Experiments and Observations of 5G NSA Reliability and Latency Performance in Metro Train Environment

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***Abstract*—Recently, commercial 5G networks have been widely deployed, enabling data traffics to have higher data rates. 5G will be useful in vertical markets, such as railway environments. In such a case, reliability and latency are key performance metrics. This study aims to understand the performance factors related to packet loss and excessive latency in the rail environment. We analyzed measurement data under the metro rail environment and verified that both location and handovers are associated with unsatisfactory performance, such as packet losses and excessive latency. We also observed that some handover events are unnecessary. With these insights, we will better understand 5G metro rail communications and design a better network system in the future.**

***Index Terms*—5G NSA, Network Measurement, Railway Communications, Handover, Communications Reliability, Packet Delivery Latency**

I. Introduction

5G networks have been deployed in recent years. The new 5G network architecture enables users to have a wireless connection under a higher data rate, but when it comes to reliability and latency for data transmitting and receiving, it has been discussed that the performance is not better than that of the 4G network [1], [2].

This situation might limit the potential use that requires little packet loss rates and low latency. For example, it will be challenging to develop the train control module in which trains will communicate with a central controller on the ground. In the environment, the data traffic needs to be reliable and has low latency, or it may result in the inappropriate action of the train. These are essential safety issues, but currently, it is not easy to directly use the commercial 5G network to implement the control module. It also takes many costs to build a private 5G network for the railway company to solve the issues.

This study aims to find what factors in the environment are related to the metrics since the information will be helpful for future improvement. However, under 5G NSA (Non-Standalone) architecture, it will be more challenging to find the factors. Since in NSA, when the end-user is under 5G connection, it will simultaneously connect to a primary 4G LTE cell (eNB) and a secondary 5G NR cell (gNB), which is called dual-connectivity (DC). The primary eNBs are not only in charge of the eNB handover but are also responsible for the addition/change/removal of gNBs. This circumstance makes the architecture complicated and, therefore, hard for research. Although some related works demonstrate how packet loss and latency differ under various data traffic parameters, there are currently no works examining how they behave when factors in the environment change, with network measurement data and direct statistics to verify the relationship. Since many factors change simultaneously in the environment, it is challenging to determine whether there is a strong relationship between one factor and the performance.

This paper focuses on the correlation between handover events and network abnormality. In this study, we conducted measurement in the MRT(Mass Rapid Transit) environment, the metro train/subway transportation system in Taipei, Taiwan. We mention network measurement methods and the used measuring tools in Section IV. After collecting the data, we conducted a data-driven analysis to understand the performance issues. We observed the correlation between packet loss, excessive latency, and handover events. The experimental results and analysis are shown in Section V. Finally, we conclude the paper in Section VI.

II. Related Works

For the prior measurement works, most of the research has been focused on the LTE network [3]–[11] since commercial 5G started to be deployed in these few years. Some have discussed data traffic under a moving environment since high moving speed degrades the performance [6]–[11].

Apart from the research about LTE networks, there are also studies with the 5G measurement [1], [2], [12], [13]. Some of the works related to both 4G and 5G networks have metrics about latency and reliability, such as the performance for RTT [1], [2], [4]–[7], [11], as well as handover interruption time and handover delay [3], [10]. As for reliability, there are also studies having measurement about it [1], [2], [4], [7], [13]. A study shows that the Android OS may limit the reliability [13], and others demonstrate how packet loss rate varies under 4G or 5G, under different TCP algorithms, under different bandwidth, or other data traffic parameters.

Nevertheless, they are all different from our work. Firstly, we focus on the factors in the railway environment. In addition, most of the above measurements are conducted under TCP. In this work, we aim to investigate the UDP packet loss performance and excessive latency instead of the overall latency performance. With insights obtained in these experiments, we will have a better understanding of the performance bottleneck of the future 5G vertical deployment in the railway environment.

III. Handover Events in 5G NSA

We will firstly discuss the relationship between handovers and network performance. We categorize handover events into several types according to 3GPP standard [14]. All types of UE connection change to different serving LTE eNB and/or 5G gNB are listed in Table I. Note that the terms Master Node for eNB and the Secondary Node for gNB are used, in 5G NSA dual-connectivity operations. Each handover event is divided into intervals to study the performance in different handover stages, as shown in Fig. 1. If a packet loss or an excessive latency occurs in the intervals of a handover event, we say that the packet loss/excessive latency is in the *handover-related intervals*.

