NB-IOT Report

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(5ISS)

I. Introduction

Narrowband Internet of Things (NB-IoT) is a specialized wireless technology crafted for the unique demands of the Internet of Things (IoT). It operates on designated radio frequencies, utilizing specific methods of signal modulation and low-power features. This technology ensures efficient, dependable, and expansive connectivity for a diverse range of IoT devices.

In the continually expanding realm of the Internet of Things, where various devices, from sensors to smart appliances, are interlinked, the demand for seamless connectivity has risen significantly. Traditional cellular networks face limitations in IoT applications due to concerns about power consumption and the requirement for extended coverage, especially in remote or challenging environments.

That's where NB-IoT comes in a meticulously designed solution tailored to meet the specific needs of IoT devices. As the number of connected devices continues to escalate, the necessity for a connectivity solution that is both low-power and capable of reaching long distances becomes crucial. NB-IoT rises to the occasion by presenting a solution that is not only cost-effective and energy-efficient but also scalable. This makes NB-IoT an instrumental player in the ongoing evolution of IoT ecosystems.

As we explore the inner workings of NB-IoT, we'll delve into its physical, MAC, and network layers. This exploration will shed light on how NB-IoT adeptly maintains a balance between power efficiency and reliable connectivity, paving the way for a more interconnected and seamlessly integrated IoT world.

II. Key characteristics and features

1) Low power consumption

Using the power saving mode (PSM) and expanded discontinuous reception (eDRX), longer standby time can be realized in NB-IoT. Therefore, PSM technology is newly added in Rel-12 , where in the power saving mode the terminal is still registered online but cannot be reached by signaling in order to make the terminal deep sleep for a longer time to achieve the power saving. On the other hand, the eDRX is newly added in Rel-13, which further extends the sleep cycle of the terminal in idle mode and reduces unnecessary startup of the receiving cell. Compared to PSM, eDRX promotes downlink accessibility significantly. NB-IoT requires that the terminal service life of a constant-volume battery is 10 years for typical low-rate low frequency service. According to simulated data of TR45.820, for coupling loss of 164 dB and using both PSM and eDRX, the service life of 5-Wh battery can be 12.8 years if a message of 200 byte is sent once per day by terminal.

Estimation on service life of battery in integrated PA

	Battery life / year		
Message size / message interval	Coupling loss = 144 dB	Coupling loss = 154 dB	Coupling loss = 164 dB
50 bytes / 2 hours	22.4	11.0	2.5
200 bytes / 2 hours	18.2	5.9	1.5
50 bytes / 1 day	36.0	31.6	17.5
200 bytes / 1 day	34.9	26.2	12.8

2) Enhanced coverage and low latency sensitivity

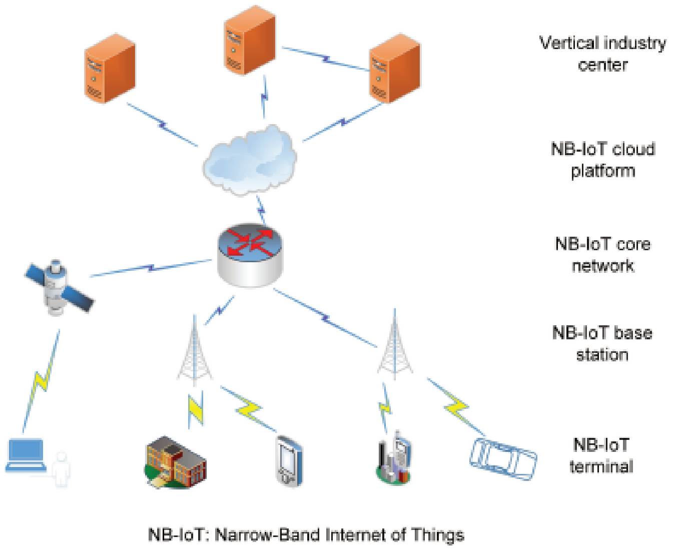
According to simulated data of TR45.820, it can be confirmed that the covering power of NB-IoT can reach 164 dB in independent deployment mode. The simulation test was conducted for both in-band deployment and guard band deployment. In order to realize coverage enhancement, mechanisms such as retransmission (200 times) and low frequency modulation are adopted by NB-IoT. At present, the NB-IoT support for 16QAM is still in discussion. For coupling loss of 164 dB, if a reliable data transmission is provided the latency increases due to retransmission of mass data. Simulations for TR45.820 show the latency for irregular reporting service scenarios and different coupling losses (header compressing or not) with reliability of 99%. Currently, the tolerable latency in 3GPP IoT is 10 s. In fact, lower latency of about 6 s for maximal coupling losses can be also supported. For more details, please refer to simulation results of NB-IoT for TR45.820

