Designing High-Speed Directional Communication Capabilities for Unmanned Surface Vehicles

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***Abstract*—Machine-Type Communications (MTC) is one of the important use cases of fifth-generation (5G) wireless networks. The ability of networked devices to communicate with each other in a fully automated manner without human interaction is an emerging area wherein both academia and industry are putting significant efforts. One of the aspects of MTC that has been studied in this paper is focused on enabling high-speed long-range communication specifically used in autonomous robotic off-shore operations. For this purpose, a system comprising 3GPP LTE and directional IEEE 802.11 (Wi-Fi) radio links was designed, installed, and tested on an unmanned surface vehicle to enable high-speed bi-directional connectivity.**

***Keywords*—5G, antenna, antenna tracking, beamsteering, wireless network.**

I. INTRODUCTION

A. Motivation and scope

The substantial growth in mobile communication and usage of smart devices, such as smartphones and tablets, has led to an exponential increase in data traffic demand over the past decade [1]. The appearance of many new applications in the upcoming years, with higher bandwidth and reliability plus lower latency requirements, will cause an annual growth of 40% in data traffic demand [2], [3]. This will introduce new challenges in wireless communication and system design.

To meet these challenges, the next generation of mobile networks (a.k.a. 5G) is being developed. According to Nokia [4], [5], Huawei[1], Ericsson[2], and 3GPP (TR 22.891 [6]), 5G is evolving mainly based on the following use cases:

- *Enhanced Mobile Broadband* covers the high data rate and low latency communications in crowded areas, suitable for real-time applications, such as virtual and augmented reality (VR/AR).
- *Massive Machine-Type Communications* covers the connection between millions of wireless devices around the world, e.g. different sensors interchanging and using their respective data to manage the distribution of resources. This can be used in smart agriculture and smart city concepts.
- *Critical Machine-Type Communications* focuses on critical applications, such as health-related ones, e.g. tactile Internet, and automation in industry and transportation where intelligent machines are operating without human intervention.

As can be seen, Machine-Type Communications (MTC) is an important use case in 5G; and high-speed long-range connectivity is one of its main aspects. One of the areas related to MTC that has attracted academia and industry is autonomous robotics in offshore operations aiming to support future services needed in unmanned maritime ecosystems [7], [8]. As one of the leading marine equipment manufacturing countries, Finland is assigning resources for the developments in this fields by investing into a project launched in 2016 with the goal of creating the world's first unmanned maritime systems and services by the year 2025[3].

B. Problem formulation

The goal of the research project named Autonomous and Collaborative Offshore Robotics (aColor) is to construct a prototype of an automated system operating in an offshore environment[4]. The aColor project involves cooperation between industry and academia, and focuses on creating a methodology for an autonomous robotic system. That includes collaborative features between aerial, surface, and under water systems further referred to as Unmanned Aerial Vehicle (UAV), Unmanned Surface Vehicle (USV), and Autonomous Underwater Vehicle (AUV), respectively. The project is funded by the Technology Industries of Finland Centennial Foundation and supported by Alamarin-Jet Oy[5]. The final goal of the project is to connect these three subsystems together using different radio technologies and decrease the human intervention on all actions of the overall collaborative system. The schematic of how the overall system should be implemented is depicted in Fig. 1. The communications related sub-task of the project is targeted to evaluate the performance of different directional radio links for the aforementioned system. The first part of the

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[1] https://www.huawei.com/en/industry-insights/outlook/mobile-broadband/xlabs/use-cases/5g-top-10-use-case

[2] https://www.ericsson.com/en/5g/use-cases

[3] https://www.trafi.fi/en/maritime/maritime_automation_experiments

[4] https://techfinland100.fi/mita-rahoitamme/tutkimus/tulevaisuuden-tekijat/autonomous-and-collaborative-offshore-robotics-aColor/

[5] https://www.alamarinjet.com/

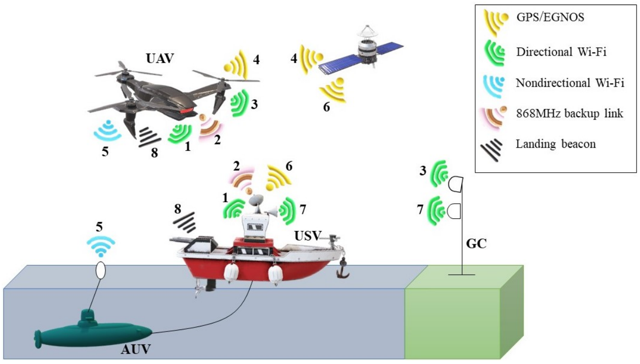


Fig. 1: Overall communication layout of the aColor project. 1. USV-UAV directional link, 2. USV-UAV backup link, 3. GC-UAV directional link, 4. UAV GPS, 5. UAV-AUV link, 6. USV GPS, 7. GC-USV directional link, 8. UAV landing system.

