Experimental Evaluation of Roaming Performance of Cellular IoT Networks

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***Abstract*—As the growth of the Internet of Things (IoT) devices continues, more and more wireless technologies are getting introduced into the market. NarrowBand-IoT and Long-Term Evaluation Cat M1 (LTE-M) are two Low-Powered Wide Area Network (LPWAN) communication technologies introduced by 3GPP in release 13 of LTE. Some of the features supported by these Cellular-IoT (C-IoT) technologies include low power consumption, extended coverage, low cost of deployment, roaming between Mobile Network Operator's (MNO) networks, etc. This paper focuses on the experimental evaluation of NB-IoT and LTE-M networks in an international roaming scenario. The goal behind the experiments is to test and benchmark the performance of NB-IoT and LTE-M by calculating network Key Performance Indicators (KPIs) such as bitrate, end-to-end latency, and packet drop in a home and in roaming network scenarios. In order to perform the experiments, a Danish operator is chosen with nationwide coverage in Denmark (DK), Sweden (SE), and Norway (NO). A total of 6000 packets with varying payload sizes are sent using both the C-IoT technologies in all three countries combined. The idea behind the experiments is to test whether or not C-IoT technologies are reliable for supporting roaming applications in the IoT paradigm.**

***Index Terms*—Cellular IoT (C-IoT), IoT-roaming, LTE-M, NB-IoT, IIoT**

I. Introduction

Internet of Things (IoT) is now known to everyone, and there are spaces to dig deep and make this technology more reliable and secure. In the last ten years, there has been spectacular growth in the IoT domain. In 2018, approximately 7 billion IoT devices were connected to the internet, and by the year 2019, the number of IoT devices connected to the internet reached 26.66 billion. Based on a projection given by the experts, this number will be 75 billion by the year 2025 [1]. Today, most IoT devices functioned over WiFi or Local Area Network (LAN). This implies that these IoT devices are deployed at a fixed location where they can get network connectivity through WiFi or LAN. This technology is considered a superior choice when IoT end devices do not need to move or roam. Therefore, what if a user needs an IoT-based application with roaming capability? In such cases, LPWAN technologies are capable of supporting the roaming or mobility of devices.

We have several LPWAN technologies, such as LoRaWAN, Sigfox, etc., to support the IoT applications. These LPWAN technologies have better coverage and low power consumption than traditional communication technologies (e.g., WiFi, LTE, etc.), but they have some drawbacks. These LPWAN technologies operate on unlicensed bands and have power & duty-cycle restrictions that only allow data transmission a few times during the day. On the other hand, C-IoT technologies operate on the legacy of cellular technologies LTE. Compared to other LPWAN technologies, C-IoT technologies have lower latency, better coverage, and roaming capability. Therefore, C-IoT is an attractive option for implementing an IoT application such as asset tracking or location tracking that demands low latency, better coverage, low power consumption, roaming capability, etc.

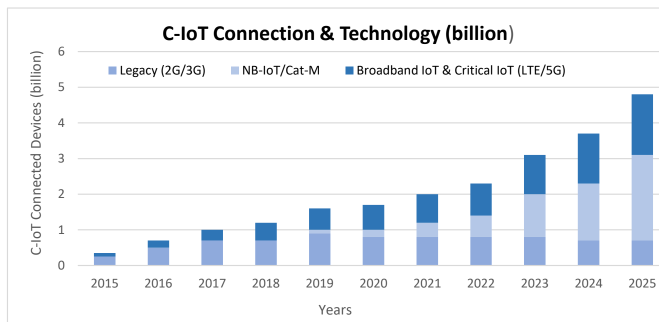

Fig. 1. C-IoT Connected Devices [2]

Based on the Ericsson Mobility Report 2020, 1 billion IoT devices were connected to the internet using C-IoT technologies. Figure 1 shows the forecast of IoT end-devices numbers operating on C-IoT. By the year 2024, more than 20 % of overall IoT devices will function on the C-IoT [2]. For these reasons, it is really interesting to investigate the roaming capability of NB-IoT and LTE-M.

This paper has performed an empirical test to analyse the roaming performance on both NB-IoT and LTE-M networks in neighboring countries, Sweden and Norway. Then the performance is compared in the home vs. roaming network conditions. To perform tests, we selected one operator with a cellular network deployed in Scandinavia. In order to compare network performance, we calculated network KPIs such as end-to-end delay, bit-rate, and packet drop. The outcomes of this paper will help the IoT developer design their C-IoT-based application that requires roaming. Along with this, it will also help the network operators to configure their network parameters related to IoT roaming capability.