Latency under environment with different coupling loss in service scenario of irregular report, where reliability of 99% is guaranteed

Processing time	Send report headless compression (100 bytes load)			Send report header compression (65 bytes load)		
	Coupling loss/dB			Coupling loss/dB		
	144	154	164	144	154	164
Tsync/ms	500	500	1125	500	500	1125
TPSI/ms	550	550	550	550	550	550
TPRACH/ms	142	142	142	142	142	142
T uplink allocation/ms	908	921	976	908	921	976
T uplink data/ms	152	549	2755	93	382	1964
T uplink ACK/ms	933	393	632	958	540	154
T downlink allocation/ms	908	921	976	908	921	976
T downlink data/ms	152	549	2755	93	382	1964
Total time/ms	4236	4525	9911	4152	4338	7851

3) NB-IoT network

- The NB-IoT network is shown in Fig. 6 [31] wherein it can be seen that it consists of 5 parts: NB-IoT terminal. IoT devices in all industries have access to NB-IoT network as long as the corresponding SIM card is installed;
- NB-IoT base station. It mainly refers to the base station that has already been deployed by telecom operators, and it supports all three types of deployment modes mentioned before;
- NB-IoT core network. Through NB-IoT core network, NB-IoT base station can connect to NB-IoT cloud;
- NB-IoT cloud platform. NB-IoT cloud platform can process various services and results are forwarded to the vertical business center or NB-IoT terminal;
- Vertical business center. It can obtain NB-IoT service data in its own center and take control of the NB-IoT terminal.

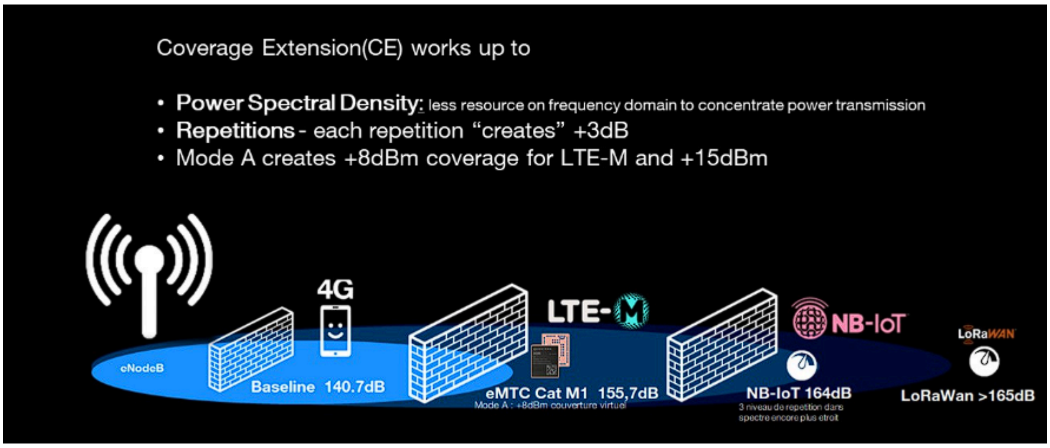


4) Coverage power

In the realm of Internet of Things (IoT) connectivity, NB-IoT stands out with its extended coverage capabilities, surpassing LTE and making it particularly suitable for applications that can accommodate higher latency. A crucial aspect contributing to this extended coverage is the Coverage Enhancement (EC) feature shared with LTE-M. This repetition-based mechanism significantly enhances coverage capabilities, ensuring robust connectivity for IoT devices.

Moreover, NB-IoT exhibits remarkable interference resilience, thanks to its narrow spectrum (Narrow Band) and the utilization of repetition mechanisms. This narrow bandwidth not only facilitates a more efficient use of the available spectrum but also bolsters the network's ability to withstand interference, providing a stable and interference-resistant communication environment.

A notable advantage further fortifying NB-IoT is the increased transmission power enabled by its narrow spectrum. This heightened transmission power translates to more reliable and secure message delivery, essential for the seamless operation of IoT applications. In summary, NB-IoT's extended coverage, coupled with Coverage Enhancement, interference resilience, and increased transmission power, positions it as a robust and dependable choice for diverse IoT applications.



III. NB-IoT network architecture

1. Protocol Stack

NB-IoT protocol stack has been categorized into user plane and control plane.The User Plane is active during actual data transmission, while the Control Plane plays a crucial role in session management, signaling, and resource allocation to ensure efficient and controlled communication within the network. The interaction between these planes is fundamental to the operation of a modern telecommunication system.