TABLE I
Description for different handover event types

Event type	Description
eNB handover	(eNB1) → (eNB2)
Inter-Master Node (MN) handover without Secondary Node change	(eNB1, gNB1) → (eNB2, gNB1)
Secondary Node (SN) addition	(eNB1) → (eNB1, gNB1)
Secondary Node (SN) change	(eNB1, gNB1) → (eNB1, gNB2)
Secondary Node (SN) removal	(eNB1, gNB1) → (eNB1)
Inter-Master Node (MN) handover with Secondary Node (SN) change	(eNB1, gNB1) → (eNB2, gNB2)
eNB to Master Node (MN) change	(eNB1) → (eNB2, gNB1)
Master Node (MN) to eNB change	(eNB1, gNB1) → (eNB2)

In successful handovers, the UE interacts with the base station using the Downlink (DL) *rrcConnectionReconfiguration* message and the Uplink (UL) *rrcConnectionReconfigurationComplete* message, which vary according to different successful handover types. In this work, we choose them as signals for event starts and event ends. We define the intervals [*event start*-x, *event start*] as *before event*, [*event start*, *event end*] as *during event*, and [*event end*, *event end*+x] as *after event*. X is a variable and we set x=1 for successful handovers.

As for handover failures, the event messages are different for eNB handover failures and gNB handover failures. For eNB handover failures, the UE will transmit an uplink *rrcReestablishmentRequest* message to the target LTE cell, and we choose this message as the eNB handover failure event. There are two types of eNB handover failures as eNB will respond to the UE to accept or decline the request. For gNB handover failures, the UE transmits an *scgFailureInformationNR-r15* message to the serving eNB, and we select this message as the gNB handover failure event. Different from the 4G eNB handover failure, the serving eNB will reply the *rrcConnectionReconfiguration* message to manage the handover failure. We define the intervals [*handover failure event time*-x, *handover failure event time*] as *before event*, and [*handover failure event time*, *handover failure event time*+x] as *after event*.

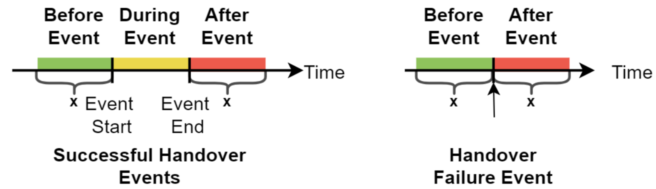


Fig. 1. Handover events and intervals

IV. Measurement Tools and Methodology

A. Measurement Tools

In this study, smartphones are used to capture their real-time locations and the information of the neighboring cells on the moving MRT train. The smartphones are all the same (Xiaomi 10T with Android 10.) A server in our laboratory is used for data transmitting and receiving to/from the phones.

To record the information of the UE and the cells, we firstly used Android programming to develop an Android application that periodically records the data. The data types include the GPS location of the end-users and signal strength indicators (RSRP, RSRQ) of both the serving LTE/NR cells and the detected neighboring LTE eNBs. To get more detailed LTE and 5G NR information between UEs and the cells, we utilized Mobile Insight [15] for experiments. This study uses the application to collect the lower layer messages between mobile phones and cells, especially Radio Resource Control (RRC) messages. These messages enable us to better understand the state of the wireless connection.

To evaluate the network's reliability and latency, we measure packet loss rate and one-way (end-to-end) latency, respectively. We utilized iperf3 to transmit/receive packets, and we used Tcpdump to capture the packets. With the captured packets, we can get their transmitted/received timestamps and their sequence number in their payloads. Then, we can get detailed information for the packet loss and the end-to-end latency with the data. We set the scenario as the connection for train controlling messages, where the packet size is small. As a result, we set the payload size and data rate to 250 bytes and 200K bits/sec, respectively. We adopt UDP as the transmitting protocol since we do not need a congestion algorithm and the ACK procedure in TCP. Note that both the client and the server are synchronized with the Network Time Protocol server.

B. Network Measurement in MRT

We conducted the measurement under two different routes in Taipei MRT for data collection: between Xinhai Station and Taipei Zoo Station in the brown line (Route A) and between Shisizhang Station and Zhongyuan Station in the yellow line (Route B). We traveled Route A 19 times and Route B 22 times. Route A and Route B's overall legit measurement duration (sum of each whole-route traveling time) are 2.20 hours and 4.70 hours, respectively. Under the measurement, the UEs have both UL/DL data traffic with the server simultaneously. We used the same telecom operator service to collect the data for the following analysis and results.