The remainder of the paper is divided into the following sections. Section II focuses on C-IoT roaming applications and the applications we have decided to focus on while evaluating the network performance. Section III gives a brief technical overview of NB-IoT and LTE-M deployment. Section IV and V describe the test scenario and compare the results obtained. Finally, in Section VI, the authors conclude the findings from the experiments and discuss future research directions.

II. ROAMING APPLICATIONS

Roaming is one of the key features offered by the C-IoT networks. As the number of connected devices increases, it allows various businesses to consider implementing IoT-based solutions to improve the Quality of Experience (QoE) (e.g., by providing preventive maintenance, etc.) of their customers and get a deeper understanding of their products. Roaming in IoT networks enables client devices to continue sending valuable information back to the server, even when the device is no longer connected to a particular MNO. Roaming in C-IoT, just like in LTE standards, allows these devices to roam in different MNOs, including both national as well as international roaming scenarios. Availability of connectivity globally motivates businesses to deploy IoT communication technologies into their product without worrying about changing the connectivity providers depending upon the part of the world where their product ends up being deployed. Raming requirements may vary depending on the IoT use case (e.g., logistic tracing, automotive, industrial machinery, etc.). Some of these applications may temporarily require roaming capabilities, and others may opt for a more permanent solution.

III. TECHNICAL OVERVIEW OF C-IOT

C-IoT is a wireless technology that can connect IoT devices to the internet without using cell phones. It connects end devices to a cellular base station and provides connectivity for any IoT applications [3].

In release 13, 3GPP introduced two new technologies for machine type (MTC) communication, and they are known as Narrowband IoT (NB-IoT), and Long Term Evaluation Category-M (LTE-M) [4] [5]. To strengthen these IoT technologies, some more enhancements are done, such as roaming, low latency, low power consumption, etc., and 3GPP has considered and defined these specifications in Release 14,15 & 16 [6] [7]. Depending upon the application, NB-IoT and LTE-M have their places in the IoT market. However, compared to NB-IoT, LTE-M has better throughput, bandwidth, and lower latency. Table I shows some technical differences between NB-IoT and LTE-M.

A. NB-IoT

The operating frequency for NB-IoT is in the range of 450 MHz to 3.5 GHz. For NB-IoT operation, 14 bands are available, and band 20 (800 MHz), band 8 (900 MHz), and band 3 (1800 MHz) are used in Europe. It has 180 MHz of bandwidth, which is equal to 1 Physical Resource Block (PRB) [8]. NB-IoT has three deployment modes, which depend upon the utilization of this PRB.

- **In-Band** In this mode of operation, NB-IoT can use one or more than one physical resource blocks of the LTE carrier.
- **Guard-Band**- In this mode of operation, NB-IoT is deployed in the guard band of the LTE carrier.
- **Stand Alone**- In this mode, NB-IoT uses 200 kHz of GSM carrier. In this deployment, NB-IoT can use one or multiple GSM carriers for NB-IoT signaling [9] [10].

NB-IoT uses Quadrature Phase Shift Keying (QPSK) or Binary Phase Shift Keying (BPSK) modulation technique for uplink transmission. The Orthogonal frequency-division multiple access (OFDMA) modulation technique is used for the downlink transmission. It has 159 and 127 kbit/s data rate for uplink and downlink transmission respectively [6] [15].

B. LTE-M

LTE-M is also known as Category-M1 cellular technology. We can say that LTE-M is the up-gradation of LTE or 4G network. It uses an LTE base station and packet core to connect and transmit the LTE-M enabled end-devices data. Since it uses the LTE network, it can provide connectivity to sophisticated locations [11]. In release 14, 3GPP has listed 21 supporting bands for the LTE-M signaling. To achieve the global roaming capability, 11 bands are selected to design a global module that can support global roaming in the region of Europe, North and Latin America, and some parts of Asia. The selected bands are 1, 2, 3, 4, 5, 12, 13, 20, 25, 26 and 28 [13] [14].