In user-plane LTE-NB protocol stack consists of the physical layer (PHY), MAC layer, RLC layer and PDCP layer.

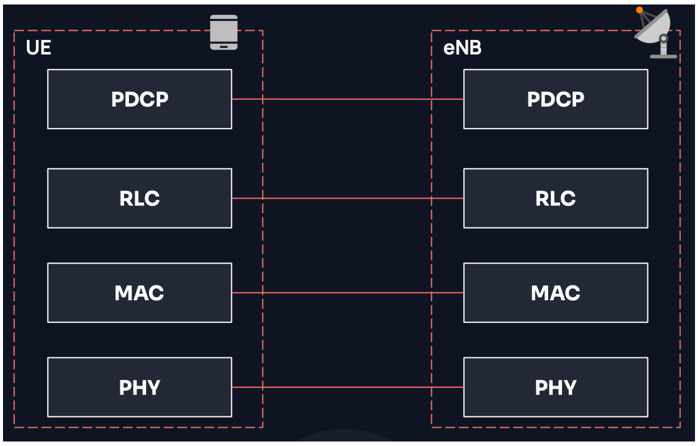


Figure 1 - NB-IoT Protocol Stack - User Plane

In Control-plane LTE-NB protocol stack consists of PHY, MAC, RLC, PDCP, RRC and NAS layers.

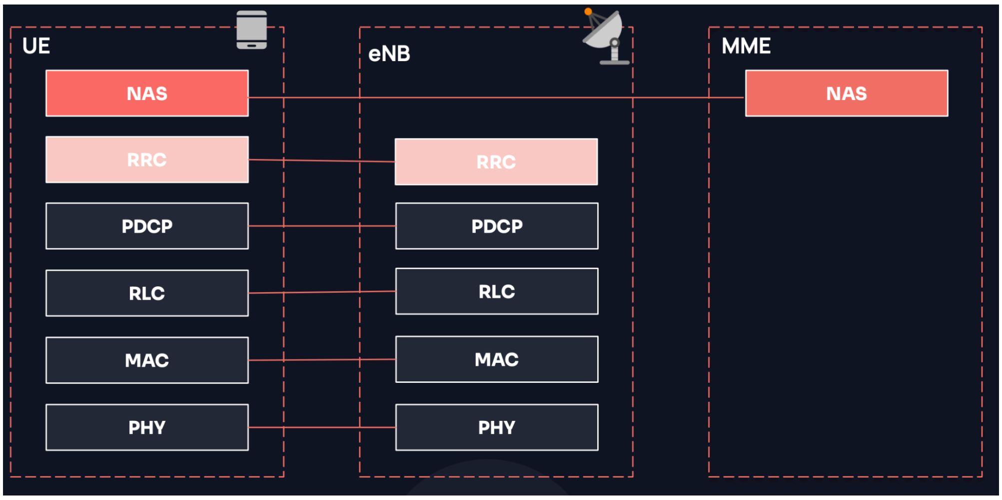


Figure 2 - NB-IoT Protocol Stack - Control Plane

2. Physical Layer

The modulation schemes utilized in the Narrowband Internet of Things (NB-IoT) protocol play a crucial role in the physical layer. In fact, according to [1], the uplink (UL) transmission uses Narrowband Physical Uplink Shared Channel (NPUSCH) Format 1 with a 15 kHz subcarrier spacing. This channel accommodates data transmissions and can be scheduled for either a single-tone allocation (using π/2-Binary Phase Shift Keying or /4-QPSK) or a multi-tone allocation (QPSK) with 3, 6, or 12 subcarriers. In the time domain, the Transport Block Size (TBS) is mapped over one or more resource units (RUs), each lasting 8 ms for a single-tone allocation and 4 ms, 2 ms, or 1 ms for 3, 6, or 12 subcarrier allocations, respectively.

On the downlink (DL), the Narrowband Physical Downlink Shared Channel (NPDSCH) with a 15 kHz subcarrier spacing is utilized for data transmissions. This channel employs a 12-subcarrier allocation with QPSK modulation. In the time domain, the Transport Block Size (TBS) is scheduled via the Narrow-band Physical Control Channel (NPDCCH) to be mapped over one or more subframes (SF), each lasting 1 ms.

In summary, the physical layer performs the following functions [2]:

- Data Exchange and Control: Facilitating the exchange of data and control information between the evolved NodeB (eNB) and User Equipment (UE). Additionally, it enables the transport of data to and from higher layers in the communication stack.

- Error Detection and Correction: Performing crucial tasks such as error detection, Forward Error Correction (FEC), antenna processing, and synchronization to ensure reliable communication.