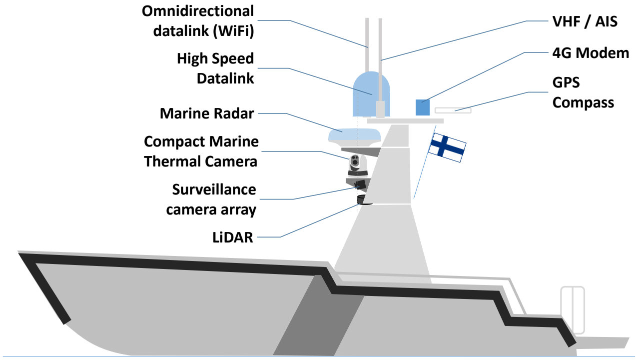


Fig. 2: USV system layout.

task, which is the subject of this paper, is focused on the long-distance backhaul link that connects the USV as the access network entity to the backbone represented by the ground control (GC). This work also aims to demonstrate the benefits of using multi-radio technology solutions in future wireless IoT (Internet of Things) applications.

The radio technologies used to interconnect the spatially separated entities in this work are IEEE 802.11 (Wi-Fi) and 3GPP LTE (Long-Term Evolution). There are three reasons for choosing these technologies. The first reason is their adequate throughput for our use cases, which includes transmitting high quality video stream, telemetry, and radar measurements [9]. The second reason is acceptable coverage range [10], [11]. The third reason is their low cost and high availability, which make them suitable for our experimental prototyping.

C. Our contribution

The first phase of this project, which is the focus of this paper, concentrates on the autonomous mobility of the USV and its connection with the GC. A sketch of how the USV should be implemented and all the technologies deployed on it are shown in Fig. 2. In order to improve the performance while keeping low transmit power, reduce interference, and ensure connectivity at hundreds of meters distance, the communication between GC and USV is expected to utilize directional antennas. Furthermore, low power consumption allows for safe and license-free operation of such equipment. However, the use of directional antennas will require designing a reliable beamsteering system, which maintains a point-to-point connection between both parts at all times. In Section II, a detailed description related to the design of our directional antenna system between the USV and the GC together with the proposed beamsteering algorithm is given. The test scenario along with the target metrics of interest is also discussed in this section. Section III introduces the results obtained from the field-test using the designed system. It also includes a conclusion and outlines future work related to this project.

II. METHODOLOGY AND OBJECTIVES

In this paper, we discuss three important tasks that are shaping the communication part of the target project:

- Enable high-speed long-range wireless connection between GC and USV using 802.11ac Wi-Fi (5GHz central frequency) with directional antennas.
- Develop and test mechanical beamsteering algorithm for both antennas.
- Test LTE as an alternative communication technology between GC and USV in case of Wi-Fi outage.

In this section, the design of our system covering all three mentioned tasks is explained in detail.

