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Potential benefits of 5G communication for autonomous ships

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Abstract. 5G, the next generation of mobile networks, aims to deliver wireless connectivity for new applications beyond traditional connectivity and mobile broadband for the smartphone market. For the maritime industry, 5G has the potential to address a wide range of usage scenarios within ship-to-ship, ship-to-shore, and onboard communication. In this paper, we give an introduction to mobile network technologies and systems in general, as well as an overview of technical capabilities and novelties introduced by the forthcoming 5G specifications relevant for maritime operations. Furthermore, perspectives related to applications and opportunities enabled by 5G networks are discussed, along with the potential benefits for unmanned and autonomous ships.

1. Introduction

In recent years, technological advances in the fields of electronics, automation, and machine learning have been the foundation for the introduction of digitalization, Internet of Things, and autonomy in industrial domains. This also includes the maritime industry, where "smart ships" and "smart harbors", as well as remote-controlled, unmanned, and autonomous ships are being introduced. These new concepts may disrupt the whole maritime value chain, redefine the roles within the industry and provide new business opportunities for shipyards, equipment manufacturers and ship owners.

Advances have also been made in communication technologies, and we have seen new standards and technologies addressing different types of communication, ranging from low power sensor networks to high capacity systems with significantly longer range. Common for previous generation of technologies is that they were targeted at specific applications, and custom made for that application. Examples are 3G and 4G targeting mobile broadband communications, and WirelessHART [1] which is custom designed for industrial process automation applications with low capacity demands and high volume of sensors with more deterministic behavior than for instance the very similar ZigBee standard [2]. This traditional way of thinking was challenged in 2015, when the International Telecommunication Union (ITU) released a vision-document, detailing a framework and overall objectives for the future development of International Mobile Telecommunications (IMT) for 2020 and beyond [3]. In this vision, ITU has for the first time expanded the scope of mobile communication systems to include emerging new use cases beyond traditional connectivity and mobile broadband for the consumer and business market. Example applications include wireless control within industrial manufacturing or production process, remote medical surgery, distribution automation in smart grids, and transportation. Mobile networks addressing these objectives are formally classified as IMT-2020 systems but are more commonly referred to as 5G.

With 5G, mobile communication networks will, for the first time, address use cases beyond mobile voice and broadband for the consumer and business market. Examples of target applications include industrial control systems, remote medical surgery, smart grid, and transportation. We believe this technology has a potential of taking a key role also in maritime communications in general, and for autonomous ships in particular since such ships will require both high capacity communications as well as highly reliable and low-latency sensor communications.

The structure of the paper is as follows; section 2 gives a short introduction to mobile communication components and technology in general, the target technical capabilities of 5G communication are presented in section 3, while section 4 summarizes relevant novelties in 5G compared to the previous generations of mobile networks. The potential benefits of 5G for the maritime domain are analyzed in section 5, classified into ship-to-shore communication, ship-to-ship communication, and onboard communication, and conclusions and further work are discussed in section 6.

2. Mobile communication components

Mobile communication networks operate in licensed frequency bands which are regulated by national authorities. The telecom operators must typically purchase licenses for the use of the frequency bands through national auctions. In addition to the exclusive rights for operation in a frequency band, a license also includes an obligation to provide a certain nationwide network coverage. When multiple telecom operators purchase licenses in a country, the frequency bands are divided into sub-bands to avoid interference between operator networks. Countries with more than one telecom operator will thus end up with a redundant mobile communication infrastructure, one for each license owner.

A mobile communication network provides wireless connectivity to end devices called *User Equipment* (UE), which is typically a mobile phone. The wireless coverage is provided by base stations called *Radio Access Networks* (RAN). The area covered by a single RAN can be referred to as a cell, which is the origin of the term cellular networks which is often used interchangeably with mobile networks. The RANs of a telecom operator are connected to the operator *Core Network*, which is responsible for network and data management, user authentication, routing, subscriptions, billing, and more. A (simplified) schematic description of the basic components in a mobile network is shown in Figure 1.