- Physical Signals and Channels: Comprising physical signals used for system synchronization, cell identification, and channel estimation. Physical channels play a key role in transporting control, scheduling, and user payload processing between higher layers and the physical layer.

- Modulation Scheme: Employing Quadrature Phase Shift Keying (QPSK) as the highest modulation scheme. QPSK allows efficient encoding of digital information onto the carrier signal.

- Support for HD FDD and TDD: Providing support for both Half Duplex Frequency Division Duplex (HD FDD) and Time Division Duplex (TDD) modes, offering flexibility in the duplexing scheme for communication.

3. MAC Layer

The MAC layer takes care of cell access related messages between UE and network. This Random Access Procedure helps in establishing RRC connections. It uses principally 2 types of multiple access schemes : OFDMA (with 15 KHz subcarrier spacing) in the downlink and SC-FDMA (with 3.75 KHz for single mode transmissions, 15 KHz for multi-tone transmissions) in the uplink.

According to [2], the MAC (Medium Access Control) layer in NB-IoT is responsible for handling various tasks related to channel access. These tasks include:

- Handling Retransmissions (HARQ): Managing the retransmission of data to ensure reliable communication.
- Multiplexing: Managing the simultaneous transmission of multiple data streams over a shared channel.
- Random Access: Controlling the random access procedures for devices to initiate communication.
- Timing Advance: Adjusting the timing of transmissions to account for signal propagation delays.
- Choice of Transport Block Formats: Selecting the appropriate format for transporting data blocks.
- Priority Management: Managing the priority of different data transmissions.
- Scheduling: Determining the timing and allocation of resources for data transmissions.

4. Network Topology

As mentioned in reference [3], the mesh network topology encounters difficulties because of the "bottleneck problem" and high deployment costs when the NB-IoT system spans a wide geographic region and a big number of coupled objects. Because traffic must pass through several hops before reaching a gateway, particular devices may become congested due to factors like as their location or the patterns of network traffic. This is known as the bottleneck problem. As a result, the network lifetime is reduced to a few months or years due to the reduction in battery life caused by this congestion.

Most NB-IoT systems choose the star network architecture to overcome these issues. This topology connects end devices directly to base stations, removing the requirement for expensive and dense relay and gateways deployments.

There are large energy savings as a result of this calculated decision. Devices in the star topology do not need to continuously listen to other devices that are trying to relay their communication, in contrast to those in the mesh topology. In the widely used star topology, which is characteristic of various Low-Power Wide-Area Network (LPWAN) technologies and is particularly used by NB-IoT systems, base stations are always turned on, providing end devices with convenient and timely access when needed.

IV. Operating modes

The NB-IoT system was conceptualized with a substantial reliance on the LTE system, leading to the optimization of the NB-IoT air interface. This optimization aimed to ensure harmonious coexistence with LTE carriers while upholding the performance standards of the LTE system. Within this framework, 3GPP delineated three distinct operation modes for NB-IoT :

1. In-Band Mode: In this mode, the NB-IoT signal is allocated one Physical Resource Block (PRB) from the LTE bandwidth. This approach facilitates seamless integration with existing LTE networks and offers cost savings.

2. Guard-Band Mode: Under the Guard-Band Mode, the NB-IoT signal occupies one PRB within the unused guard band PRBs of the LTE bandwidth. This mode is designed to optimize spectral utilization while avoiding interference with LTE channels.

3. Stand-Alone Mode: In the Stand-Alone Mode, the NB-IoT signal is intended to utilize the freed-up spectrum from the global system for mobile communications (GSM) system. Specifically, the NB-IoT signal occupies 180 kHz within the 200 kHz GSM carrier, with a 10 kHz band-guard on both sides of the spectrum.

