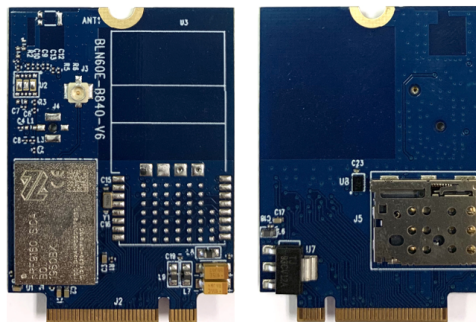


Fig. 2.11: LN60E[26]

LN60E is a simple modem provided by Fansel, having a U.FL antenna connector, SIM connector and M.2 card connector for nRF9160 peripherals [26].

Pebble Tracker

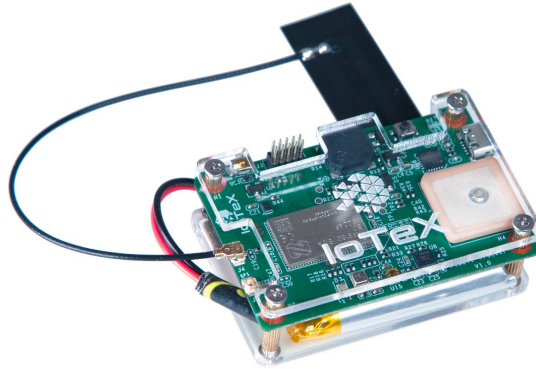


Fig. 2.12: Pebble Tracker[27]

Pebble Tracker, a crowdfunding 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 [27]

Icarus SoM



Fig. 2.13: Icarus SoM[28]

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 [28].

Icarus Bee

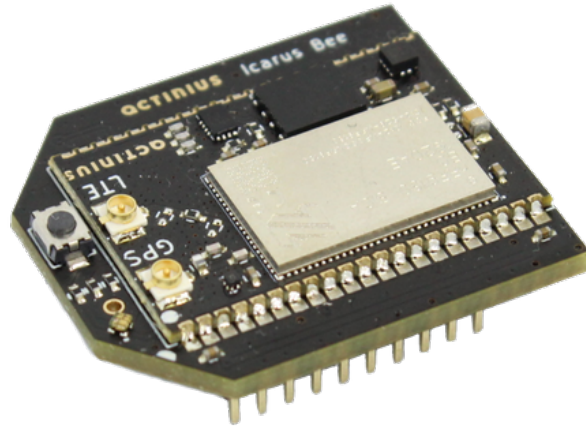


Fig. 2.14: Icarus Bee[29]

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 [29].

Icarus IoT Board v2

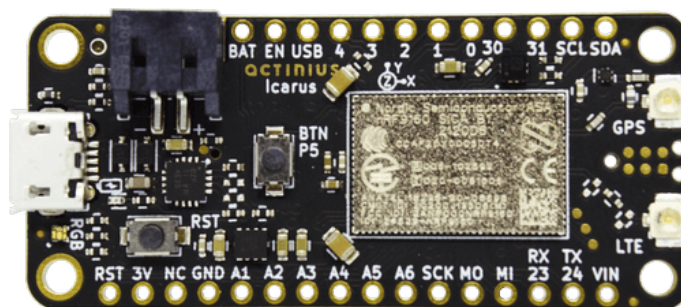


Fig. 2.15: Icarus IoT Board v2[30]

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 [30].

nRF9160 Feather

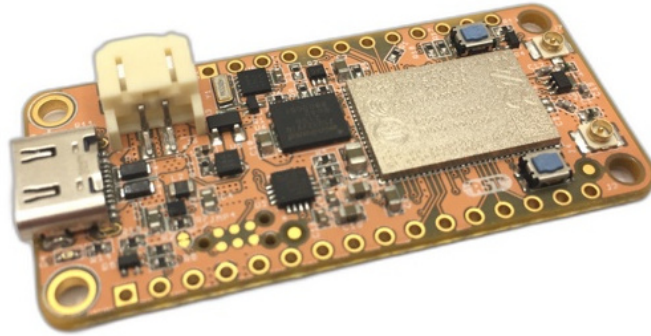


Fig. 2.16: nRF9160 Feather[31]

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 [31].

SparkFun Thing Plus nRF9160

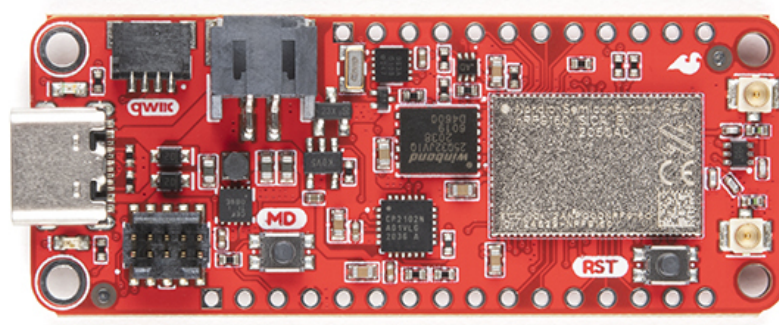


Fig. 2.17: SparkFun Thing Plus nRF9160[32]

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 [32].

Connexio Stratus

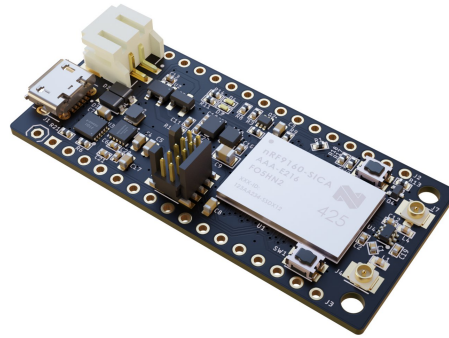


Fig. 2.18: Connexio Stratus[33]

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 [33].

Connexio Stratus Pro

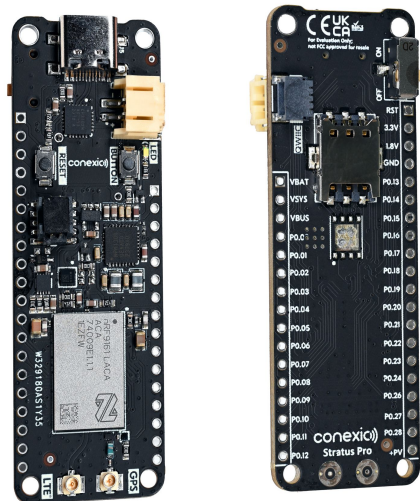


Fig. 2.19: Connexio Stratus Pro[33]

Connexio Stratus Pro is largely based on Connexio Stratus but it uses nRF9151 instead of nRF9160.

[33].

3 Practical demonstration - tracker with meteo sensor

For practical demonstration of an IoT device with 4G/5G connectivity, a development kit Connexio Pro with nRF9161 was selected.

Practical demonstration of an IoT device with LTE-M or NB-IoT connectivity was made on an example of an GPS tracker with meteo sensor, transferring data to a remote cloud server via MQTT protocol, simulating a data transfer to a central panel. For mobile field testing the GNSS was disabled due to long time needed to get fixed location and that get connection to LTE network. Both of these action will reset the state to the other so the behavior is very similar to cold start.

3.1 Hardware

Connexio Pro development kit was adapted with an add-on board made from a universal line *Printed Circuit Board* (PCB) with headers fitting to its headers. The add-on PCB contains connections for Li-ion accumulator and meteo sensor BME680.

Electronic and PCB schemes with 3D render of PCB can be found in appendix C.

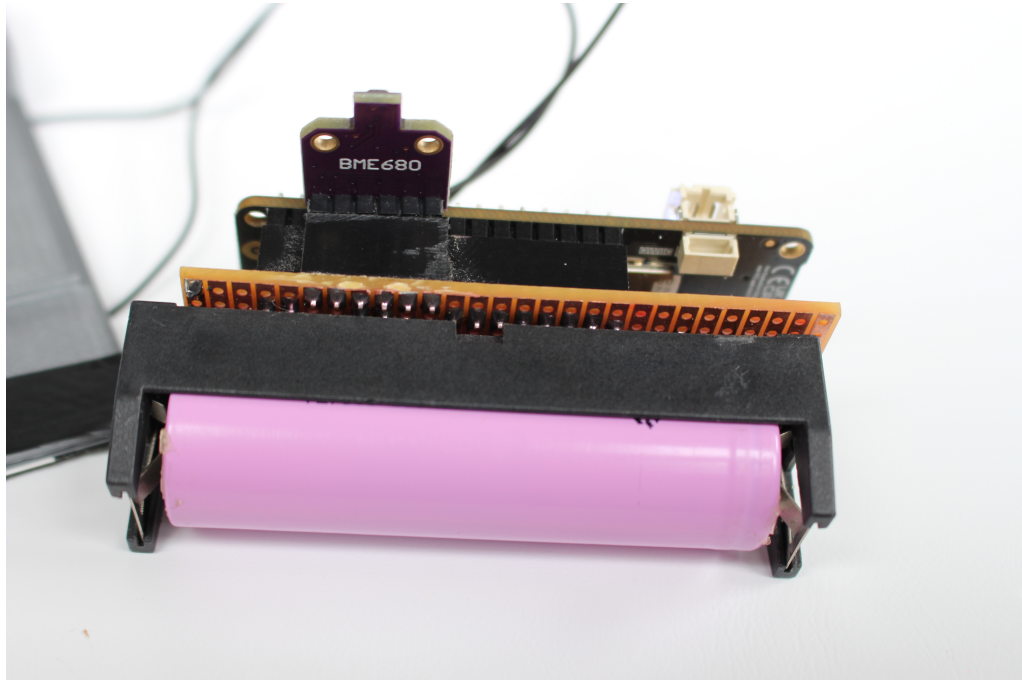


Fig. 3.1: PCB of demonstrator tracker

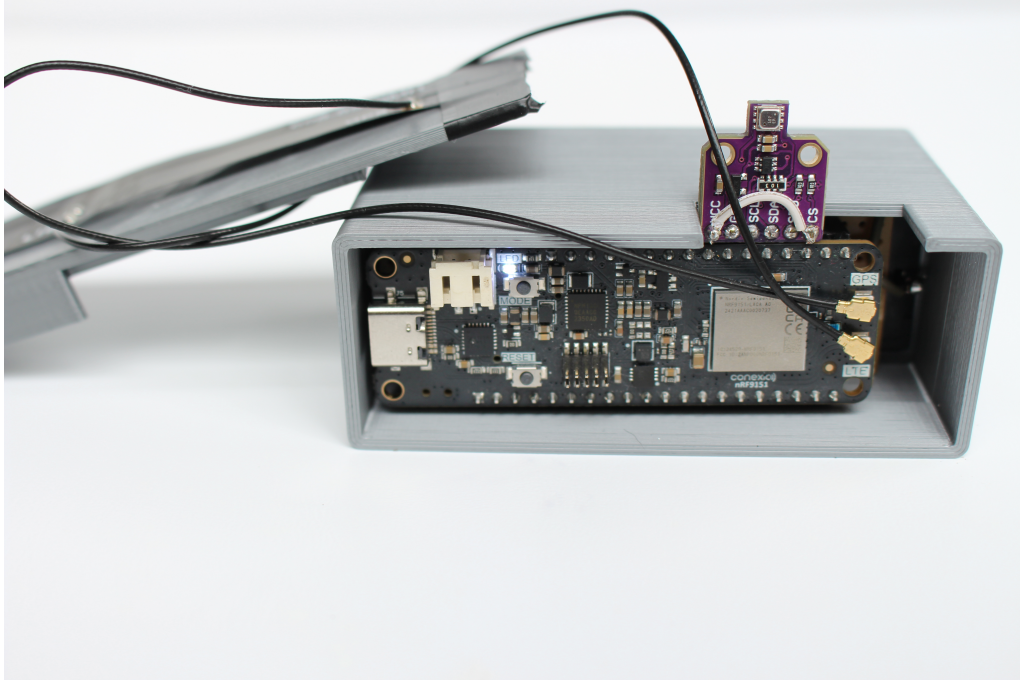


Fig. 3.2: Demonstrator tracker in 3D printed case

3.2 Firmware tools

nRF Connect SDK was used as a software platform for the demo application. nRF Connect SDK is a unified software development kit for building products based on all Nordic nRF Series wireless devices. It integrates the Zephyr RTOS and wide range of samples, application protocols, protocol stacks, libraries and hardware drivers [54].

It offers a single code base for all Nordic devices and software components. It simplifies porting modules, libraries and drivers from one application to another, thus reducing development time. nRF Connect SDK is publicly available under OpenSource license, offers source code management with Git and has free nRF Connect for Visual Studio Code IDE support. Zephyr RTOS furthermore provides extensive amount of libraries including standardized access to basic peripherals, IP stack and *Message Queuing Telemetry Transport* (MQTT) library [51].

MQTT is a lightweight, publish-subscribe protocol that enables efficient and reliable communication between devices in the IoT domain. MQTT is based on a broker-client architecture, where a broker is a server that receives and routes messages from multiple clients, and a client is any device that can publish or subscribe to a topic. A topic is a hierarchical identifier that defines the content and scope of a message[52].

This firmware is based on nRF Connect SDK example named Simple MQTT[53] and GNSS example.

3.3 Firmware outline

3.3.1 LTE network connection

First task for the demo firmware is an establishment of a connection to LTE network. This is mostly handled by function `modem_configure()`, which turns off power saving modes for better responsivity and calls HAL function `lte_lc_init_and_connect()`.

`lte_lc_init_and_connect()` takes all modem settings from text config files transferred to macros by Kconfig. This illustrates a possibility of cross-platform or regionally independent application, where only the config files for given platform or region are needed to be changed.

3.3.2 MQTT

Communication with MQTT server is done by `zephyr/net/mqtt.h` library. Connection with the server is attempted after LTE and sensors setup with function `mqtt_connect()`. Publishing of message is achieved by function `mqtt_publish()` upon a digital sensor is activated or analog sensor exceeds the set threshold value. Example of the MQTT communication sent to a virtual server is shown in figure 3.3.

```
nrf/dk/temp +28.290
nrf/dk/pres +96.537
nrf/dk/humi +66.213
nrf/dk/gas +9365.000
nrf/dk/rsrp 71
nrf/dk/rsrq 29
nrf/dk/snr 38
nrf/dk/enerest 7
nrf/dk/band 20
nrf/dk/txp 9
nrf/dk/dlpl 96
nrf/dk/ltemode +2.000
nrf/dk/temp +28.270
nrf/dk/pres +96.537
nrf/dk/humi +64.574
nrf/dk/gas +9554.000
nrf/dk/rsrp 79
nrf/dk/rsrq 30
nrf/dk/snr 43
nrf/dk/enerest 8
nrf/dk/band 20
nrf/dk/txp 4
nrf/dk/dlpl 88
nrf/dk/ltemode +2.000
[]
```

Fig. 3.3: Sample of resulting MQTT communication

3.3.3 Application loop

The program after establishing LTE connection enters main loop which main where it disables LTE, enable GNSS and waits for modem to get from GNSS fixed location. After that it disables GNSS, enables LTE, waits for LTE connection to be established.

With fresh location data it loads data over I2C from BME680 meteo sensor and gets from modem values about radio connection with *Base Transceiver Station* (BTS). All these data are than transmitted using MQTT to remote server. After this program waits for specified time and than runs the loop again.

4 Laboratory testing

This chapter will evaluate selected IoT modules in laboratory setting based on their two critical performance indicators: their wireless data transmission capabilities and their associated power consumption depending on signal quality.

Here is an overview of the main aspects considered in the chosen measurement method:

The goal for this chapter is to evaluate the nRF916x performance parameters in different operating conditions. For each of these conditions RF parameters are gathered directly from the modem and information of power consumption using external ampere meter.

Chosen simulated conditions are payload size, signal strength and operating mode.

To include most of potential use-cases the outlined parameters will be measured for three different payload sizes:

- 0 B - empty transmission for reference on protocols overhead
- 64 B - usual amount of data for simpler IoT devices
- 1024 B - larger continuous data block transfer

This is done for ever increasing signal attenuation until communicating can be no longer established. Decline of signal strength is simulated using addition attenuators between RF output and antenna. Additional shielding was necessary for prevention of RF leaking. EMC chamber is sufficient for this case.

This procedure is done for both NB-IoT and LTE-M.

4.1 RF parameters - nRF modem

The radio parameters can be measured with specialized measurement equipment to evaluate objective characteristics or directly on the specific RF chip/modem. Usage of "on-chip" statistics has lower resolution compared to specialized measurement equipment such as spectrum analyzer but their integration into existing RF circuits can introduce even more variability and thus lower the accuracy of measuring and still without getting the real signal that decoded by the modem. Another key point for consideration of "on-chip measurement" is the fact that these are the values that the modem considers for its signal quality evaluation and for subsequent setting of radio output parameters regardless on the opinion of more accurate measuring instrument.

As described in chapter 2.1 Nordic SiPs consist of application core and modem core. The modem is responsible for all radio and communication related tasks. Among other it is a evaluation of signal quality based on which it select different

BTSs and optimal communication parameters. Communication with application core is done using the AT commands. As a form of human-machine abstraction layer *Nordic Core SDK* (NCS) includes a *Modem Shell* (MoSh). MoSh is an application that runs in application core and encapsulates AT commands in unix-like commands. [55]

First used command for communication evaluation is `ping`. This command establishes a *Internet Control Message Protocol* (ICMP) connection and outputs packet drop and transfer duration both are gathered for later analysis.

The destination of these pings is a Cloudflare DNS service 1.1.1.1. It was chosen for their massive network infrastructure and according to them the fastest connection [58].

Example from testing of NB-IoT on nRF9161 with 10 dB additional attenuation:

```
mosh:~$ ping -d 1.1.1.1 -c 10 -t 10000 -i 100 -l 1024
Initiating ping to: 1.1.1.1
Source IP addr: 100.97.68.179
Destination IP addr: 1.1.1.1
Pinging 1.1.1.1 results: time=1.448secs, payload sent: 1024, payload received 1024
Pinging 1.1.1.1 results: time=2.082secs, payload sent: 1024, payload received 1024
Pinging 1.1.1.1 results: time=1.490secs, payload sent: 1024, payload received 1024
Pinging 1.1.1.1 results: time=3.103secs, payload sent: 1024, payload received 1024
Pinging 1.1.1.1 results: time=1.089secs, payload sent: 1024, payload received 1024
Pinging 1.1.1.1 results: time=1.171secs, payload sent: 1024, payload received 1024
Pinging 1.1.1.1 results: time=1.364secs, payload sent: 1024, payload received 1024
Pinging 1.1.1.1 results: time=1.891secs, payload sent: 1024, payload received 1024
Pinging 1.1.1.1 results: time=1.581secs, payload sent: 1024, payload received 1024
Pinging 1.1.1.1 results: time=1.124secs, payload sent: 1024, payload received 1024
Ping statistics for 1.1.1.1:
    Packets: Sent = 10, Received = 10, Lost = 0 (0% loss)
Approximate round trip times in milli-seconds:
    Minimum = 1089ms, Maximum = 3103ms, Average = 1634ms
Pinging DONE
```

Second command for communication evaluation is `link status`. This command prints out last done report of BTS connection. For it to be accurate it is done after all `ping` commands. Items saved for analysis are *Reference Signal Received Power* (RSRP) and *Signal to Noise Ration* (SNR).

Example from testing of NB-IoT on nRF9161 with 10 dB additional attenuation:

```
mosh:~$ link status
Modem functional mode: normal
Network registration status: Connected - roaming
Modem config for system mode: NB-IoT
Modem config for LTE preference: No preference, automatically selected by the modem
Currently active system mode: NB-IoT
Battery voltage:      5054 mV
Modem temperature:    28 C
Device ID:             nrf-358299840012328
Operator full name:    "Vodafone"
Operator short name:   "VF"
Operator PLMN:         "23003"
Current cell id:       269600 (0x00041D20)
Current phy cell id:    400
Current band:          20
Current TAC:           48024 (0xBB98)
Current rsrp:          57: -84dBm
Current snr:           26: 2dB
Mobile network time and date: 25/05/19,13:08:15+08
PDP context info 1:
  CID:                 0
  PDP ID:              0
  PDP context active:  yes
  PDP type:            IP
  APN:                 lpwa.vodafone.com
```

```

IPv4 MTU:          1430
IPv4 address:      100.97.68.179
IPv6 address:      ::
IPv4 DNS address:  217.14.160.130, 217.14.164.35
IPv6 DNS address:  ::, ::
}

```

Another two commands are `link sysmode` for switching between NB-IoT and LTE-M and `link funmode` for turning the modem to and from flight-mode for save antenna and attenuators reconfiguration.

4.2 Power consumption - ampere meter

Power consumption can be accurately measured with negligible influenced by introduction of additional measurement equipment so measurement with external meter was chosen over the modem estimates or table values. For the power consumption evaluation of IoT devices there are two different factors to consider. First is standby or sleep power that is usually long (orders of minutes or hours) and very small (orders of miliamps) and second are short rapid transmission spikes in orders of amperes. This requires ampere meter with very high sampling speed and very high dynamic range.

For measuring of power consumption was done using Nordic *Nordic Power Profiler Kit II* (PPK II), seen in picture 4.1. PPK II was chosen for its high sampling rate, large dynamic range and its good integration with other Nordic applications and development kits.

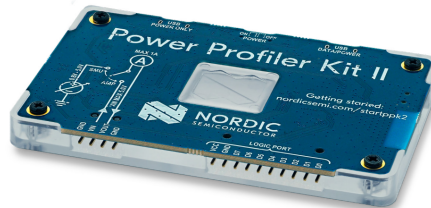


Fig. 4.1: Nordic Power Profiler Kit II[56]

Its key features are [56]:

- 200nA to 1A current measurement range with a resolution that varies between 100nA and 1mA
- Source mode and ampere meter mode
- 100 ksps sampling rate
- 8 digital inputs for logic analyzer support
- Supported through nRF Connect for Desktop's Power Profiler app

The measurement setup of nRF9161 DK with PPK II in EMC chamber and addition attenuators can be seen in figure 4.2. Antennas connected to the other end of coaxial cable can be seen in figure 4.3. These development kits from Nordic enable a direct connection of serial ampere meter using special pins. This is them main reason why both boards were chosen for this measurement.

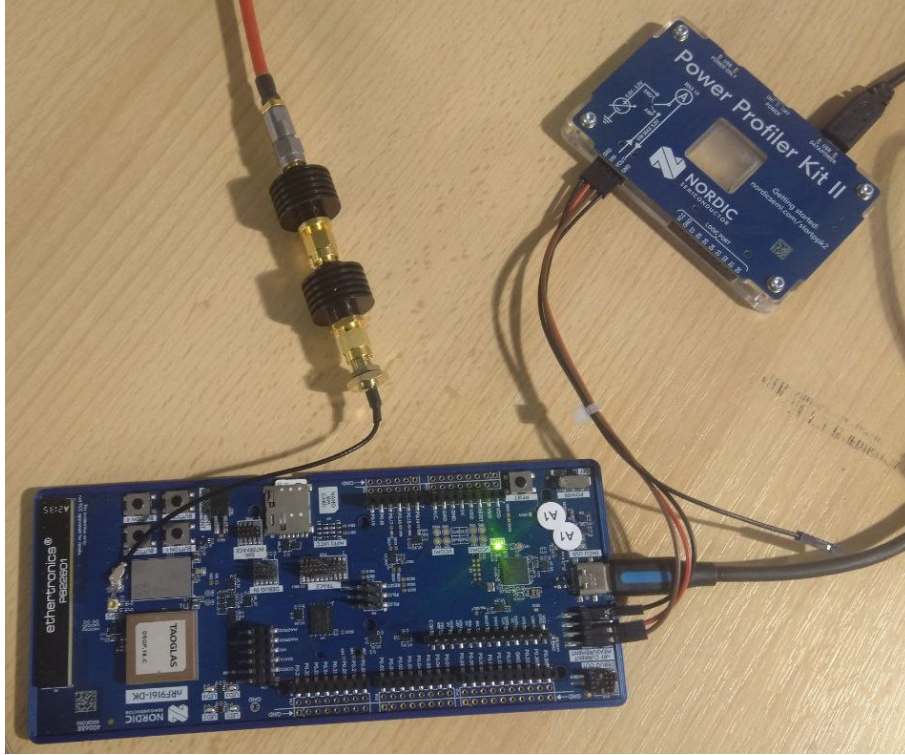


Fig. 4.2: Nordic Power Profiler Kit II measuring setup with nRF9161 in EMC chamber[56]

The output of PPK II can be seen in figure 4.5 for LTE-M and and in figure 4.4.

Yellow vertical lines mark a start of ping set and red vertical it end. These boundaries were set due to noise manually. Green horizontal line indicates average draw in idle state where the modem does not communicate in cellular network. Red horizontal line indicates average draw in ready state where communication is established without need for active communication. Both "horizontal" values are calculated using Python script from the measured data.

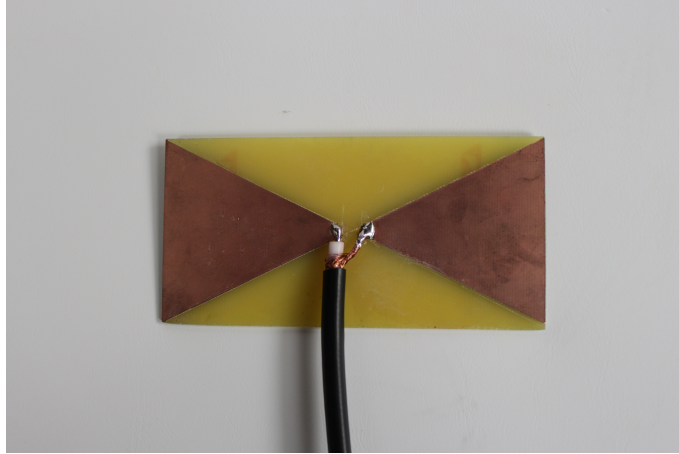


Fig. 4.3: Custom LTE antenna for bands around 800 MHz

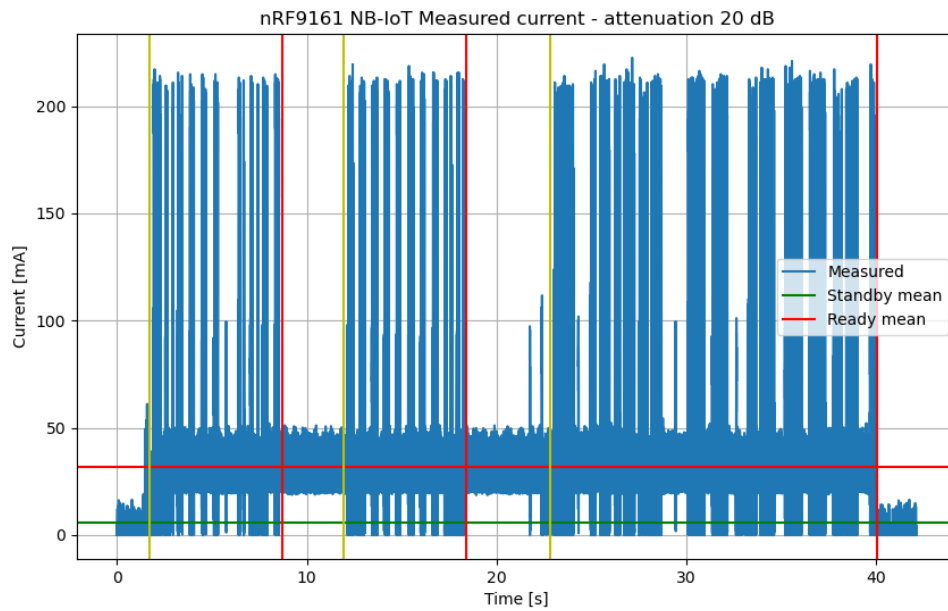


Fig. 4.4: Current plot of nRF9161 communicating using NB-IoT

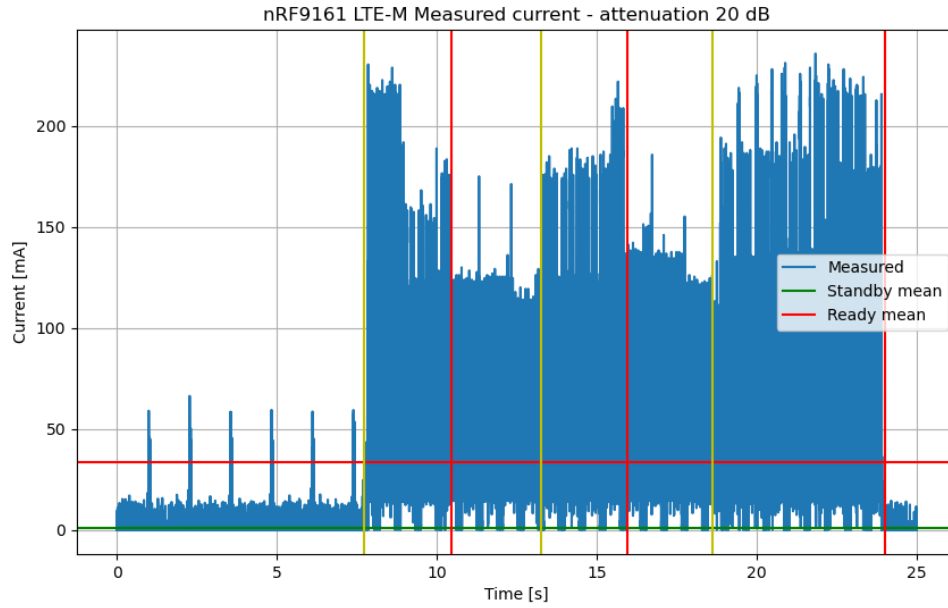


Fig. 4.5: Current plot of nRF9161 communicating using LTE-M

Another value that is calculated from these data and cannot be depicted in the chart is the raw charge needed for transmission of one packet. This is calculated by integration of the current over time set by the boundaries. This value expressed in coulombs or more commonly in mAh.