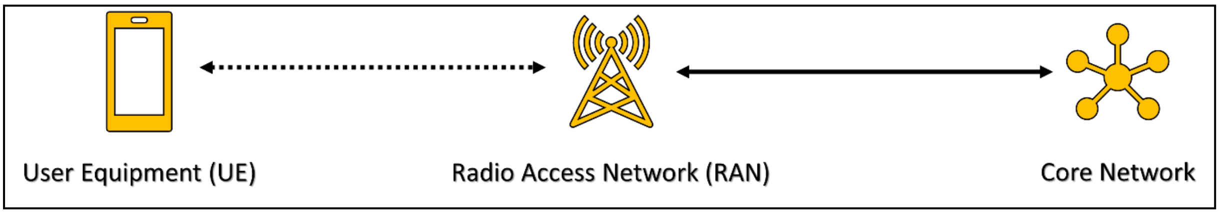

Figure 1. Basic components in a mobile network

To handle network access and user authentication, the telecom operators issue Subscriber Identify Module (SIM) cards to their subscribers. User Equipment (UE) with a valid SIM card can connect to a local RAN and thus make and receive phone calls and send/receive data. From a data flow perspective, all connections, calls and data transfers are routed through the centralized operator Core Network, regardless of the location of the sender and recipient.

3. 5G technical capabilities

As mentioned in section 1, ITU's new vision for IMT-2020 is pushing the telecom industry to address new applications beyond traditional connectivity and mobile broadband for the smartphone market. To easier distinguish between different applications and their requirements, IMT-2020 defines a set of three usage scenarios [4]:

- Enhanced massive broadband (eMBB)
- Massive machine type communication (mMTC)
- Ultra-reliable low latency communication (URLLC)

Due to the diversity of the applications introduced by these new usage scenarios, future IMT-2020 mobile networks must be able to offer a broad variety of capabilities in order to fulfil the various use case requirements. To ensure adequate performance of the future mobile networks, IMT-2020 identifies a set of key capabilities and their target values, which are beyond what current generations of mobile networks can deliver. These key capabilities are listed in Table 1.

Table 1. IMT-2020 key capabilities for future mobile networks [3]

Key capability	Target value
Peak data rate	20 Gbit/s
User experienced data rate	100 Mbit/s
Latency	1 ms
Mobility	500 km/h
Connection density	10^6 devices per km^2
Area traffic capacity	10 Mbit/s/m^2
Energy efficiency	100x (*compared to 4G*)
Spectrum efficiency	3x (*compared to 4G*)

It is important to note that it is not possible to achieve all key capabilities simultaneously through a single service or frequency range. New spectrum resources are therefore being assigned for 5G networks, with initial pioneer bands being 700 MHz, 3.6 GHz and 26 GHz bands.

The three usage classes, and their requirements, are presented in more detail in the following sections.

3.1. Enhanced mobile broadband (eMBB)

The main target of eMBB is mobile broadband for the consumer and business market, with the aim of providing high-speed access to multi-media content, services, and data. eMBB can be considered an evolution of 4G, with key capabilities focusing on improved data rates and network capacity.

Selected minimum technical performance requirements for eMBB as defined by IMT-2020 are listed in Table 2.

Table 2. Key requirements for eMBB [4]

Key capability	Target value
Peak data rate	20 Gbit/s downlink 10 Gbit/s uplink
Peak spectral efficiency	30 bit/s/Hz downlink 15 bit/s/Hz uplink
User experienced data rate	100 Mbit/s downlink 50 Mbit/s uplink
Area traffic capacity	10 Mbit/s/m2
Latency	4 ms
Mobility	Up to 500 km/h
Mobility interruption time	0 ms

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3.2. Massive machine-type communication (mMTC)
The usage scenario mMTC addresses Internet of Things (IoT), which can be defined as a network of physical objects which communicate and collaborate to generate and share information. IoT consists of so-called 'smart' objects embedded with sensors, electronics, software, and wireless communication. IoT covers a large variety of technologies and applications, both in public, private and industrial domains. Key capabilities for mMTC include support for a very large number of connected devices typically transmitting a relatively low volume of non-critical data. The devices are furthermore required to be low cost and have very long battery life.

The key minimum technical performance requirement for mMTC as defined by IMT-2020 is listed in Table 3.

Table 3. Key requirement for mMTC [4]

Key capability	Target value
Connection density	10^6 devices per km^2

3.3. Ultra-reliable low latency communication (URRLC)
URLLC shall provide fast and reliable communication for use cases within e.g. industry, transport, medical and power generation and distribution. Typical requirements are low latency combined with high availability and reliability.

The key minimum technical performance requirements for URLLC as defined by IMT-2020 are listed in Table 4.