LTE-M has a bandwidth of 1.4 MHz, whereas traditional LTE has a bandwidth of 20 MHz. Therefore LTE-M has a more extended coverage range and less throughput than traditional LTE. The data rate is 1 Mbps for both uplink, and downlink transmission [12]. The throughput is approximately 375 and 300 kbps for uplink and downlink transmission. LTE-M uses an in-band deployment mode, and it leverages the same handover features as in traditional LTE communication. LTE-M has full roaming capability, which means it can be considered a viable solution for applications that needs roaming ability [12]. It also has latency in the millisecond range; therefore, it can be used for real-time communication for developing critical applications.

Cellular IoT is the only IoT technology with actual roaming network functionality, and it uses the same roaming functionality design for traditional LTE communications.

IV. EXPERIMENTAL SETUP

This section describes the experimental setup used for evaluating the performance of C-IoT networks in a roaming environment.

One of the features that separate the C-IoT networks from other LPWAN technologies such as LoRaWAN and others is the capability of this technology to support roaming among different MNO networks both nationally and internationally. Sigfox, out of the box, supports roaming in the countries

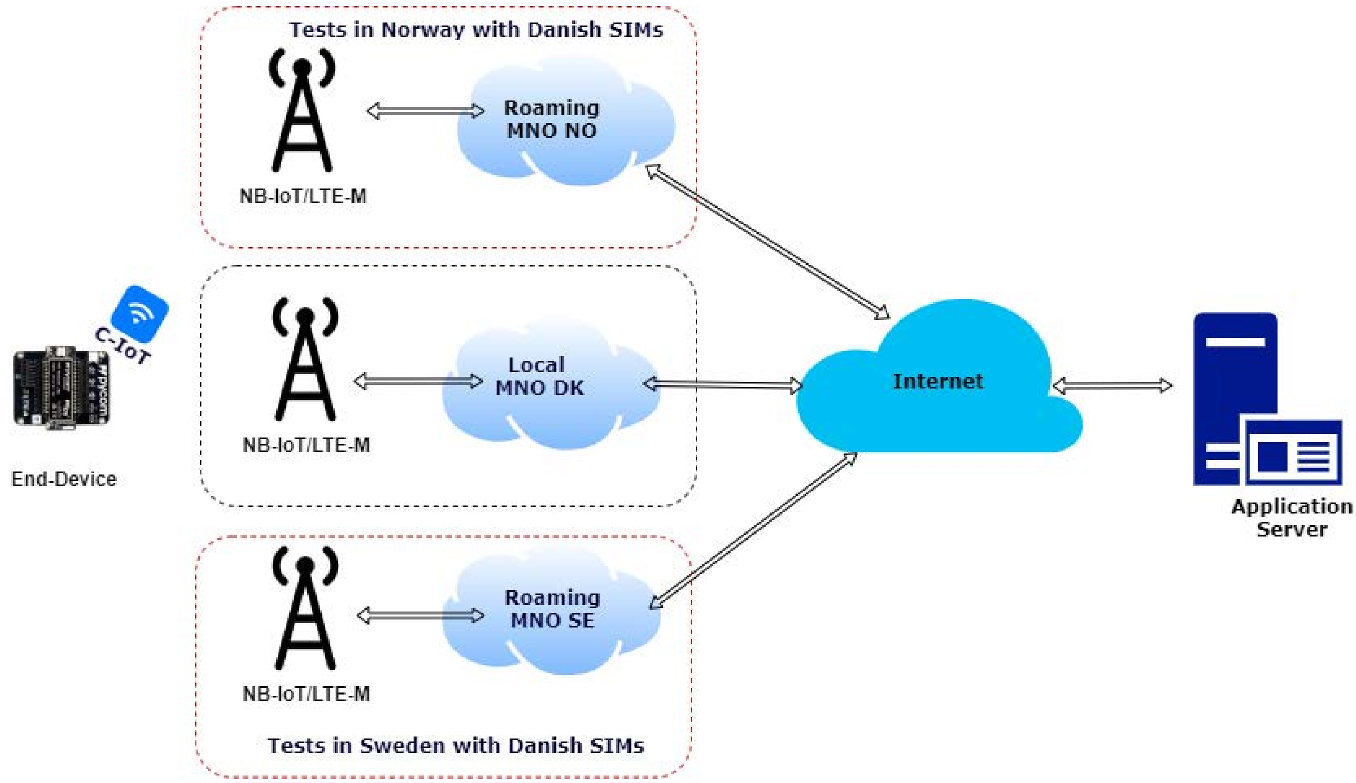

Fig. 2. C-IoT Roaming tests architecture

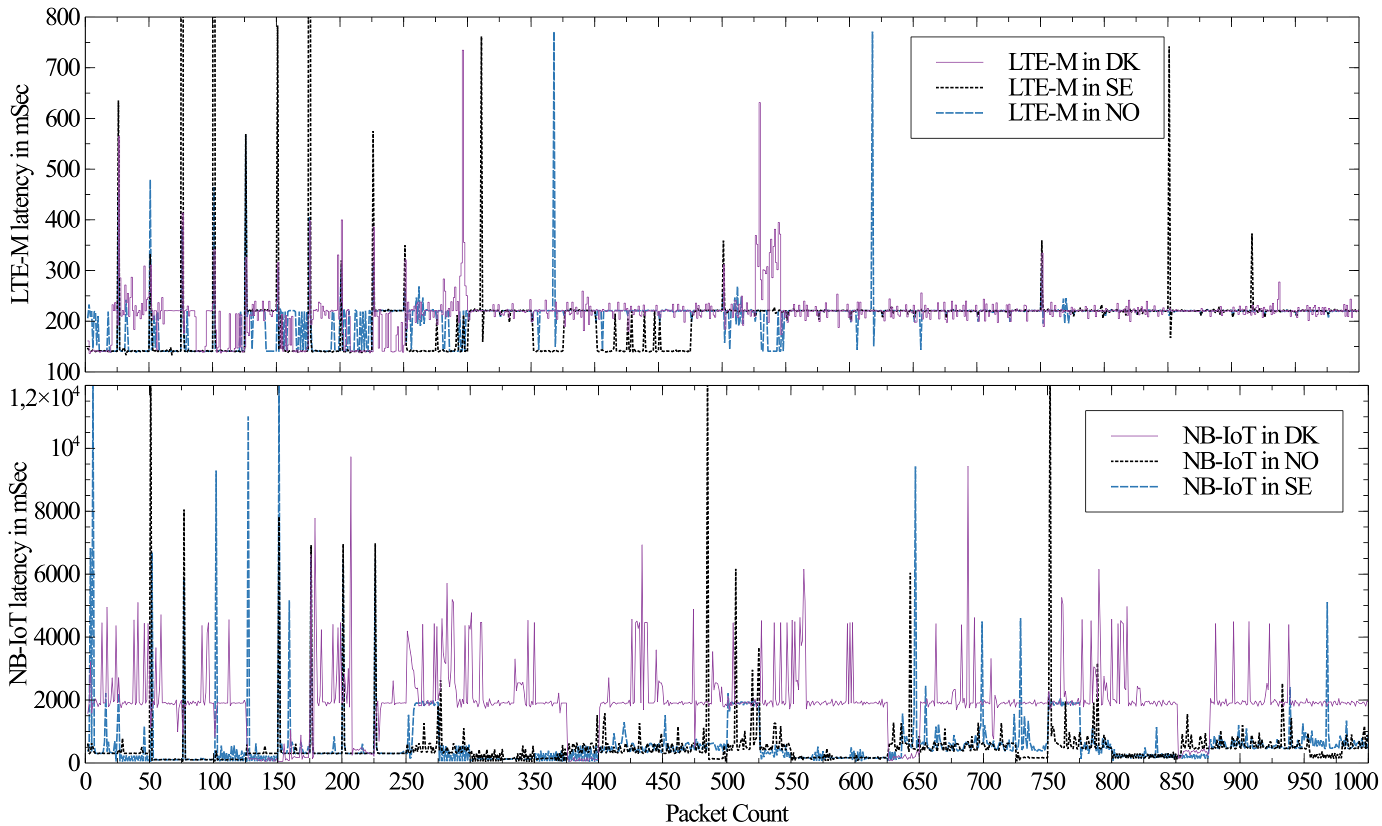

Fig. 3. C-IoT Roaming tests latency overview

TABLE I
COMPARISON BETWEEN LTE-M AND NB-IOT [15]

