Development of Narrow Band Internet of Things Testbed for Proximity Services

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Citation | Jafri. S. T. J, Amin. S. R, Amanat. F, Aslam. T, Ali. S, Ahmed. I, Aslam. M. I, "Development of Narrow Band Internet of Things Testbed for Proximity Services", IJIST, Special Issue. pp 146-157, Oct 2024

Received | Oct 08, 2024 **Revised |** Oct 14, 2024 **Accepted |** Oct 19, 2024 **Published |** Oct 23, 2024.

With the evolution of Internet of Things (IoT), Narrowband IoT (NB-IoT) emerged to provide IoT connectivity using existing cellular network utilizing limited resources but with increased possibility of outage at the cell-edge. In this wok, we developed a testbed for NB-IoT systems to implement innovative idea of enabling proximity service for NB-IoT so that devices beyond the coverage area of eNodeB may transmit their data using a network relay. The testbed is developed using a software defined radio working as eNodeB that wirelessly connects to the NB-IoT node at the frontend and to the Evolved Packet Core (EPC) at the backend. The EPC is implemented on a Linux machine using open-source software packages whereas NB-IoT node is implemented using commercially available devices. In this paper, we report the results of this deployment indicating that the NB-IoT device is properly connecting and communicating with the eNodeB. The session logs presented in the paper indicate that the EPC successfully initiates the session and authenticate the user equipment (UE). Furthermore, the eNodeB also establishes a successful connection with the UE based on the parameters set by the EPC. The Wireshark traces presented in the paper clearly indicate that the UE has got the capability to transmit data to the server through internet connection. The average latency observed is 40 ms. Through this work, the benefits of proximity services are being explored for NB-IoT networks providing a platform for experimental testing and prototyping.

Keywords: Internet of Things (IoT); Narrowband IoT (NB-IoT); Proximity Services (ProSe); Network Relay, and Cellular IoT (C-IoT).

Introduction:

Background:

The evolution of wireless technologies and the emergence of the Internet of Things (IoT) have enabled a wide range of new applications through the interconnection of IoT devices, leading to the development of Low Power Wide Area Networks (LPWAN). LPWAN was initially introduced as a component of Long-Term Evolution-Advanced (LTE-A), designed to support long-range connectivity for massive IoT services and applications. Various LPWAN technologies have been developed that operate in both licensed and unlicensed bands [1], [2]. A comparative summary of popular LPWAN technologies is presented in Table 1.

Table 1. A comparative summary of popular LPWAN technologies

Specification	LTE-M	NB-IoT	LoRaWAN	Sigfox
Standardization	3GPP	3GPP	LoRa Alliance	Open standard
Licensed	Yes	Yes	No	No
Channel Bandwidth	1.08MHz	200kHz	125KHz	0.1KHz
Duplexity	Full/Half	Half	Half	Half
Downlink Throughput	1Mbps	26kbps	300bps	100bps
Uplink Throughput	1Mbps	66kbps	50bps	600bps
Latency	10-15ms	1600-10000ms	>20s	1-100ms
UE Bandwidth	1.4MHz	200kHz	200KHz	125KHz

Narrowband IoT:

The integration of IoT with cellular infrastructure, referred to as Cellular-IoT (C-IoT), has the potential to connect billions of devices, enabling a wide array of services such as industrial automation and monitoring, remote health monitoring, e-commerce, public safety networks, device-to-device communication, vehicular communication, social networks, and multimedia services. The authors in [3] evaluate both cellular IoT and non-cellular LPWAN technologies concerning scalability and deployment costs. According to the Ericsson Mobility Report 2023 [4], the number of C-IoT connections is expected to exceed six billion by 2029, with more than 50% projected to be Narrowband IoT (NB-IoT) [4], which is designed for low-data rate and low-power applications. Introduced in the Third Generation Partnership Project (3GPP) Release 13, NB-IoT utilizes a narrowband channel within the existing LTE network to upload data to servers [5].

Several researchers have focused on the hardware and simulation aspects of NB-IoT deployment and the analysis of its challenges. The authors of [6] detail the design of an NB-IoT system and address coverage challenges related to path loss and interference in specific cells of an LTE network. Evaluations in [7] indicate that NB-IoT can achieve around 20 dB of coverage enhancement across various deployment scenarios compared to existing LTE technologies. Studies in [8] and [9] investigate NB-IoT network deployment, highlighting its superior performance over LTE networks in terms of coverage area and uplink time delay, while also proposing robust security measures for data transmission within NB-IoT networks. Furthermore, [8], [9], and [10] present analytical models of NB-IoT networks to assess performance indicators under different deployment and environmental conditions [11], [12], [13], [14], [15], [16], [17]. Given the increasing density of NB-IoT devices and the inherent resource constraints, further investigation into their performance using comprehensive analytical and simulation frameworks is warranted [18].

