LTE massive MIMO (Pre-5G) test with an updated boat user terminal solution for land-to-boat scenarios in Oslo fjord

Kun Yang*, Ning Zhou*, Terje Røste*
*Super Radio AS, NO-0556 Oslo, Norway.
Email: kun@superradio.no

Abstract. Autonomous shipping is considered to be one of the most important technologies in the maritime industry. Remote control of autonomous shipping is supported by communication solutions featuring long coverage, high throughput and low latency. Since 2018, together with the Norwegian Internet Service Provider (ISP) Telia, we have performed tests with a massive MIMO (Pre-5G) LTE base station, using the 3.7 GHz band, in Horten close to the Oslo fjord. The first Pre-5G tests with user terminal mounted on a 40 feet sailboat performed in 2018, showed great potential for maritime applications in terms of throughputs [1]. The Customer Premise Equipment (CPE) used in 2018 was a LTE Pre-5G terminal from Telia for fixed LAN use, and a modified version of it in 2019. However, since both the base station and the user terminal/CPE are not originally designed and optimized for maritime radio propagation environments, the test results in 2018 unveiled that a CPE designed for land usage experienced limited coverage and instability caused by received unstable signal level. Since 2019, a new user terminal prototype dedicated and optimized for maritime propagation conditions, was designed by Super Radio AS. This new CPE was tested in autumn 2019 under the similar setups as in 2018. The test results of the Reference Signal Receive Power and throughput are analysed and compared the test results in 2018. The comparison proved that the new user terminal solution showed considerable improvement with respect to stability and throughputs in the harsh maritime environments, which means that the new designed solution can be a potential maritime terminal solution for the remote control of autonomous shipping. The prototypes mounted at different places of the sailboat also show different system performances at the same TX-RX distances, which indicates the potential of exploiting the system diversity in the similar propagation environments.

1. Introduction
Reliable and high throughput maritime communications are considered to play an important role in maritime activities involving various types of ships and vessels, offshore installations, unattended buoy platforms, autonomous underwater utilities, offshore and onshore observation sites, etc. Autonomous ship and the digitalization of numerous maritime activities including oil exploitation, maritime transportation, fish farming, environmental surveillance and other activities need to be supported by communication solutions with low latency, long coverage, high throughput and low cost.

All these performance criteria drive the needs of broadband maritime communication technology. In 2018 the deployment of LTE base stations with Massive MIMO capability began in Norway. For maritime applications, the radio propagation conditions from land-to-sea will change considerably from the open sea to close to the coastline with narrow fjords, straits and islands. For maritime applications, the question is the following: Will conventional 5G massive MIMO systems originally designed for the terrain propagation environments (Urban, Suburban, etc) still demonstrate high performance for maritime applications? To answer this question, a pre-5G LTE Massive MIMO base station (BS) (8T8R)
provided by the MAMIME [2] project partner, Telia Norge AS, was installed, in Horten at a site close to the Oslo fjord. This BS installed by Telia for pilot test purposes, covers the 3.7 GHz band (band 43). The pre-5G, 8T8R BS supports the features beamforming soft split of beams, and beam adjustment like beamwidth adjustments in azimuth, elevation together with tilt adjustments. The BS during the tests had a fixed configuration that was optimized for the test routes of the ship on which the CPEs were mounted. LTE massive MIMO tests with CPEs mounted on a 40 feet sailboat were conducted in Oslo fjord in autumn 2018 and autumn 2019. In 2018 user terminals made for fixed installation on land were installed on the ship, and in 2019, optimized user terminals for the maritime propagation environment were installed. It also needs to be mentioned that the BS at Horten provides a very good coverage for a national authorized autonomous ship test area in the Oslo fjord outside Horten. This will provide the possibility for future cooperation between autonomous ship companies and the Norwegian research community to investigate pre-5G system performance for autonomous ship applications.

The paper is organized as follows: In Section II, a discussion of the land-to-sea propagation conditions for different scenarios is given. In Section III, selected Reference Signal Receive Power (RSRP) measurement results from 2018 and 2019, and corresponding analysis results are presented. In section V, the measurement results and analysis of throughput in Mbit/sec in 2018 and 2019, are presented. Finally, in section VI, conclusions are drawn, and further research work is suggested. In Table 1, a list of abbreviations and definitions used in this paper is given.