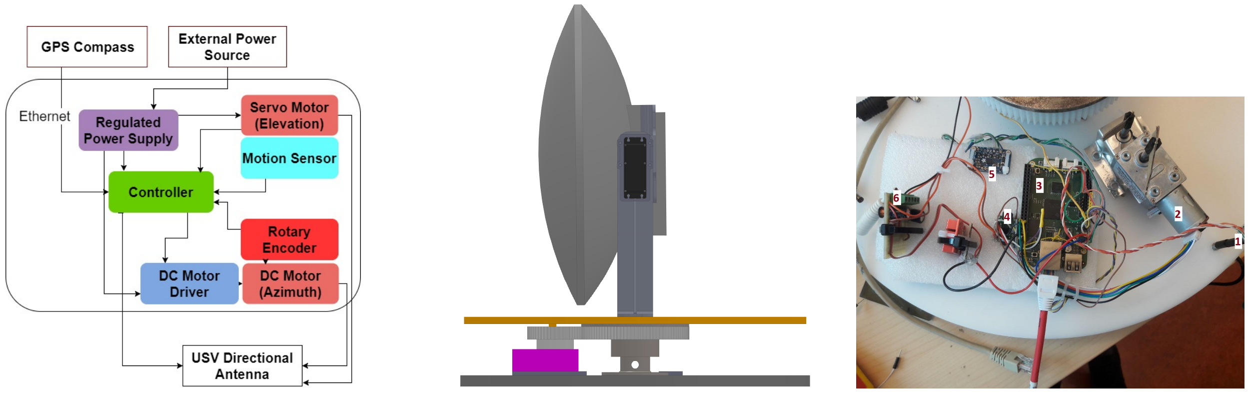
A. System design

The design of the communication system between GC and USV with beamsteering capabilities on the USV side requires the following elements: an external power source, motor controller and driver, DC motor with rotary encoder, motion sensor, and servo motor. On the GC side, the same components are used except for motion sensor and servo motor, since those are used for vertical steering in the USV and are not required on the GC side. The designed layout is demonstrated in Fig. 3a and all the elements used in the design of the system are presented in Table I.

The final design and implementation of the communication subsystem, which consists of mechanical and electrical layouts, is shown in Fig. 3. The implementation of the control

TABLE I: List of the components used in the system

Item	**Model**	**Quantity**	**Supply voltage [V]**
DC motor	CHIHAI GM4632-370	2	12
Servo motor	HS-805BB	1	4.8-6
Rotary gears	Mekanex OY	2	-
Housing	Build by MEI	2	-
Directional antenna	Mikrotik DynaDish 5	2	11-60
Router	Mikrotik hEX PoE	2	12-57
LTE router	Teltonika RUT950	2	9-30
Controller	Beaglebone green	2	5
Motor driver	POLOLU-713	2	2.7-5.5
Sensor	Adafruit LSM9DS0	1	2.4-3.6
Magnetic sensor	SS460P HONEYWELL	1	3-24



(a) Layout of USV directional subsystem.

(b) 3-D model of USV directional subsystem. The elements shown in Fig.3c are placed between two housings.

(c) Beamsteering control system. 1:magnetic sensor, 2:DC motor, 3:beaglebone green, 4:motor driver, 5:LSM9DS0 motion sensor, 6:voltage regulator.

Fig. 3: Final mechanical and electrical design of the system.

system can be seen in Fig. 3c. Different parts of the electrical circuit are marked and explained in the figure. Fig. 3b depicts a 3-D model of the final state of our prototype. As it can be seen, the mechanical design consists of two housings. The lower housing is static and used as a mounting point, while the upper housing is kinematic with one degree of freedom; it is used to hold and rotate the antenna horizontally. Hence, every time a horizontal rotation should happen to keep the point-to-point connection between GC and USV, the DC motor rotates, which will lead to the rotation of a small gear on its shaft. The rotation of the small gear then leads to the rotation of a bigger gear connected to the upper housing, which will lead to the appropriate rotation of the antenna. Furthermore, the antenna is attached to the upper housing using two aluminum brackets. The servo motor for vertical rotation of the USV antenna is attached to the mounting bracket. If a vertical rotation occurs, the servo motor rotates, which will lead to the vertical rotation of the antenna.

A gold-plated slipring is used to maintain data and power connection between the housing and the rotating side of the antenna. This allows for continuous tracking of a target during arbitrary maneuvers of the USV. In our implementation, the slipring carries the following contact pairs: 8 contacts for gigabit Ethernet with PoE for data and power to be supplied to the antenna dish; 3 contacts for the servo motor that control vertical steering. This setup allows to use a relatively low-cost slipring with just a few contacts while achieving very high throughput. Passing gigabit PoE through slipring has multiple advantages in terms of component cost and reliability. Extra reliability is due to relatively low cost of individual packet loss on Ethernet (as re-transmissions can be arranged via local VPN), as well as solving the issue of routing the signal from the slipring to the antenna dish itself. In cases where traditional RF (Radio Frequency) slipring is used, another slipring is necessary to couple with vertically rotated dish, since any coaxial cable would be destroyed by repeated bending, and for Ethernet it is not a major issue.

B. *Beamsteering algorithm*

As it was discussed before, in order to maintain a point-to-point connection between GC and USV at all times, a beamsteering algorithm is required. In this research, a GPS-based algorithm was developed for the purpose of horizontal beamsteering. This algorithm, which is implemented inside the beaglebone green, takes GPS data as input and sends a signal as output to GPIO pins controlling the DC motor. The program implementing this algorithm is written in Python and its main part is the calculation of the rotation angle based on the location data received from the GPS compass (placed in the USV). The subject procedure is shown in Algorithm 1.