4.3 Cellular Results

Data described in sections above are aggregated into data tables using Python scripts. Example of such table can be seen in table 4.1. Complete data for both LTE modes and all payload sizes are, for their large extent, placed in Appendix A.

These final data tables are used for generating more visually understandable plots. Lets have a closer look at some of them that would evaluate the performance of nRF916x as outlined in beginning of this chapter. All charts can be found in appendix B.

4.3.1 Validity of attenuation and sensitivity

Firstly to ensure validity of this measurement it is important to check if the addition attenuation really corresponds to attenuation of input signal. This can be seen in figure 4.6. The sudden jump at 20 dB is due to transition of the physical attenuator

KU	RSRP	SNR	RT min	RT max	RT avg	Transmit	Max I	Ready I	Standby I	Charge	DR
[dB]	[dBm]	[dB]	[ms]	[ms]	[ms]	[s]	[mA]	[mA]	[mA]	[uAh]	[kB/s]
0	-75	1	1190	4500	3146	3.57	233.39	30.90	2.38	37.16	0.30
3	-77	2	1039	3731	1869	1.95	222.60	31.11	2.21	19.20	0.56
6	-82	-1	983	2201	1618	1.74	220.29	31.56	2.71	17.59	0.63
10	-84	2	1089	3103	1634	1.79	217.21	30.82	2.35	18.38	0.61
16	-89	2	994	2888	1379	1.53	217.21	31.03	2.32	17.08	0.71
20	-94	1	1089	2618	1660	1.72	222.60	31.56	5.71	19.04	0.63
21	-92	3	1037	1542	1254	1.48	222.60	30.60	0.60	16.80	0.74
26	-98	4	976	1364	1162	1.32	222.60	30.52	2.36	15.51	0.82
30	-101	4	961	1670	1244	1.40	225.68	31.01	0.82	16.44	0.78
36	-109	3	1127	1562	1327	1.52	221.83	30.58	2.02	17.68	0.72
40	-112	4	1315	2352	1737	1.94	224.91	28.93	2.38	27.68	0.56
46	-119	3	1370	2040	1717	1.92	248.06	28.84	2.22	34.42	0.57
50	-124	1	1734	2917	2228	2.44	224.91	31.18	2.22	55.45	0.45
51	-124	2	1645	2501	2072	2.30	224.91	30.13	2.22	53.41	0.47
56	-131	-3	3393	5091	4307	4.54	226.45	31.08	2.42	115.42	0.24
60	-133	-5	11772	13685	12833	11.91	222.60	29.30	2.22	435.51	0.09

Table 4.1: NB-IoT nRF9161 measurements with payload size 1024 B

form the inside of the EMC chamber to outside to prevent RF leakage. The same thing happened at 50 dB. Other than that the slope of the curve seems linear.

Another key observation is that NB-IoT has by 3 dB better sensitivity over LTE-M (-133 dBm and -130 dB respectively). This is in contrast to datasheet values of -114 dBm and -108 dBm (see chapter 2.1) where the difference between the modes should be 6 dB and measured sensitivity is better by 19 dB and 22 dB.

Alternative value provided by modem that could be used to guess the sensitivity is its reported *Downlink* (DL) path loss. This was 159 dB for NB-IoT and 148 for LTE-M. If the same transmit power of 23 dBm is assumed for the BTS it would give a sensitivity of -136 dBm for NB-IoT and -125 dBm for LTE-M. This method or reported DL path loss in general are used sporadically in subsequent analysis for the author's doubts about validity and accuracy of such numbers.

Seemingly big difference is RSRP at same attenuation between both modes. This has multiple possible explanation:

- Slightly different bands - LTE-M was measured on LTE band 8 (UL: 880 - 915 MHz DL: 925 - 960 MHz) while NB-IoT was on LTE band 20 (UL: 832 - 862 MHz DL: 791 - 821 MHz)
- Different settings on actual BTS for both modes

- Higher robustness of NB-IoT

For this reason subsequent analysis will be done using RSRP supplied by modem.

From these possibilities the advantage of NB-IoT compared to LTE-M for detection of very weak signals is 3 dB if RSRP is to be believed, 6 dB according to datasheet, 11 dB according to reported DL path loss and 14 dB according to attenuation.

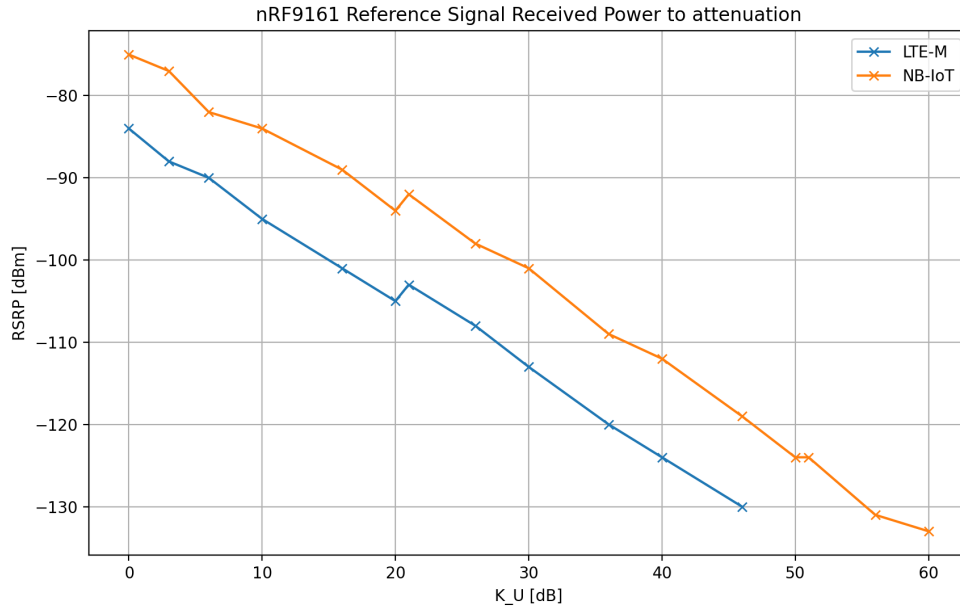


Fig. 4.6: Reference Signal Received Power to attenuation

4.3.2 Power consumption analysis

The value crucial for calculation of needed battery capacity in IoT devices is electrical charge that is consumed by the transmission, together by constant current of ready and idle states and planned lifetime of such device.

In figure 4.7 can be seen a comparison of LTE-M and NB-IoT in regards to this needed charge per single transmission of given payload size dependent to the signal strength reported using RSRP from the LTE modem.

From this figure can be concluded following:

1. LTE-M uses consistently less energy for every payload size compared to NB-IoT. If the total attenuation is taken as a determinative value even when NB-IoT consumes less energy than LTE-M only at the limit of LTE-M abilities. See appendix figure B.20 for this chart.

2. Rapid increase in used energy for LTE-M happens only at signal levels close to connection loss. Gradual mild increase can be better seen in appendix table B.30
3. NB-IoT is able to transmit messages at the cost of vastly higher energy consumption in worse conditions where LTE-M is unable to operate.

Summed up this means that usage of NB-IoT is only advisable for situations where signal conditions are so bad that the better resilience is needed.

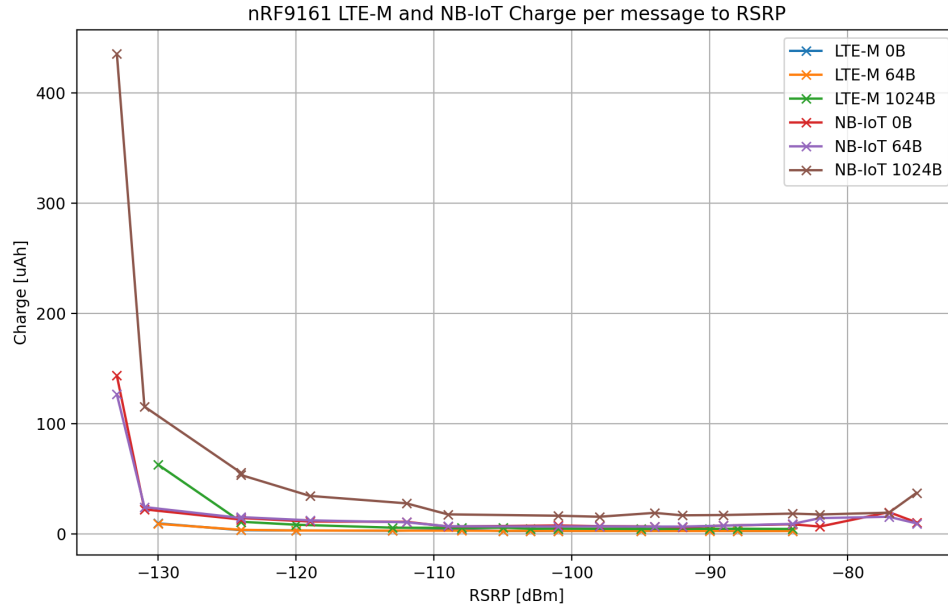


Fig. 4.7: nRF9161 LTE-M and NB-IoT Charge per message to RSRP

4.3.3 Transmission speed and comparison to LoRa

Difficulty of direct comparison of LTE modes to other technologies such as LoRa are described in depth the discussion chapter 6. But since LoRa is the main "competitor" of LTE IoT protocols it should at least be tried with data that are available.

As a representative of LoRa the Semtech SX1262 chip was chosen. Primarily for similar band (around 800 MHz) and usage in similar applications[38].

Values of data rate and formula for sensitivity of SX1262 were obtained from its datasheet [38].

The formula is following:

$$S = (12 - SF) * 2.5 - 137$$

S is sensitivity in dBm, SF is LoRa speeding factor number, 2.5 is lowering of sensitivity in dB per SF and -137 is sensitivity of SX1262 for SF 12 in dBm.

These data were integrated into chart with measured data for NB-IoT and LTE-M as you can see in figure 4.8.

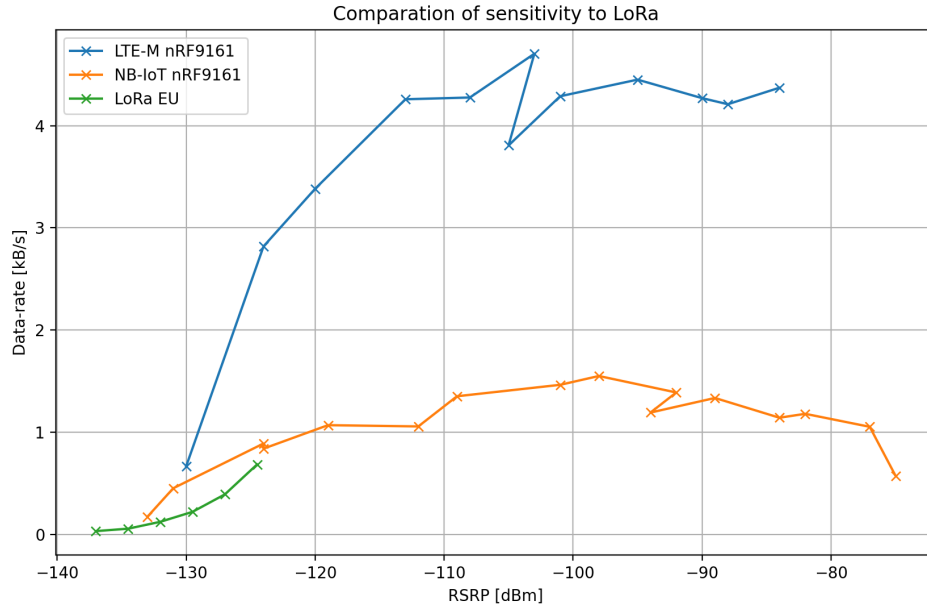


Fig. 4.8: Comparison of sensitivity and transmit speed of LTE to LoRa

Getting conclusions from comparing measured data and datasheet data without any assurance of measurement method comparability is hard but lets at least try to find some meaning in this.

NB-IoT seems to be slightly faster and so better than LoRa up to SF 10 at RSRP -132 dBm where we set a limit of NB-IoT abilities. Since attributes of fair measurement compression were not met, from current data and from knowledge of their limitation there can be made a vague statement that abilities of NB-IoT and LoRa would seem comparable.

LTE-M is a considerable improvement in aspect of data rate over NB-IoT. Over LoRa even though the difference seems huge, in case of real data they share on the signal strength axis only one point. From this it seems that these two are not very comparable in their target ideal use-cases.

4.4 DECT NR+

An additional measurement was made to test the capability of nRF9161 to transmit and receive using DECT NR+.

Measurements were done similarly to these of LTE but with other nRF9161 DK in place of LTE antenna. Measurement of current was done on the node.

The fixed slot timing property of DECT NR+ means that device can transmit only in fixed time window. This gets rid of need for integration and power consumption can be established from maximal current and number of time slots used.

The two DKs do not communicate P2P strictly speaking but one operates as a beacon that periodically sends information needed to establish communication with itself. The other operates as node, in 5G terminology named as *Protocol Data Unit* (PDU). In implementations with more than 2 devices some devices can be beacon with established connection to other beacon and by this manner it is possible to create the mesh trees described in chapter 1.4.2.

In the analysis there is used a term of *Free space path loss* (FSPL) distance. This represents the attenuation as distance in completely free space that would have the same attenuation (ignoring latency increase). Here is how it was calculated. This is equation for freespace path loss:

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

When frequency of 1.9 GHz is substituted, the equation solved for distance and signal loss expressed in decibels it forms this equation that was used in later analysis:

$$d = 10^{\frac{K_U - 98}{20}}$$

Results of these measurement can be seen in table 4.2 and visualized in figures 4.10 and 4.9. Note to the data: maybe contrary to common sense beacon TX power is output power transmitted from the beacon but its RSSI is value measured from PDU of the beacon's signal. Same thing is true for the PDU and its values.

K_U [dB]	Beacon		PDU		FSPL d [km]	Max I [mA]	Att conf [dB]
	RSSI [dBm]	PWR [dBm]	RSSI [dBm]	PWR [dBm]			
106	-105	4	-91	23	2.51	213.28	60+46
103	-103	4	-88	23	1.78	218.63	60+43
93	-93	4	-78	23	0.56	220.93	60+33
83	-83	4	-68	23	0.18	221.69	40+43
73	-72	4	-60	16	0.06	160.71	40+33
63	-62	4	-59	7	0.02	97.30	40+23
53	-52	4	-60	-4	0.01	89.05	40+13
43	-41	4	-58	-12	0.00	88.30	40+03

Table 4.2: Result table of DECT NR+ measurements

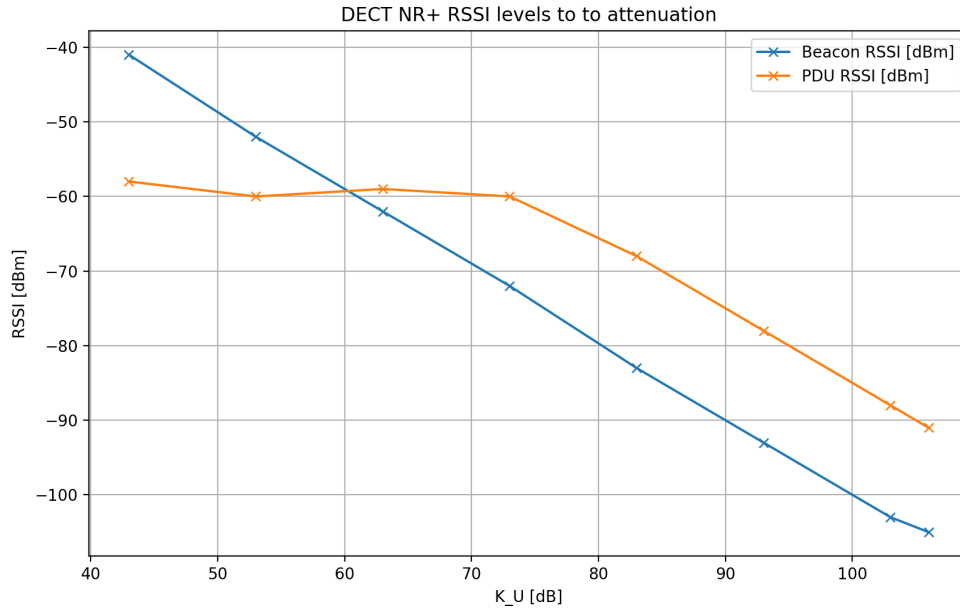


Fig. 4.9: DECT NR+ RSSI levels to to attenuation

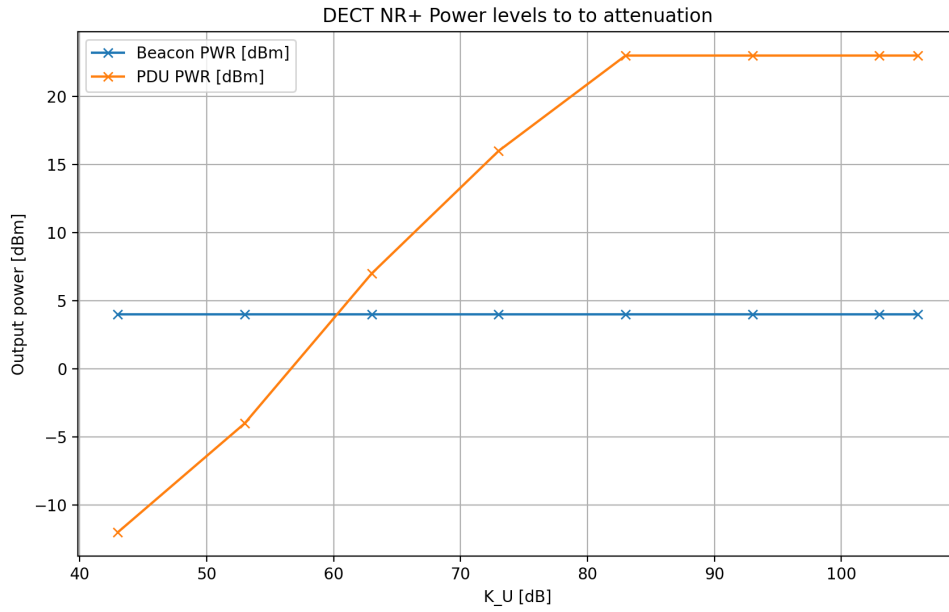


Fig. 4.10: DECT NR+ Power levels to to attenuation

From these can be conclude following:

1. Beacon did not had automatic adjunction of power but PDU did. This can be clearly seen in figure 4.10. This could be due to using experimental MoSh for DECT NR+ that supports only the physical layer of DECT NR+.
2. Maximal current grows in discrete jumps with PDU power level.
3. Maximal theoretical range for measured power of 4 dBm is 2.5 km.
4. If maximal power of 23 dBm on both boards is assumed, the maximal possible attenuation is 125 dB and theoretical range is 22.4 km.
5. Minimal signal strength was -105 dBm. According to nRF9161 documentation its sensitivity for DECT NR+ is -103 dBm.

5 Field testing of mobile capabilities of NB-IoT and LTE-M

Standard notion on selecting between LTE-M and NB-IoT when one has a choice is to choose LTE-M when one needs higher speed or needs for the device to be mobile while not having not so extreme requirements for continual communication or environment with extreme attenuation and to choose NB-IoT for smaller payload applications with potential of very weak signal.

To test this hypothesis an experiment was created where the created demonstrator from chapter 3 was placed inside a personal car as can be seen in figure 5.1. One way to test LTE-M on road from north Moravia to Brno and to test NB-IoT on return path.

Because of large intervals (orders of minutes) needed for switch between GNSS and LTE connection on nRF916x, it was chosen to perform only reading from the meteo sensor, reading of connection quality report and periodical sending of these data to MQTT server. On the same server there was running Python script that saved all data in json format to the server storage. Location data were collected by smartphone with GNSS logging application and later these two datasets were joined by time.



Fig. 5.1: Demonstrator secured in car for mobile measurement

Gathered data included from GPS tracker included latitude, longitude, accuracy of position, smartphone battery, computed elevation, number of visible satellites, and speed.

Evaluation data from LTE modem were LTE band, down link path loss, LTE mode (1 is LTE-M 2 is NB-IoT), Reference Signal Received Power (RSRP), Reference Signal Received Quality (RSRQ), Signal to Noise Ratio (SNR) and TX power.

Lastly to demonstrate transfer of useful data the values from sensor BME680 were also included. These were atmospheric pressure, inside car temperature, car humidity, resistance of gas sensor representing amount of for example volatile organic compounds in the air.

All of these data joined by Python script were then used to create interactive maps for better data visualization.

An example of such map of reported signal power can be seen in figure 5.2 for LTE-M and 5.3 for LTE-M.

Findings from this data are:

- LTE-M provided stable connection for transmission of packet about 0.5 kB in size every second in speeds lesser than 130 km/h. Higher speed of due to highway laws and technical state of used car. With exception near Lipník na Bečvou where most likely due to change in network operating LTE band

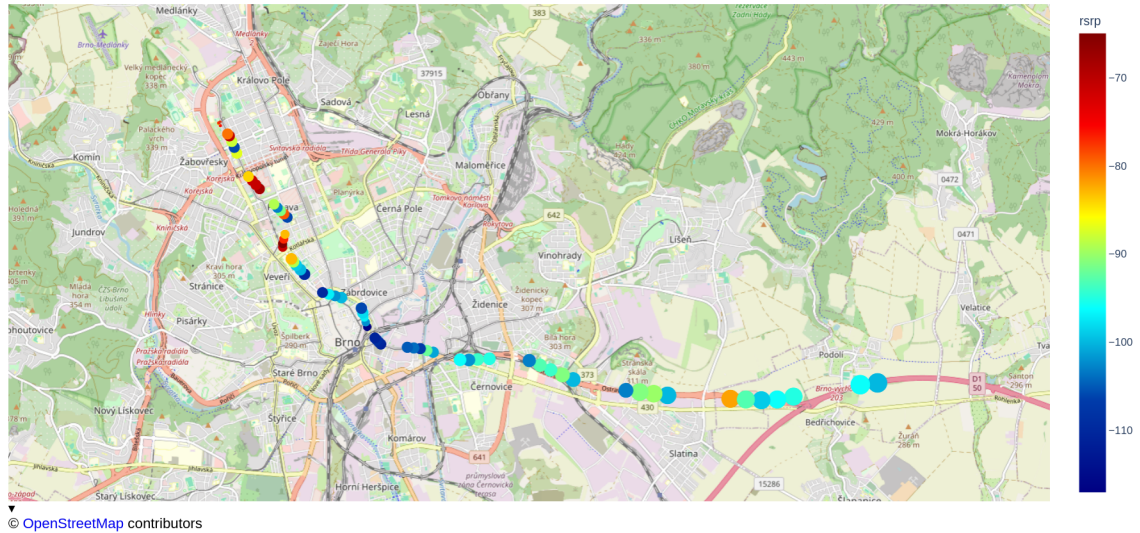


Fig. 5.2: Map RSRP reported by demonstrator operating using LTE-M

demonstrator lost connection for 1.5 minutes. This transition from band 8 to band 20 can be clearly seen in figure 5.4.

- NB-IoT also provided fairly stable connection for at least 130 km/h with 2 minute connection loss near Brno airport and nearly 2 minute loss between Nový Jičín and Hranice na Moravě at borderline of Olomouc and Moravian-Silesian region (whenever is this detail significant is not clear but the band change as in the LTE-M did not happened here). Last understandable signal loss was in tunnels in west Brno (different route than LTE-M due to traffic situation in Brno).

Better visualization of these data with interactive maps can be found in this GitHub page: <https://mikehanus.github.io/bcthesis-datavisualisation/> Including them in attachments were not possible due to large size of these maps but it should be possible to generate them using python scripts and data in the attachments.

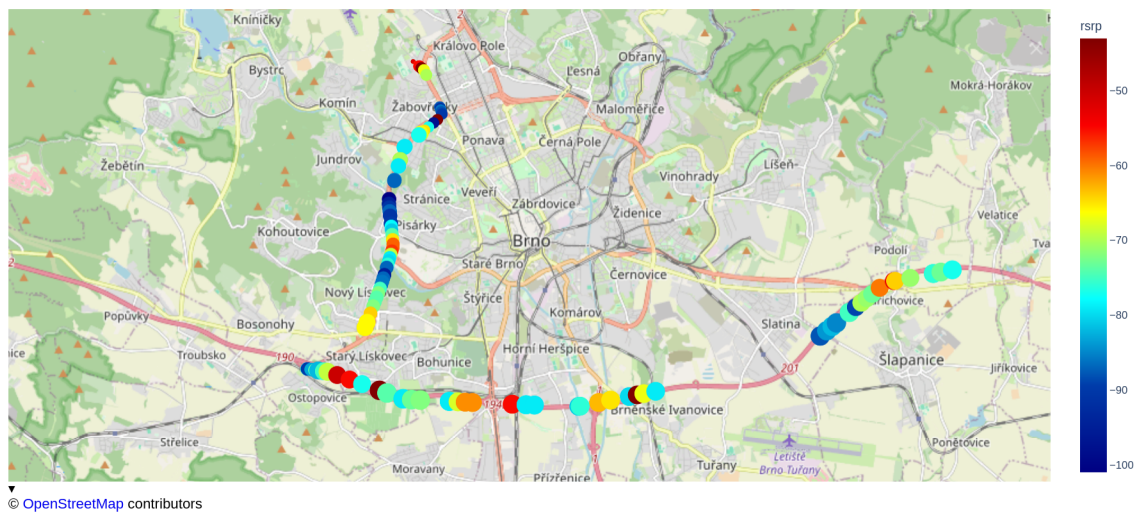


Fig. 5.3: Map RSRP reported by demonstrator operating using NB-IoT



Fig. 5.4: Map of LTE band used by demonstrator when using LTE-M

6 Discussion and usage scenarios

6.1 Comparison of discussed technology

This section will comment on

6.1.1 NB-IoT

NB-IoT is best suitable for non-moving low speed low power devices where is possibility of conditions of very bad LTE coverage or placement in locations with high RF shielding such as basements or underground and every dB of signal is appreciated.

Mobile communication is possible but should be approached with cautious when dealing with critical application.

It is very comparable to LoRa and the choice between them depends large on other factors than purely radio properties. Huge decisive factor are: size of anticipated area of service, coverage of cellular network by mobile operators, initial cost of modules and their yearly running cost, special needs and hacks that would need custom gateway.

6.1.2 LTE-M

LTE-M is optimally suited for moderate-speed, low-power embedded devices that require reliable mobile connectivity and higher data throughput than NB-IoT, but still benefit from extended battery life compared to traditional LTE. When in its signal range where it can safely communicated it should be preferred over NB-IoT because of its lower power demands and higher data speed.