Proximity Service for NB-IoT:

In 3GPP Release 12, Device-to-Device (D2D) communication was introduced to enable proximity services (ProSe) for end devices in close proximity, allowing them to exchange data directly without the need for base stations. Enabling D2D communication in the NB-IoT network is anticipated to enhance the network's functionality and coverage [19]. Despite the challenges associated with implementing ProSe for NB-IoT [20] due to resource constraints, various studies offer insights into its power efficiency and network robustness [11], [21], [22]. D2D-enabled NB-IoT opens opportunities for providing services from subscribers to devices outside the coverage area of the eNodeB [23]. Although ProSe for NB-IoT devices was introduced in Release 15, there are currently no commercially available off-the-shelf (COTS) devices capable of utilizing ProSe to upload data to the cloud.

Objectives:

Although various researchers have conducted simulation-based analyses of NB-IoT networks [21], [22], [23], there remains a need to develop relevant testbeds for experimentally evaluating NB-IoT network performance. In this work, we focus on the design, development, and prototyping of a proximity services-enabled NB-IoT network aimed at reducing power consumption, enhancing battery life, and improving overall network reliability. Our primary objective is to enable NB-IoT device-to-UE communication, where the UE acts as a Network Relay capable of forwarding uplink data to the eNodeB. To achieve this, we have defined the following objectives for the project:

- Develop a proof-of-concept and establish a flexible, sustainable testbed for implementing a ProSe-enabled NB-IoT network.
- Investigate the performance of the ProSe-enabled NB-IoT under various propagation channel scenarios and network node deployments.
- Compare the performance of ProSe NB-IoT with conventional NB-IoT communication.

Novelty:

In this work, we are developing a testbed for a ProSe-enabled NB-IoT network. In the first phase, we established a basic NB-IoT network in which an NB-IoT node wirelessly connects to the eNodeB implemented using Software Defined Radio (SDR). The SDR is configured through the Open-Air Interface (OAI) [24], installed on a dedicated Linux machine. By incorporating OAI, we gain access to standardized LTE features, ensuring compatibility with commercial LTE networks. The Evolved Packet Core (EPC) is implemented on a separate Linux machine using srsRAN4G [25], an open-source software suite specifically designed for Radio Access Network (RAN) functionality. This network configuration is detailed in the results and discussion section. The technical contributions of this work are as follows:

- Development of a system model for implementing ProSe services in an NB-IoT network.
- Configuration of the SDR to function as the eNodeB/NB-IoT gateway, integrated with the EPC.
- Setup of commercially available off-the-shelf (COTS) devices as NB-IoT end-user devices to wirelessly communicate with the eNodeB.
- Successful configuration of the EPC, eNodeB, and NB-IoT node to establish communication according to NB-IoT standards, resulting in the development of a basic end-to-end NB-IoT testbed.

In the next phase of the project, we will deploy an additional SDR as a UE relay to enable NB-IoT device-to-UE relay communication, where the UE will function as a network relay capable of forwarding uplink data from the NB-IoT device to the eNodeB.

Material and Methods:

Methodology Overview:

As this work focuses on the design, development, and prototyping of a proximity services-enabled NB-IoT network, we have divided the methodology into three stages, as illustrated in Figure 1.

The first stage involves designing the system model to enable proximity services within the NB-IoT network. In the second stage, we established direct communication between the

NB-IoT node and the eNodeB. The third stage, which is currently under development, focuses on integrating ProSe into the system.