Table 4. Key requirement for mMTC [4]

Key capability	Target value
Latency	1 ms
Mobility interruption time	0 ms
Reliability	99.99%

4. 5G novelties
As discussed in the previous section, IMT-2020 defines three usage scenarios for mobile networks (eMBB, mMTC and URLLC), each targeting applications with different requirements. To achieve the target key capabilities listed in Tables 1,2,3 and 4, 5G will introduce a set of novelties which are beyond the capabilities of previous generations of mobile network technology. The novelties we believe are more relevant for maritime applications are described in the following sections.

4.1. Network slicing
In 4G and earlier generations of mobile networks the available network capacity is in principle shared equally amongst all users connected to a specific RAN. This means that the experienced Quality of Service (QoS) for a specific user will change depending on the activity level of other users in the vicinity. For more critical applications such as factory and process automation, health, transport, and energy, a non-deterministic QoS performance of a wireless network is not acceptable. To address this challenge, a local 5G RAN will have the capability to support multiple service classes with different requirements through a new feature called *network slicing*. A legal entity (e.g. a public or private company, enterprise, or organization) can negotiate QoS agreements with the telecom operator to reserve bandwidth and resources and get a private "slice" of the network in order to get guaranteed communication performance. A legal entity which acquires a network slice is called a *tenant* in 5G terminology. An example of network slicing is illustrated in Figure 2, where an industrial robot can have dedicated QoS despite other user traffic from mobile phones on the same RAN.

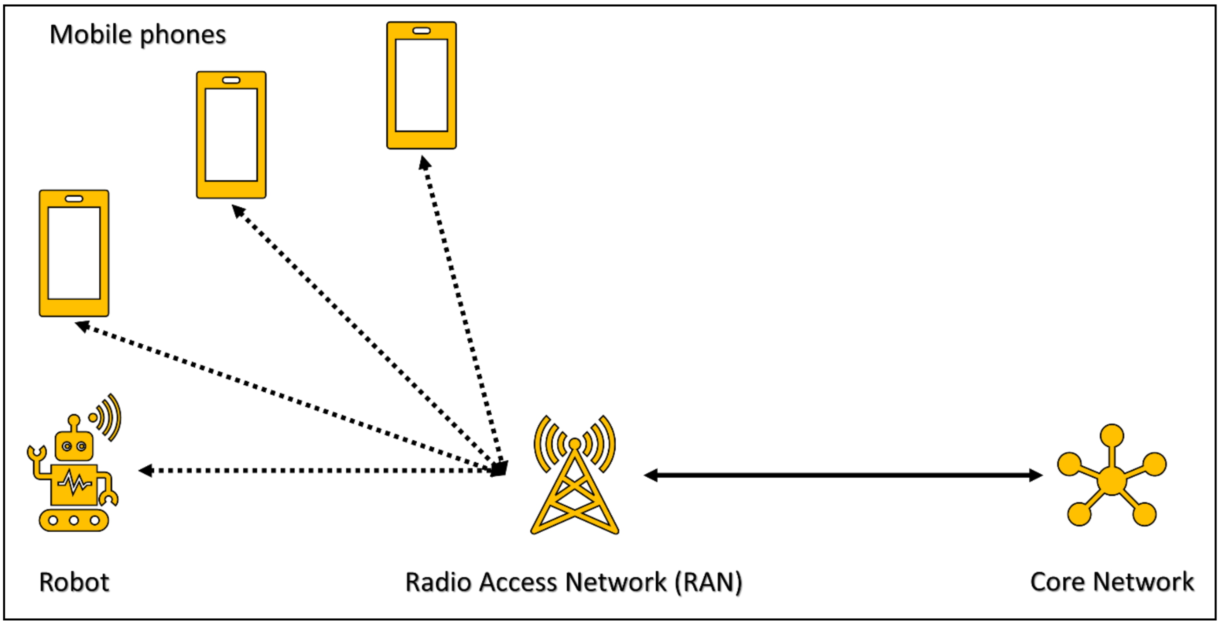

Figure 2. Network slicing

4.2. Edge computing

As described in section 2, data traffic in 4G and earlier generations of mobile networks are routed through the centralized Core Networks of the telecom operators. While this is of no specific relevance in traditional consumer smartphone applications, this model is not always well suited for industrial and maritime applications due to the following drawbacks:

- Sensitive production data is not under complete control of the data owner as it is transmitted from the RAN to the Core Network.
- Routing data through the Core Network introduces unnecessary latency, making the technology potentially unsuitable for low latency applications.