It is effective in scenarios where devices might experience fluctuating signal conditions, high mobility or need to send larger data packets periodically.

6.1.3 DECT NR+

DECT NR+ waits for itself to matured and be used in application not clearly foreseen now. Its very low latency with ability to maintain connectivity of very large and dense network of devices would enable it to be game changer in massive IoT applications described below.

6.2 Scenarios of IoT applications and recommended protocol

This section will shift focus from particular protocol to possible scenarios in various industry sectors and evaluate best protocol from this point of view.

6.2.1 Classic stationary IoT

The most ubiquitous form of IoT are devices such as simple sensors such as remote environmental of river water level or remote reading of home water meters. This category includes even slightly more complex devices such as control of street lamps, control of different gates. For new application like these the choice of communication technology would have negligible impact on performance of the device. Only in places with limited coverage of cellular network some larger considerations will be needed.

6.2.2 Mobile IoT

For scenarios involving tracking, wearables, and mobile smart metering in areas such a smart agriculture or logistics LTE-M or possibly NB-IoT would be most suitable choices for their universal adaption and ability to communicate even while moving.

6.2.3 Remote tracking

There starts to emerge a new way of doing maintenance or at least diagnostics of different machines on remote using integrated IoT devices. This would save time and money of maintenance workers that would not need travel to diagnostics a trivial problem from their view. Suggestion of protocol is dependent on required data usage and LTE coverage for typical installation of such project.

6.2.4 Massive critical industrial IoT

Smart grid - A massive number of smart meters and controllers deployed across residential, commercial, and industrial sites, providing real-time data on energy consumption and grid conditions. This could lead to possibility to optimize the power distribution to the point where residential user could access benefits of spot market both on consumption and on production side.

Machine Health Monitoring - Connection of virtually every machine in a large production line with sensors to monitor performance, vibration patterns, power consumption, and production output. This enables predictive maintenance, reduces

unexpected breakdowns, and optimizes production schedules. Cost of the additional IoT devices would in most scenarios be far lesser than the possibility of machine prenamenet damage or production delay due to not foreseen maintenance. This would could lead to massive adaption of these sensors and need for more robust protocols. DECT NR+ is from the list of mentioned protocols ideal choice

6.2.5 Low Earth orbit satellites

Attenuation of frequency around 800 MHz to Low Earth Orbit around 400 - 1500km is about 144 dB to 154 dB. LoRa is already used in some of these satellites as cost effective way to communicate with a satellite without the need for expensive ground station. NB-IoT demonstrated to be able to manage attenuation of very similar magnitude. Use of NB-IoT to space and imagining nano satellites as new frontier of IoT devices is certainly very pleasing but any such attempt would need at least some support from at least one of established mobile operators. Until then established communication manners with occasional LoRa will prevail.

6.3 Future work

This section outlines some parts that would benefit from expansion of current data or repetition of existing experiment with slight tweaking.

Direct comparison to LoRa

Extension of LoRa measurements to comparable RF measurements with power consumption for fairer direct comparison of that and LTE protocols.

Mobile usage with very low signal strength

Check if the advantage of NB-IoT over LTE-M for weak signal decode is still present when the devices are moving and if speed has influence to it

Conclusion

This thesis described the principles of 4G and 5G mobile networks focusing architecture, communication protocols, and specific features relevant to IoT use cases.

It further analyzed LPWAN protocols NB-IoT, LTE-M and noncellular 5G protocol DECT NR+.

After providing an overview of the Nordic Semiconductor nRF9160, nRF9161 and nRF9151 chipsets with a review of commercially available development modules.

Based on this research, the Connexio Pro development kit was selected for its usage of new chipset, very small form-factor and integrated features suitable for rapid prototyping of IoT devices.

To demonstrate practical usage, a universal low-cost tracking application was developed using the selected kit. This kit demonstrated function of rapid prototype of tracker of smart sensor.

Laboratory experimental measurements were done on nRF9160 and nRF9161 using all supported protocol (NB-IoT, LTE-M, DECT NR+), focusing on key communication parameters such as power consumption measured by Nordic Power Profiler II, signal strength measured by the LTE modem itself, and data throughput calculated from combination of these. The collected data were arranged, extensively visualized and compared with theoretical expectations and to the LoRa technology.

The mentioned demonstrator was then used in field experimental measurements were carried out using car on highway to verify ability of suggested scenarios to communicate in mobile setting.

Important parts of findings throughout this theses were summarized in discussion chapter with comparison of mentioned protocols and outline of IoT scenarios with suggested appropriate protocols.

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Symbols and abbreviations

3GPP	3rd Generation Partnership Project
4G, 5G	4th and 5th Generation mobile networks
ADC	Analog-Digital Converter
CSS	chirp spread spectrum
DL	Downlink
E2E	End-to-End
FSPL	Free space path loss
GNSS	Global Navigation Satellite System
GPIO	General-Purpose Input/Output
GSM	Global System for Mobile communications
HAL	Hardware Abstraction Layer
HRLLC	Higher-Reliability and Low-Latency Communication
I2C	Inter-Integrated Circuit
IP	Internet Protocol
IoT	Internet of Things
LED	Light Emitting Diode
LE	Low Energy
LGA	Land Grid Array
LPWAN	Low-Power Wide-Area Network
LTE-M	Long-Term Evolution Machine Type Communication
LTE	Long-Term Evolution
Li-Po	Lithium-Polymer
Li-ion	Lithium-Ion
LoRaWAN	Long-Range wide area network
LoRa	Long-Range
M2M	Machine-to-Machine
MQTT	Message Queuing Telemetry Transport
NB-IoT	Narrowband Internet of Things
NFC	Near-Field Communication
NSA	Non-Stand Alone
PCB	Printed Circuit Board
PCIe	Peripheral Component Interconnect Express
PC	Personal Computer
PDM	Pulse-Density Modulation
PIR	Passive Infra Red
PWM	Pulse-Width Modulation
RAN	Radio Access Network

RF Radio Frequency
RGB Red Green Blue
RTC Real-Time Clock
SA Stand-alone
SDK Software development kit
SIM Subscriber Identity Module
SMA Subminiature Version A
SMS Short Message Service
SPI Serial Peripheral Interface
SiP System-in-Package
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
eMBB Enhanced Mobile Broadband
eSIM embedded SIM card
mMTC Massive Machine Type Communications
2G 2nd generation of cellular networks
BTS Base Transceiver Station
DECT NR+ Digital Enhanced Cordless Telecommunications: New Radio plus
DECT Digital Enhanced Cordless Telecommunications
ETSI European Telecommunications Standards Institute
FDMA Frequency-Division Multiple Access
FOTA Firmware Over The Air
GPS Global Positioning System
HARQ Hybrid Automatic Repeat Request
ICMP Internet Control Message Protocol
ITU International Telecommunication Union
MAC Medium Access Control
MoSh Modem Shell
NCS Nordic Core SDK
NTN Non Terrestrial Network
P2P point-to-point
PDU Protocol Data Unit
PPK II Nordic Power Profiler Kit II
QZSS Quasi-Zenith Satellite System

RFFE Radio Frequency Front End
RSRP Reference Signal Received Power
RSSI Received signal strength indicator
SC-FDMA Single-Carrier Frequency-Division Multiple Access
SNR Signal to Noise Ration
TDD Time-Division Duplex
TDMA Time-Division Multiple Access
UNB Ultra Narrowband
WLAN wireless local area network
WPAN wireless personal area network

List of appendices

A	Result measurement - tables	67
B	Result of measurement - charts	74
B.1	nRF9161	78
B.2	nRF9160	94
C	Demonstrator electronic schemes	111

A Result measurement - tables

KU	RSRP	SNR	RT min	RT max	RT avg	Transmit	Max I	Ready I	Standby I	Charge	DR
[dB]	[dBm]	[dB]	[ms]	[ms]	[ms]	[s]	[mA]	[mA]	[mA]	[uAh]	[kB/s]
0	-71	4	359	1612	773	0.82	243.01	29.12	4.46	6.87	0.00
3	-72	7	432	2147	933	0.94	247.62	29.79	0.47	8.15	0.00
6	-78	4	374	2328	911	0.89	238.40	30.32	5.19	7.80	0.00
10	-80	4	548	1473	815	0.86	233.03	29.98	5.63	7.59	0.00
20	-88	6	406	2254	911	0.89	238.40	30.04	7.43	8.17	0.00
30	-102	2	373	1961	897	0.90	269.20	30.37	6.24	8.59	0.00
36	-108	4	570	1823	934	0.96	271.51	30.35	5.50	11.43	0.00
40	-109	5	408	1463	836	0.88	257.63	30.40	0.47	12.12	0.00
50	-129	-8	46	2356	1148	1.90	246.86	29.85	3.74	35.68	0.00
60	-129	-2	873	2335	1305	2.40	249.16	28.17	1.77	66.14	0.00
63	-132	-4	754	5633	3200	3.34	249.16	30.64	25.26	80.41	0.00

Table A.1: NB-IoT nRF9160 measurements with payload size 0 B

KU	RSRP	SNR	RT min	RT max	RT avg	Transmit	Max I	Ready I	Standby I	Charge	DR
[dB]	[dBm]	[dB]	[ms]	[ms]	[ms]	[s]	[mA]	[mA]	[mA]	[uAh]	[kB/s]
0	-71	4	305	1536	757	0.83	243.78	29.12	4.46	7.25	0.15
3	-72	7	273	1157	699	0.80	247.62	29.79	0.47	7.23	0.16
6	-78	4	532	967	734	0.85	243.78	30.32	5.19	7.68	0.15
10	-80	4	229	1202	698	0.76	234.56	29.98	5.63	7.01	0.17
20	-88	6	431	1427	830	0.90	242.24	30.04	7.43	8.82	0.14
30	-102	2	379	1476	821	0.91	242.24	30.37	6.24	9.18	0.14
36	-108	4	526	963	744	0.84	248.39	30.35	5.50	8.69	0.15
40	-109	5	338	1327	821	0.92	251.47	30.40	0.47	12.05	0.14
50	-129	-8	580	2462	1434	1.30	246.09	29.85	3.74	20.88	0.10
60	-129	-2	1658	5822	3579	3.51	249.93	28.17	1.77	89.72	0.04
63	-132	-4	2761	8577	4193	4.65	251.47	30.64	25.26	154.96	0.03

Table A.2: NB-IoT nRF9160 measurements with payload size 64 B

KU	RSRP	SNR	RT min	RT max	RT avg	Transmit	Max I	Ready I	Standby I	Charge	DR
[dB]	[dBm]	[dB]	[ms]	[ms]	[ms]	[s]	[mA]	[mA]	[mA]	[uAh]	[kB/s]
0	-71	4	574	1171	858	0.94	249.93	29.12	4.46	8.41	1.16
3	-72	7	498	1381	892	1.04	243.78	29.79	0.47	9.75	1.05
6	-78	4	429	1332	820	0.95	244.55	30.32	5.19	9.13	1.15
10	-80	4	436	1552	923	1.01	236.10	29.98	5.63	9.84	1.07
20	-88	6	706	1464	1018	1.09	236.10	30.04	7.43	12.34	1.00
30	-102	2	514	1251	848	0.97	243.78	30.37	6.24	11.89	1.12
36	-108	4	485	1233	862	0.98	246.09	30.35	5.50	12.04	1.11
40	-109	5	871	1540	1074	1.16	244.55	30.40	0.47	14.38	0.94
50	-129	-8	1368	2685	2104	2.49	246.09	29.85	3.74	78.05	0.44
60	-129	-2	3572	7450	5305	2.69	249.93	28.17	1.77	76.64	0.40
63	-132	-4	5963	9803	8384	4.67	249.16	30.64	25.26	205.87	0.23

Table A.3: NB-IoT nRF9160 measurements with payload size 1024 B

KU	RSRP	SNR	RT min	RT max	RT avg	Transmit	Max I	Ready I	Standby I	Charge	DR
[dB]	[dBm]	[dB]	[ms]	[ms]	[ms]	[s]	[mA]	[mA]	[mA]	[uAh]	[kB/s]
0	-86	-3	111	596	209	0.43	103.86	5.38	10.24	2.61	0.00
3	-95	-3	87	502	241	0.47	126.46	5.39	1.06	2.91	0.00
6	-92	-4	72	421	161	0.39	162.80	5.31	9.80	3.03	0.01
10	-98	-4	99	392	155	0.38	208.51	6.44	0.78	2.84	0.01
20	-108	-3	87	409	165	0.36	309.44	35.93	1.06	3.68	0.01
30	-118	-2	77	380	153	0.35	322.65	35.81	1.07	3.86	0.01
40	-129	-7	124	604	231	0.46	337.45	36.00	15.51	6.97	0.00
50	-130	-1	83	361	177	0.38	271.51	34.49	34.76	4.29	0.01

Table A.4: LTE-M nRF9160 measurements with payload size 0 B

KU	RSRP	SNR	RT min	RT max	RT avg	Transmit	Max I	Ready I	Standby I	Charge	DR
[dB]	[dBm]	[dB]	[ms]	[ms]	[ms]	[s]	[mA]	[mA]	[mA]	[uAh]	[kB/s]
0	-86	-3	117	478	244	0.51	88.83	5.38	10.24	3.32	0.25
3	-95	-3	95	416	195	0.44	87.33	5.39	1.06	3.04	0.29
6	-92	-4	90	335	163	0.38	91.83	5.31	9.80	3.09	0.33
10	-98	-4	97	327	146	0.37	95.59	6.44	0.78	3.00	0.35
20	-108	-3	103	333	160	0.37	166.60	35.93	1.06	3.79	0.35
30	-118	-2	132	281	208	0.41	300.13	35.81	1.07	4.32	0.31
40	-129	-7	165	421	270	0.49	330.44	36.00	15.51	7.05	0.26
50	-130	-1	197	584	328	0.53	270.74	34.49	34.76	6.12	0.24

Table A.5: LTE-M nRF9160 measurements with payload size 64 B

KU	RSRP	SNR	RT min	RT max	RT avg	Transmit	Max I	Ready I	Standby I	Charge	DR
[dB]	[dBm]	[dB]	[ms]	[ms]	[ms]	[s]	[mA]	[mA]	[mA]	[uAh]	[kB/s]
0	-86	-3	178	358	212	0.44	94.84	5.38	10.24	3.39	2.48
3	-95	-3	175	620	270	0.50	91.83	5.39	1.06	3.59	2.16
6	-92	-4	167	496	256	0.48	97.84	5.31	9.80	3.18	2.25
10	-98	-4	162	232	198	0.44	107.62	6.44	0.78	3.18	2.47
20	-108	-3	127	388	213	0.43	226.12	35.93	1.06	4.53	2.55
30	-118	-2	37	264	187	0.39	322.65	35.81	1.07	4.51	2.82
40	-129	-7	327	669	497	0.71	272.28	36.00	15.51	13.99	1.54
50	-130	-1	389	850	530	1.11	272.28	34.49	34.76	14.37	0.98

Table A.6: LTE-M nRF9160 measurements with payload size 1024 B

KU	RSRP	SNR	RT min	RT max	RT avg	Transmit	Max I	Ready I	Standby I	Charge	DR
[dB]	[dBm]	[dB]	[ms]	[ms]	[ms]	[s]	[mA]	[mA]	[mA]	[uAh]	[kB/s]
0	-75	1	453	4453	1338	1.09	233.39	30.90	2.38	10.42	0.00
3	-77	2	417	3306	2163	2.13	227.22	31.11	2.21	19.69	0.00
6	-82	-1	452	940	611	0.72	222.60	31.56	2.71	6.64	0.00
10	-84	2	360	1842	914	0.96	214.13	30.82	2.35	8.66	0.00
16	-89	2	260	1233	746	0.83	215.67	31.03	2.32	7.52	0.00
20	-94	1	371	1271	606	0.70	217.21	31.56	5.71	6.74	0.00
21	-92	3	307	1135	569	0.63	220.29	30.60	0.60	6.05	0.00
26	-98	4	350	1017	627	0.71	240.34	30.52	2.36	6.97	0.00
30	-101	4	294	1846	672	0.76	234.94	31.01	0.82	7.60	0.00
36	-109	3	382	691	512	0.64	243.43	30.58	2.02	6.63	0.00
40	-112	4	351	1016	616	0.72	234.16	28.93	2.38	10.95	0.00
46	-119	3	403	1130	590	0.65	249.61	28.84	2.22	11.20	0.00
50	-124	1	468	1100	678	0.79	226.45	31.18	2.22	12.98	0.00
51	-124	2	367	1570	862	0.93	224.91	30.13	2.22	14.35	0.00
56	-131	-3	657	2032	1029	1.07	225.68	31.08	2.42	22.21	0.00
60	-133	-5	942	8991	3782	4.05	233.39	29.30	2.22	143.52	0.00

Table A.7: NB-IoT nRF9161 measurements with payload size 0 B

KU	RSRP	SNR	RT min	RT max	RT avg	Transmit	Max I	Ready I	Standby I	Charge	DR
[dB]	[dBm]	[dB]	[ms]	[ms]	[ms]	[s]	[mA]	[mA]	[mA]	[uAh]	[kB/s]
0	-75	1	463	2258	999	0.98	232.62	30.90	2.38	9.44	0.13
3	-77	2	482	3765	1600	1.66	231.08	31.11	2.21	15.48	0.08
6	-82	-1	455	3857	1378	1.49	224.14	31.56	2.71	14.27	0.09
10	-84	2	328	1985	933	0.97	214.90	30.82	2.35	9.01	0.13
16	-89	2	357	1266	686	0.76	217.21	31.03	2.32	7.45	0.17
20	-94	1	466	762	562	0.64	219.52	31.56	5.71	6.58	0.20
21	-92	3	386	887	560	0.64	219.52	30.60	0.60	6.62	0.20
26	-98	4	301	693	557	0.66	225.68	30.52	2.36	6.85	0.19
30	-101	4	355	758	550	0.63	218.75	31.01	0.82	6.71	0.20
36	-109	3	432	777	551	0.63	231.08	30.58	2.02	6.88	0.20
40	-112	4	213	1025	580	0.68	224.14	28.93	2.38	10.49	0.19
46	-119	3	415	957	606	0.72	248.06	28.84	2.22	12.23	0.18
50	-124	1	427	845	621	0.71	224.91	31.18	2.22	14.37	0.18
51	-124	2	411	1095	746	0.86	224.14	30.13	2.22	15.19	0.15
56	-131	-3	799	1441	1156	1.29	225.68	31.08	2.42	24.32	0.10
60	-133	-5	1570	5783	3795	3.97	231.08	29.30	2.22	126.48	0.03

Table A.8: NB-IoT nRF9161 measurements with payload size 64 B

KU	RSRP	SNR	RT min	RT max	RT avg	Transmit	Max I	Ready I	Standby I	Charge	DR
[dB]	[dBm]	[dB]	[ms]	[ms]	[ms]	[s]	[mA]	[mA]	[mA]	[uAh]	[kB/s]
0	-75	1	1190	4500	3146	3.57	233.39	30.90	2.38	37.16	0.57
3	-77	2	1039	3731	1869	1.95	222.60	31.11	2.21	19.20	1.05
6	-82	-1	983	2201	1618	1.74	220.29	31.56	2.71	17.59	1.18
10	-84	2	1089	3103	1634	1.79	217.21	30.82	2.35	18.38	1.14
16	-89	2	994	2888	1379	1.53	217.21	31.03	2.32	17.08	1.33
20	-94	1	1089	2618	1660	1.72	222.60	31.56	5.71	19.04	1.19
21	-92	3	1037	1542	1254	1.48	222.60	30.60	0.60	16.80	1.39
26	-98	4	976	1364	1162	1.32	222.60	30.52	2.36	15.51	1.55
30	-101	4	961	1670	1244	1.40	225.68	31.01	0.82	16.44	1.46
36	-109	3	1127	1562	1327	1.52	221.83	30.58	2.02	17.68	1.35
40	-112	4	1315	2352	1737	1.94	224.91	28.93	2.38	27.68	1.06
46	-119	3	1370	2040	1717	1.92	248.06	28.84	2.22	34.42	1.07
50	-124	1	1734	2917	2228	2.44	224.91	31.18	2.22	55.45	0.84
51	-124	2	1645	2501	2072	2.30	224.91	30.13	2.22	53.41	0.89
56	-131	-3	3393	5091	4307	4.54	226.45	31.08	2.42	115.42	0.45
60	-133	-5	11772	13685	12833	11.91	222.60	29.30	2.22	435.51	0.17

Table A.9: NB-IoT nRF9161 measurements with payload size 1024 B

KU	RSRP	SNR	RT min	RT max	RT avg	Transmit	Max I	Ready I	Standby I	Charge	DR
[dB]	[dBm]	[dB]	[ms]	[ms]	[ms]	[s]	[mA]	[mA]	[mA]	[uAh]	[kB/s]
0	-84	7	112	339	152	0.28	152.08	33.59	1.25	2.52	0.01
3	-88	7	115	350	153	0.27	171.18	33.74	1.22	2.48	0.01
6	-90	7	89	543	181	0.31	238.79	33.69	0.92	2.86	0.01
10	-95	7	122	322	151	0.28	231.85	33.70	1.24	2.66	0.01
16	-101	7	112	371	152	0.27	232.62	33.63	1.24	2.63	0.01
20	-105	7	126	313	152	0.27	230.31	33.81	0.93	2.66	0.01
21	-103	9	106	335	151	0.26	241.11	33.83	1.23	2.50	0.01
26	-108	9	108	348	154	0.38	234.16	35.30	0.92	3.80	0.01
30	-113	8	78	321	148	0.26	249.61	35.38	1.23	2.81	0.01
36	-120	6	108	323	158	0.26	261.99	35.52	0.92	3.07	0.01
40	-124	4	114	377	157	0.28	264.31	35.94	0.92	3.30	0.01
46	-130	-2	147	7057	942	0.62	269.74	35.40	1.27	9.50	0.00

Table A.10: LTE-M nRF9161 measurements with payload size 0 B

KU	RSRP	SNR	RT min	RT max	RT avg	Transmit	Max I	Ready I	Standby I	Charge	DR
[dB]	[dBm]	[dB]	[ms]	[ms]	[ms]	[s]	[mA]	[mA]	[mA]	[uAh]	[kB/s]
0	-84	7	108	159	133	0.27	84.52	33.59	1.25	2.54	0.48
3	-88	7	112	167	133	0.28	80.74	33.74	1.22	2.64	0.46
6	-90	7	109	149	132	0.27	82.25	33.69	0.92	2.57	0.47
10	-95	7	110	173	139	0.27	92.84	33.70	1.24	2.62	0.47
16	-101	7	115	171	142	0.27	146.75	33.63	1.24	2.63	0.47
20	-105	7	102	154	129	0.27	221.83	33.81	0.93	2.70	0.47
21	-103	9	108	201	148	0.28	149.03	33.83	1.23	2.68	0.46
26	-108	9	116	148	132	0.27	231.08	35.30	0.92	2.86	0.47
30	-113	8	111	162	133	0.27	246.52	35.38	1.23	2.91	0.48
36	-120	6	123	196	141	0.25	262.77	35.52	0.92	3.03	0.51
40	-124	4	110	202	149	0.30	265.09	35.94	0.92	3.64	0.43
46	-130	-2	296	578	384	0.56	270.51	35.40	1.27	9.07	0.23

Table A.11: LTE-M nRF9161 measurements with payload size 64 B

KU	RSRP	SNR	RT min	RT max	RT avg	Transmit	Max I	Ready I	Standby I	Charge	DR
[dB]	[dBm]	[dB]	[ms]	[ms]	[ms]	[s]	[mA]	[mA]	[mA]	[uAh]	[kB/s]
0	-84	7	246	371	304	0.47	83.76	33.59	1.25	4.45	4.37
3	-88	7	272	382	316	0.49	89.05	33.74	1.22	4.63	4.21
6	-90	7	253	346	303	0.48	94.35	33.69	0.92	4.59	4.27
10	-95	7	249	345	298	0.46	106.46	33.70	1.24	4.44	4.45
16	-101	7	246	409	302	0.48	163.53	33.63	1.24	4.77	4.29
20	-105	7	296	441	355	0.54	235.71	33.81	0.93	5.68	3.81
21	-103	9	200	300	272	0.44	237.25	33.83	1.23	4.62	4.70
26	-108	9	240	375	305	0.48	238.79	35.30	0.92	5.37	4.28
30	-113	8	241	377	312	0.48	240.34	35.38	1.23	5.59	4.26
36	-120	6	364	470	414	0.61	255.80	35.52	0.92	8.28	3.38
40	-124	4	459	650	553	0.73	265.09	35.94	0.92	10.97	2.82
46	-130	-2	2383	3421	2868	3.08	272.84	35.40	1.27	62.66	0.67