	LTE-M		NB-IoT	
	LTE-M1	LTE-M2	Cat NB1	Cat NB2
3GPP Release Version	Release 13	Release 14	Release 13	Release 14
Downlink Data Rate	1 Mbps	∼4 Mbps	26 Kbps	127 Kbps
Uplink Data Rate	1 Mbps	∼7 Mbps	66 kbps (multi-tone) 16.9 kbps (single-tone)	159 Kbps
Latency	10-15 ms	N/A	1.6-10 s	N/A
Voice Facility	Yes	Yes	No	No
Bandwidth	1.4 MHz	5 MHz	180 KHz	200 KHz
Transmit Power	20/23 dBm	20/23 dBm	20/23 dBm	14/20/23 dBm

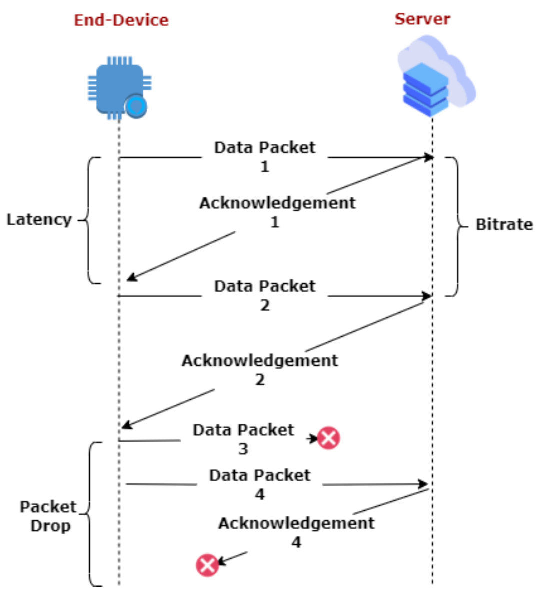

Fig. 4. C-IoT Roaming Experiment Setup Sequence

where there is a Sigfox operator present. However, since this technology operates in a non-licensed spectrum and supports only 140 messages/day, it is challenging for applications that require continuous Uplink transmission in roaming conditions.

In order to conduct the C-IoT roaming tests, we selected an operator in Nordic countries which has a nationwide C-IoT network deployed in Denmark, Sweden, and Norway. The tests aimed to benchmark the C-IoT performance in home and roaming environments. For the performance evaluation, it is decided to calculate network KPIs such as end-to-end latency, bitrate, and packet drop in different countries and evaluate the performance in different environments. In order to keep the results comparable, networks are tested in good radio conditions (CSQ> -85dBm) and are kept in a fixed location. Figure 2 show the test architecture used for conducting the test. A PyCOM-FiPy end device is first tested for C-IoT KPIs in the operator's home network, i.e., with a Danish C-IoT SIM card in Denmark at the Technical University of Denmark premises. Both NB-IoT and LTE-M networks are tested by sending 1000 packets from a location with varying packet sizes of 128, 256, 512, and 1024 bytes as payload and User Datagram Protocol (UDP) as the transport protocol. The same device is then tested in Norway with a Danish C-IoT SIM card in a roaming network. The tests in Norway are conducted at the Norwegian University of Science and Technology (NTNU) premises. Similar to the tests conducted in Denmark, 1000 packets are sent using NB-IoT and LTE-M in roaming conditions. The tests are conducted by sending UDP packets with varying packet sizes from 128-to 1024 bytes.

In order to test the roaming performance in Sweden, the device is kept in the Lund University premises. Similar to the tests performed in Denmark and Norway, the C-IoT technologies are tested by sending 1000 packets using UDP as the transport layer protocol. During the tests, the payload of the UDP packets is varied from 128 to 1024 bytes. In all three tests, the network parameters at the device end are kept the same. The device is configured with Danish MNO's Access Point Network (APN) in both the roaming test scenarios in Norway and Sweden. The rest of the device's network parameters are kept to default settings, e.g., the device is configured to be in automatic attach mode, in which the device connects to the authorized network without forcing any predefined network configuration. For all conducted tests, application server is kept the same, which is hosted on a cloud service provider's platform in Frankfurt, Germany. The server location is approximately 825KM, 827KM, and 2100KM from test locations in Denmark, Sweden, and Norway respectively.

Figure 4 gives an overview of the experiment setup sequence. Once the device is connected to the network, it opens a UDP socket and sends data to the application server. Once the server receives the UDP packet, it sends an acknowledgment back to the device. The end device keeps track of the time interval between sending the packet to the server and receiving the acknowledgment to calculate the end-to-end latency of the network. Similarly, the server keeps track of the interval between the arrival of successive UDP packets from the device to calculate the bitrate. At any point, either the packet to the server or the acknowledgment back from the server does not arrive in the predefined cutoff time; the packet is considered a dropped packet.