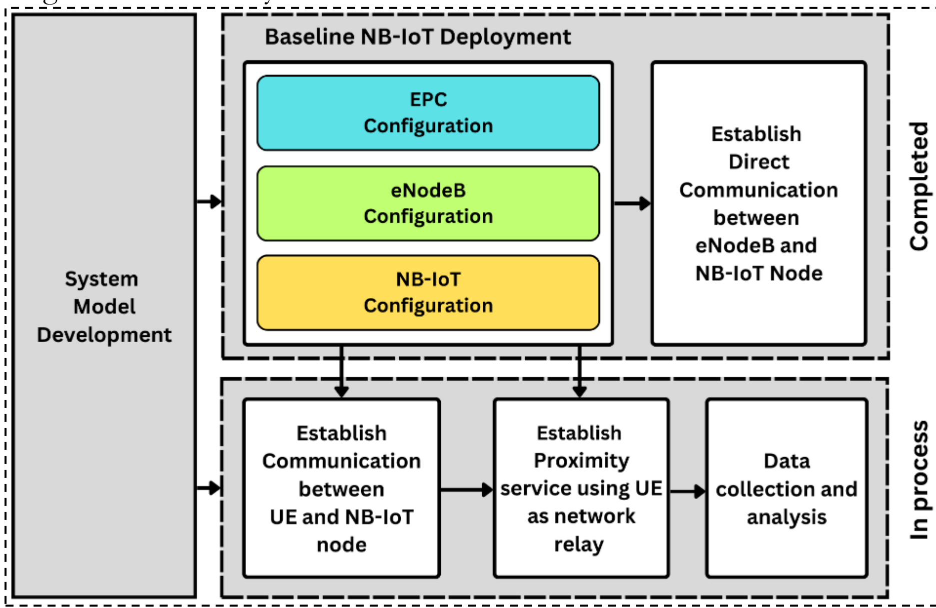

Figure 1. Illustration of the methodology being used to implement proximity services in an NB-IoT network

System Model:

The conceived system model is illustrated in Figure 2. As depicted, the eNodeB provides wireless connectivity to the nodes within its coverage area. However, nodes located beyond this boundary can connect to the eNodeB through a proximity service-enabled UE within the coverage area, functioning as a network relay. On the backend, the eNodeB is connected to the EPC, which facilitates data transmission to the application server.

The next stage of the methodology involves configuring the network, which includes setting up the EPC, eNodeB, and NB-IoT node. This task has been successfully completed, and the team has established a direct communication link between the eNodeB and the NB-IoT node. A detailed description of the hardware setup and system configuration can be found in the Experimental Setup subsection. The final stage of the project, which is currently in progress, focuses on establishing communication between the UE network relay and the eNodeB, followed by connecting the NB-IoT node to the UE relay to enable a ProSe-capable network.

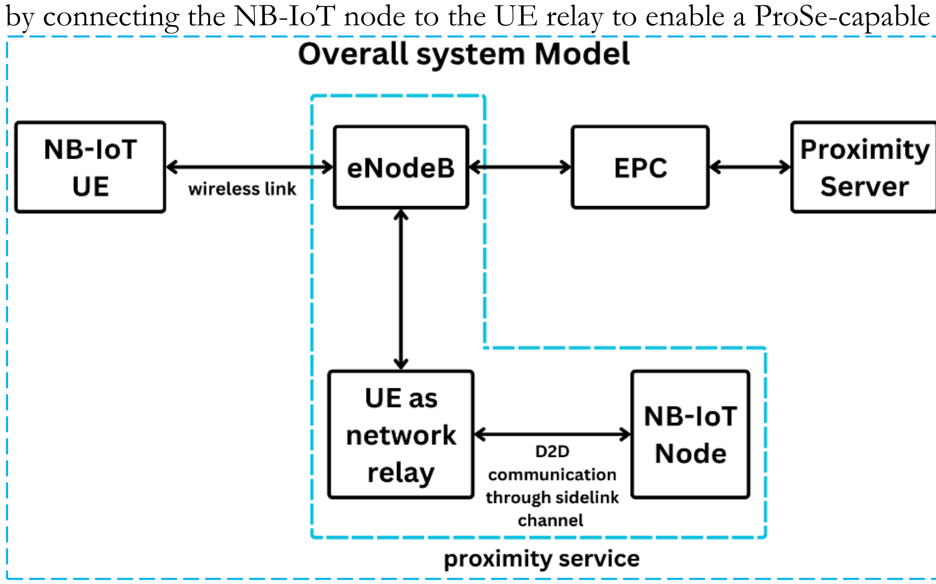

Figure 2. System model for an NB-IoT network capable of providing proximity service

Experimental Setup:

This section provides a description of the hardware setup and configuration for the implementation of the NB-IoT network. We have established an end-to-end LTE network using SDR and commercially available IoT devices. The LTE network offers high-speed data transmission, low latency, and seamless connectivity for a wide range of applications. We built the LTE network from the ground up, utilizing National Instruments' Universal Software Radio Peripheral (USRP) devices along with open-source software stacks. The hardware components and their connectivity are illustrated in the system model in Figure 2.

The system consists of three main components: the NB-IoT node, eNodeB, and EPC. The NB-IoT node serves as the end device, while the eNodeB, hosted on a machine connected to the USRP, provides over-the-air communication to the NB-IoT device. The EPC is set up on a separate machine and includes the essential components for data and user management. Thus, the setup involves two Linux machines, as shown in Figure 3.