Table A.12: LTE-M nRF9161 measurements with payload size 1024 B

B Result of measurement - charts

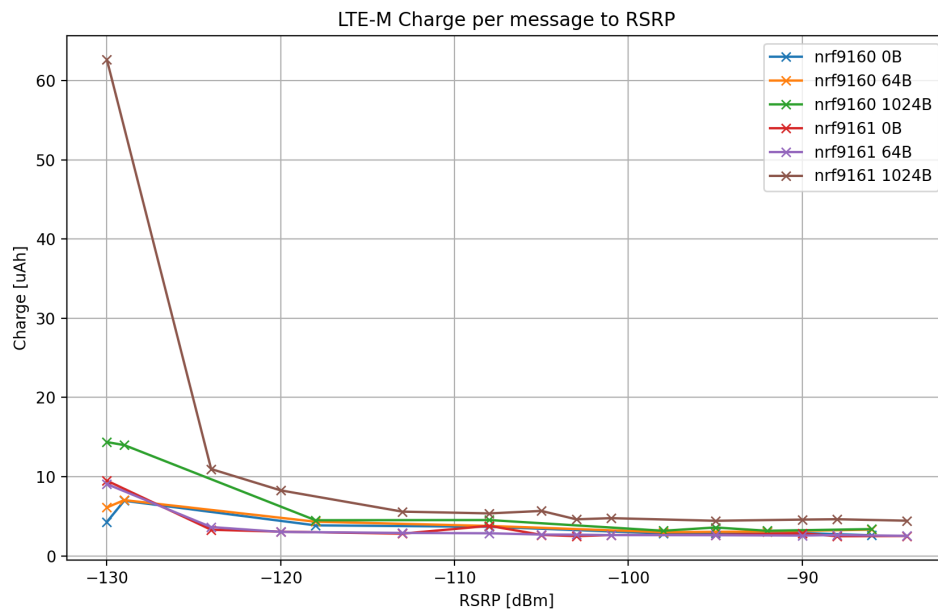


Fig. B.1: Charge per message to RSRP

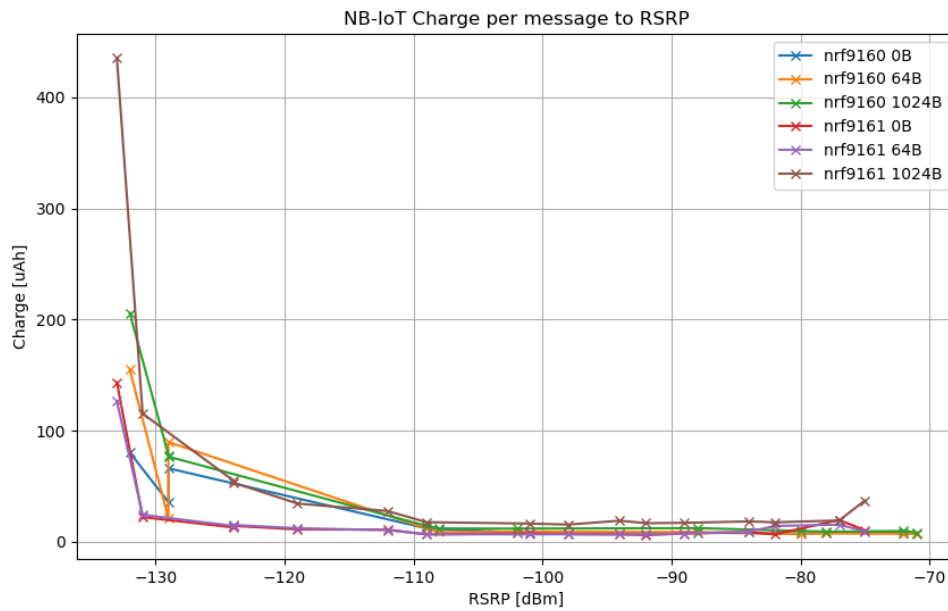


Fig. B.2: Charge per message to RSRP

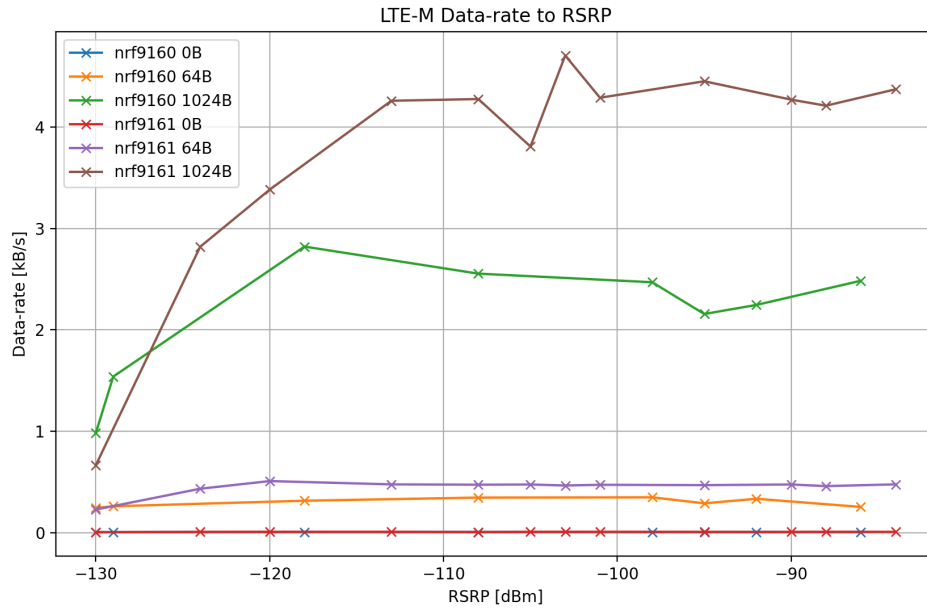


Fig. B.3: Data-rate to RSRP

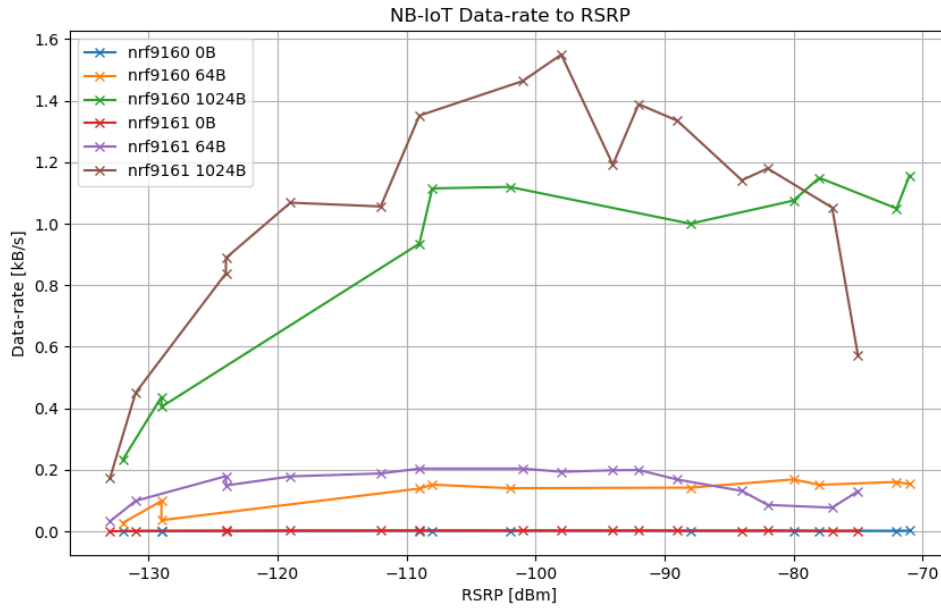


Fig. B.4: Data-rate to RSRP

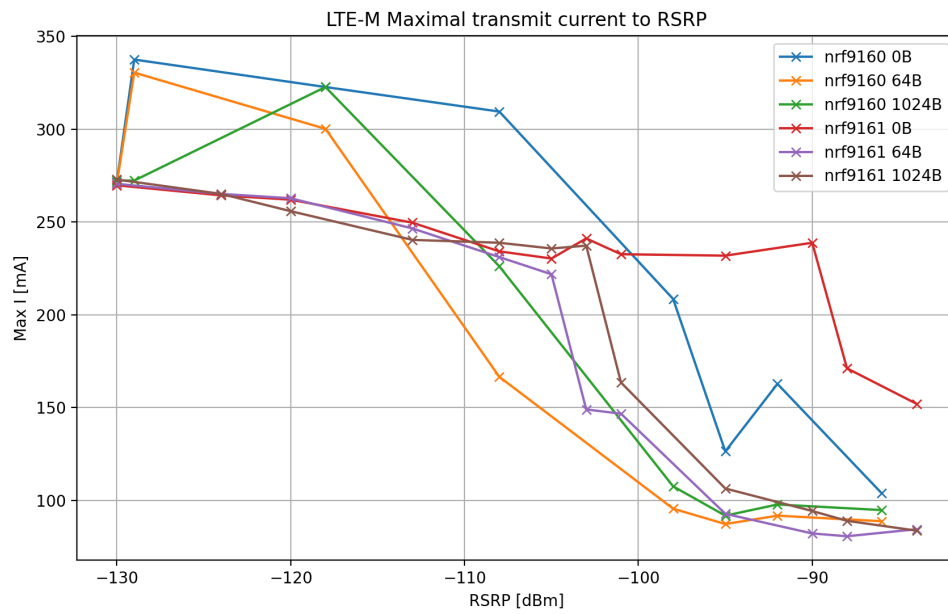


Fig. B.5: Maximal transmit current to RSRP

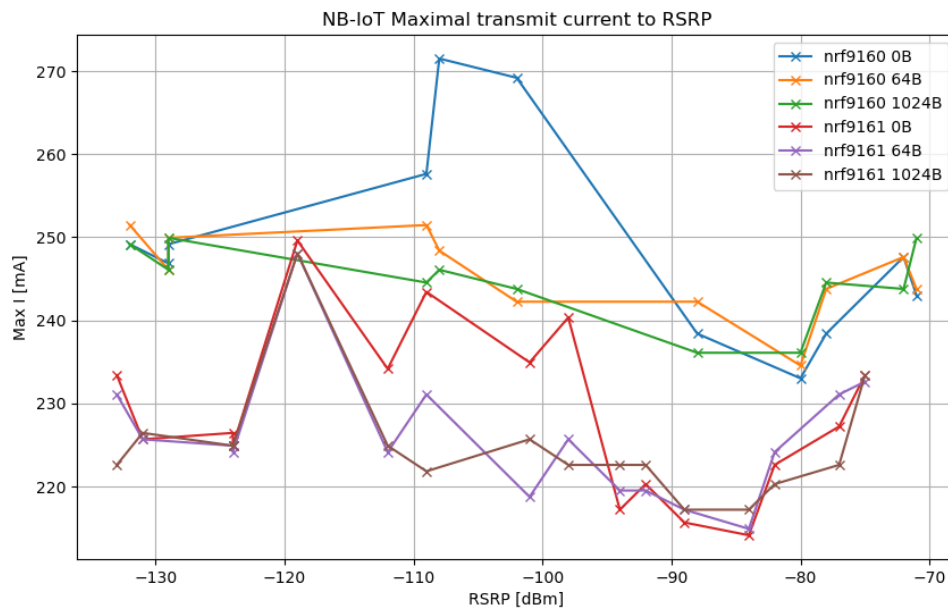


Fig. B.6: Maximal transmit current to RSRP

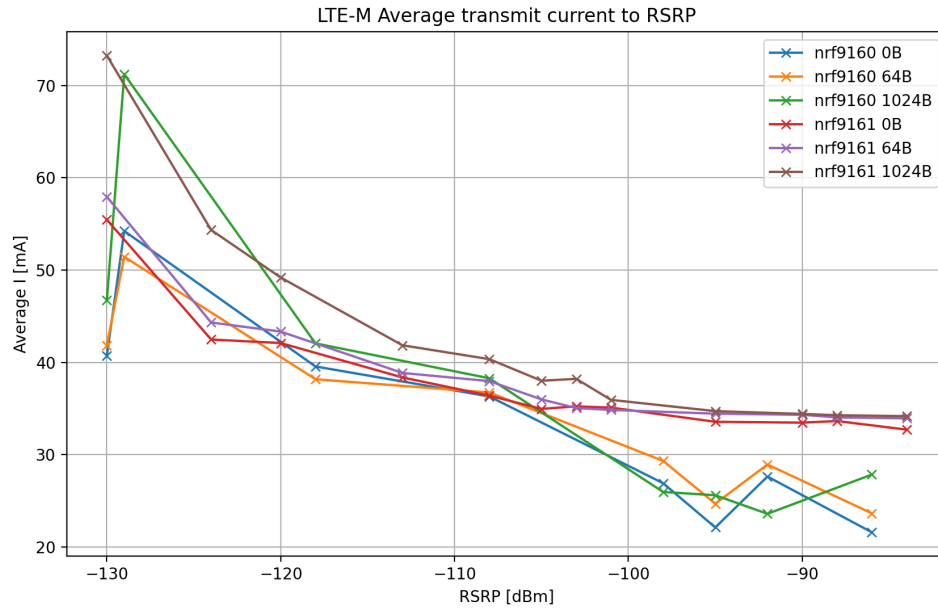


Fig. B.7: Average transmit current to RSRP

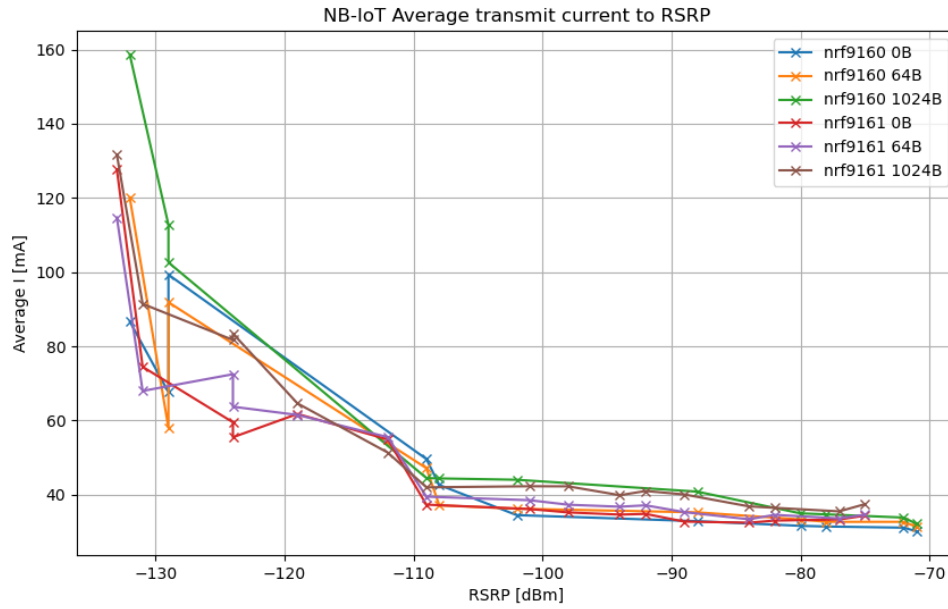


Fig. B.8: Average transmit current to RSRP

B.1 nRF9161

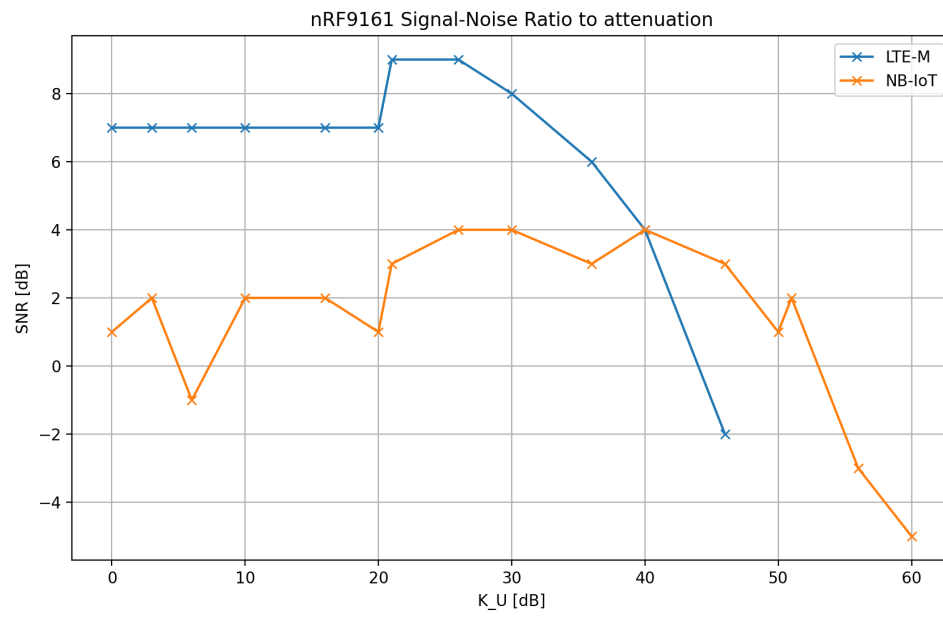


Fig. B.9: Signal-Noise Ratio to attenuation

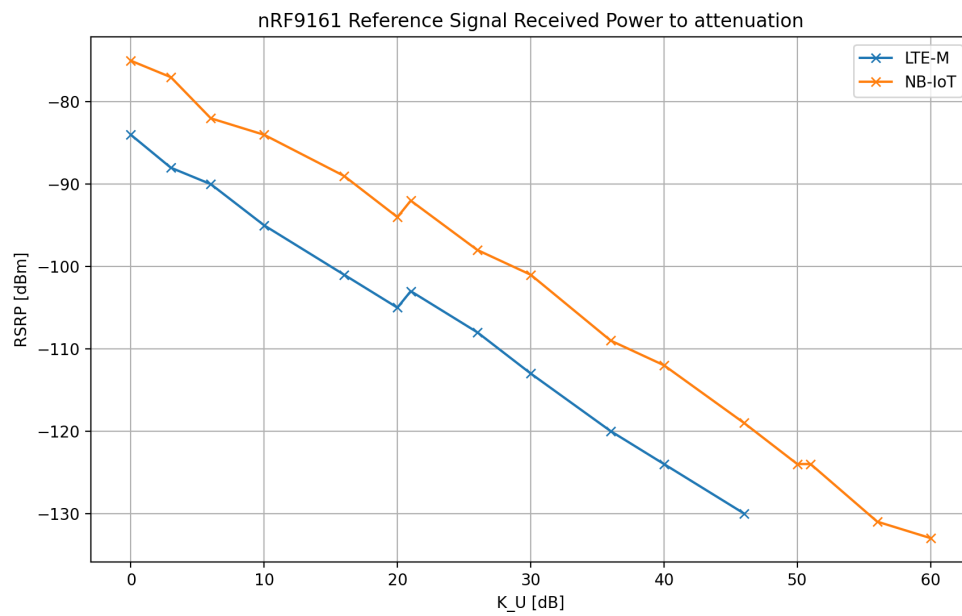


Fig. B.10: Reference Signal Received Power to attenuation

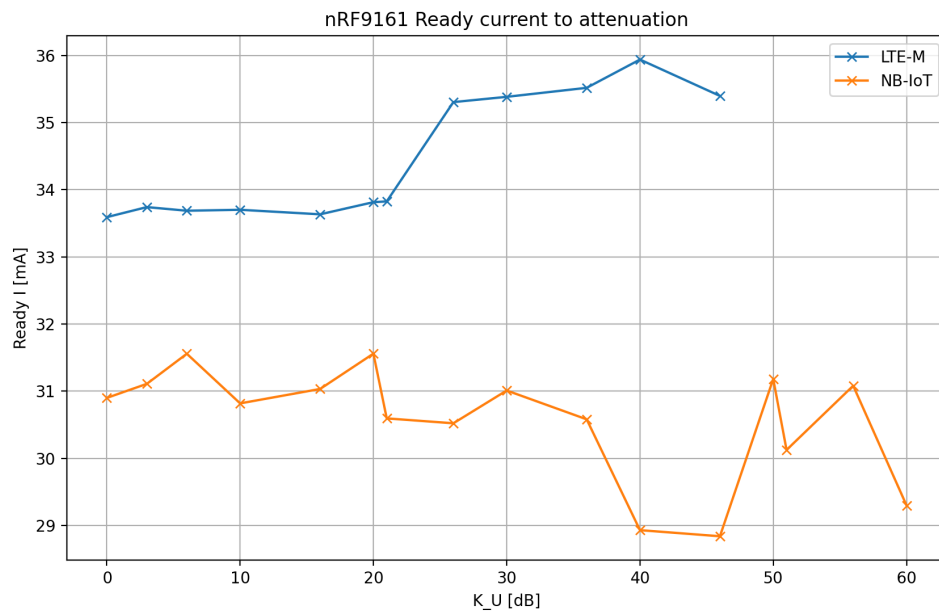


Fig. B.11: Ready current to attenuation

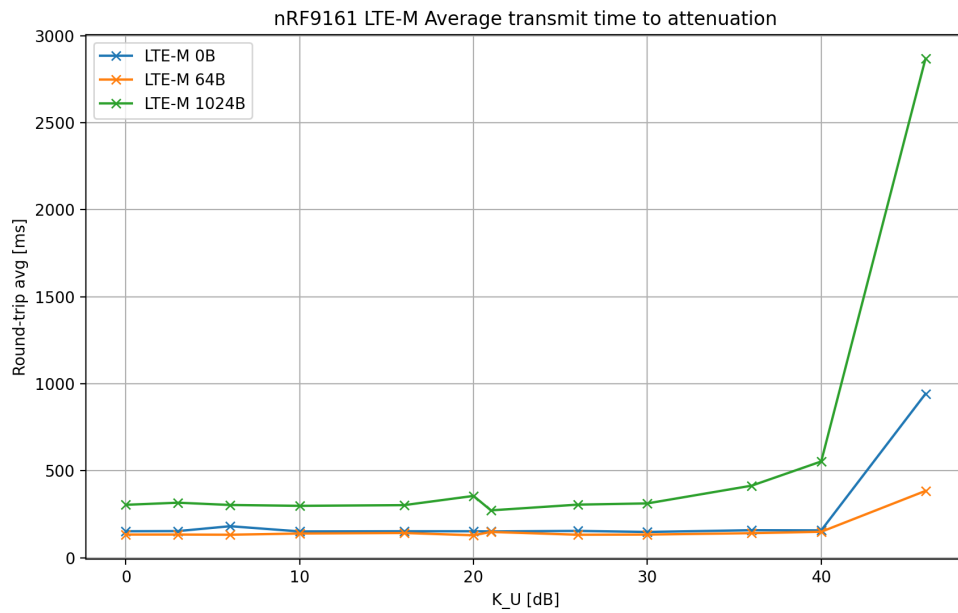


Fig. B.12: nRF9161 LTE-M Average transmit time to attenuation

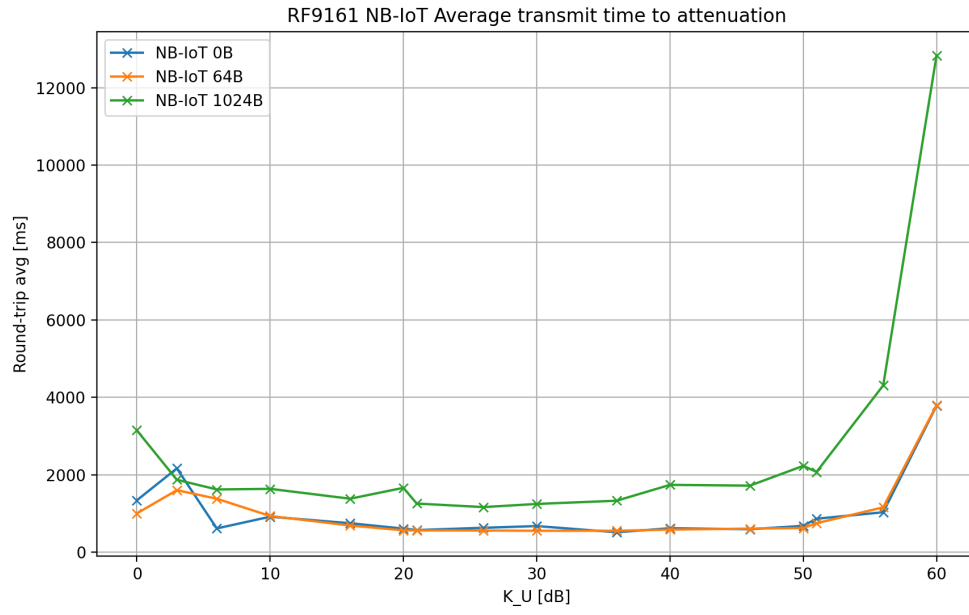


Fig. B.13: RF9161 NB-IoT Average transmit time to attenuation

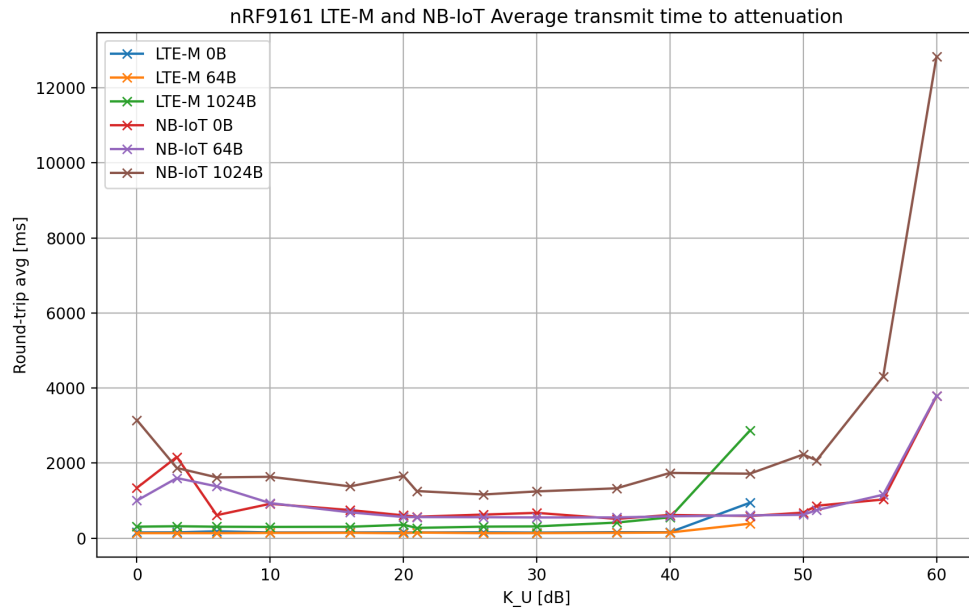


Fig. B.14: nRF9161 LTE-M and NB-IoT Average transmit time to attenuation

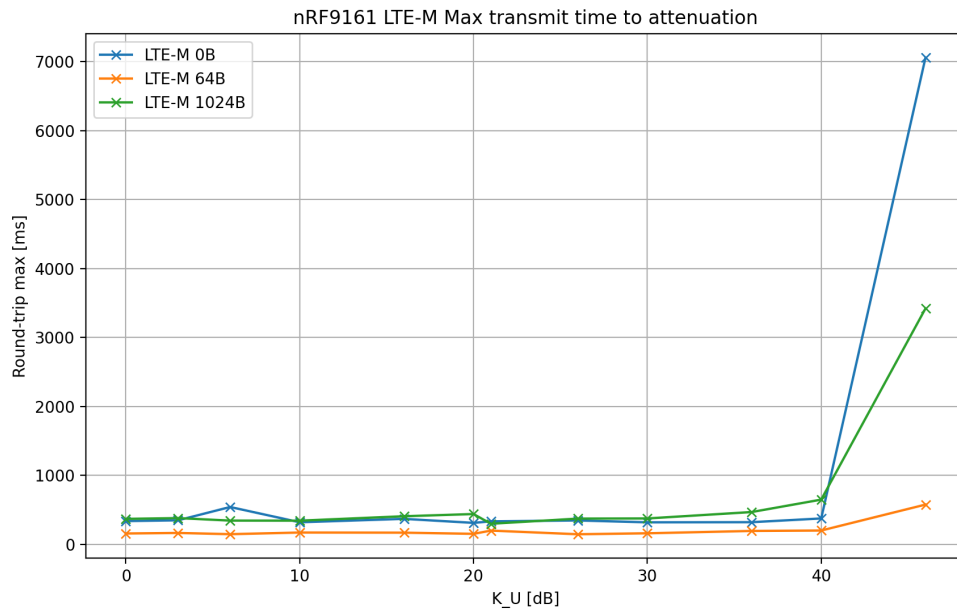


Fig. B.15: nRF9161 LTE-M Max transmit time to attenuation

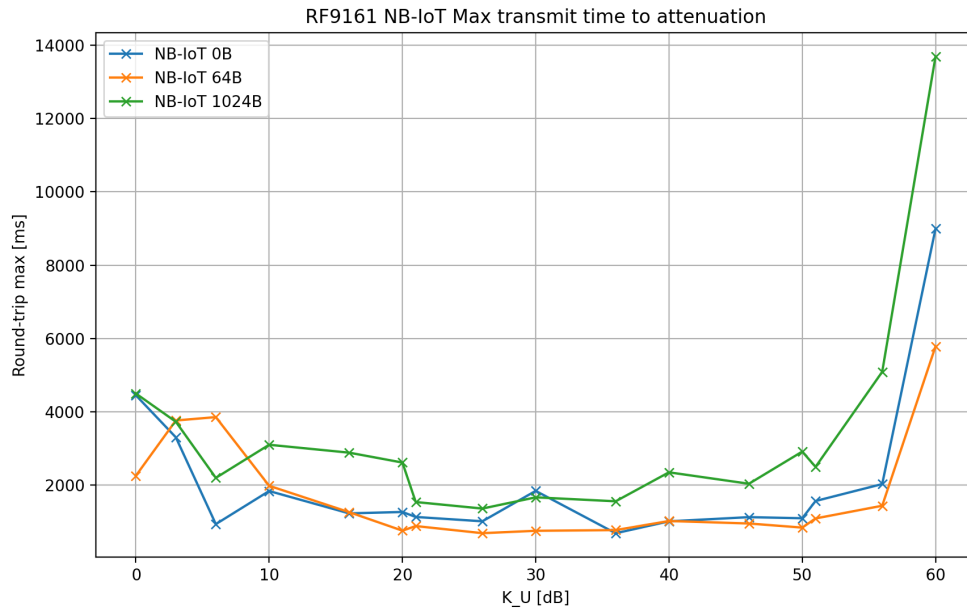