V. RESULTS AND DISCUSSION

In this section we will go over the results obtained from the roaming tests.

Figure 3 gives an overview of the end-to-end latency observed during LTE-M and NB-IoT in DK, SE, and NO. As seen from the LTE-M graph, the latency experienced by the packets with a payload of 128 bytes has more variation than rest of the packet sizes. This network behavior can be observed in all three countries with LTE-M communication technology. The latency performance smoothness out after initial fluctuation in the performance. Similarly, the performance of NB-IoT across countries is not very stable, constant spikes in the value of latency can be observed throughout the tests. An interesting observation that can be seen in the graph is that NB-IoT's end-to-end latency performance is much worse in the home network (DK) than when the device is tested while roaming

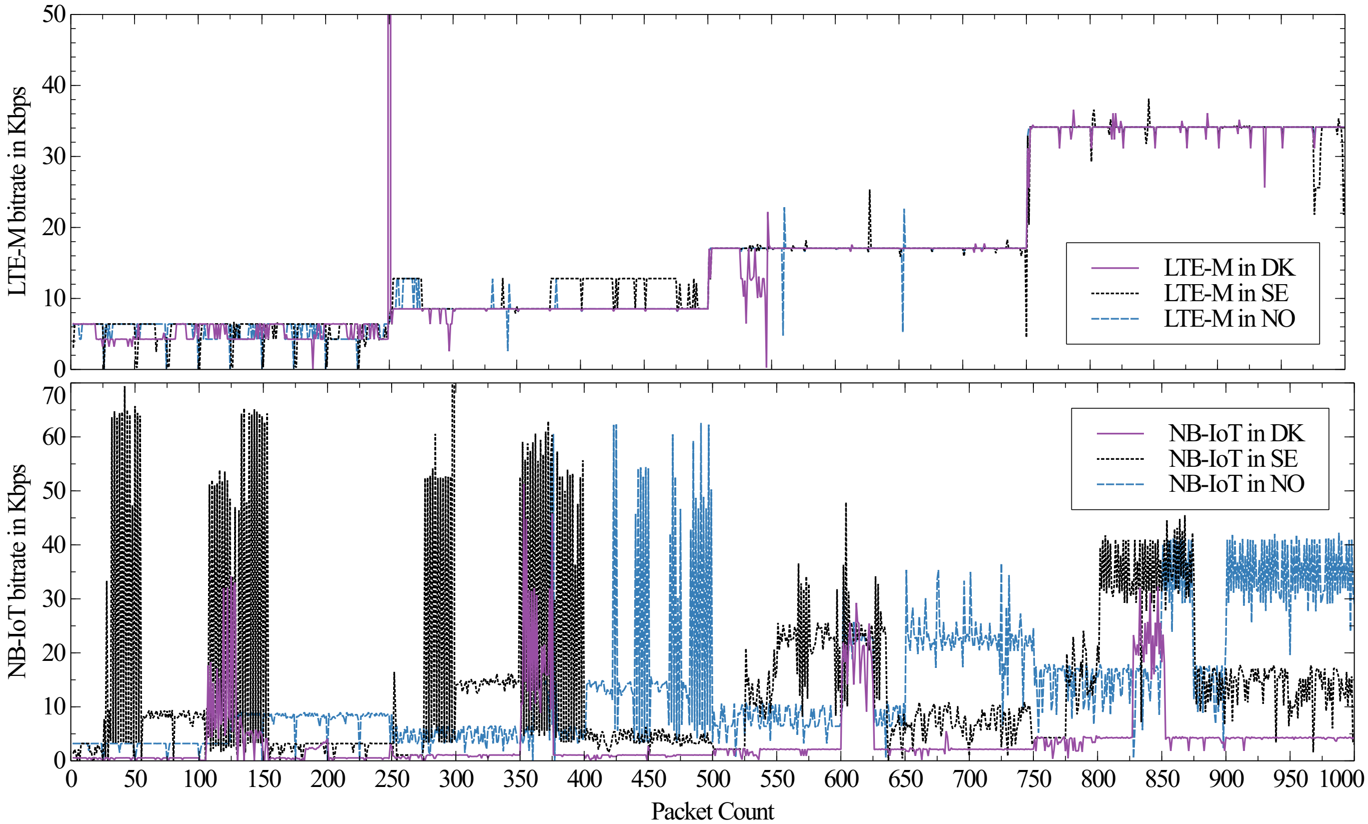

Fig. 5. C-IoT Roaming tests bitrate overview

in Sweden and Norway. The end-to-end latency experienced during NB-IoT tests in Sweden and Norway is much closer to that observed during the LTE-M tests.