One machine is configured to function as the EPC, emulating core network entities responsible for user authentication, mobility management, and session management. The EPC ensures seamless handovers, manages bearer contexts, and maintains user profiles. By running EPC software, we replicate the backbone of a real-world LTE network. The second machine is configured to operate as the eNodeB, which controls radio resources, allocates time slots, and manages the connectivity of multiple UEs. Our eNodeB configuration includes parameters such as modulation schemes, coding rates, and transmit power.

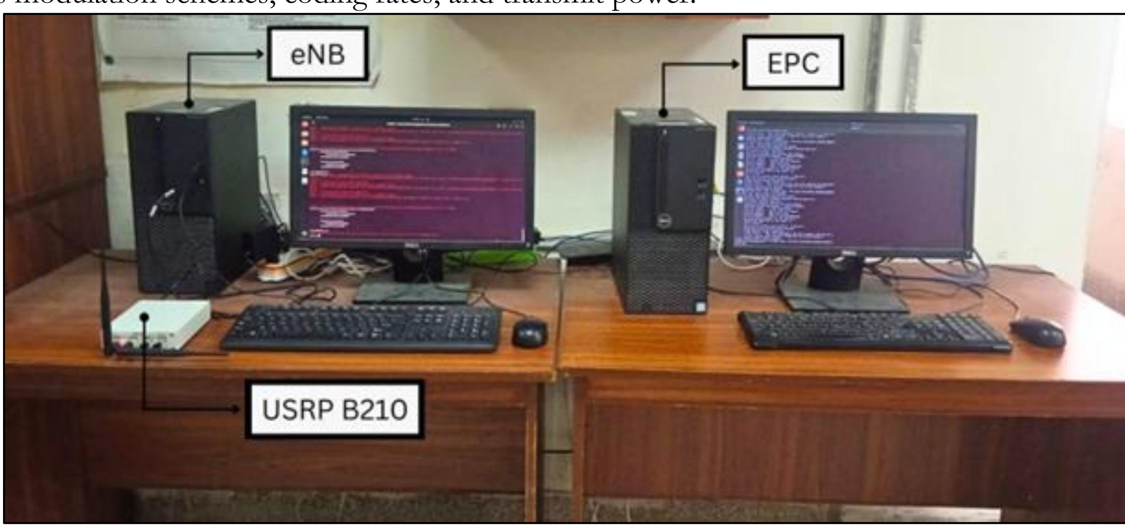

Figure 3. Experimental setup for OAI-based NB-IoT network

EPC and eNodeB Configuration:

The EPC and eNodeB are implemented using two separate computing machines. Both machines, as shown in Figure 3, are installed with Ubuntu 22.04 LTS and kernel version 5.4.0 (low-latency). An Ettus B210 USRP is connected to the eNodeB, utilizing the USRP Hardware Driver (UHD) version 4.6.0 for the latest drivers. To configure the eNodeB and EPC, we selected two open-source tools to serve as the underlying framework.

SRSRAN4G is used to implement RAN functionality, effectively bridging the gap between the physical layer and higher-level network protocols. To complete our LTE protocol stack, we integrated the Open-Air Interface (OAI) developed by Eurecom. This comprehensive software package covers the entire LTE architecture, from the physical layer to radio resource control (RRC), enabling us to simulate LTE UEs, manage radio channels, and establish end-to-end communication. By incorporating OAI, we gain access to standardized LTE features, ensuring compatibility with commercial LTE networks.

COTS UE Configuration:

The complete setup requires at least one COTS device for testing connections and analyzing the NB-IoT network KPIs. A COTS device serves as the end device, which is connected to a general-purpose Windows-based computer, as shown in Figure 4. Several COTS UEs are available in the market that support various NB-IoT bands and are compatible with LTE, LTE-A, and 5G capabilities. For this work, we procured a total of six COTS devices from three different vendors: Sixfab [26], 5GHUB [27], and Waveshare [28]. Each device is equipped with a global Subscriber Information Module (SIM) card, providing worldwide coverage.