Fig. B.16: RF9161 NB-IoT Max transmit time to attenuation

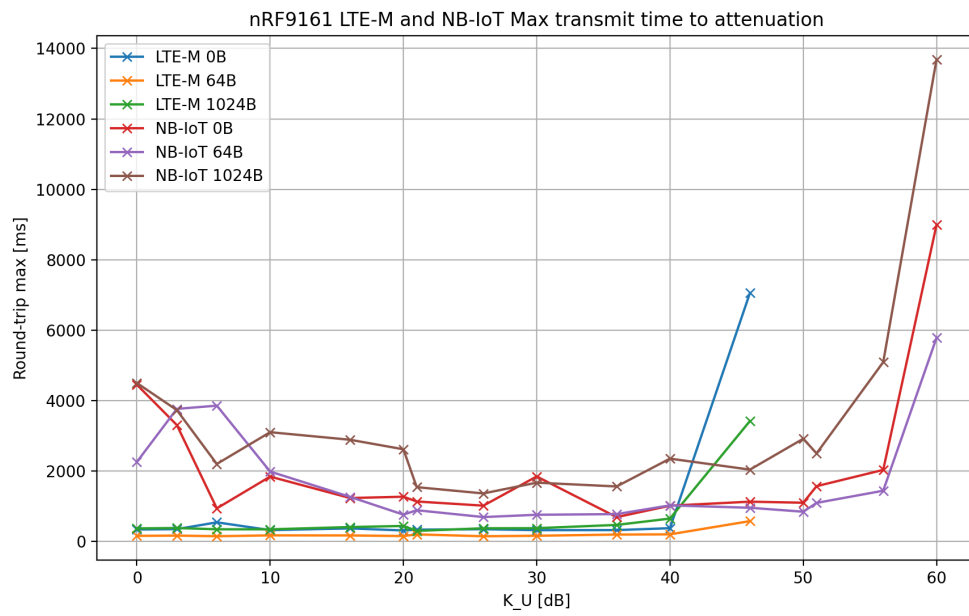


Fig. B.17: nRF9161 LTE-M and NB-IoT Max transmit time to attenuation

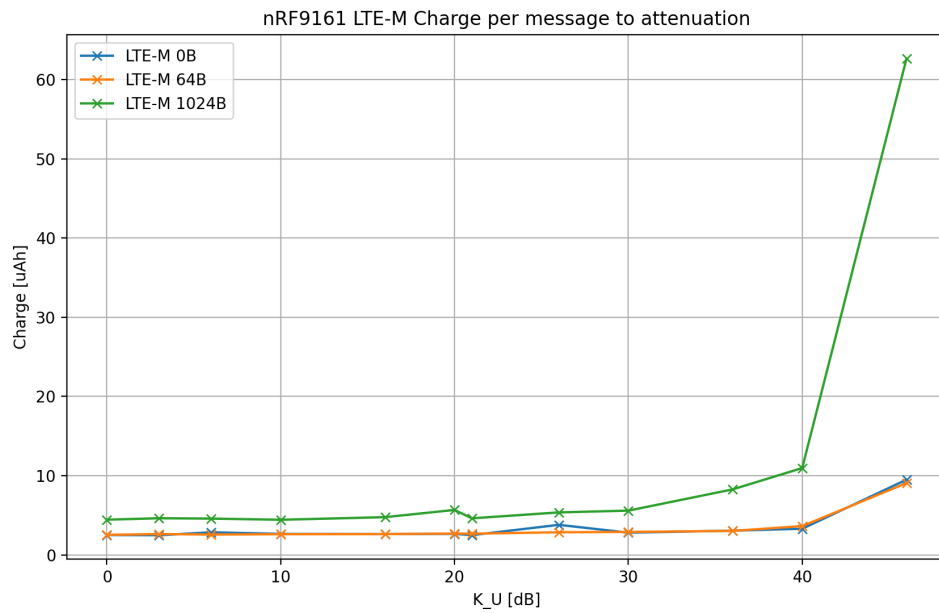


Fig. B.18: nRF9161 LTE-M Charge per message to attenuation

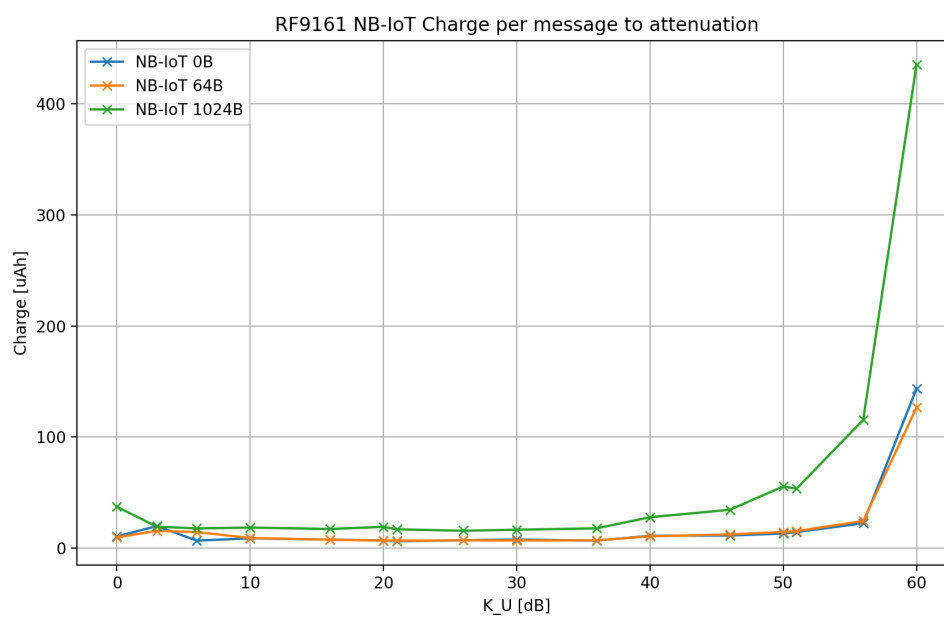


Fig. B.19: RF9161 NB-IoT Charge per message to attenuation

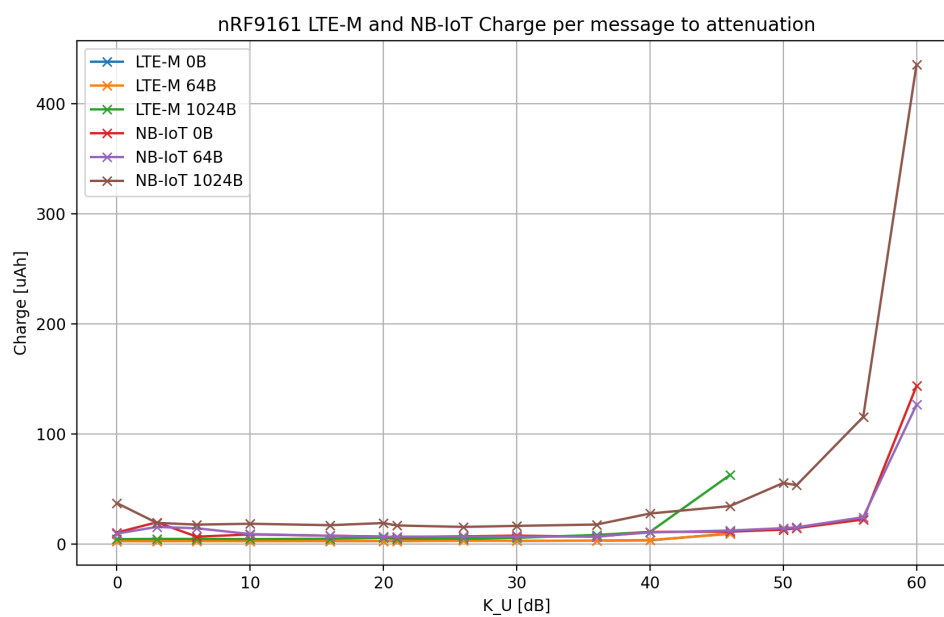


Fig. B.20: nRF9161 LTE-M and NB-IoT Charge per message to attenuation

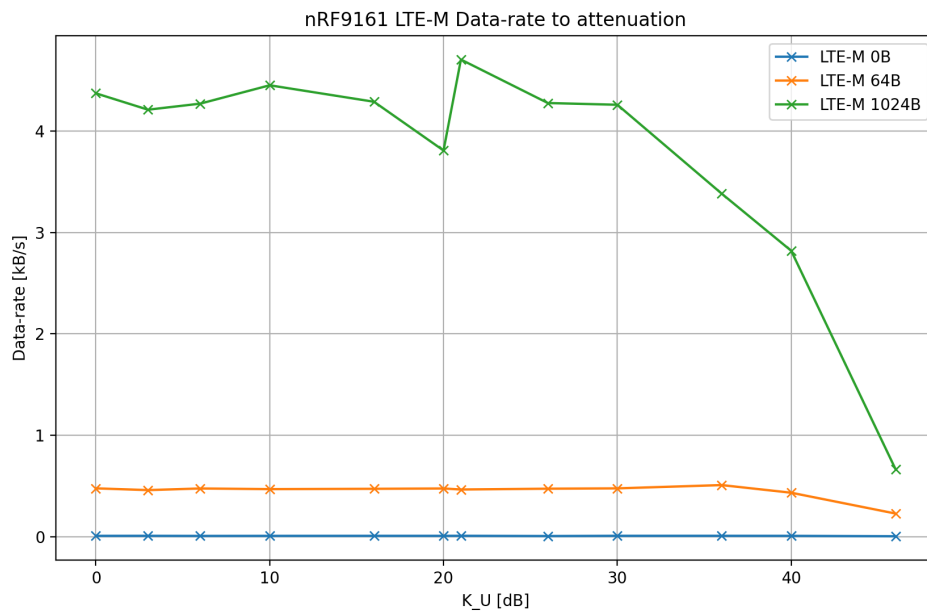


Fig. B.21: nRF9161 LTE-M Data-rate to attenuation

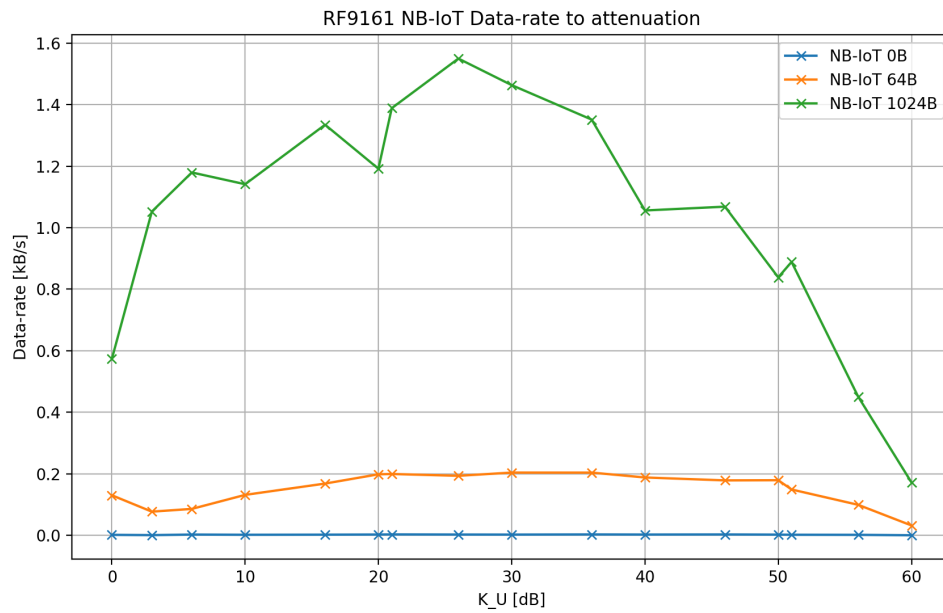


Fig. B.22: RF9161 NB-IoT Data-rate to attenuation

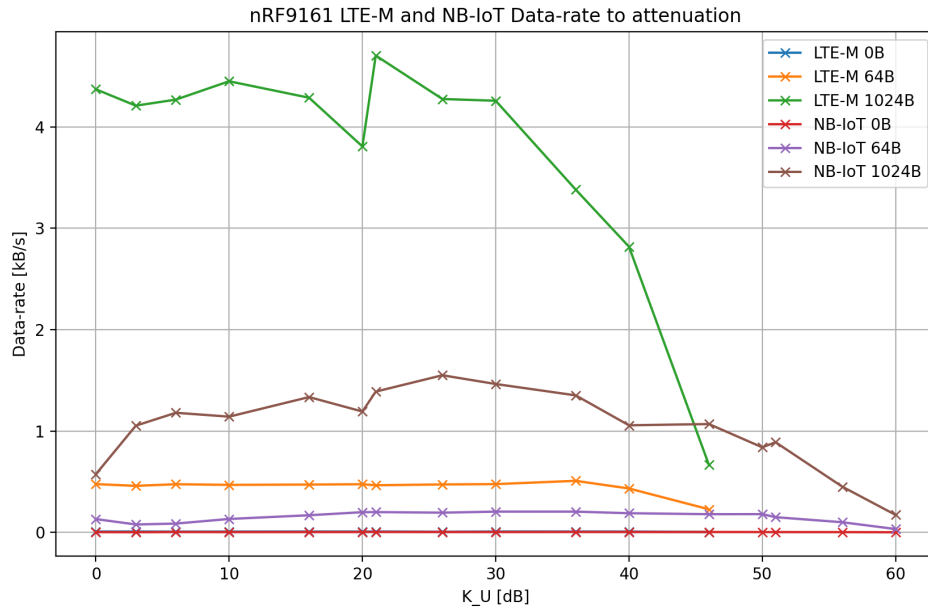


Fig. B.23: nRF9161 LTE-M and NB-IoT Data-rate to attenuation

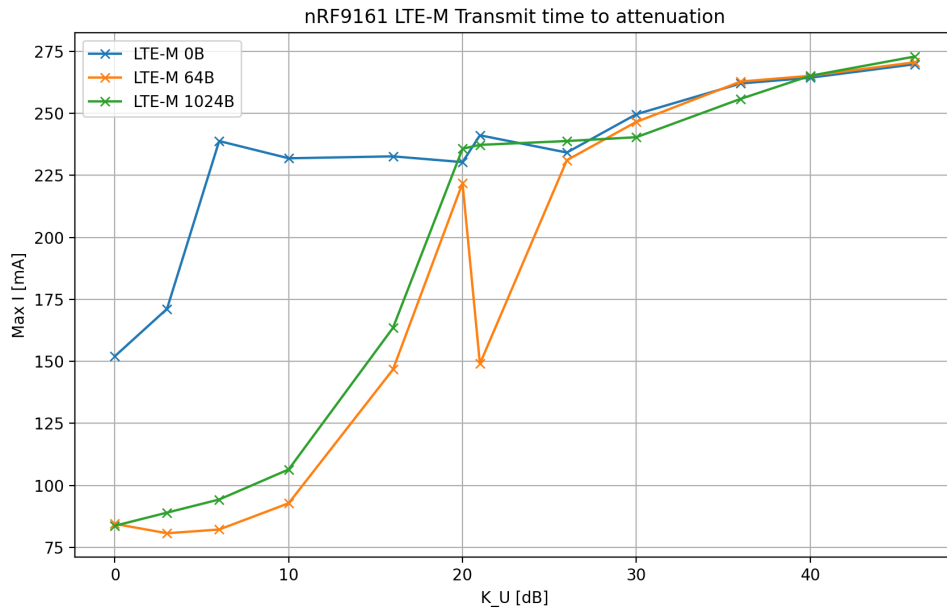


Fig. B.24: nRF9161 LTE-M Transmit time to attenuation

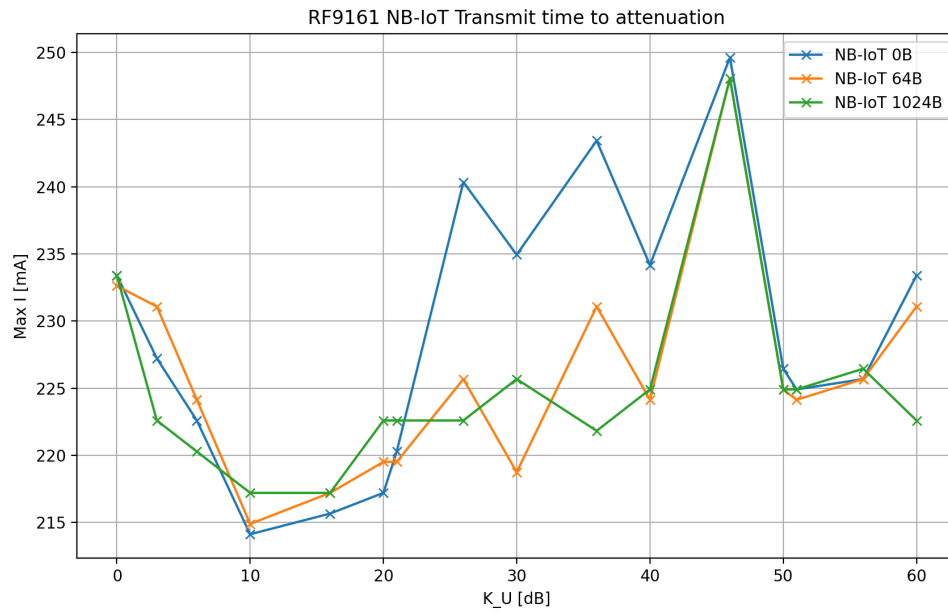


Fig. B.25: RF9161 NB-IoT Transmit time to attenuation

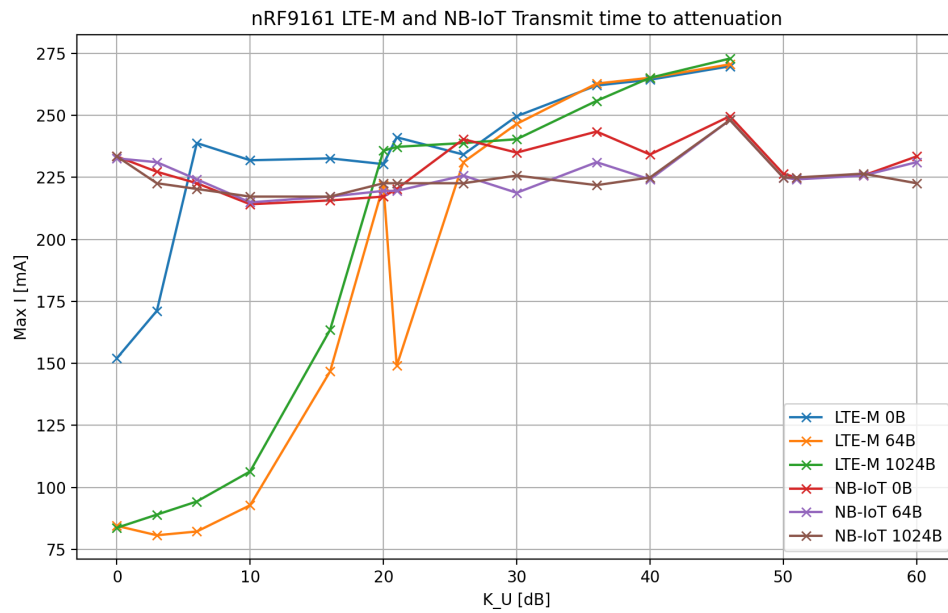


Fig. B.26: nRF9161 LTE-M and NB-IoT Transmit time to attenuation

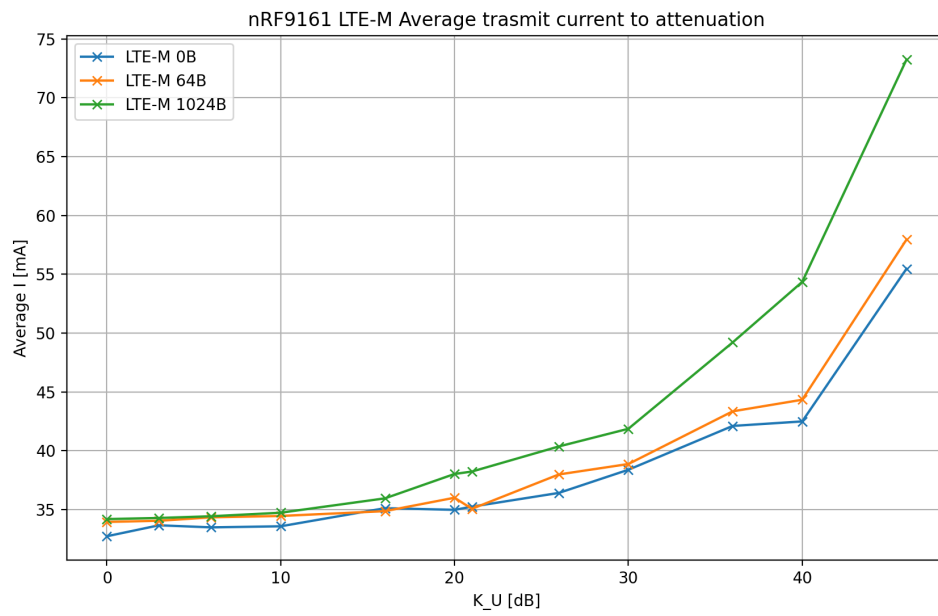


Fig. B.27: nRF9161 LTE-M Average transmit current to attenuation

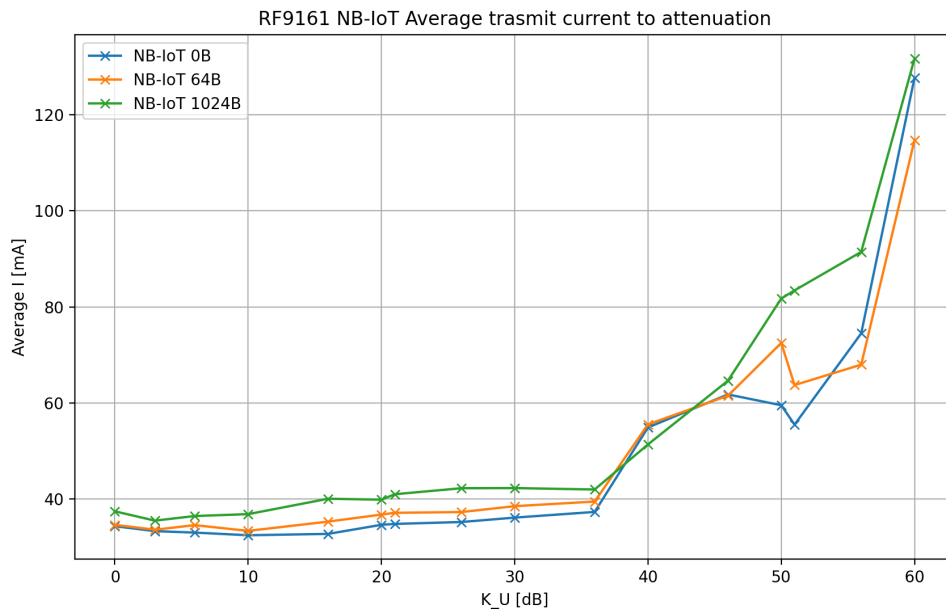


Fig. B.28: RF9161 NB-IoT Average transmit current to attenuation

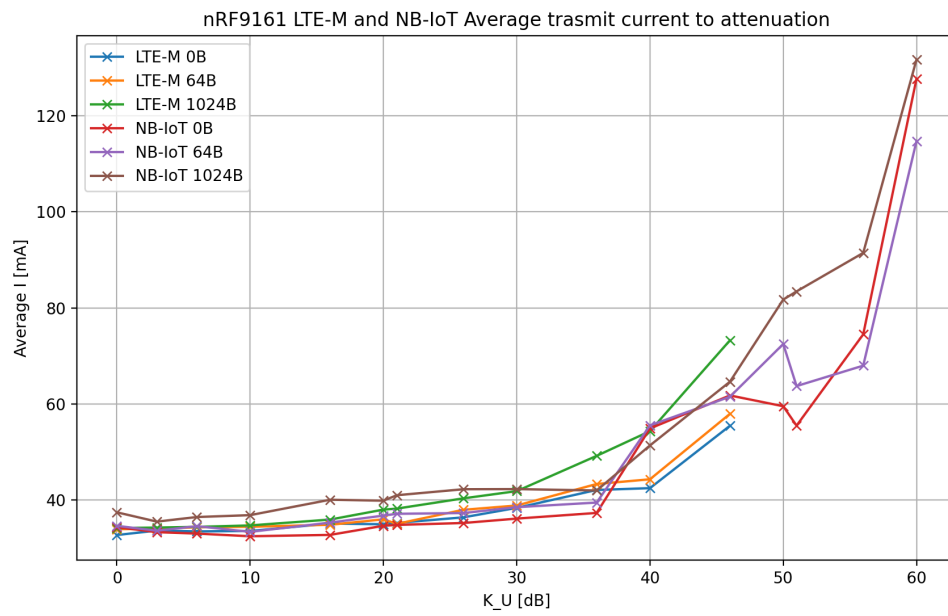


Fig. B.29: nRF9161 LTE-M and NB-IoT Average transmit current to attenuation

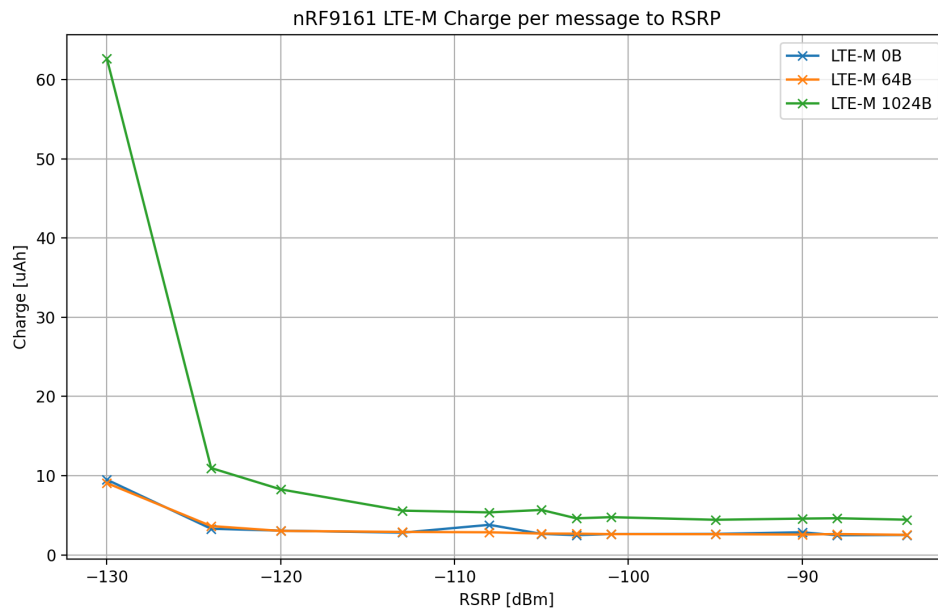


Fig. B.30: nRF9161 LTE-M Charge per message to RSRP

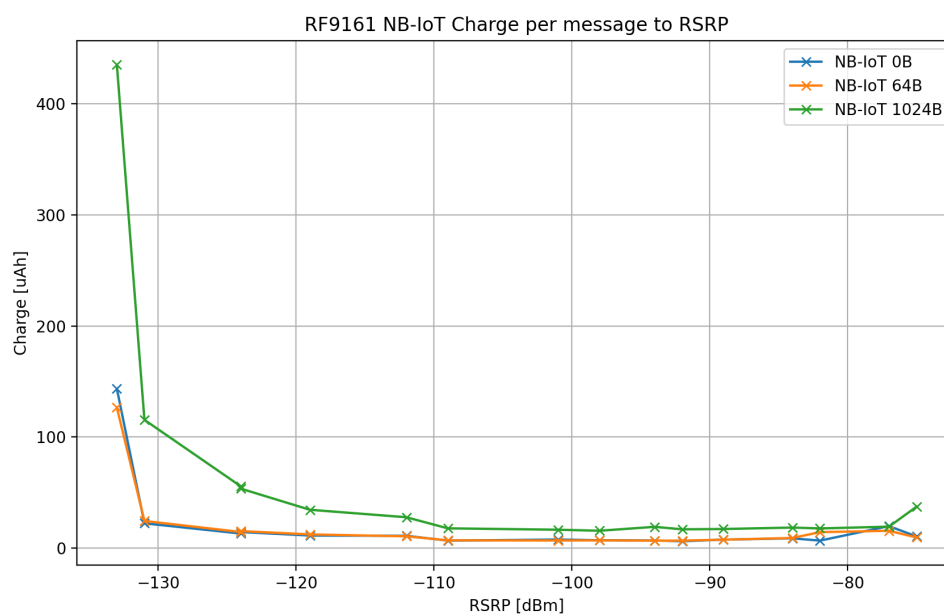