| Abbreviation | Definition |
|--------------|------------|
| RSRP         | Reference Signal Receive Power |
| LOS          | Line of Sight |
| LTE          | Long Term Evolution |
| MIMO         | Multiple in Multiple out |
| BS           | Base Station |
| MS           | Mobile Station |
| CPE          | Customer Premises Equipment |
| MAMIME       | LTE, WIFI and 5G Massive MIMO Communications in Maritime Propagation Environments |
| MIMO         | Multiple In Multiple Out |
| 8T8R         | 8 Transmit and 8 Receive antenna elements |

Table 1. Abbreviations and definitions

2. Propagation conditions land to sea

2.1. Radio propagation between a BS and a MS on land has been subject to extensive research over many years. Models and RSRP prediction tools for coverage analysis have been developed and extensively used to roll out the different generations of mobile communications systems on land, including urban, sub-urban and rural areas. When it comes to the land-to-sea radio propagation, the research has been limited compared to terrain environments. The MAMIME research project [2] funded by the Research Council of Norway has been dedicated to developing a better understanding of the radio propagation between land and sea with focus on 4G and 5G mobile systems. Further, the gain of using MIMO for terrestrial mobile systems compared to mobile systems for the land-to-sea environments, may be different.

A fixed BS is placed at the coast. Land-to-sea mobile radio communications may be categorised into the following main scenarios:

- Scenario 1: A vessel (i.e. a MS) moving in fjords, narrow straits and in-between islands
- Scenario 2: A vessel in the open sea with LOS to the BS
- Scenario 3: A vessel in the open sea with non-LOS where the terrain (either island or hills on land) obstruct the radio propagation
- Scenario 4: A vessel in the open sea where the round earth will obstruct the propagation
- Scenario 5: A fixed object (i.e. a sensor either on the sea surface or a fixed installation) instead of a moving vessel and with the 4 above mentioned scenarios

In scenario 1, there will be propagation conditions close to rural areas on land, with LOS, non-LOS and reflections, either many or few reflections depending on the topography.

In scenario 2, the propagation will be a LOS component together with reflections and scattering from the sea surface. The movement of the ship will heavily depend on the ship size and sea wave size (i.e. weather conditions). The ship movement and the sea surface condition will cause small scale fading. The LOS component will change caused by ships angular movements (i.e. roll, pitch, yaw) and the antenna pattern properties. The reflections and scattering from the sea will change with the change of the part of the sea surface that reflect the radio waves towards the antenna. Finally, the antenna placement on ship is important.

With scenario 3, the ship will move in and out of conditions with non-LOS and LOS causing loss of communication due to shadowing. Diffraction loss will be significant. In addition there may be reflected components coming from nearby islands or hills along the coastline. A multiple element antenna may be configured to high gain steered towards the LOS component or the non-LOS component undergoing diffraction loss. The latter may be important when the 700 MHz band is used.

With scenario 4, the ship is far out on the sea with LOS to the BS. In this case, the loss may be determined by the earth curvature. It is referred to [3] where a propagation model for this scenario is presented.

Scenario 5, is an important case, but is outside the scope of this paper.

As the measurements reported here were made by using a 40 feet sailboat, and with the topography in the Horten – Moss area of the Oslo fjord, Scenarios 2 and 3 are most relevant and will be focused hereafter.

Small scale fading will occur due to the angular and linear movements of the ship, antenna properties and its placement on the ship, the sea surface condition (wave height etc.), and sea surface movement surrounding the ship. Large scale fading will occur when the ship changes the distance between the ship and the BS along its route, or when the ship moves between LOS and non-LOS conditions caused by e.g an island.

As discussed above, with scenario 2, the impact of sea waves on propagation are heavily depending on the size of the ship, the placement of antennas and number of antennas. In our case with a small vessel, the ship movements are significant in sea conditions experienced in the Oslo fjord. Ideally, the antennas should be placed high up in the masts or ships construction, which is not always practical or possible. Further, with scenario 2, the reflections and scattering of radio waves from the sea surface sea, will change considerably with time causing RSRP small scale fading. When the sea waves become large, in case of a small vessel, the sea waves may even shadow the LOS component (See Fig. 1)). The following discussions and results keep this as a focal point.

Figure 1. Small vessel on the sea surface. Possible shadowing by sea waves.
3. Result RSRP

The measurement campaign was described in detail in [1], from which the radio coverage prediction, campaign setups and facilities can be found. It needs to be mentioned that the CPE we used for test in 2019 has been updated according to our research of maritime radio propagation environments. The test routes in 2018 and 2019 shown in figures Fig 2 (a) and Fig 2 (b), respectively, are very similar, which makes it meaningful to compare with each other to demonstrate the enhancement of the updated CPE system performance.