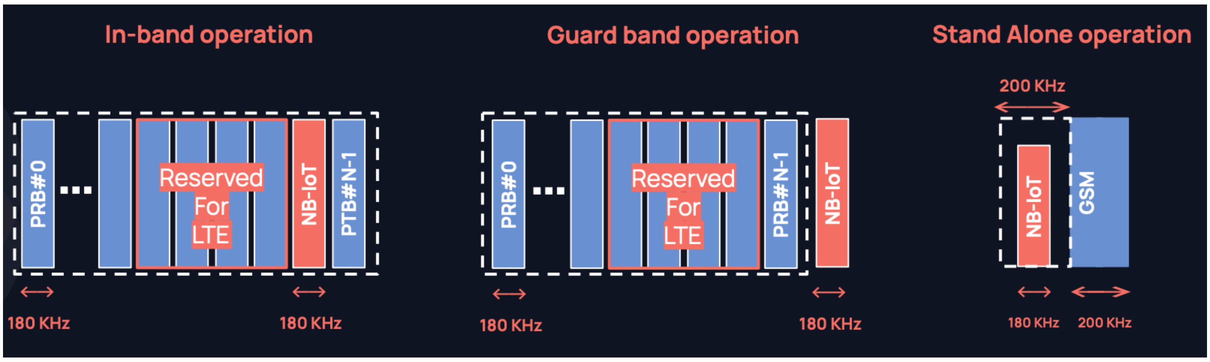


Figure 3 - NB-IoT operating modes

Referring to figure 3 the In-Band Operation Mode stands out as the most advantageous. It offers benefits such as cost savings and ease of integration into legacy LTE networks. However, it comes with a constraint – the NB-IoT anchor carrier is limited to a predefined set of possible carriers.

Furthermore, a restriction is imposed in all modes[4]: the six middle PRBs of the LTE system are consistently off-limits for NB-IoT use. This restriction is in place to prevent conflicts between NB-IoT transmissions and critical LTE channels and signals, including the physical broadcast channel and synchronization signals. This careful allocation ensures the integrity and functionality of both NB-IoT and LTE within the shared spectrum.

V. Security in the context of NB-IoT

Security within the intricate landscape of NB-IoT is paramount, ensuring the resilience and trustworthiness of this dedicated IoT ecosystem. Delving deeper into the core mechanisms, NB-IoT employs a comprehensive array of security protocols to fortify its infrastructure against potential vulnerabilities and threats. These protocols address various facets of security, ensuring robust protection across multiple dimensions.

Cryptography and Data Confidentiality : To uphold data confidentiality during transmission and storage, NB-IoT relies on robust encryption techniques. The Advanced Encryption Standard (AES), a symmetric encryption algorithm, plays a pivotal role in safeguarding data integrity. By utilizing encryption keys, AES encrypts and decrypts data, thwarting unauthorized access attempts and bolstering the network's security posture.(Ref [5] Security Features Part of : NB-IoT vs Zigbee: A detailed comparison (narrowband.com))

Device Authentication and Integrity : NB-IoT implements rigorous device authentication protocols to verify the legitimacy of connected devices. Protocols like the Extensible Authentication Protocol (EAP) and EAP-TLS facilitate secure device authentication using digital certificates. X.509 certificates, integral to these protocols, ascertain the identity and integrity of devices, ensuring that only authorized entities access the network.

Protection Against Attacks : Mitigating diverse cyber threats is a cornerstone of NB-IoT security. To counter threats like Denial of Service (DoS) attacks, NB-IoT employs Internet Protocol Security (IPsec). IPsec shields IP communications by furnishing encryption and integrity mechanisms that safeguard data integrity during transit. Furthermore, Domain Name System Security Extensions (DNSSEC) fortify domain name system integrity, averting manipulation of naming information and upholding its validity.

(Ref [6] Security Features Part 3.2 of : Security-Features-of-LTE-M-and-NB-IoT-Networks.pdf (gsma.com))

Key and Identity Management : Central to NB-IoT security is the meticulous management of encryption keys and device identities. Protocols like Public Key Infrastructure (PKI) oversee the issuance and management of digital certificates and cryptographic keys (Ref [7] Part 5 of IEEE

Xplore Full-Text PDF:) . PKI ensures secure authentication and encryption processes. Additionally, OAuth (Open Authorization) facilitates secure authorization between disparate IoT services, guaranteeing controlled and secure data exchanges.

Compliance with Security Standards : NB-IoT adheres rigorously to established security standards, aligning with guidelines delineated by organizations like the 3rd Generation Partnership Project (3GPP). These meticulously detailed specifications encompass security protocols for mobile networks, encapsulating NB-IoT security requisites. Compliance with such standards fortifies NB-IoT's foundation, establishing a robust shield against potential vulnerabilities. (Ref [8] Security Features Part 3.1 of : Security-Features-of-LTE-M-and-NB-IoT-Networks.pdf (gsma.com)

VI. Practical applications, power consumption and challenges :

1) Practical applications :

Narrowband Internet of Things (NB-IoT) stands out for its remarkable versatility, adapting seamlessly to an array of IoT scenarios. Its unique combination of low-power consumption, extended coverage, and efficient connectivity positions NB-IoT as a versatile solution for diverse applications such as :

- Smart Agriculture: By giving real-time data on crop health, weather, and soil moisture, NB-IoT enables precision farming. With informed choices, farmers may maximize the use of available resources and raise productivity.