Fig. B.31: RF9161 NB-IoT Charge per message to RSRP

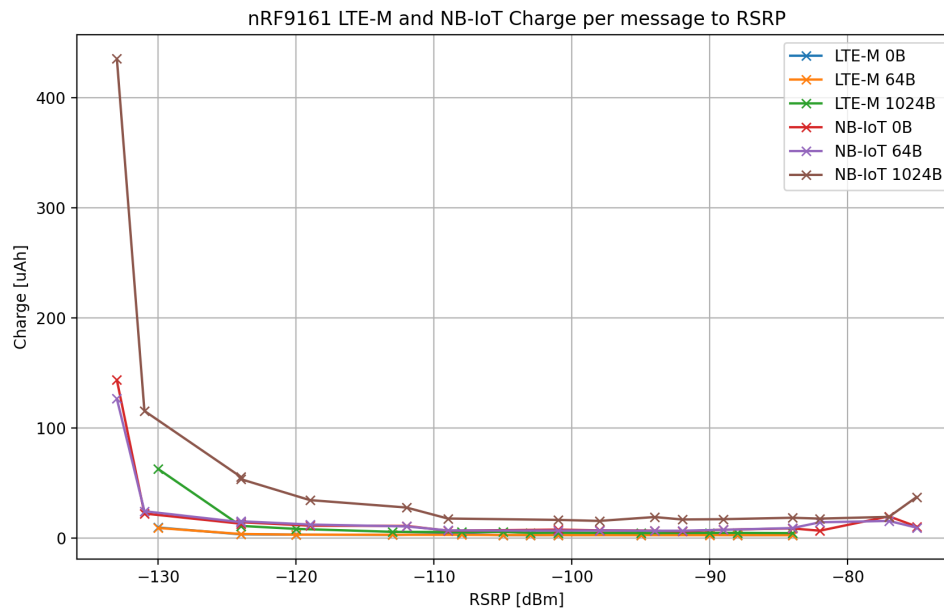


Fig. B.32: nRF9161 LTE-M and NB-IoT Charge per message to RSRP

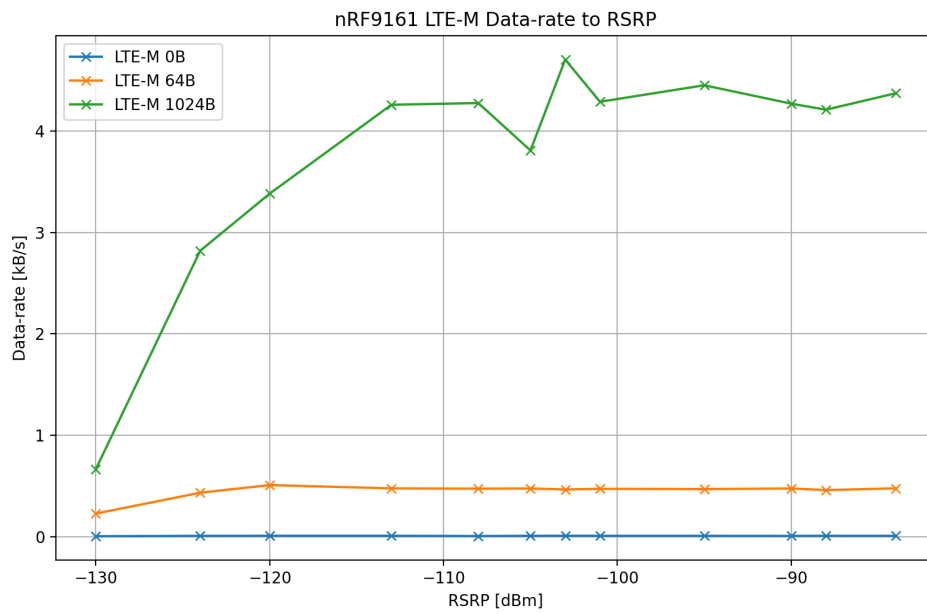


Fig. B.33: nRF9161 LTE-M Data-rate to RSRP

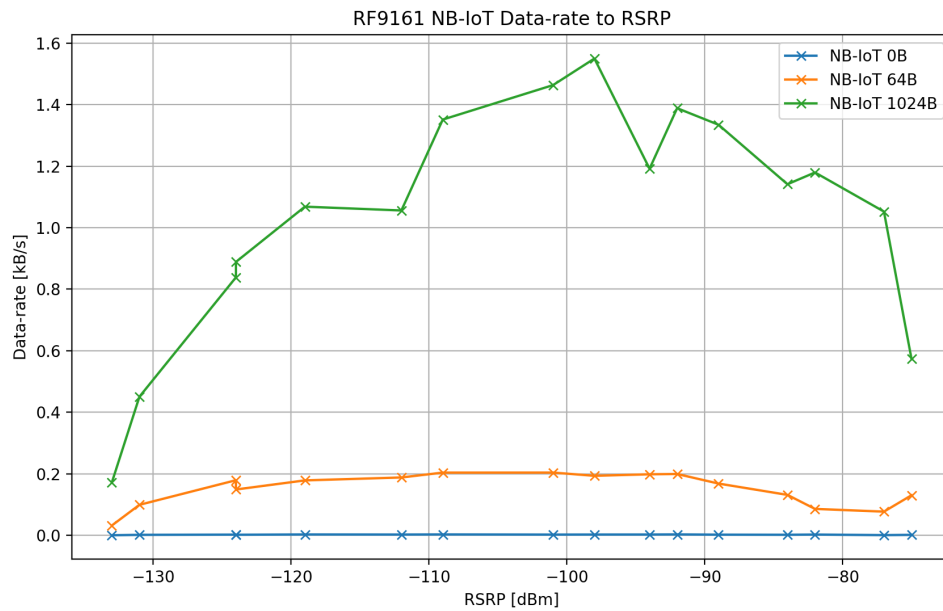


Fig. B.34: RF9161 NB-IoT Data-rate to RSRP

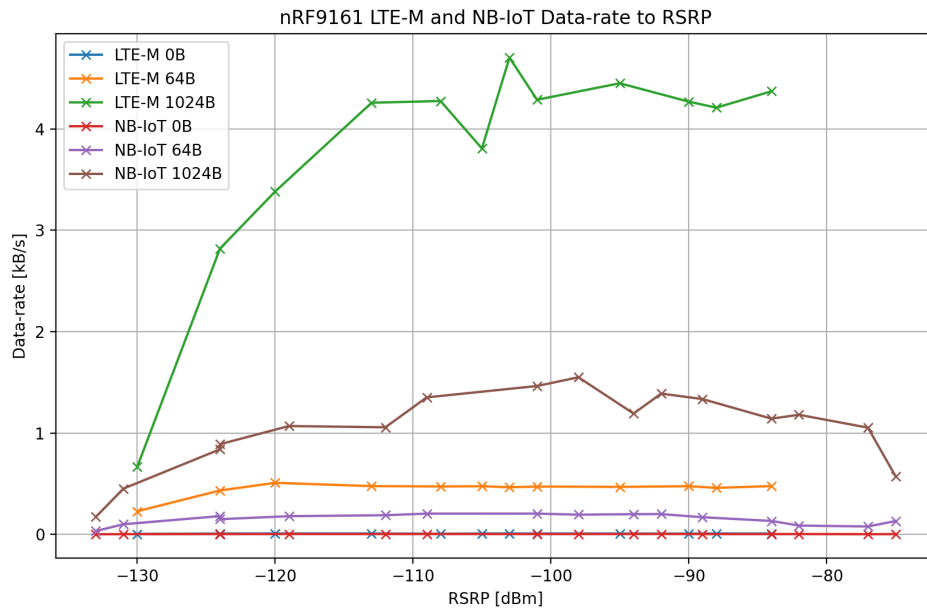


Fig. B.35: nRF9161 LTE-M and NB-IoT Data-rate to RSRP

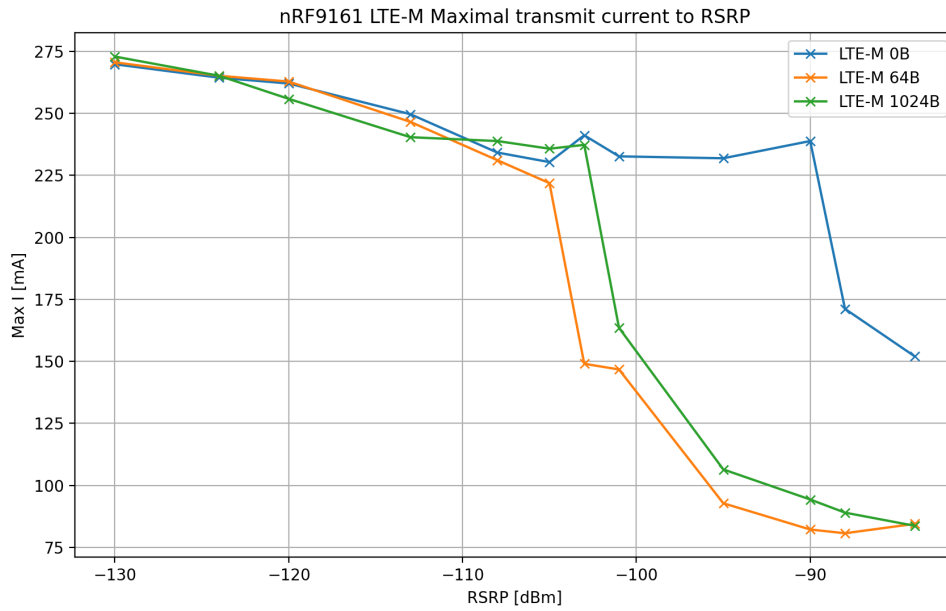


Fig. B.36: nRF9161 LTE-M Maximal transmit current to RSRP

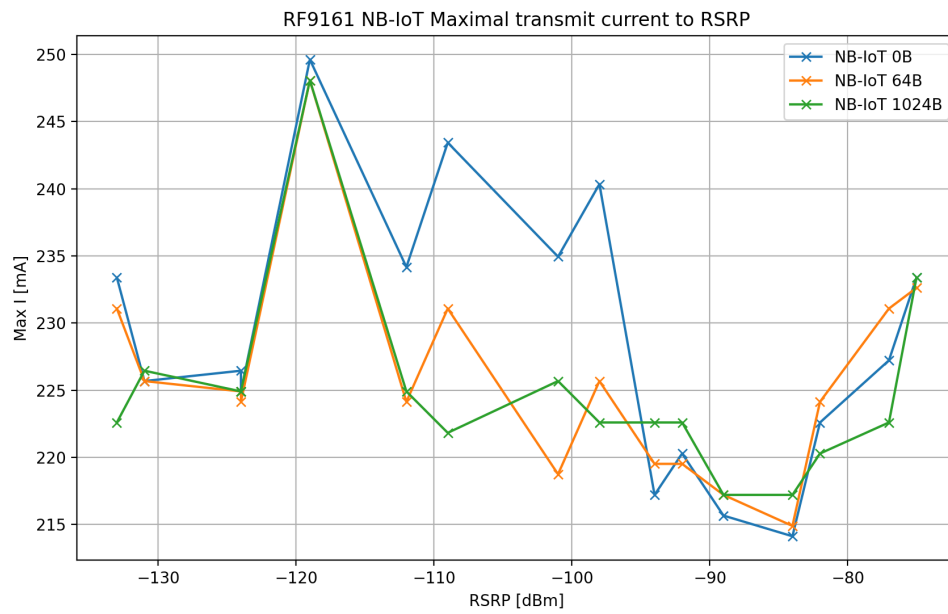


Fig. B.37: RF9161 NB-IoT Maximal transmit current to RSRP

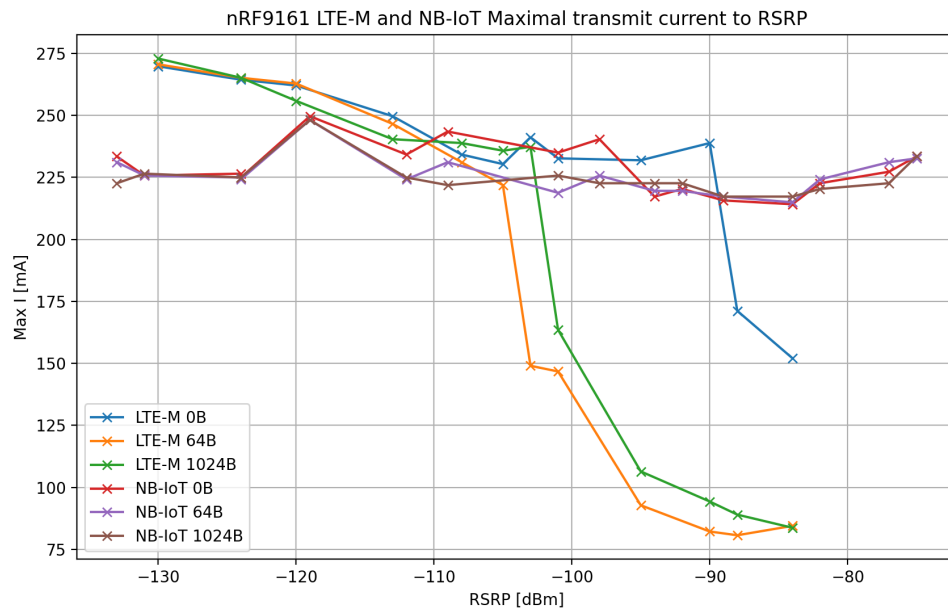


Fig. B.38: nRF9161 LTE-M and NB-IoT Maximal transmit current to RSRP

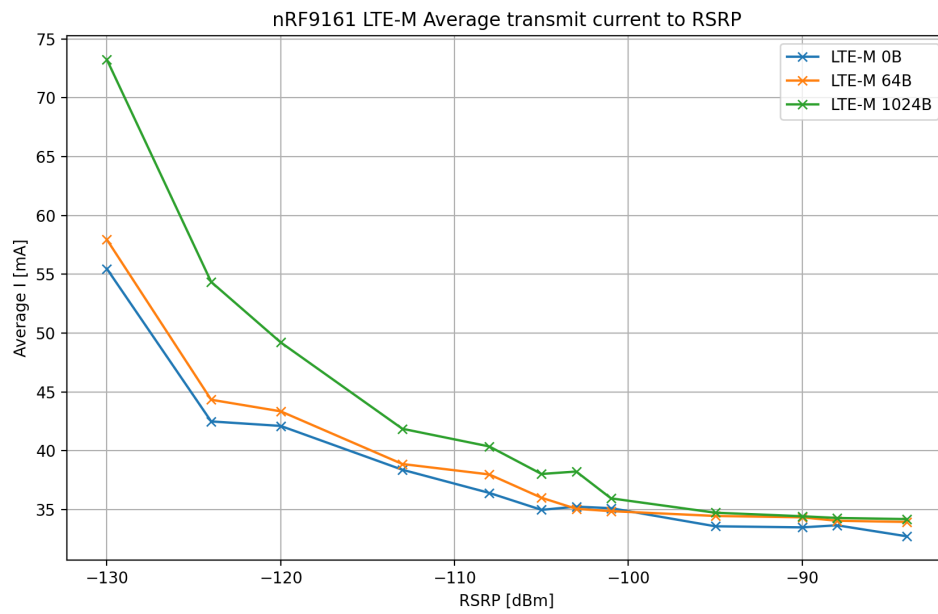


Fig. B.39: nRF9161 LTE-M Average transmit current to RSRP

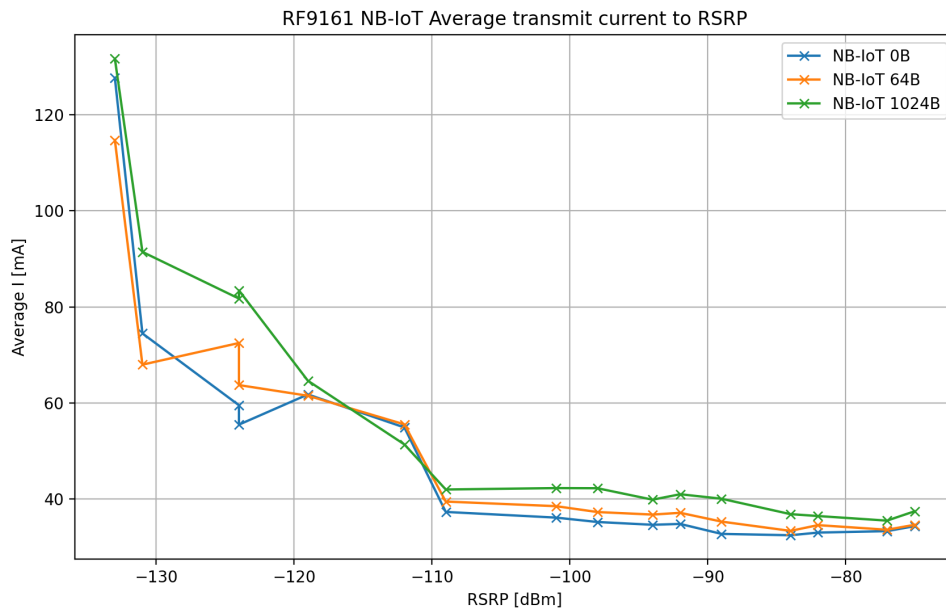


Fig. B.40: RF9161 NB-IoT Average transmit current to RSRP

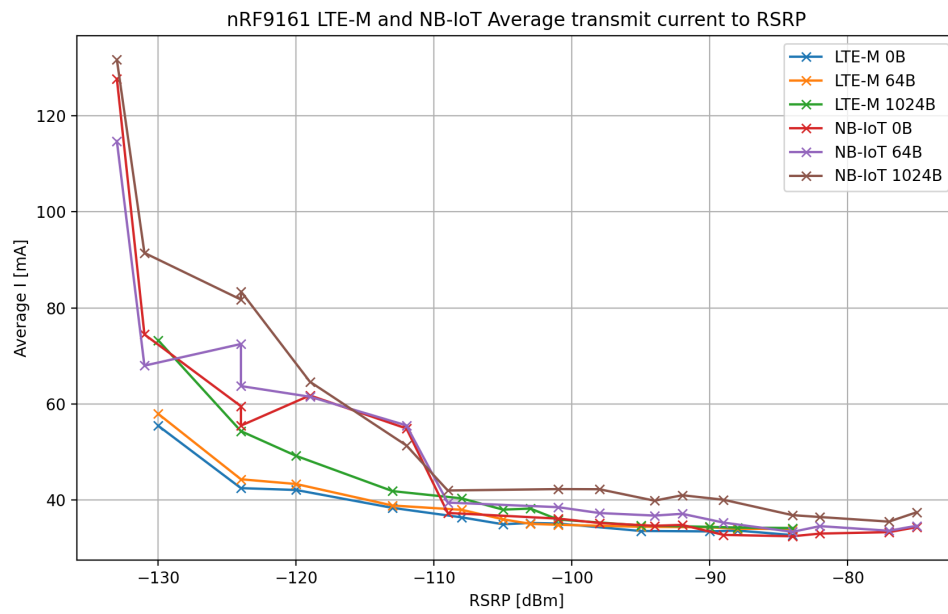


Fig. B.41: nRF9161 LTE-M and NB-IoT Average transmit current to RSRP

B.2 nRF9160

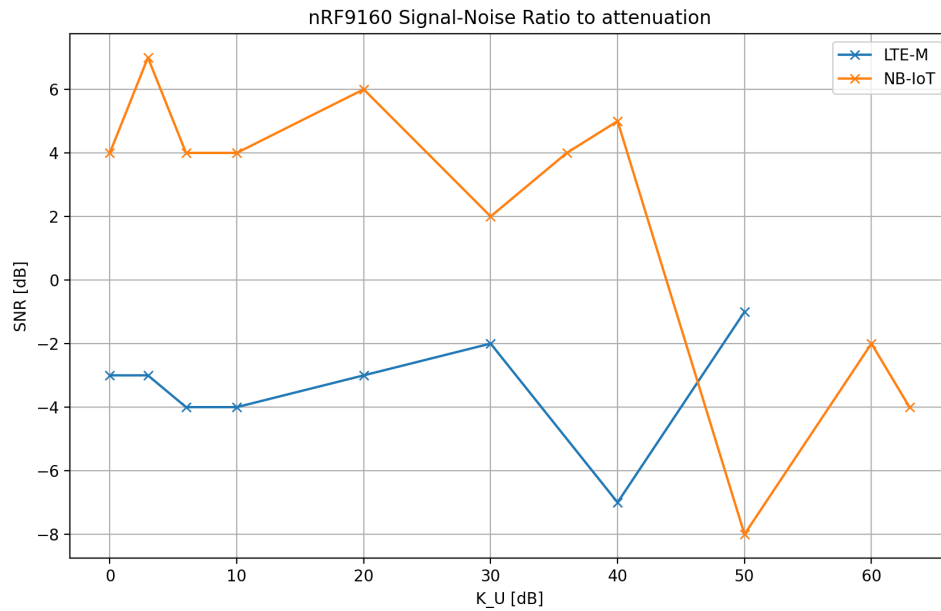


Fig. B.42: Signal-Noise Ratio to attenuation

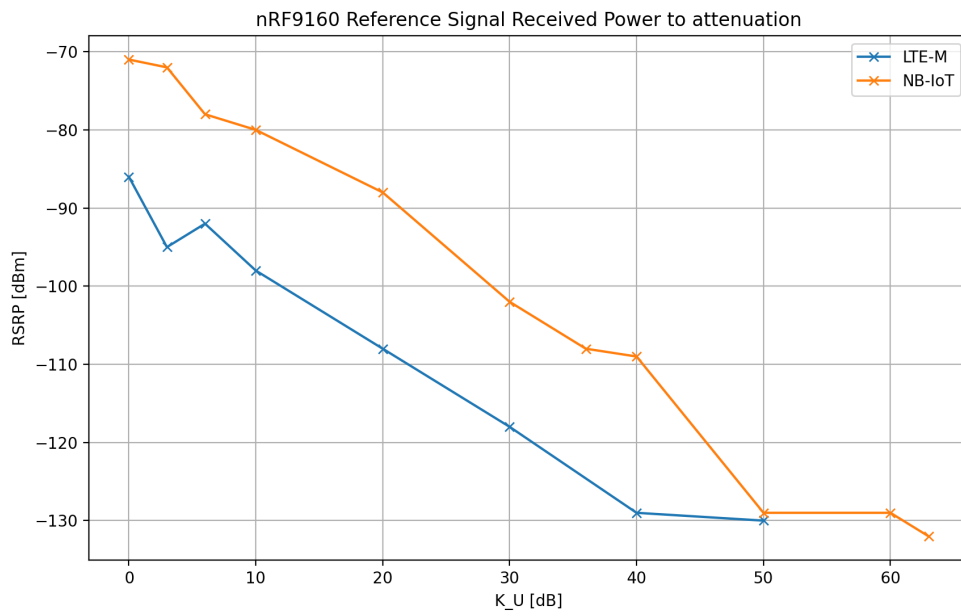


Fig. B.43: Reference Signal Received Power to attenuation

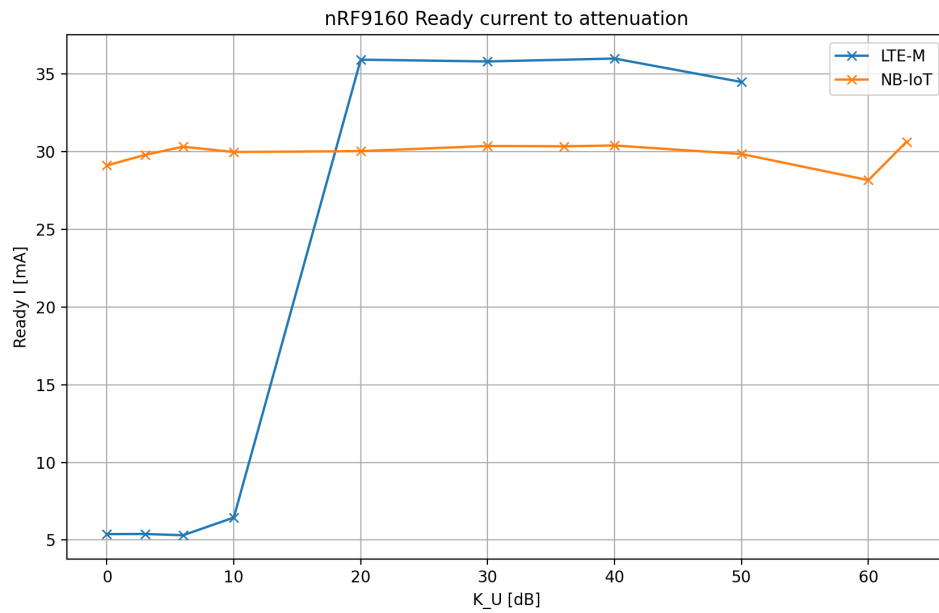


Fig. B.44: Ready current to attenuation

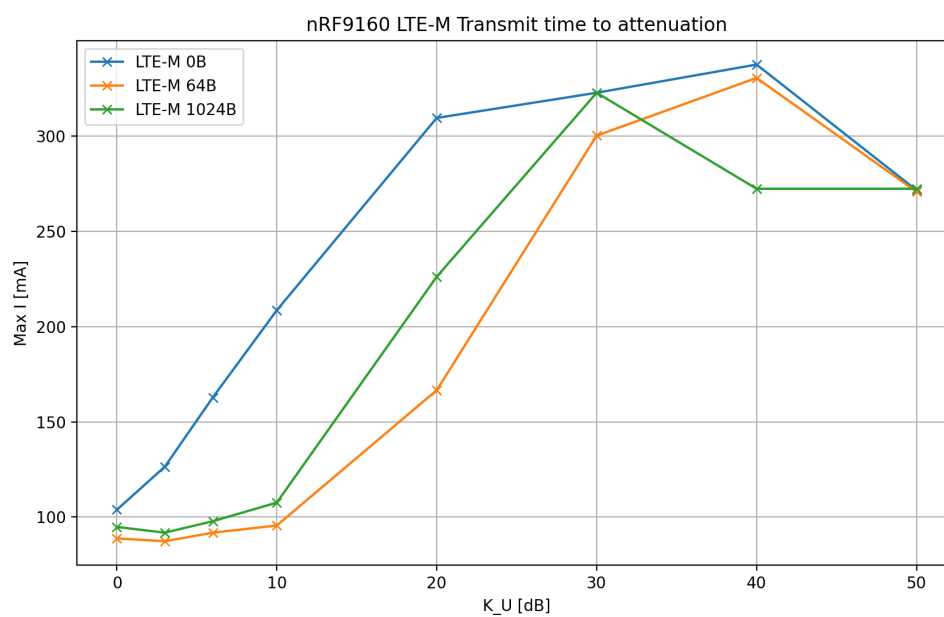


Fig. B.45: nRF9160 LTE-M Transmit time to attenuation

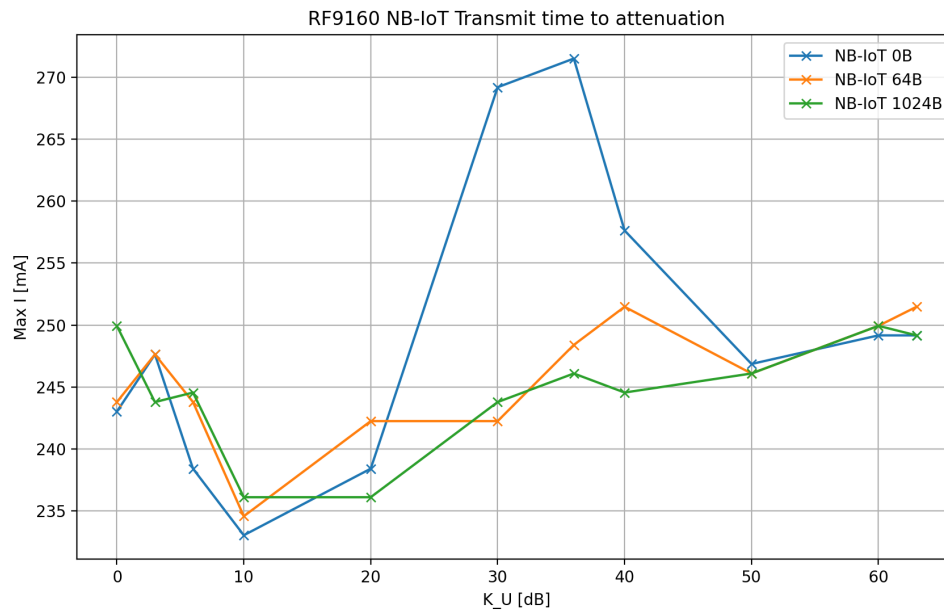


Fig. B.46: RF9160 NB-IoT Transmit time to attenuation