The result of the angle calculation is later sent to the motor driver function. This function has the responsibility of physical rotation utilizing a PID (Proportional-Integral-Derivative) controller for speed rotation modifications. It stops the rotation when the current position of the DC motor is equal to the desired position. It ensures that excessive torque is not applied to the motor for small adjustments, as otherwise the system tends to rattle and cause damage to mechanical components, as well as emphasize mechanical backlash resulting in antenna misalignment. In addition, it handles the choice of rotation direction to close the distance to target in the fastest possible time. The PID controller uses equation (1), where $u(t)$ is the output of the controller at time *t*, $e(t)$ is the value of error at time *t*, k_p, k_i, and k_d are the proportional, integral, and derivative gains, which are set empirically to 1, 0.2, and 0.5, respectively, in this research:

$$u(t) = k_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{de(t)}{dt}. \tag{1}$$

The horizontal rotation system works as follows: the beaglebone placed on the USV side of the system receives the navigation data related to the USV position from a GPS compass via Ethernet. The beaglebone controls the DC motor using a rotary encoder that has a closed-loop feedback system for precise-position steering. Assuming that the GC position is known to the USV (GC is static), the DC motor will rotate the antenna on the USV to point at the GC using control signals received from the beaglebone and its encoder functionality. Later, when the connection is established the same GPS data will be sent to the GC system via Wi-Fi and is used in a similar way to steer the GC directional antenna towards the geographical location of the USV. Fig. 4 shows the message exchange process between the elements comprising the horizontal rotation system. The USV part of the system is also capable of vertical steering in case of waves at the lake. This system uses a motion sensor to detect any tilting that may occur in the USV and sends the data to the beaglebone placed in the USV part. The beaglebone then calculates the required rotation angle and sends the rotation command to the servo motor controlling the vertical steering. Then the servo motor steers the antenna accordingly along the vertical axis.

Algorithm 1: Our algorithm for rotation angle calculation

```
Result: angle_diff
lon[0] = USV longitude;
lat[0] = USV latitude;
lon[1] = GC longitude;
lat[1] = GC latitude;
while True do
    if heading!=0 then
        delta_lon = lon[1] - lon[0];
        angle = degrees(atan2(sin(delta_lon) *
          cos(lat[1]),cos(lat[0]) * sin(lat[1]) - sin(lat[0]) *
          cos(lat[1]) * cos(delta_lon)));
        heading_diff = heading - current_heading;
        angle_diff = angle - motor.current_angle -
          heading_diff;
        current_heading = heading;
        motor.current_angle = angle;
        motor.turn_by_angle(angle_diff);
    else
        sleep(0.5);
    end
end
```

C. Scenario and metrics of interest

After the implementation phase, the USV part was installed on a boat provided by Alamarin-Jet Oy and the GC part was installed on a tripod at Hatanpää harbor located in Tampere, Finland[6]. Then, a predefined route between the GC site and Laukontori area in Tampere city center on lake Pyhäjärvi was assigned to the boat for autonomous driving.

The idea of this test scenario was to evaluate how well the designed system along with the proposed beamsteering mechanism works in urban environment and open lake water for both Wi-Fi and LTE links. The metrics of interest in this field-test are received signal strength (dBm) and GC-to-USV data throughput (Mbps). The test route is shown in Fig. 5 along with the USV intermediate steps during the test marked with yellow points. These points are also the equivalent time instants shown in the below plots related to throughput and signal strength level. The height of both antennas is 3 meters from the ground and the maximum distance between them in this test run is around 900 meters. The test was conducted in a calm weather (minor waves), while the USV speed did not exceed 10km/h.

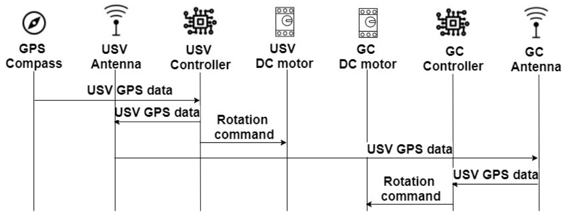


Fig. 4: Message exchange steps in horizontal rotation.

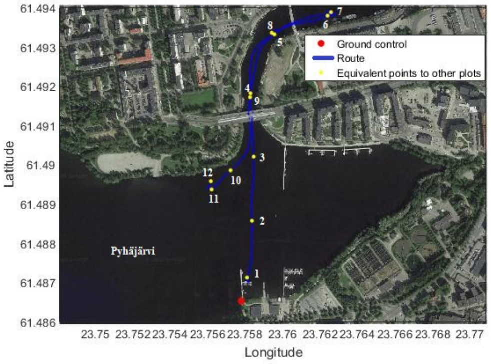


Fig. 5: Laukontori test run route.