- Smart Cities: NB-IoT enables intelligent solutions in urban settings, like trash management, smart parking, and environmental monitoring. By allocating resources effectively, these applications improve urban living.

- Industrial Applications: Asset tracking, preventive maintenance, and machinery and equipment monitoring are among the ways that industries use NB-IoT. By doing this, you can guarantee peak performance, reduce downtime, and increase the longevity of important assets.

2) Power Consumption in NB-IoT:

The goal of NB-IoT technology is to give IoT devices low-power wide area network (LPWAN) access. This indicates that NB-IoT devices require far less power than conventional cellular devices, allowing them to run for years on a single battery charge.

An NB-IoT device's power consumption is determined by a number of variables, including the state of the network, the device's capabilities, and the needs of the application.

Parameter	Typical Value
Transmit power	20-23 dBm
Receiver sensitivity	-129 to -139 dBm
Data rate	20-250 kbps
Sleep current	2-3 uA
Idle current	6-12 mA
Active current	150-180 mA

Figure - NB-IoT Power Consumption parameters

In NB-IoT, there are three power saving modes available: Power Saving Mode (PSM), extended Discontinuous Reception (eDRX), and RRC Inactive (RAI) [10].

3) Power Saving Mode (PSM)

In NB-IoT, PSM [10] is the most popular power-saving mode. It permits the device to go into a deep sleep mode, in which the majority of its features are disabled and it only wakes up infrequently to check for new messages.
For use cases like remote metering or environmental monitoring, when the device only has to send or receive data occasionally, PSM is perfect. PSM provides substantial power savings because the gadget is mostly inactive.

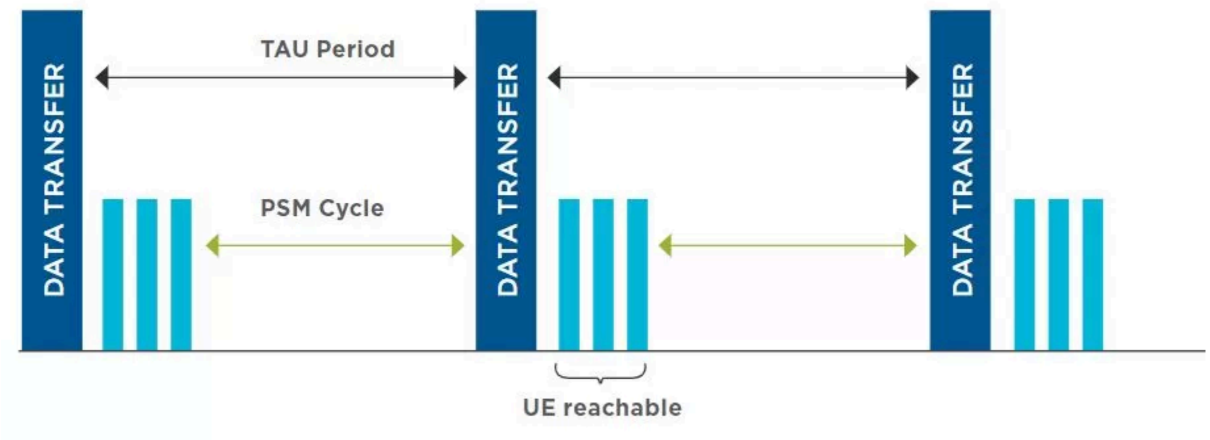


Figure - Representation of PSM cycle

4) Extended Discontinuous Reception (eDRX):

Another NB-IoT power-saving mode called eDRX [10] enables a device to go into sleep mode while continuing to scan the network for new data. The device can stay in sleep mode for a longer period of time in eDRX before waking up to check for incoming data.
When the device needs to receive data more often than with PSM, but not continuously, eDRX is

appropriate. As an illustration, consider smart parking systems, where the device has to regularly receive data in order to check for open parking spaces.

Figure - Representation of eDRX cycle

5) **RRC Inactive (RAI):**

Since RAI [10] enables a device to fully enter sleep mode and turn off all radio functions, it is the most power-efficient NB-IoT mode. Only predetermined intervals are used by the device to wake up and check for incoming messages; generally, this wake-up time is longer than in PSM or eDRX.
For use cases like asset tracking or smart agriculture, where the device only needs to send or receive data once or twice a day, RAI is perfect. The drawback of RAI is that it can result in extremely high latency when sending or receiving data because the device must constantly wake up and re-establish a connection with the network.