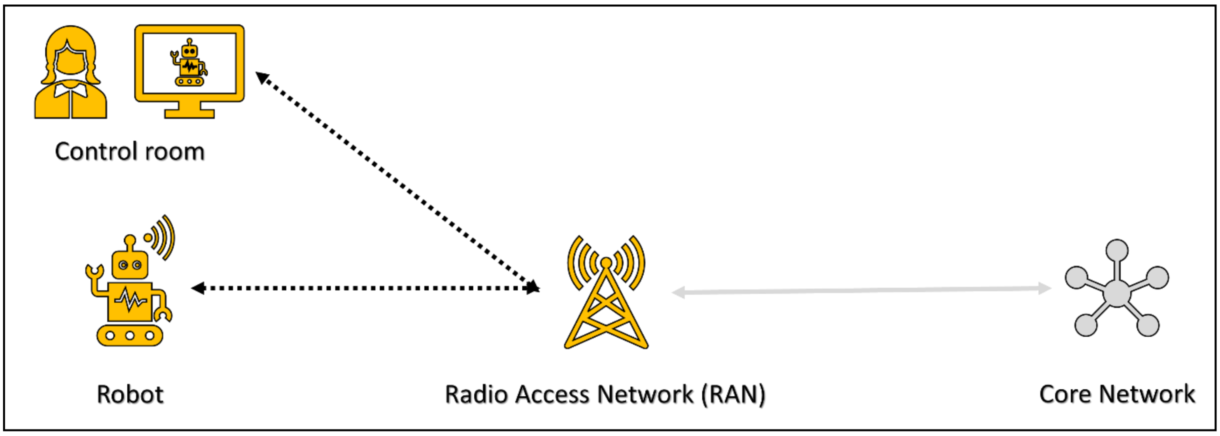

Figure 3. Edge computing

To address these issues, 5G will have the possibility for local network management, thus bypassing the need for all data to go through the Core Network. This feature is called *edge computing*, and it allows for a simplified private Core Network to be installed locally, as illustrated in Figure 7.

Latency will be reduced, and the owner will have more control of valuable operational data (provided the RAN does not also send data to the operator Core Network).

4.3. Private frequencies

The frequencies dedicated to mobile networks are managed by national authorities, and licenses for operation are traditionally auctioned off to telecom operators, under the obligation to build a nationwide infrastructure providing an adequate area and population coverage. To ensure a more open competition and hopefully enable 5G connectivity in broader range of applications and domains, ITU has recommended that 5G should allow for specific frequencies to be reserved for local, geographically limited, frequency allocations. A licence to operate in these frequencies can thus be purchased by actors other than the national telecom operators. Support for local frequency allocations must naturally be approved and managed by national telecommunication authorities.

The combination of edge computing and local frequency allocation will allow industrial actors to purchase a local frequency license and deploy their own private 5G networks, as depicted in Figure 4.

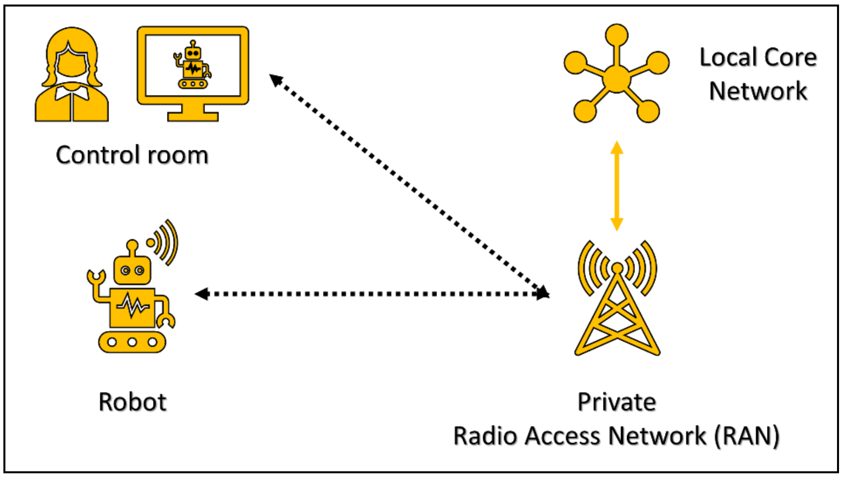

Figure 4. Private network

4.4. Radio communication and signal processing

We have already mentioned network slicing dedicating a set of radio and network resources to a user or an application enabling more deterministic performance and capacity. There are also other new and/or state-of-the art methods introduced in 5G to facilitate both even higher capacity broadband communications, and ultra-reliable low latency, and communications to and from a huge amount of extremely low power consuming sensors. The aim in this paper is not to go in detail explaining these techniques, but we give here a very brief overview.