III. Results and conclusion

A. Observations and discussion

This sub-section summarizes the field-test results followed by a discussion. Fig. 6a presents and compares the throughput results on both Wi-Fi and LTE links. The x-axis represents the time instants equivalent to the yellow points presented in Fig. 5. It can be observed in the plot that at all times, when LOS (Line-Of-Sight) is maintained on the directional connection, Wi-Fi throughput is higher than that of LTE. However, in NLOS (non-LOS) situation, when the boat moves beyond the bridge, between the fifth and the ninth time instants, Wi-Fi throughput drops to zero and LTE throughput remains nearly constant. This can be the result of better LTE coverage (several LTE base stations in the city center for the used operator[7]).

Fig. 6b presents a comparison between the received signal strength level of the Wi-Fi and LTE connections. It can be seen that the received signal strength for the LTE connection remains nearly constant with minimum variations, while the Wi-Fi received signal strength level is highly dependent on the boat position. In particular, a significant drop of 30dB between

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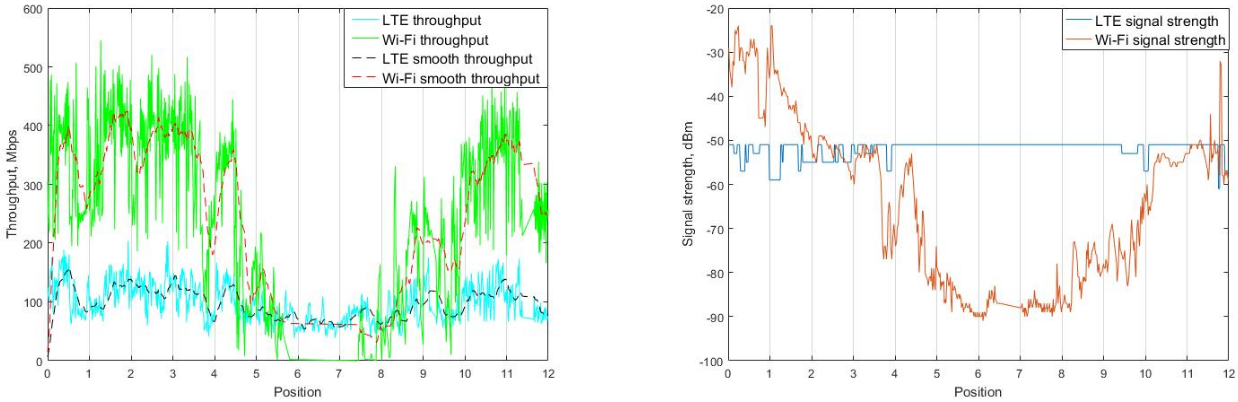
[6] Latitude: 61.493415; Longitude: 23.761406

[7] https://www.dna.fi/peittokartta



(a) Laukontori test run throughput.

(b) Laukontori test run signal strength level.

Fig. 6: Laukontori route and field-test results.

the points three and four can be observed, which is the exact time when the USV connection transitions from LOS to NLOS as the USV moves beyond the bridge. Due to the absence of GPS while the boat is under the bridge, we chose to keep the antenna in the last known position before the GPS was lost until receiving new GPS information. Comparing Fig. 6a and Fig. 6b, one can conclude that generally the connection with higher received signal strength has better throughput and thus should be used for throughput-demanding applications, such as HD video streaming, radar, and positioning data. However, reliability-dependent applications (e.g, telemetry) should switch to LTE in cases of Wi-Fi outage, to ensure uninterrupted wireless connectivity.

B. Conclusion and future work

In this paper, we outlined the design and performance evaluation of the communication part related to the first phase of the aColor project. The first phase of the project aims at autonomous navigation of the USV, while maintaining stable high-speed connection with the GC station. The communication link between GC and USV was implemented using directional Wi-Fi antennas. A system of directional antennas for both GC and USV sides has been built with the mechanical beamsteering functionality.

A field-test has also been conducted along a defined route. The results showed that the system works as planned, with near 400Mbps Wi-Fi throughput in case of LOS. However, the beamsteering mechanism should be improved because the current version is not fully accurate. One of the further research directions is the development of the system improvements, which would allow to maintain wireless connection in case of simultaneous LTE and Wi-Fi outage, e.g. when USV is blocked by an obstacle (such as an island in the lake). In the subsequent phase of the project, aerial and underwater vehicles will be connected to the current setup with the goal of making a full-fledged automotive offshore system.

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