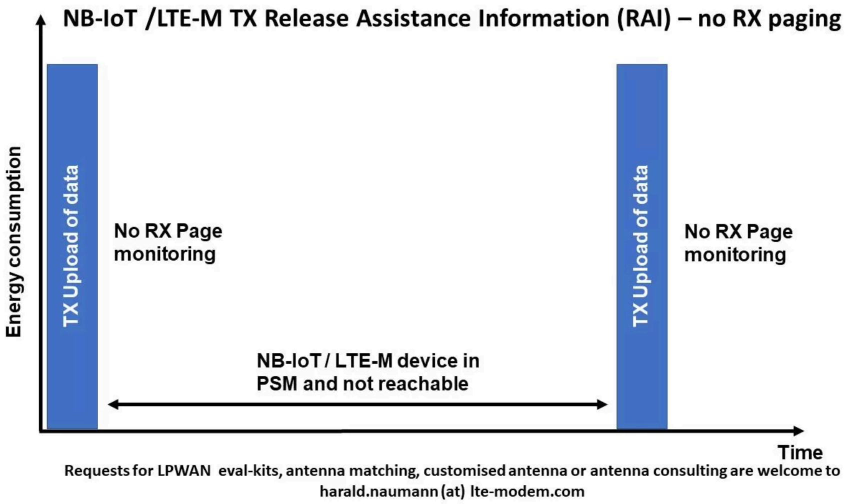


Figure - Representation of RAI cycle

Finally, different tradeoffs between latency and power consumption are available with NB-IoT devices' power saving modes. IoT device manufacturers can design low-power NB-IoT devices that offer extended battery life and dependable communication by comprehending the technical specifications of each mode and choosing the right mode based on the device's communication requirements.

Mode	Description	Power consumption mW)	Latency (ms)
PSM	Puts the device into a deep sleep mode when it is not actively transmitting or receiving data.	0.1 – 1	2 – 10
eDRX	Extends the sleep duration of the device to reduce power consumption.	1 – 10	50 – 1000
RAI	Allows the device to release the radio resources after transmission to save power.	5 – 50	10 – 100

Figure - Power saving modes in NB-IoT devices

The remarkable energy utilization metrics of NB-IoT highlight the effectiveness of data transmission. Just 1.51 millijoules per bit (mJ/B) are needed to send a meek 100 bits [9], demonstrating how energy-efficient the technology is even for small data transfers. Even when scaling up to 1000 bytes, NB-IoT remains efficient, averaging just 0.32 mJ/B. These metrics demonstrate NB-IoT's exceptional energy efficiency when handling data of different sizes, which makes it a perfect option for IoT applications where power consumption must be kept to a minimum.

https://odr.chalmers.se/server/api/core/bitstreams/2a0fdb3e-cdeb-4d92-b17a-0f633b37bb49/content **An empirical study of Cellular-IoT** Master's thesis in Communication Engineering

6) Identification of Potential Challenges in Implementing NB-IoT:

Although NB-IoT has many benefits, there are some obstacles to overcome in its implementation:

- Network Coverage: Network coverage has a major impact on how well NB-IoT works. A challenge in remote or geographically difficult areas could be maintaining reliable connectivity.

- Device Interoperability: Making sure that a variety of IoT devices are interoperable can be difficult. Although standardization is being worked on, compatibility problems could still occur.
- Initial Deployment Costs: There may be setup fees associated with implementing NB-IoT infrastructure. Nevertheless, these initial costs are frequently exceeded by the long-term advantages in terms of efficiency and dependability.

Comprehending these obstacles is imperative for an exhaustive assessment of NB-IoT's practicability in particular applications. We learn more about the enormous potential of NB-IoT and how it negotiates the complexity of the IoT environment as we investigate these aspects.

VII. Solutions and future perspectives

As NB-Iot continues to evolve as a dedicated IoT ecosystem , critical challenges emerge, notably in extending network coverage, Device Interoperability,and managing initial deployment expenses. Addressing these challenges requires innovative solutions and forward-thinking insights to solidify NB-IoT's position as a cornerstone of intelligent connectivity. Exploring current remedies and anticipating future developments in these pivotal domains is pivotal to establishing a robust, interconnected, and economically viable NB-IoT ecosystem, paving the way for diverse and extensive applications.