5G uses state of the art error correcting coding which is crucial for reliable communication in noisy areas and areas with electromagnetic interference. Such codes allow both high capacity communications as well as communication with low transmit power and low power consumption (for long battery lifetimes). The last being very important in industrial applications where the frequency of battery replacement is critical. 5G also has support for multiple antennas, the so-called Multiple Input Multiple Output (MIMO) techniques. Multiple antennas can be used to increase capacity, to increase reliability, and to steer the radio propagation in certain directions, called beamforming. Furthermore, 5G can be applied in many different radio frequency spectrums. Each frequency range has different properties, typically lower frequency having higher range than higher frequencies, whereas at higher frequencies, although shorter range, there is larger available useful bands that give higher possible data rates. Another feature of 5G is that it supports non-orthogonal multiple access. This means that a transmitter is not allocated a certain frequency slot or a certain time slot for transmission. Instead, the transmitted waveform is constructed and coded such that advanced signal processing in the receiver will be able to distinguish the different data despite “colliding in the air”. This has some capacity gain, but most of all at gives the opportunity to transmit without prior signaling to allocate a dedicated channel. This saves capacity, and even more importantly, it reduces time until transmission since prior signaling to reserve a channel is not necessary.

5. 5G communication for autonomous ships

The ongoing digitalization of the maritime industry opens new opportunities for products, applications, and services, but the full potential can only be gained if an efficient, flexible, and secure communication network for exchange of various types of data is in place. In the maritime area we see several dimensions that pave the way for new innovations within three different communication scenarios: ship-to-shore communication, ship-to-ship communication, and onboard communication. The next sections address the potential of 5G solutions within each of these three categories.

5.1. Ship-to-shore communication

Traditional bi-directional ship-to-shore communications for operation and leisure is a requirement for most ships regardless of type and mission. Future autonomous operations will put new requirements on this communication, where a secure and reliable connection to a Shore Control Centre (SCC) is needed for supervision and remote operation of unmanned and autonomous ships. In addition to navigation and control information, it is expected that various sensor feeds from the ships, such as live audio/video, radar, and LiDAR, must be available to the SCC operators.