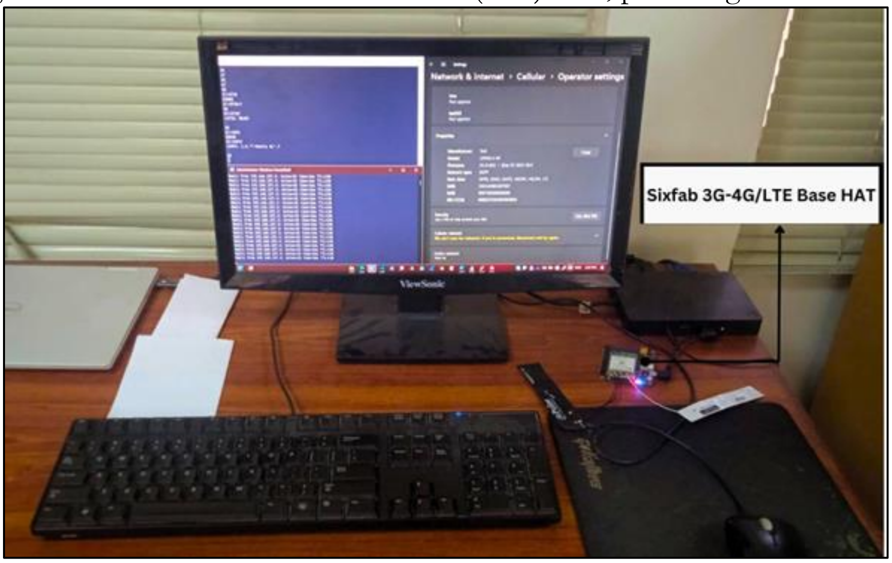

Figure 4. COTS-UE device connected to a Windows-based computer

Overall System Configuration:

To ensure that the COTS UE and eNodeB can discover each other and communicate effectively, a frequency band supported by the COTS UE is selected. The attachment procedure for the COTS UE to the EPC requires the SIM card information to be updated in the Home Subscriber Server (HSS). The SIM card is programmed using the utility pysim [29], and this information is then updated in the HSS to allow the EPC to authenticate and attach the COTS UE.

The eNodeB parameters are defined based on our system model requirements and the specifications of the COTS UE, necessitating modifications to the default configuration of the eNodeB provided by OAI. Table 2 outlines the essential eNodeB parameters that differ from the default settings.

The network configuration is established for both the EPC and eNodeB to enable communication over Ethernet, with both computers connected to a network switch. Connectivity between the EPC and eNodeB is ensured by setting the same area code, Mobile Country Code (MCC), and Mobile Network Code (MNC) values in both configurations. To secure the communication between the EPC and eNodeB, the EPS Encryption Algorithm (EEA) is utilized, which is defined in the EPC configuration.

Table 2. List of eNodeB (B210 USRP) parameters modified for the NB-IoT testbed

Parameter Description	Value
Downlink frequency	874 MHz
Uplink frequency offset	–45 MHz
EUTRA band	5
Resource blocks	50
Mobile Country Code (MCC)	16
Mobile Network Code (MNC)	204

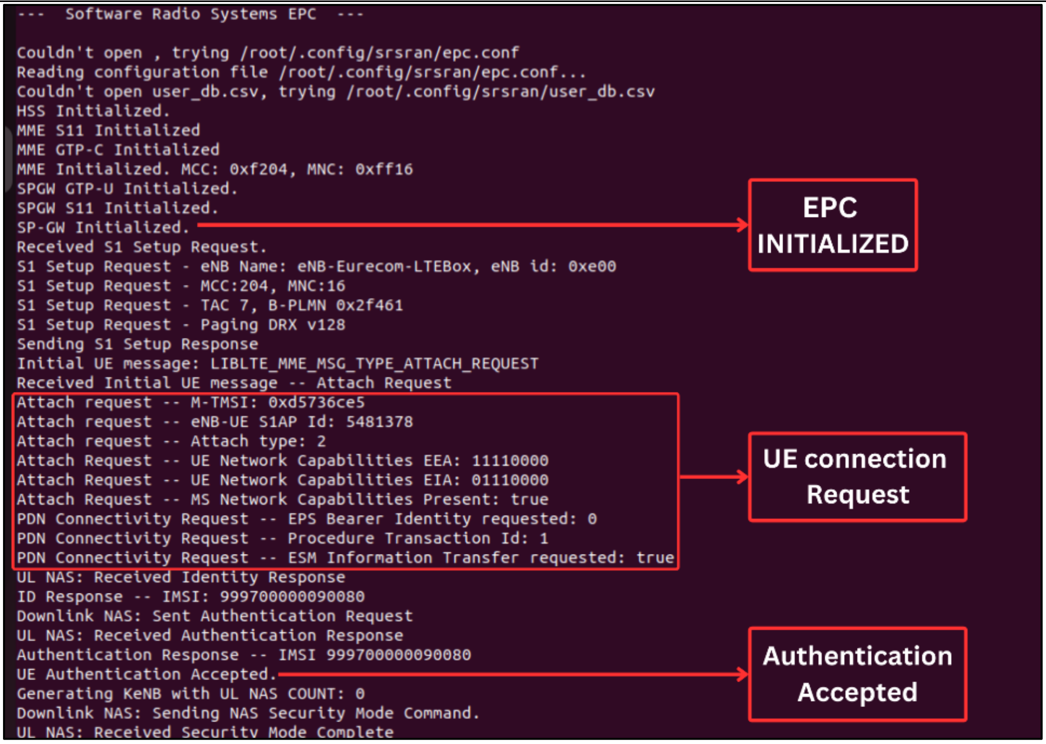

Figure 5. EPC log showing UE information

Results and Discussion:

The testbed was deployed in an indoor laboratory environment measuring 15 × 40 sq. ft. The COTS UE was positioned approximately 8 ft. away from the eNodeB (USRP SDR) for initial development and testing. The hardware testing results are categorized into three groups based on the system components under evaluation: EPC results, eNodeB results, and NB-IoT COTS UE results, all of which are discussed in this section.