V. Results and Insights of Measurement

A. Locations, Packet Losses, and Handovers

We utilize the GPS information of the smartphones and check whether the density of packet loss and the density of handovers vary in different locations. We use part of our data measured on Route A (Fig. 2a) and then visualize the results on Google My Maps. Results are shown from Fig. 2b to Fig. 2e.

Firstly, we map the packet loss locations for the Route A dataset in Fig. 2b. The sub-figure shows that denser packet losses occur at some places on the route, and most of the places are close to MRT stations. From the sub-figure, we can also see that these places slightly shift for different moving directions. It is because it takes time to have LTE handovers, and the moving speed may shift the handover locations.

Fig. 2c and Fig. 2d demonstrate the packet loss locations and the LTE handover locations for different moving directions. It is interesting that the locations with dense LTE handovers are close to the places with dense packet losses for both moving directions. With the fact that there are more LTE handovers near the MRT stations, we suggest that it is because there are more base stations near the MRT stations. We can support this statement with Fig. 2e, which indicates that there are more neighboring LTE Physical Cell IDs (7 to 13) for the locations near MRT stations, while the average number of PCI is 6.57.

Observation 1: *Most of the dense packet loss locations are close to MRT stations (Fig. 2b).*

Observation 2: *Packet loss and handover events occur at similar places. Many of the places that have frequent handovers are close to MRT stations (Fig. 2c to Fig. 2d).*

Observation 3: *Packet losses in forward direction and reverse direction occur in correlated but shifted locations (Fig. 2b).*

B. Handovers and Packet Losses

From Fig. 2c and Fig. 2d mentioned previously, we know that packet loss and handover happen at similar places. In this subsection, then, we examine whether each packet loss indeed happens near handover events.

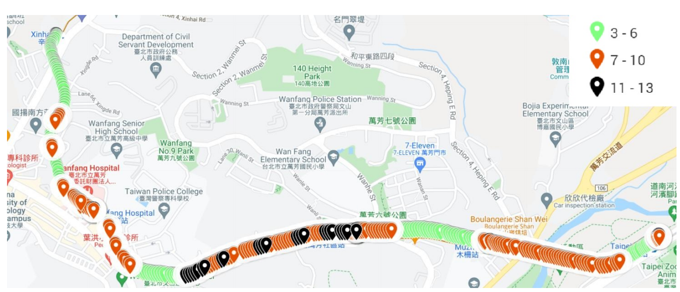
In Fig. 3., we show the packet loss rate statistics for the overall measurement dataset. We define packet loss rate (PLR) as the number of packet losses per second. There are 100 packets periodically sent or received for both UL and DL traffic for each second. Fig. 3a and Fig. 3b show the PLRs under successful handover events. From Fig. 3a, it is demonstrated that PLRs in most handover-related intervals are much higher than the overall PLR for UL. From Fig. 3b, on the other hand, it is demonstrated that PLRs in intervals related to eNB handover, SN addition/removal, and eNB to MN change are much higher. This indicates that the eNBs cannot handle these events well in the DL environment. For handover failures depicted in Fig. 3c and 3d, the PLRs are even higher than those close to successful handover events generally, since there is a period when that the UEs cannot connect to the base stations in handover failures. As a result, once a handover failure happens,

(a) Experiment route (yellow labels: MRT stations)

(b) Locations of uplink packet losses on forward route from Zoo to Xinhai (green labels) and on reverse route from Xinhai to Zoo (red labels)

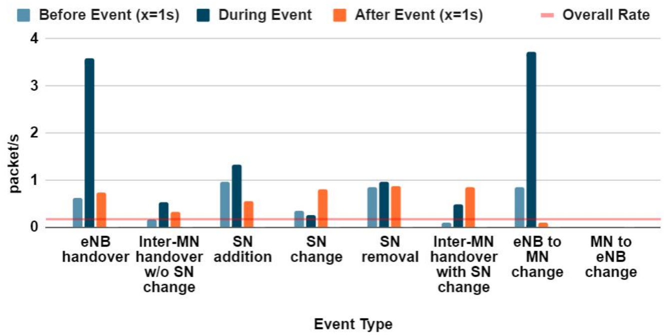
(c) Locations of uplink packet losses (green dots) and handovers (blue dots) on the route from Zoo station to Xinhai station

(d) Locations of uplink packet losses (red dots) and handovers (blue dots) on the route from Xinhai station to Zoo station