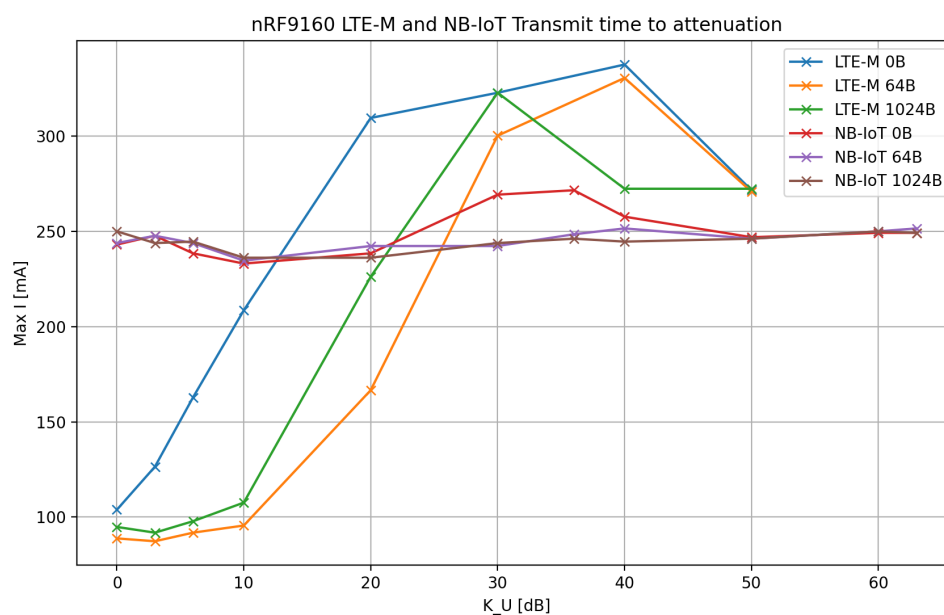


Fig. B.47: nRF9160 LTE-M and NB-IoT Transmit time to attenuation

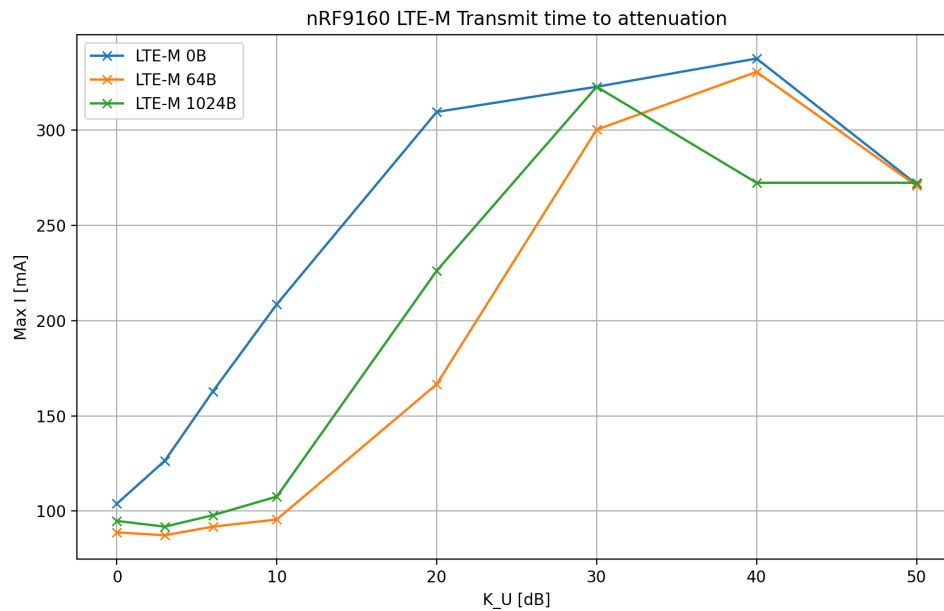


Fig. B.48: nRF9160 LTE-M Transmit time to attenuation

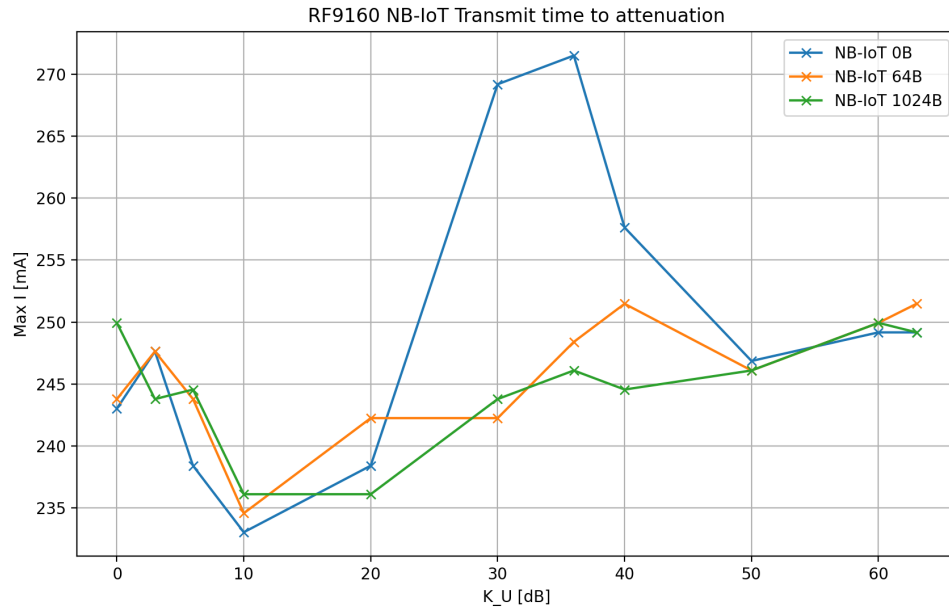


Fig. B.49: RF9160 NB-IoT Transmit time to attenuation

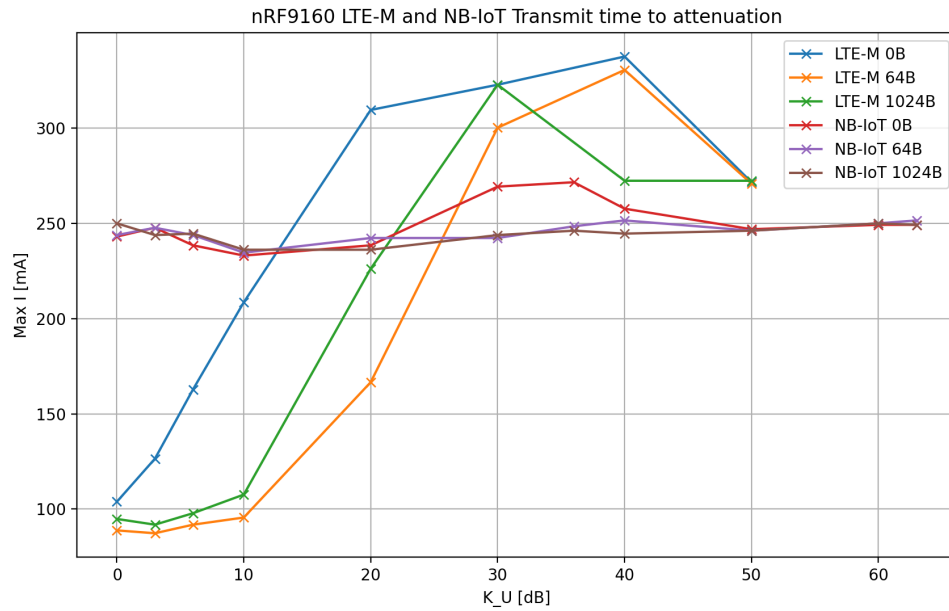


Fig. B.50: nRF9160 LTE-M and NB-IoT Transmit time to attenuation

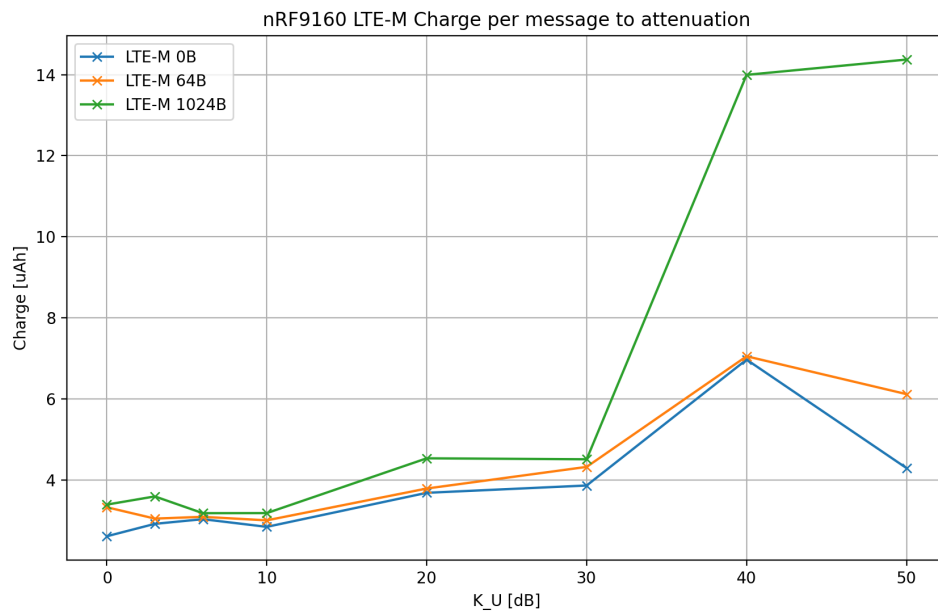


Fig. B.51: nRF9160 LTE-M Charge per message to attenuation

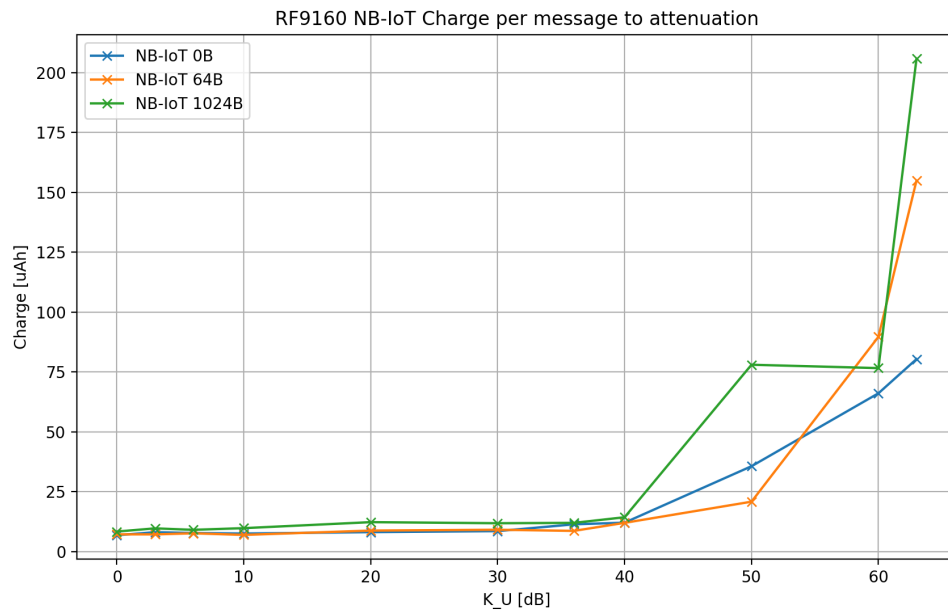


Fig. B.52: RF9160 NB-IoT Charge per message to attenuation

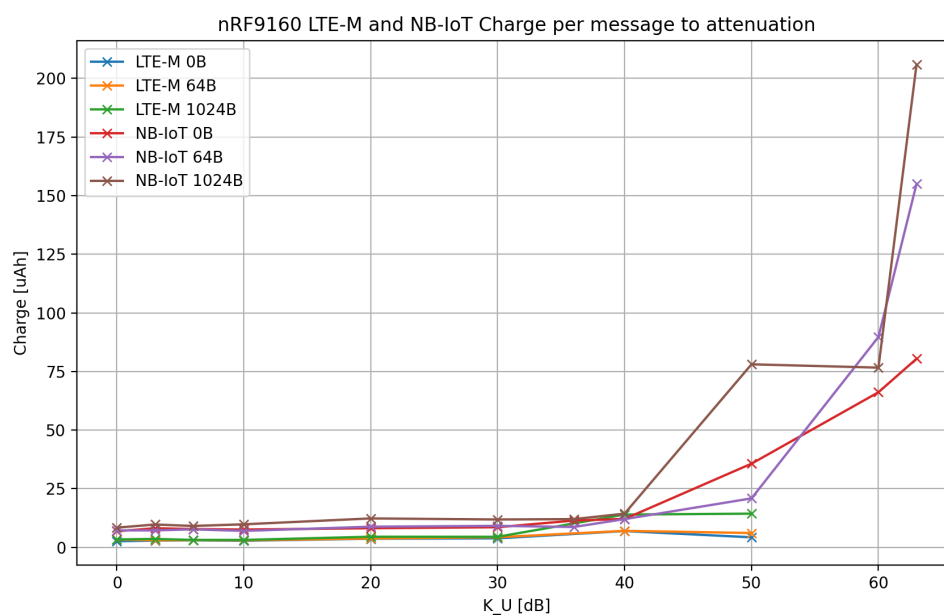


Fig. B.53: nRF9160 LTE-M and NB-IoT Charge per message to attenuation

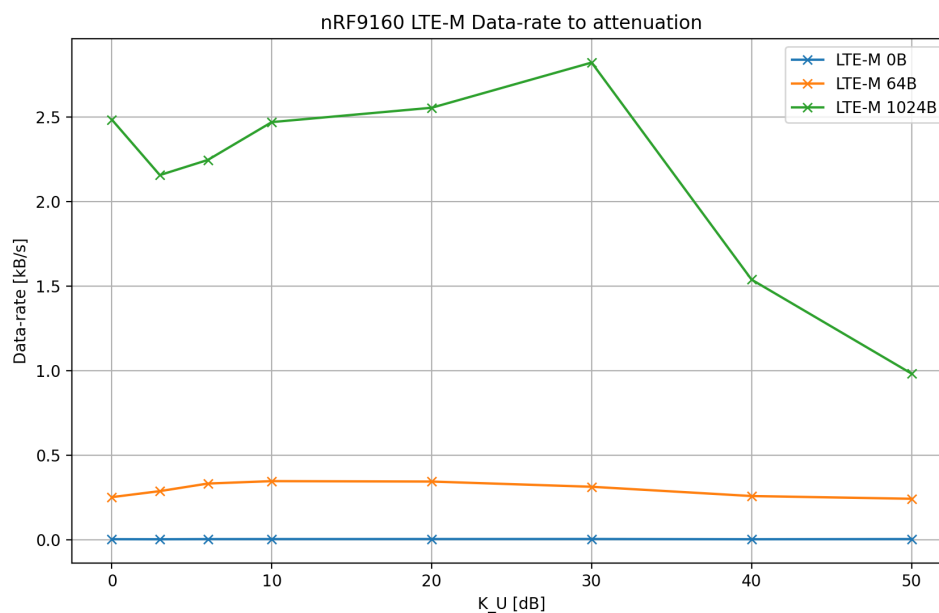


Fig. B.54: nRF9160 LTE-M Data-rate to attenuation

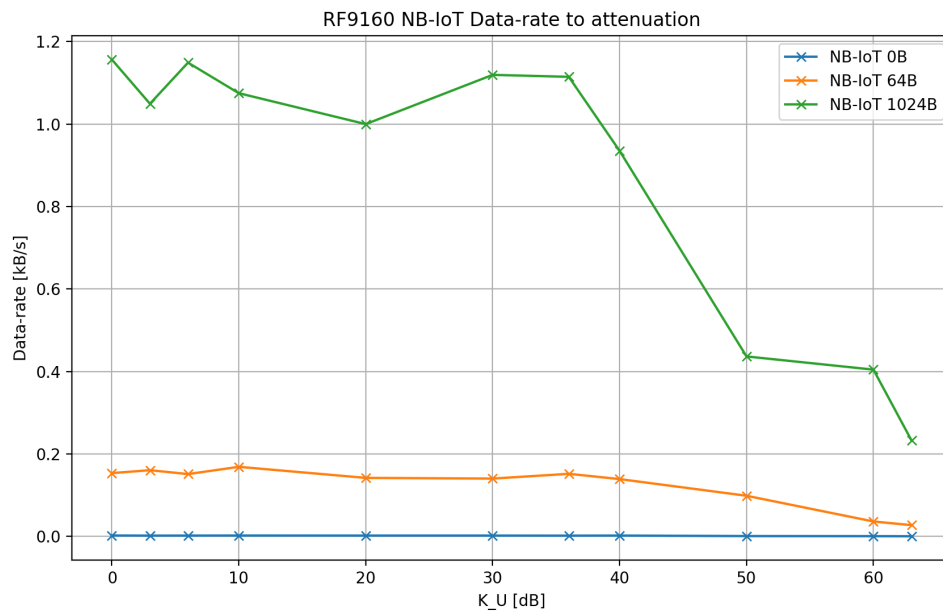


Fig. B.55: RF9160 NB-IoT Data-rate to attenuation

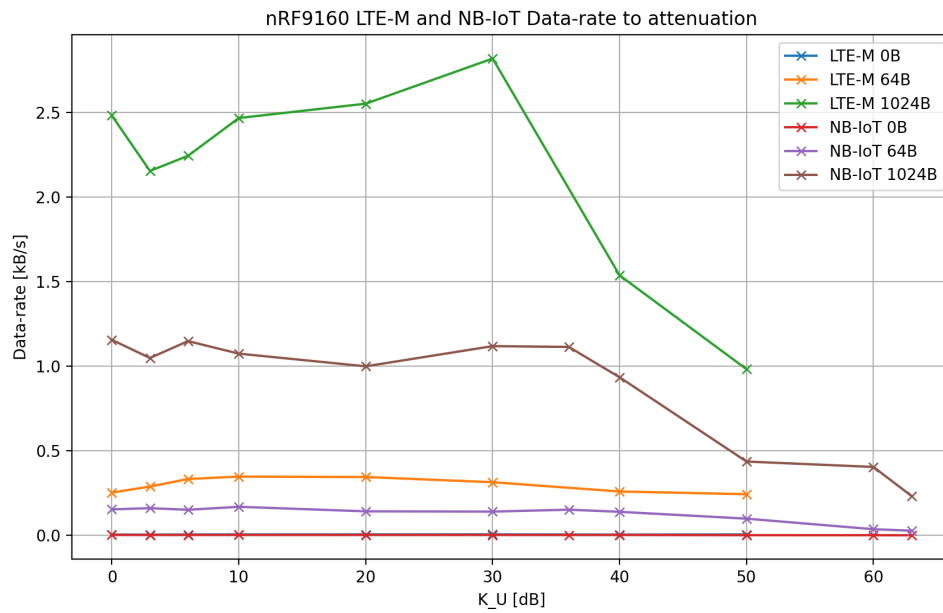


Fig. B.56: nRF9160 LTE-M and NB-IoT Data-rate to attenuation

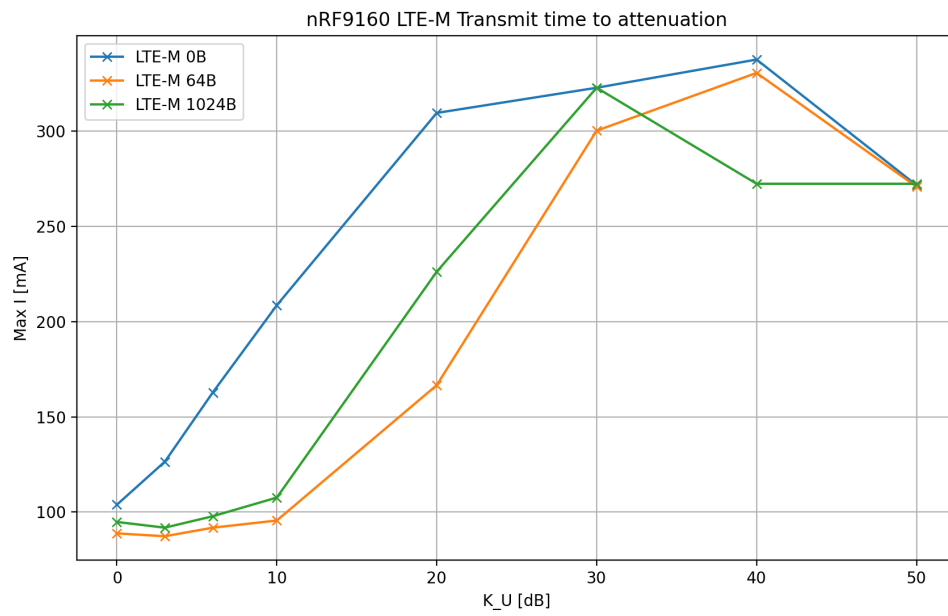


Fig. B.57: nRF9160 LTE-M Transmit time to attenuation

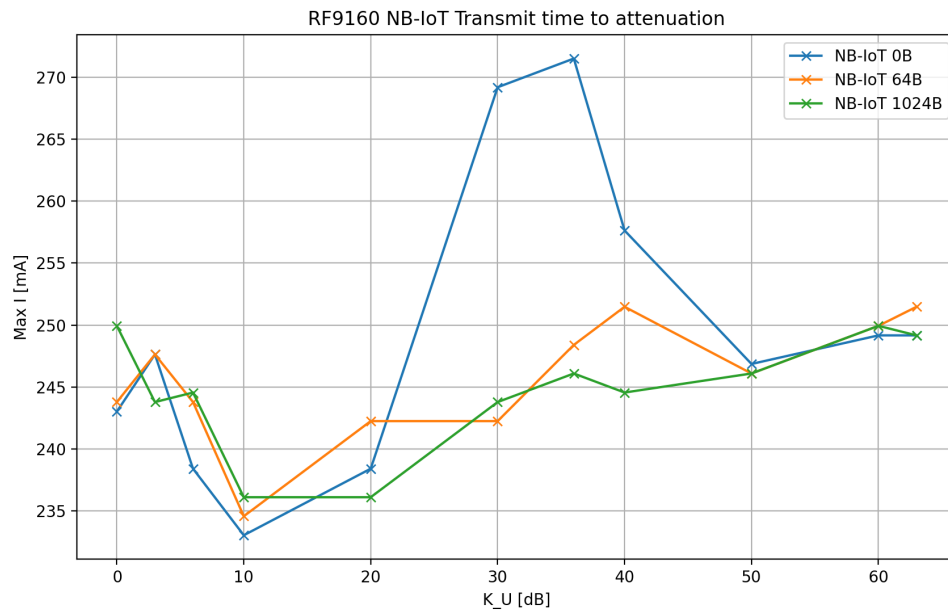


Fig. B.58: RF9160 NB-IoT Transmit time to attenuation

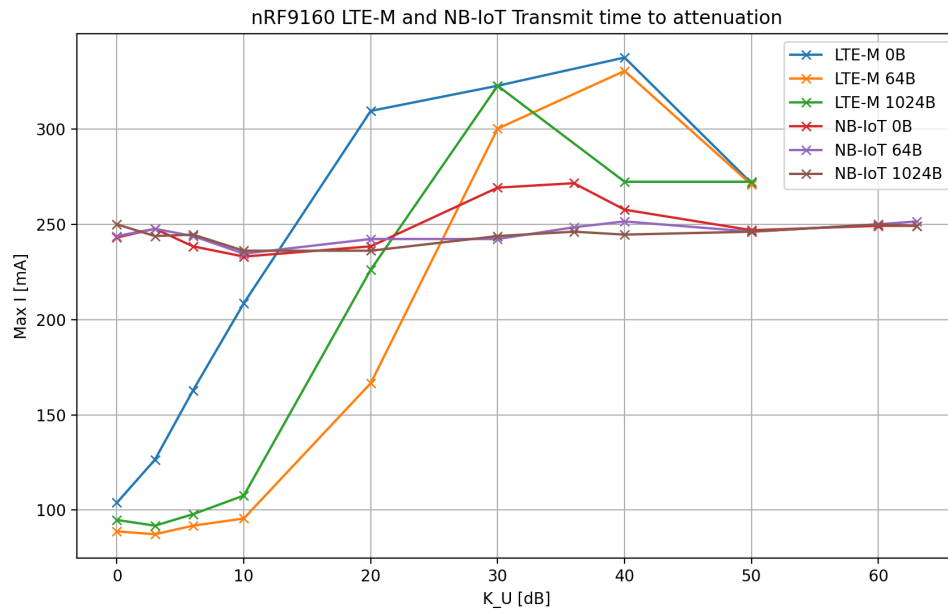


Fig. B.59: nRF9160 LTE-M and NB-IoT Transmit time to attenuation

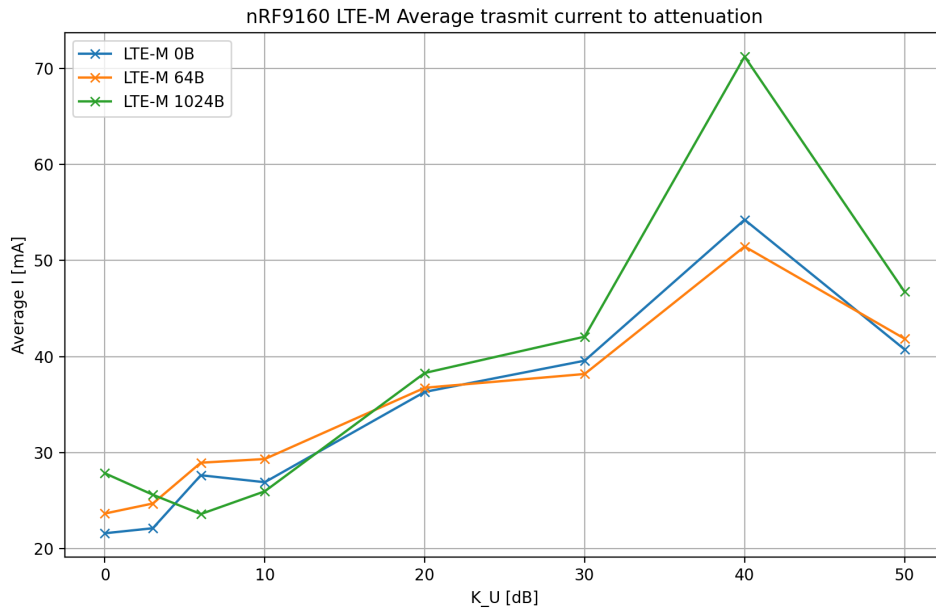


Fig. B.60: nRF9160 LTE-M Average transmit current to attenuation

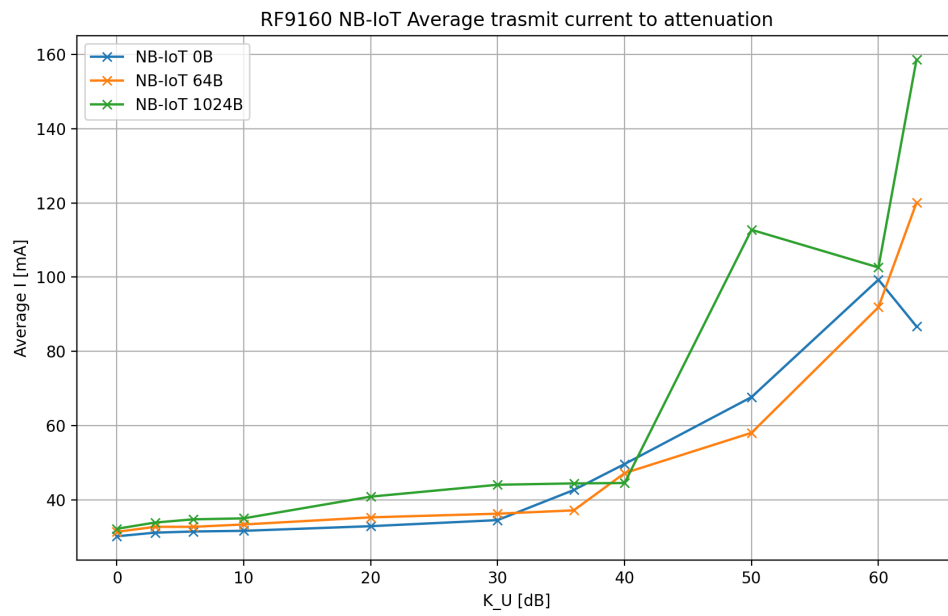


Fig. B.61: RF9160 NB-IoT Average transmit current to attenuation