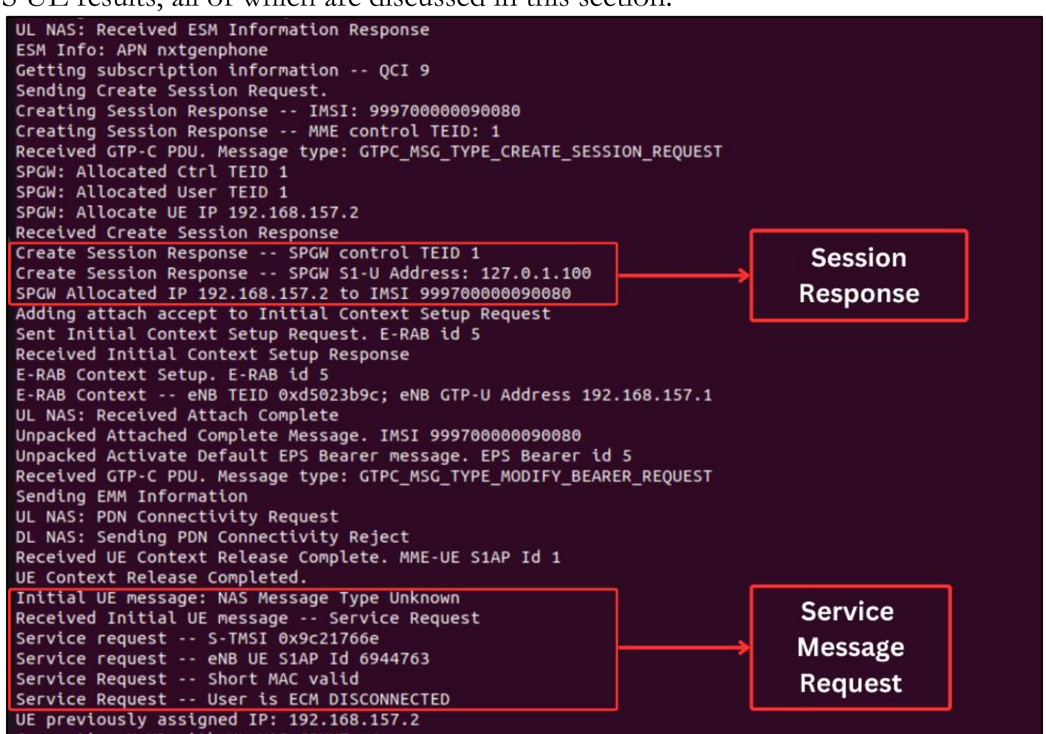

Figure 6. EPC log showing successful UE connection and service status

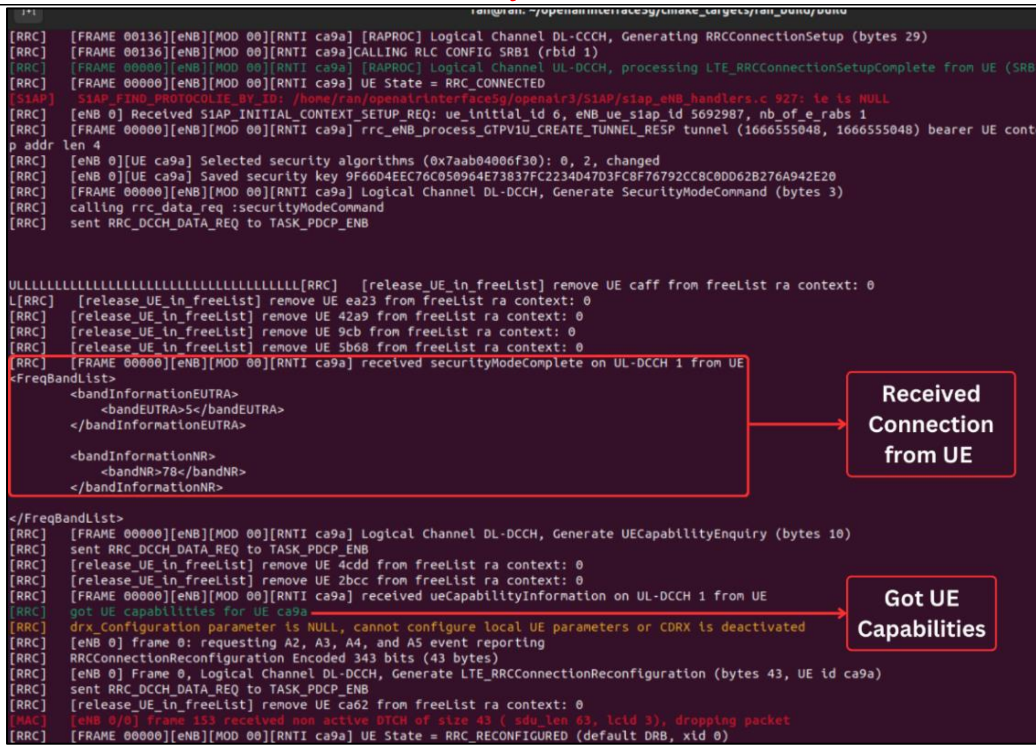

Figure 7. eNodeB showing communication between UE and eNodeB

At the EPC side, we first need to initialize the EPC and execute the RAN component, namely the eNodeB. This is accomplished using the 'lte-softmodem' utility in srsRAN4G. The EPC and eNodeB communicate and agree on preconfigured parameters to establish a connection over Ethernet. As illustrated in Figure 5, the EPC is initialized first and then connects to the eNodeB. Figure 5 also shows the response when the COTS UE sends an attach request to the EPC through the eNodeB, with the EPC authenticating the COTS UE by matching the SIM parameters configured in the HSS database. Once the authentication process is completed, the EPC initiates the procedure to allocate an IP address, as shown in Figure 6. With the assigned IP address, we can test IP traffic between the COTS UE and the LTE network.

The interface between the UE and EPC is provided by the eNodeB, which facilitates communication according to the standards set for RAN. Figure 7 shows the successful connection to the USRP and the exchange of parameters necessary for establishing the connection. The results in Figure 7 also illustrate the capabilities supported by the COTS UE, which can be used to test various types of network connections.

For the NB-IoT COTS UE results, we utilized a Sixfab NB-IoT capable LTE/5G device that can connect to any computer and function as a cellular modem for transferring IP traffic. The Wireshark [30] capture in Figure 8 displays the device and SIM information for the NB-IoT COTS UE as recognized by the operating system. Following a successful connection between the COTS UE and EPC, the COTS UE is assigned an IP address and begins to exchange IP packets, as captured in the Wireshark traces shown in Figures 9 and 10.

The COTS UE starts sending discovery messages to multicast addresses while also attempting to connect to the DNS provided (8.8.8.8 for Google DNS). Figure 10 displays other types of multicast messages for protocols running on the Windows machine, aimed at discovering possible routes. The network latency test using the Internet Control Message Protocol (ICMP) indicates an average latency of 40 ms.

The results presented here for the NB-IoT indicate successful connectivity between all components of the LTE network, including EPC-to-eNodeB and eNodeB-to-NB-IoT device connections. Data transmission over the test network deployed in a lab environment demonstrates the network's ability to further deploy NB-IoT-capable transmission channels and service nodes beyond the coverage area by utilizing ProSe specifications.