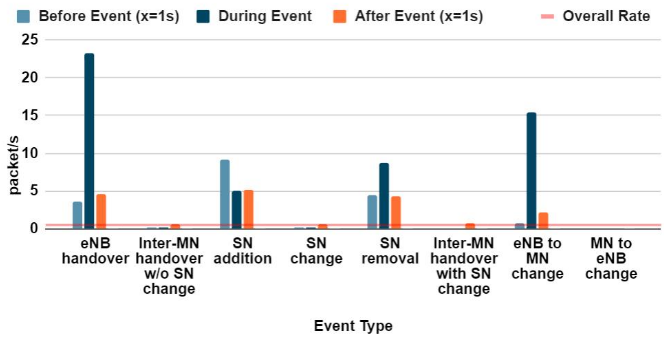


(e) Number of available neighboring Physical Cell IDs on the route

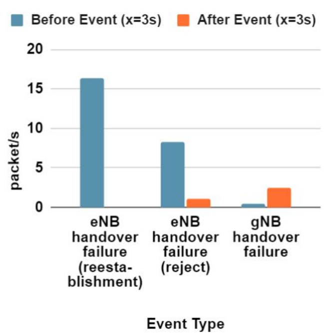
Fig. 2. Network measurement route on Taipei MRT Brown Line (between Xinhai Station and Taipei Zoo Station)



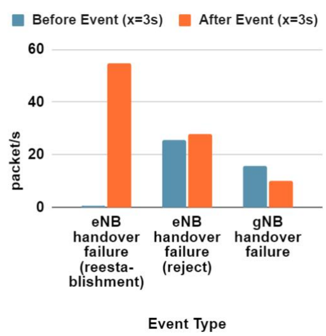
(a) UL PLR for successful handovers



(b) DL PLR for successful handovers



(c) UL PLR for handover failures



(d) DL PLR for handover failures

Fig. 3. Packet Loss Rate under different handover classes (for all dateset)

the number of packet losses would be large. Although there are few handover failures detected in our measurement data, the percentage of packet losses in handover failure intervals still reaches 45%.

In some events, we can find that their PLRs during event intervals are very high because the interval length is much shorter than one second. In addition, for the MN to eNB change event, we choose to plot it in the sub-figures but not give it values since there is no such event detected.

Next, we examine the percentage of packet losses in handover-related intervals. For the UL data, 75% of packet loss is in handover-related intervals; the ratio is 96% for the DL data. As a result, handovers are strongly related to PLR.

Along with the fact that there are more packet losses near

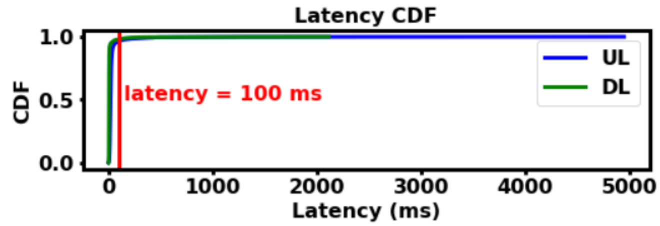


Fig. 4. Latency CDF and threshold for excessive latency

MRT stations, we suggest that there are more people in the stations, and the telecom deploys more base stations to serve them. Nevertheless, for moving end-users, the dense base stations would result in more frequent handovers, leading to more chances of happening packet loss.

Observation 4: *It shows a strong connection between handover events and packet loss, in that PLRs in handover-related intervals are much higher than the overall PLR rate, and most packet losses are also in handover-related intervals.*

C. Handovers and Excessive Latency

To analyze the latency performance, we first examine the overall latency distribution of both the UL and DL measurement data, which is shown in Fig. 4. We find that there are knee points around 100 ms for both UL and DL CDF, so we set 100 ms as the threshold for determining excessive latency in this work. According to the measurement data, there are 3.6% of the UL packets and 3.3% of the DL packets with excessive latency.

Fig. 5. shows the statistics of excessive latency rate under different handover classes. In Fig. 5a and Fig. 5b, we can see that the excessive latency rates in most successful handover-related intervals are also much higher than the overall excessive latency rate for both data traffic directions. For handover failures, as in Fig. 5c and Fig. 5d, it is shown that the excessive latency rates are even higher than those in intervals related to successful handover types. However, handover failures are not the main cause of the excessive latency, as only 20% of the excessive latency is in handover failure intervals.