- **Network Coverage Enhancement :** Expanding NB-IoT's network coverage remains pivotal for its widespread adoption. To overcome coverage limitations, strategies involving infrastructure expansion and base station densification are crucial. Leveraging existing cellular networks, augmenting infrastructure in underserved areas, and optimizing signal propagation through innovative technologies like repeaters or signal amplification are promising solutions. Collaborations between network operators and governments to incentivize infrastructure deployment in remote regions could further extend the reach of NB-IoT networks.Additionally, implementing mesh networking techniques can notably enhance network coverage by establishing resilient connections between devices, overcoming geographical limitations and ensuring more comprehensive coverage. (Ref [11] Mesh Networking : What Is a Mesh Network? How Does It Work? (lifewire.com))
- **Device interoperability and standards :** The challenge of device interoperability demands standardized protocols and compatibility frameworks. Ongoing efforts by standardization bodies to establish unified protocols for NB-IOT devices are promising. Increased adherence to these standards ensures seamless communication between various devices from different manufacturers. Moreover, fostering an ecosystem where devices from diverse vendors can interoperate without constraints is essential for scalability and versatility in NB-IoT applications.

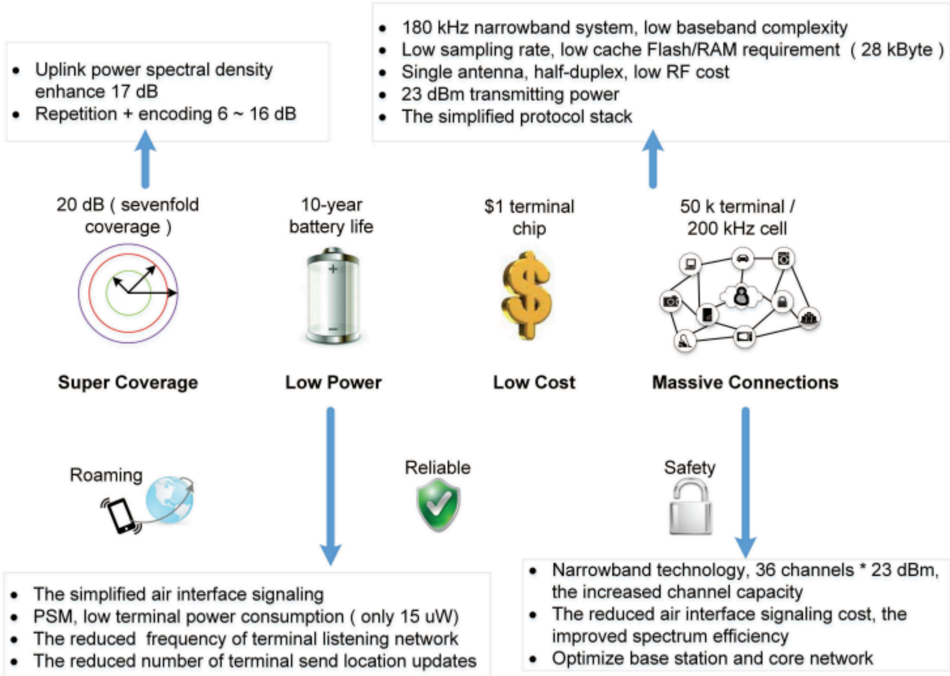
- **Mitigating Initial Deployment Costs :** Reducing the initial deployment costs associated with NB-IoT involves multiple strategies. Economies of scale in hardware production, advancements in manufacturing technologies, and streamlined deployment strategies are key solutions. Innovative business models, such as shared infrastructure agreements between stakeholders or subscription-based service offerings, can alleviate upfront costs for adopting NB-IoT technology. Furthermore, leveraging emerging technologies to optimize installation, configuration, and maintenance processes will contribute to cost-efficiency.

- Future Prospects : The future landscape of NB-IoT promises significant enhancements.

Collaborations between network operators, governments, and technology providers are expected to expand network coverage, ensuring connectivity even in remote regions. Continuous efforts toward standardization and protocol unification will drive device interoperability. Advances in manufacturing, coupled with evolving deployment strategies, will likely reduce initial costs, making NB-IoT more accessible for a diverse range of applications. These collective efforts set the stage for a robust and pervasive NB-IoT ecosystem, fostering its growth and integration across various industries and applications.

VIII. Conclusion

In conclusion, NB-IoT emerges as a formidable contender in the realm of IoT connectivity, showcasing distinct advantages over other prevalent technologies. Compared to traditional Wi-Fi and Bluetooth, NB-IoT excels in extended coverage, making it a preferred choice for applications prioritizing wide-ranging connectivity and latency tolerance. In contrast to Zigbee, GSM, and LoRa, NB-IoT stands out with its superior interference resilience, thanks to its narrow spectrum and advanced repetition mechanisms. Additionally, the heightened transmission power offered by NB-IoT enhances the reliability and security of message delivery, setting it apart as a robust solution for diverse IoT applications. As the landscape of IoT continues to evolve, NB-IoT emerges as a versatile and compelling connectivity option, addressing key challenges and ensuring seamless communication for a wide array of devices and use cases.



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