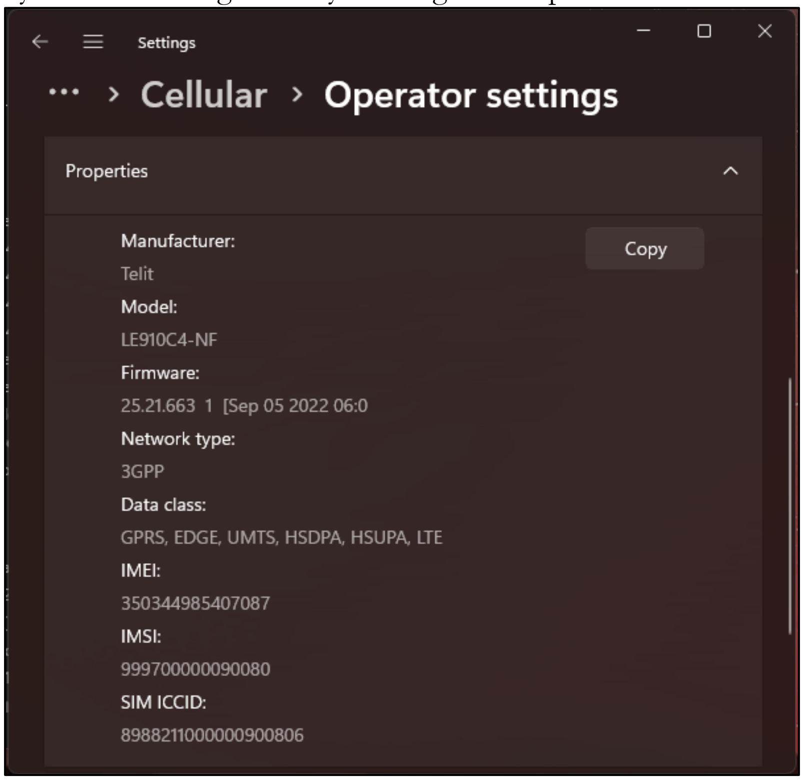

Figure 8. NB-IoT device properties as detected by operating system

885	135.220880	192.168.157.2	239.255.255.250	SSDP	203 M-SEARCH * HTTP/1.1
886	135.221874	192.168.157.2	239.255.255.250	SSDP	192 M-SEARCH * HTTP/1.1
887	135.814157	192.168.157.2	8.8.8.8	TCP	52 63768 → 53 [SYN] Seq=0 Win=65330
888	135.814330	192.168.157.2	8.8.8.8	TCP	52 63769 → 53 [SYN] Seq=0 Win=65330
889	136.221271	192.168.157.2	239.255.255.250	SSDP	203 M-SEARCH * HTTP/1.1
890	136.223352	192.168.157.2	239.255.255.250	SSDP	192 M-SEARCH * HTTP/1.1

Figure 9. Wireshark trace showing NB-IoT COTS UE sending discovery messages

1	0.000000	192.168.157.2	224.0.0.22	IGMPv3	40 Membership Report / Join group 239.255.
2	0.018914	::	ff02::16	ICMPv6	76 Multicast Listener Report Message v2
3	0.019048	192.168.157.2	224.0.0.22	IGMPv3	40 Membership Report / Join group 224.0.0.
4	0.031665	::	ff02::16	ICMPv6	76 Multicast Listener Report Message v2
5	0.031824	192.168.157.2	224.0.0.22	IGMPv3	40 Membership Report / Join group 224.0.0.
6	10.707237	192.168.157.2	224.0.0.22	IGMPv3	40 Membership Report / Join group 239.255.
7	10.715746	::	ff02::16	ICMPv6	76 Multicast Listener Report Message v2

Figure 10. Wireshark trace of NB-IoT COTS UE device sending multicast messages for routing purposes

Conclusion:

This paper reports on the progress of developing a testbed to implement proximity services in NB-IoT networks. To date, we have established a baseline NB-IoT network by configuring the EPC, eNodeB, and NB-IoT end node. The configuration details and results are presented herein, demonstrating that we have successfully deployed an NB-IoT network by properly setting up all its components. However, this work has encountered several challenges.

Firstly, the COTS devices exhibit limited functionality and flexibility, restricting their application in new scenarios, such as a limited number of bands for specific regions. Additionally, ensuring compatibility among devices from different manufacturers has proven to be a significant challenge throughout this project. To address these issues, we plan to replace the COTS NB-IoT device with a fully programmable SDR. Implementing the NB-IoT end device on an SDR will enhance the flexibility of the testbed and improve compatibility with the eNodeB, which is also implemented on another SDR.

Furthermore, to analyze the impact of user density, we will need to integrate additional COTS devices into the system to increase the number of NB-IoT nodes. Future work on this project will include configuring a UE to function as a network relay. This will be achieved by programming another SDR (Ettus B200) to operate as a UE and network relay when needed. By utilizing SDRs alongside COTS devices, we aim to successfully implement proximity services in NB-IoT networks.

Acknowledgement: Authors would like to acknowledge the financial support from Higher Education Commission (HEC), Pakistan under National Research Program for University Project number 17060.

Author's Contribution: S.A. and M.I.A. conceived the idea; M.I.A, S.A. and I.A. prepared the proposal, developed the project objectives and managed all resources; S.T.A.J., S.R.A., F.A., and T.A. developed the hardware and system configuration; All authors contributed to the paper write up.

Conflict of Interest: Authors declare no conflict of interest.

Project Details. The work presented in this paper is conducted under National Research Program for University Project number 17060 supported by Higher Education Commission (HEC), Pakistan. The project title is "NB-IoT ProSe: Proximity Services enabled NB-IoT for Reliable and Critical Communication in Low-Powered Applications". This two-year duration project was started in June 2023 and is expected to be completed by June 2025.

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