![Fig 2. (a) Test route 1 in 2019](a)  ![Fig 2. (b) Test route 1 in 2018](b)

In the 2018 measurement campaign, two antennas were mounted one at the bow and one at the rear, 10 m apart, and both 1 m above the sea level. In the 2019 three antennas were mounted on the ship. The placement of the antennas was the following:

- One at the bow 1 m above the sea level
- One at the rear ca 1 m above the sea level and ca 10 m apart from the bow antenna
- One up in the masts pillar ca 2 m above the sea level

During the test route 1 in 2019, the sea conditions were calm, and boat speed was about 5-6 knots. The wind conditions on that day was 1-7 m/sec. The wave height on that day, typical wave bottom to top around 0.25 meters. The measurement data structure and RSRP analysis method are described in detail in [1]. In this paper, only the RSRP results of outbound trips in 2018 and 2019 are shown and compared in Fig. 3, from which it can be found that the RSRP of the new CPE shows much better stability than the old CPE in the route 1. It needs to be mentioned that large fading of the new CPE RSRP at the TX-RX distance of 10.5 km is due to the blockage of the LOS when the sailboat moved into the bay area of Moss. Therefore, our comparison analysis focuses on the TX-RX distances between 4 km and 9.5 km. To have a better understanding of the stability improvement, we further study the small-Scale fading and the corresponding the standard deviation (STD), which are shown in Fig. 4 (a) and Fig. 4 (b), respectively. The staircase diagram of Fig. 4 (b) is caused by the 150 sec block length of the STD analysis time window. It can be found that the STD in 2019 is around 3-14 dB less than in 2018, which proves the great improvement on stability in our new updated CPE, compared with the old CPE.
Fig 3. RSRP comparison between measurement data in 2018 and in 2019, route 1

Fig 4. (a) Comparison of Small-scale fading. (b) Comparison of standard deviation of the small-scale fading.
4. Results throughput

The system throughput (Mbit/sec) is one of the most important factors for the maritime applications. In our test campaign, we used Iperf which is an open-source software and widely used to measure the transmission throughput. It can measure the throughput between the two end users for both uplink and downlink. The transmission protocol can be set to either TCP or UDP. In this paper, the UDP throughput was recorded in the route 2 shown in Fig. 5, from which it can be found that the test routes 2 in 2018 and 2019 are close to the same so that we can use them for comparison. It also needs to be mentioned that the weather condition in route 2 in 2019 was very harsh with heavy rain and wind. The boat speed was about 6-7 knots. The wind conditions on that day was 6-16 m/sec. The wave height on that day, typical wave bottom to top around 0.75 meters. This is why the RSRP in 2019 is less than in 2018, which is shown in Fig. 6. Further study shown in Fig. 7 also indicates that the STD of the small-scale fading of the RSRP in 2019 is within [1, 7] dB while the STD in 2018 is within [4, 13] dB. Even though the test in 2019 was conducted in harsh weather, the stability of RSRP obtained in the updated terminal is higher the old terminal in 2018. The corresponding UDP throughput results are shown in Fig. 8, from which it can be found that the data rate in the new updated CPE terminal is around 90 Mbps while the data rate in the old CPE terminal is around 30 Mbps. It needs to be addressed that the stability of the throughput has been greatly improved as well. Since the CPE mounted on the top of the sail boat experienced much severe boat movement than the CPE mounted on the rear of the sail boat, the throughput variation in the new CPE on the top is larger than the new CPE on the rear, which is also can be found in the Fig. 8. It also suggested the difference of the CPE placement will caused different system performance, which may be exploited for the system diversity. It can be concluded that the stability is highly related to the throughput, which should be paid great attention in the maritime communication system design.
Fig 6. RSRP comparison between the route 2 measurement data in 2018 and in 2019.

Fig 7. (a) Comparison of Small-scale fading. (b) Comparison of standard deviation of the small-scale fading.
5. Conclusion
A Pre-5G LTE system measurement campaign with an updated CPE terminal at 3.7 GHz has been carried out in maritime propagation environment in Oslo fjord, Norway. The obtained RSRP is compared with the previous LTE test results obtained by using the old CPE terminal. The comparison of RSRP and the small-scale fading STD prove great enhancement on the stability by using the updated CPE terminal. Similarly, another comparison of the RSRP and STD in the Route 2 shows the improvement on the stability. Besides, the corresponding throughput is greatly increased, which further proves the importance of the stability and the effectiveness of the updated CPE terminal. The system diversity of the different CPEs on the same sailboat is also shown in the variation of the throughput large, which shows the potential of the multi-user diversity under the current solutions.

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