Figure 5 gives an overview of the bitrate calculated during the LTE-M and NB-IoT tests in both home as well as in roaming conditions. As can be observed from the LTE-M bitrate performance graph, the network behavior in all the countries is very similar, with minor variations from time to time. It is also very clear from the graphs that the bitrate increases as the payload size of the UDP packet during the test increases. In the case of NB-IoT, similar to the latency performance, the bitrate performance suffers fluctuations. As observed from the NB-IoT graph, bitrate for some chunks of packets is higher than LTE-M. Another observation that can be made is that, similar to latency performance in the home network (DK), the bitrate performance in NO and SE is much higher. This is very obvious since the observed end-to-end latency is very low in Norway and Sweden; more data can be sent through the network quickly, leading to higher bitrate numbers.

Table II shows the median bitrate and latency performance values for all the tests conducted in DK, SE, and NO. As seen from the table, NB-IoT bitrate performance in Denmark is the lowest with a median value of 2.102 Kbps and the highest observed end-to-end latency of 1.9 Seconds. In the case of LTE-M, the median end-to-end latency performance across countries is identical. In contrast, bitrate performance in Denmark is the lowest, with a median value of 8.5665 Kbps.

TABLE II
MEDIAN BITRATE AND LATENCY

Technology	Median Bitrate (Kbps)			Median end-to-end Latency (mSec)		
	Denmark	Norway	Sweden	Denmark	Norway	Sweden
NB-IoT	2.102	8.9805	8.7515	1905.004	314.77	373.571
LTE-M	8.5665	12.8055	12.8115	220.326	220.623	219.795

Table III gives an overview of the total number of dropped packets for both LTE-M & NB-IoT at home as well as roaming network conditions. In the case of LTE-M, a maximum packet drop of 40 packets occurred during the tests in Norway. While in the case of NB-IoT, the maximum packet drop of 180 occurred during the tests performed in the operator's home network in Denmark.

After analyzing the results obtained from these tests, it is clear that there is a significant observed performance difference in the NB-IoT tests, unlike LTE-M. The noticeable gap in the performance could be because of one or a combination of reasons in our hypothesis below:

1) The core and backbone network could be configured and implemented differently in all countries where the tests are conducted.
2) The number of resources available both radio and rest of the network for C-IoT can vary from country to country.

Therefore, peak network activity due to other LTE users in the cell can impact the results.

3) The way NB-IoT is deployed in these countries can be different, especially the in-band and guard-band deployment supported by NB-IoT.

Unfortunately, deployment details of these technologies by the MNO are confidential and thus make it difficult for us to conduct further testing to verify our hypothesis.

TABLE III
PACKET DROPS

Technology	Number of Packet Drops			Number of Packets Sent
	Denmark (Home Location)	Norway (Roaming Location)	Sweden (Roaming Location)	
NB-IoT	180	31	64	1000
LTE-M	36	40	16	1000

VI. CONCLUSION

In this paper authors have presented results obtained from testing roaming performance of LTE-M and NB-IoT communication technologies in home and international roaming scenarios. The network technologies are benchmarked by generating network KPIs such as end-to-end latency, bitrate, and packet drop for varying data-payload sizes. After comparing the results, it is observed that LTE-M performance across the board for the chosen MNO is approximately similar. On the other hand, the NB-IoT performance in home network setting is much worse than that of roaming conditions. Therefore, further in-depth analysis of these technologies using multiple MNO networks is required for thoroughly understating the nature of C-IoT in roaming conditions. Nevertheless, as per the results obtained from initial testing presented in this paper, it is clear that C-IoT can serve as a viable option for consumer-IoT as well as industrial-IoT applications that require roaming support. We hope that, work conducted as a part of this paper can serve as a good starting-guide for wide range of IoT applications those need roaming or moving capability.

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