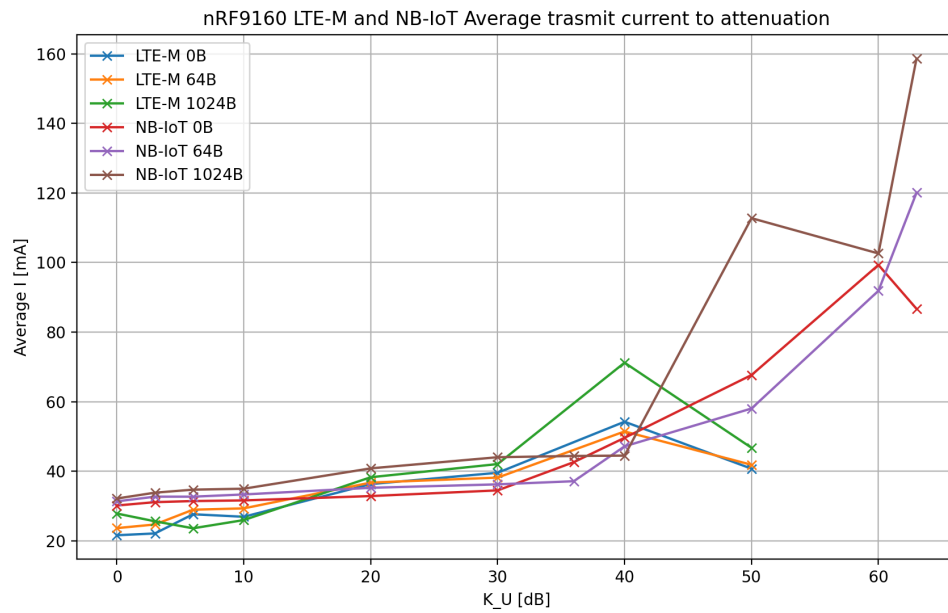


Fig. B.62: nRF9160 LTE-M and NB-IoT Average transmit current to attenuation

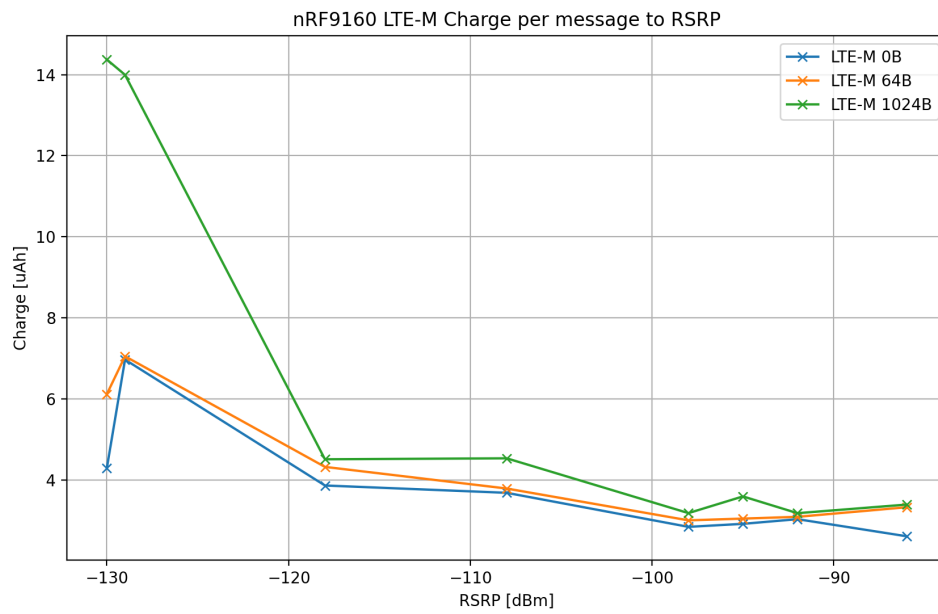


Fig. B.63: nRF9160 LTE-M Charge per message to RSRP

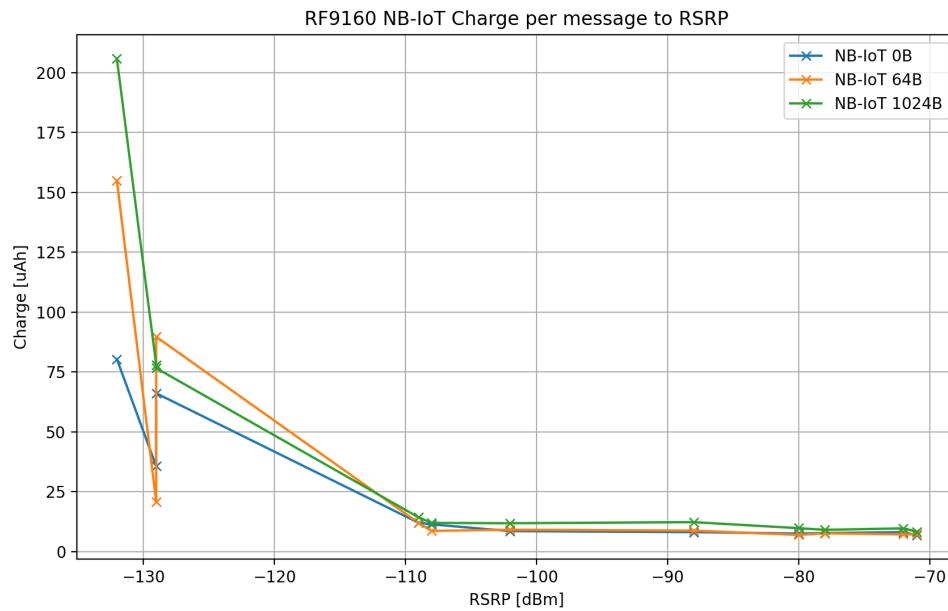


Fig. B.64: RF9160 NB-IoT Charge per message to RSRP

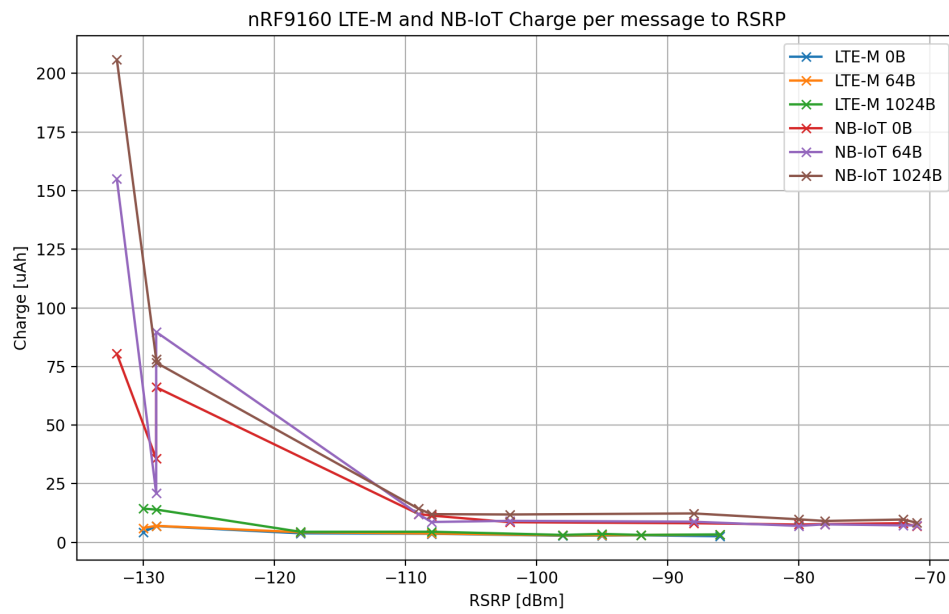


Fig. B.65: nRF9160 LTE-M and NB-IoT Charge per message to RSRP

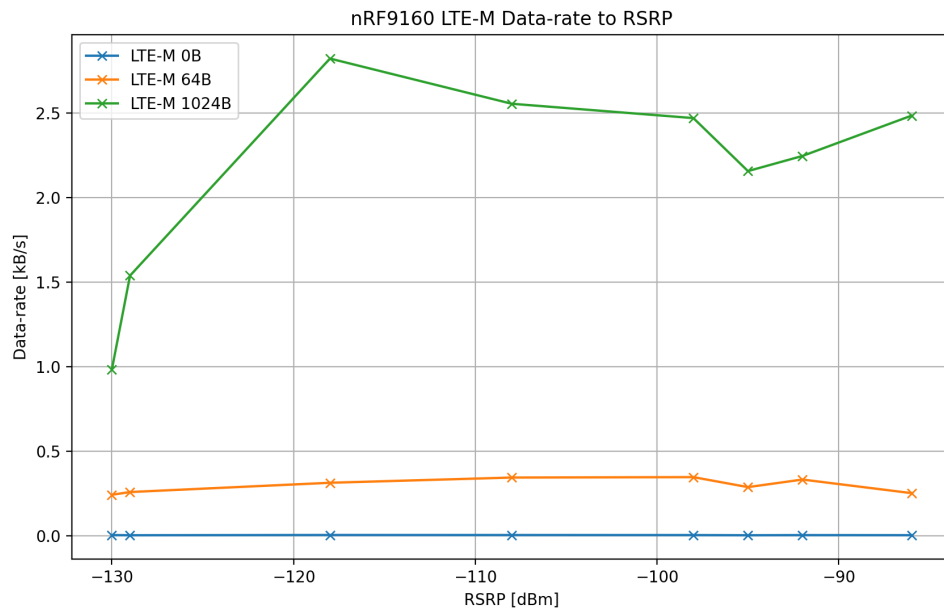


Fig. B.66: nRF9160 LTE-M Data-rate to RSRP

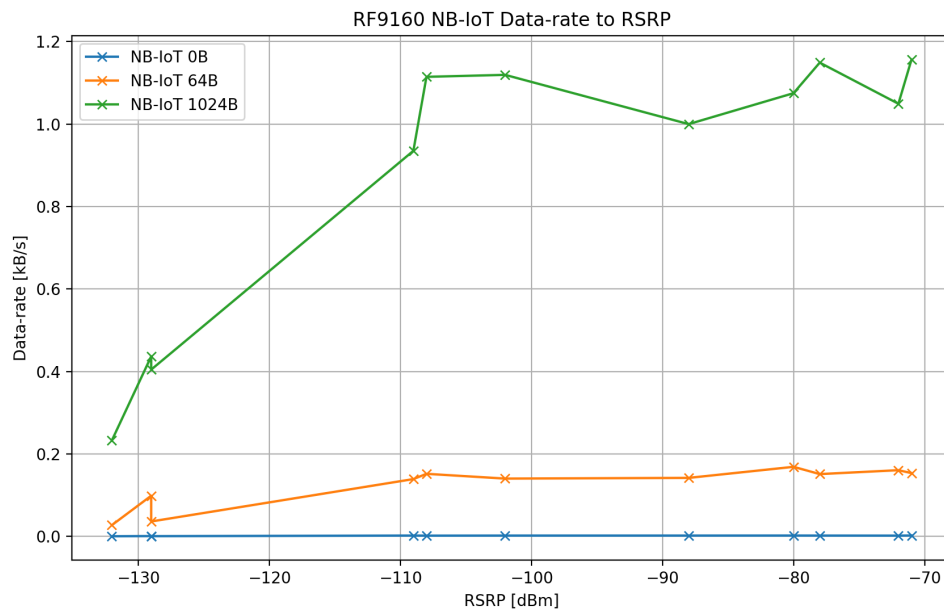


Fig. B.67: RF9160 NB-IoT Data-rate to RSRP

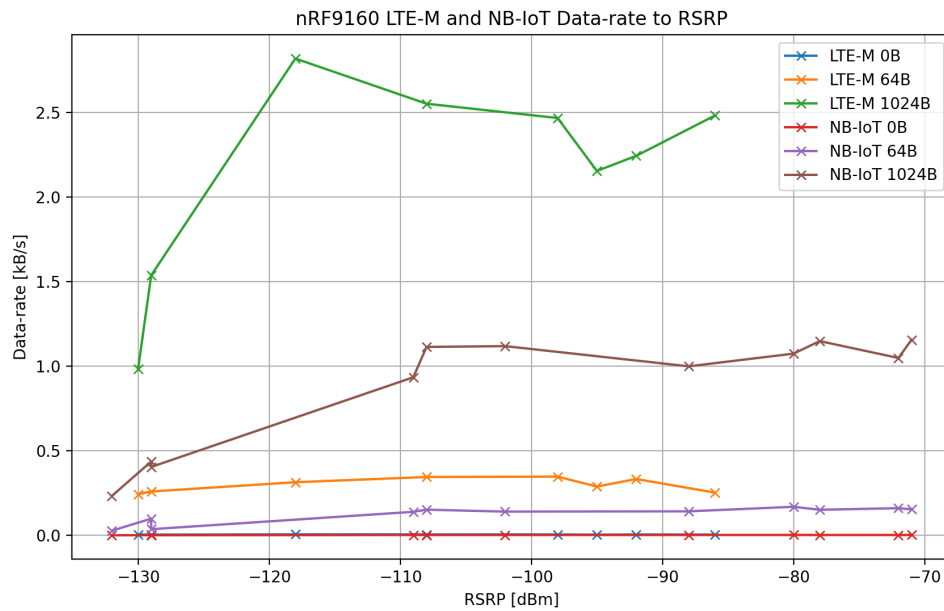


Fig. B.68: nRF9160 LTE-M and NB-IoT Data-rate to RSRP

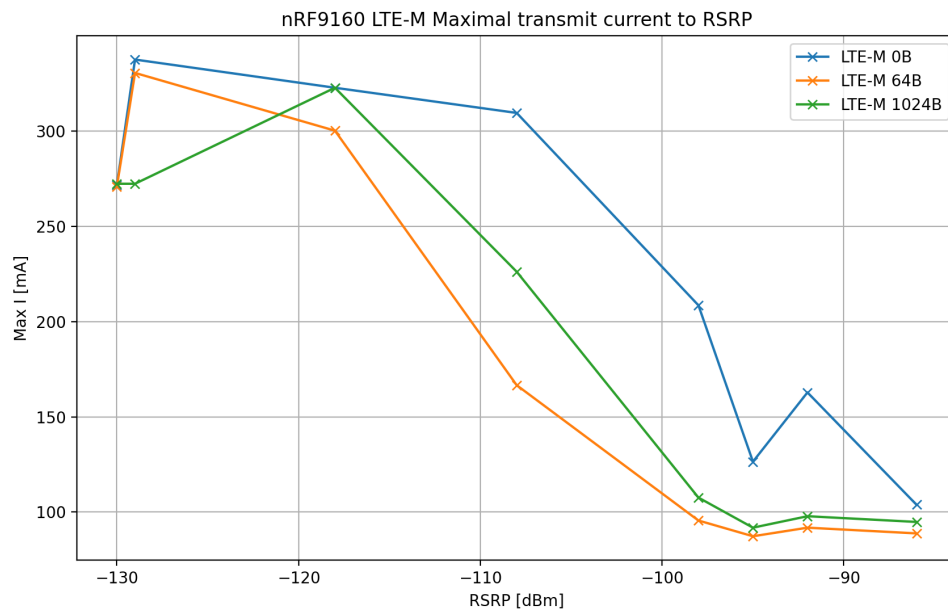


Fig. B.69: nRF9160 LTE-M Maximal transmit current to RSRP

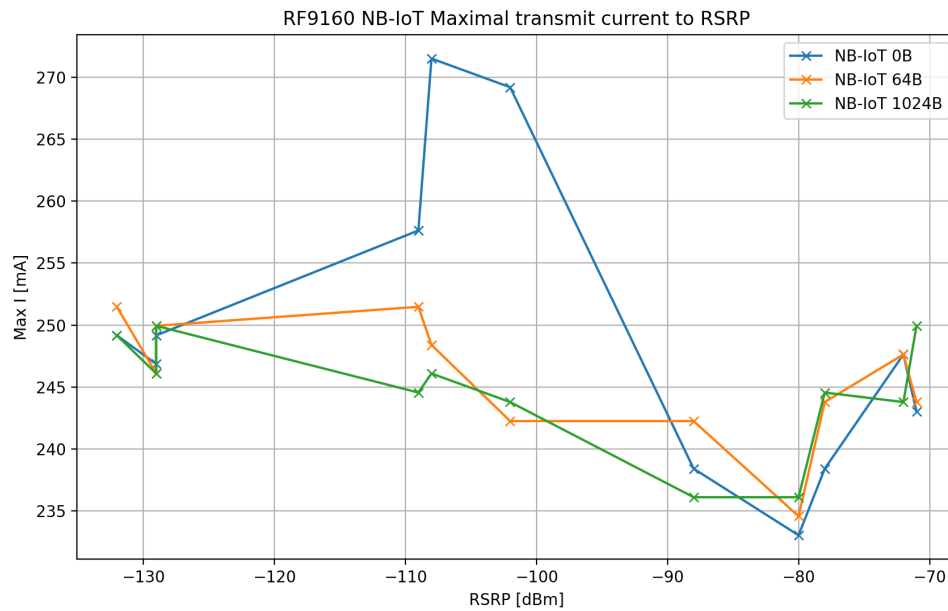


Fig. B.70: RF9160 NB-IoT Maximal transmit current to RSRP

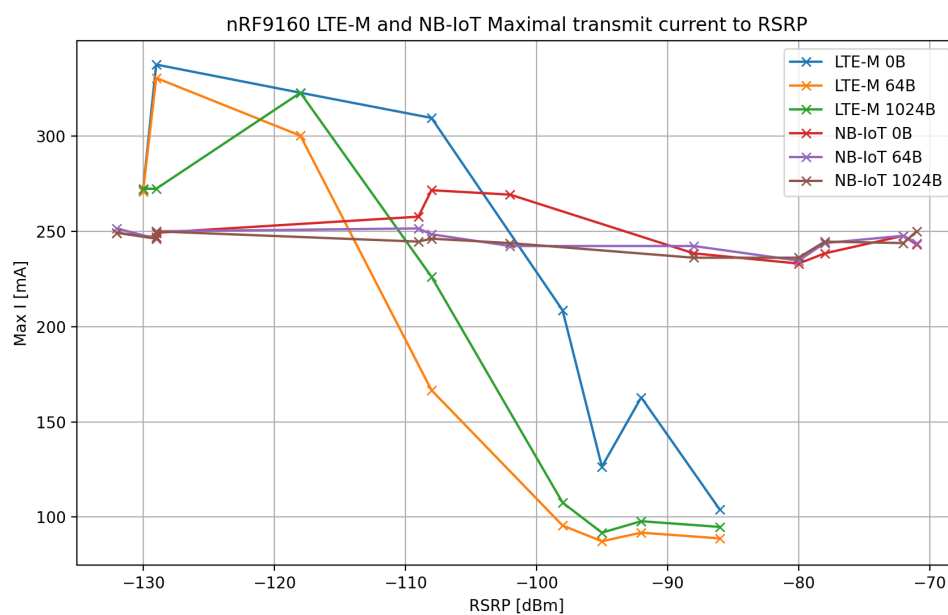


Fig. B.71: nRF9160 LTE-M and NB-IoT Maximal transmit current to RSRP

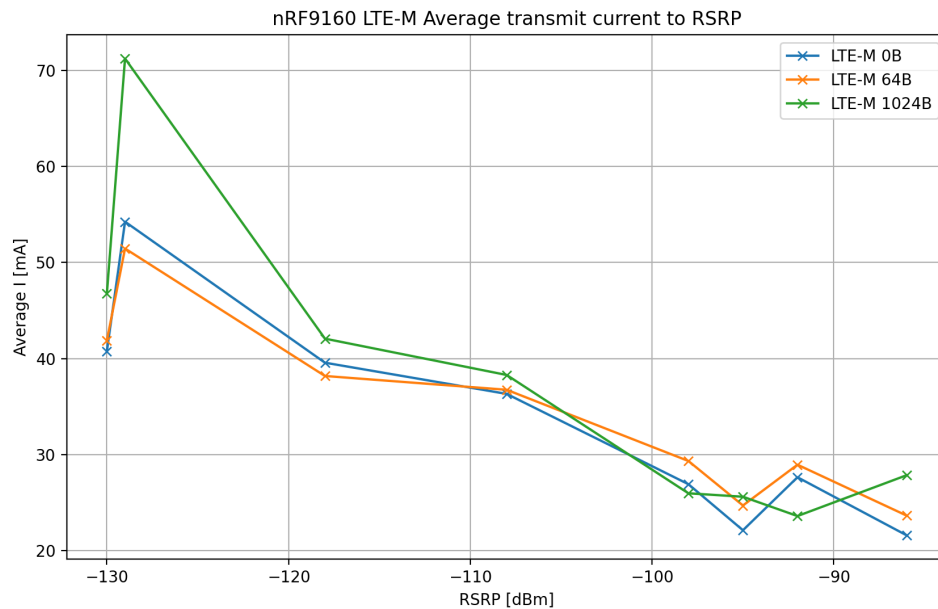


Fig. B.72: nRF9160 LTE-M Average transmit current to RSRP

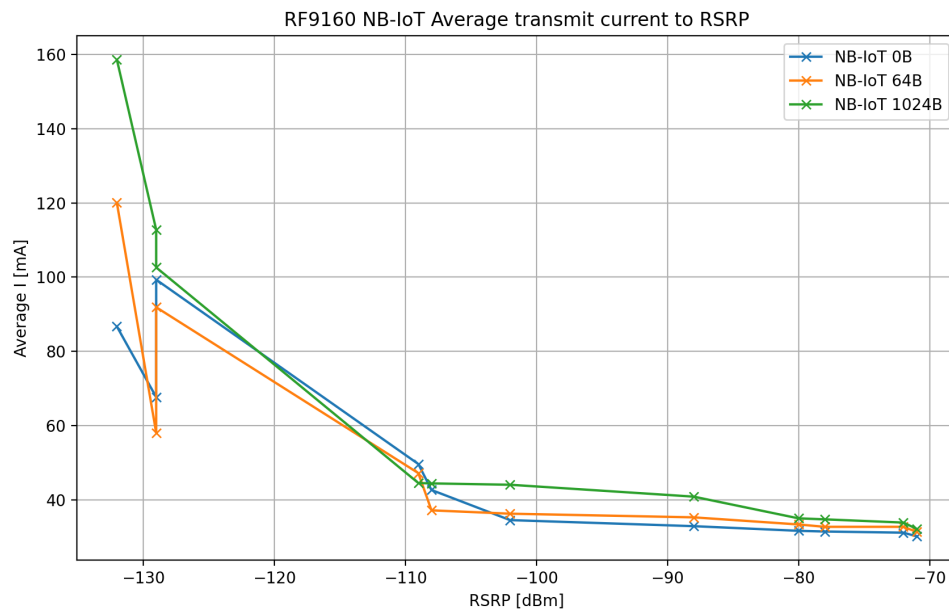


Fig. B.73: RF9160 NB-IoT Average transmit current to RSRP

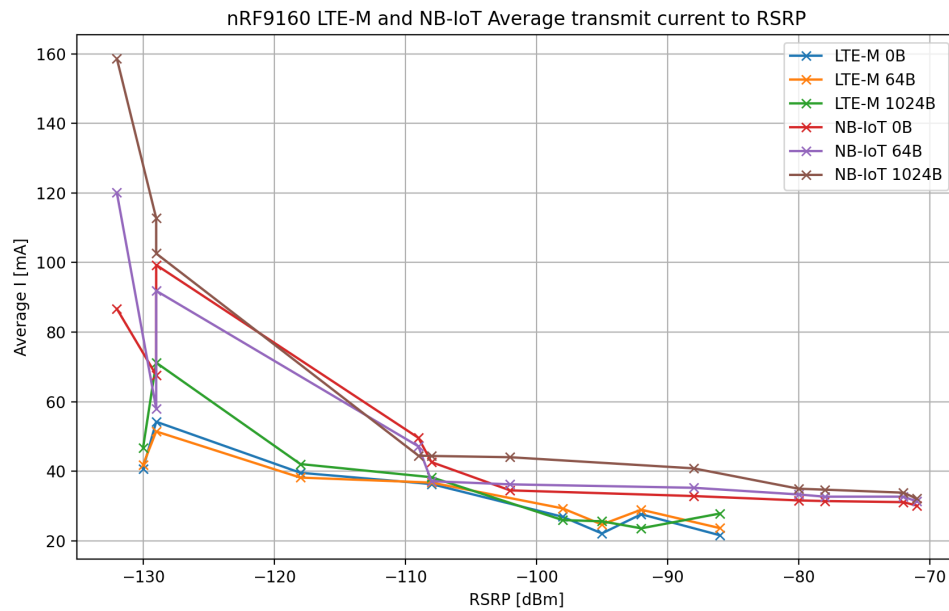


Fig. B.74: nRF9160 LTE-M and NB-IoT Average transmit current to RSRP

C Demonstrator electronic schemes

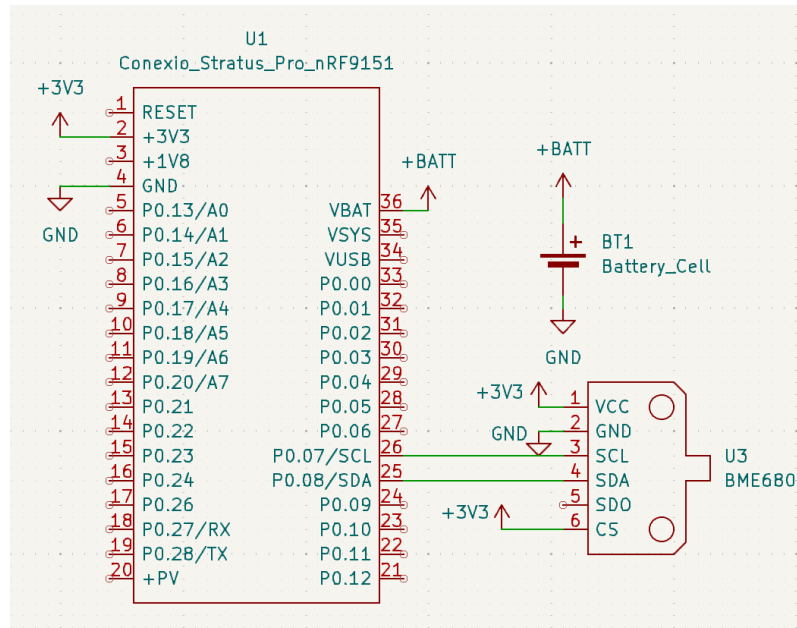


Fig. C.1: Demonstrator electronic schema

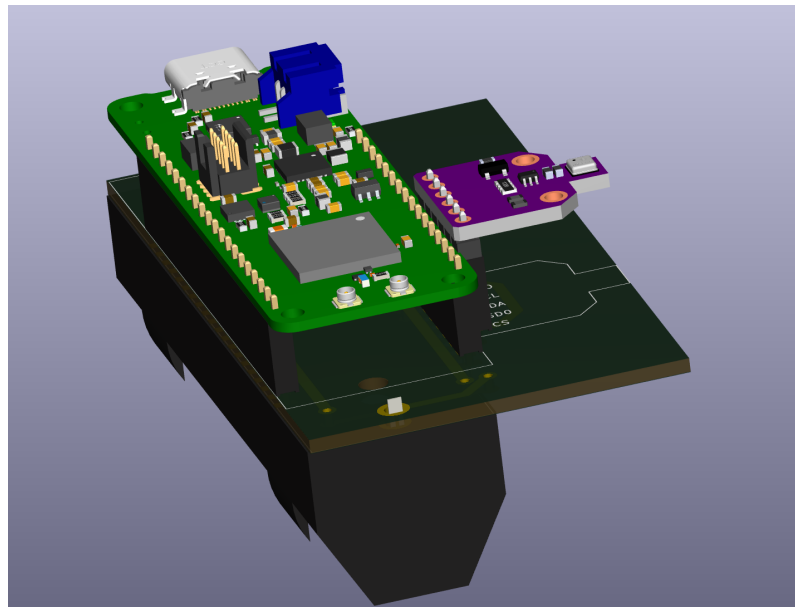


Fig. C.2: Demonstrator PCB 3D model render