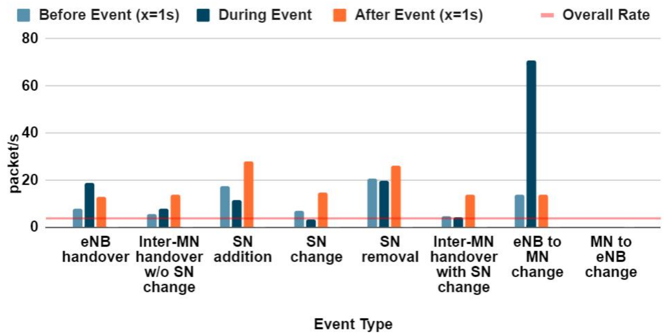
There are 66% of UL excessive latency and 67% of DL excessive latency in handover-related intervals. They are relatively smaller than the ratio of packet loss, which indicates that there may be other factors that can trigger excessive latency aside from handovers. However, handover is still a factor that affects the latency performance.

Observation 5: *Handover events and excessive latency are highly relevant since excessive latency rates in handover-related intervals are much higher than the overall excessive latency rates.*

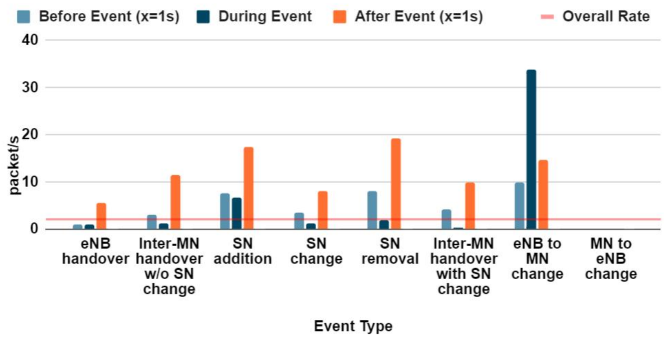
Observation 6: *There may be other factors that can trigger excessive latency. Although one-third of packets are not in handover-related intervals, they have excessive latency.*

D. Necessity of Handover

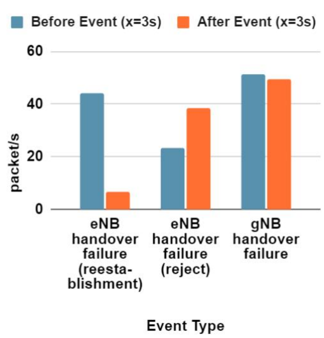
After supporting a solid relationship between handovers and events of packet loss and excessive latency, we examine



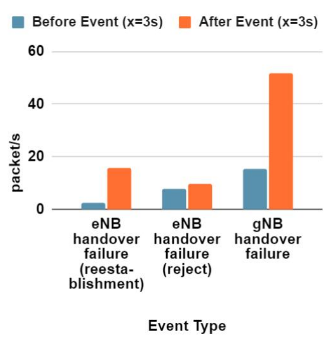
(a) UL excessive latency rate for successful handovers



(b) DL excessive latency rate for successful handovers



(c) UL excessive latency rate for handover failures



(d) DL excessive latency rate for handover failures

Fig. 5. Excessive latency rate under different handover classes (for all dataset)

whether these handovers are all necessary. Therefore, we statistically analyze the available choices of neighboring LTE cells during the measurement.

In the measurement data, LTE handovers are recorded 1572 times. Only 1.3% of the handovers have a single neighboring target cell. In addition, in 54.2% of the LTE handovers, the UE can still detect the original serving cell for more than 5 seconds, which means that these handover executions can be potentially deferred by at least 5 seconds. Furthermore, there are even 6.36% of the LTE handovers where the signal strength of the original serving cell is the same or even stronger after handover, which means that the original serving cell is still qualified for service. With these statistics, we can sufficiently support the possibility that not all the handovers are must-dos.

Observation 7: *There are unnecessary handovers as original serving cells sometimes can still be detected for a while, or their signal strengths do not become weaker after handover.*

VI. Conclusions

To better understand the performance of 5G railway communications, we have conducted measurement experiments in the Taipei MRT metro railway. Performance and factors related to packet loss and latency have been investigated. On MRT routes, packet loss and excessive latency occur in similar locations, where handover usually occurs. On average, 6.57 physical cells are available on the MRT route. We also found that some handovers are unnecessary and cause additional packet losses. With these insights, there is room for improvement for the 5G handover algorithm for better reliability. Our future works will improve the 5G railway communications performance with these insights.

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