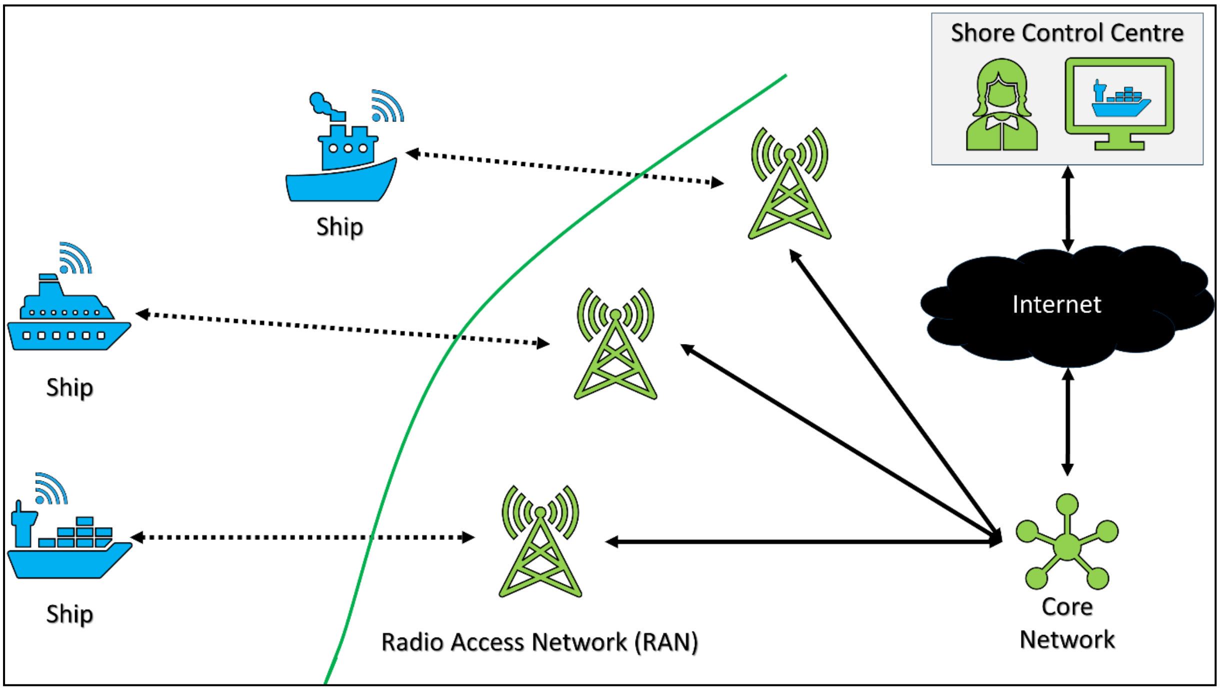

Figure 5. Ship-to-shore communication using 5G infrastructure

The applicability of using 5G for ship-to-shore communication is highly dependent on the type of maritime operation. Mobile communication networks are built on the premises of providing coverage by having many RANs, each with a communication range in the order of a few kilometers. Ship-to-shore communication using 5G is thus only relevant for ships operating in coastal-near waters or inland waterways. This includes quays and harbors with 5G infrastructure as well. For coastal-near waters, it will potentially require dedicated RANs located along the coast, with antennas directed towards the sea. For inland waterways, coverage will be provided by national 5G infrastructure in urban areas, while some remote rural areas could end up without 5G coverage. An example of ship-to- shore communication using 5G is illustrated in Figure 5. Here, several ships are in range of a set of land-based RANs, and the 5G infrastructure provides internet access (and communication to a SCC) through the Core Network of the 5G network operator. Note that is this scenario, each ship is considered as a User Equipment (UE) in 5G terminology. In order to communicate with a RAN, the ship must have a 5G UE modem with an antenna, as well as SIM card from the relevant network operator. For ships operating across international borders, it will be necessary to facilitate international roaming agreements with telecom operators.

From a communication requirement perspective, all communication between ship and shore must have high reliability and low latency. For navigation and control data, the date rate requirement is low, while the sensor feeds, on the other hand, require a high data rate. Ship-to-shore communication is thus expected to be best addressed with 3.6 GHz eMBB (see Table 2 for key eMBB requirements), although communication range may be a challenge. To get increased range, the 700 MHz band could be considered, but this will come at a cost of data rate, as this frequency is primarily dedicated for mMTC and IoT applications with many devices with low data rates.

5.2. Ship-to-ship communication

Communication between ships is relevant for scenarios like simultaneous operations and navigation in narrow channels and waterways and has the potential to increase efficiency and traffic safety when ships are in the vicinity of each other. Ship-to-ship communication can also be used for non-operational data exchange, e.g. one ship can offer internet connection to another, and non-satellite communication to shore can be extended by setting up mesh networks between multiple ships in coastal-near waters.

Ship-to-ship communication with 5G can be solved in two ways:

A. Communication through a land-based 5G infrastructure as shown in Figure 5.
B. Communication through a private 5G network located onboard a ship as shown in Figure 6.

In option A, the communication between two ships are routed through a land-based 5G infrastructure. This has inherent drawbacks as the ships must be within range of a RAN on land, and relevant scenarios are thus limited to operations in coastal-near waters and inland waterways. The upside to this solution is low requirement on communication infrastructure, as each ship only needs to install a 5G UE modem and antenna with a SIM card from the relevant telecom operator. For ships operating across international borders, it will also be necessary to facilitate international roaming agreements with telecom operators.

For option B, a *primary* ship participating in the ship-to-ship communication must be equipped with infrastructure for a private 5G network, comprising a private RAN and a local Core Network connected to the bridge systems. The *secondary* ships only need a 5G UE modem and antenna, compatible with the private 5G network of the primary ship with regards to frequency and radio parameter configurations. With this solution, the ship-to-ship communication can technically take place in any waters, and the communication setup is controlled by the ships themselves. The main challenge related to this solution is related to the acquisition of local frequencies for private 5G networks. Current regulations by national authorities in different counties reserves frequencies on either a national level for the telecom operators, or on a regional/local level for private 5G networks within a *geographically limited area*. So far, the concept of a mobile RAN has not been addressed, and it is still an open issue whether it will be resolved soon. The complexity of this situation is further increased if ships are in international traffic, as regulations for private 5G networks are handled different in different countries.

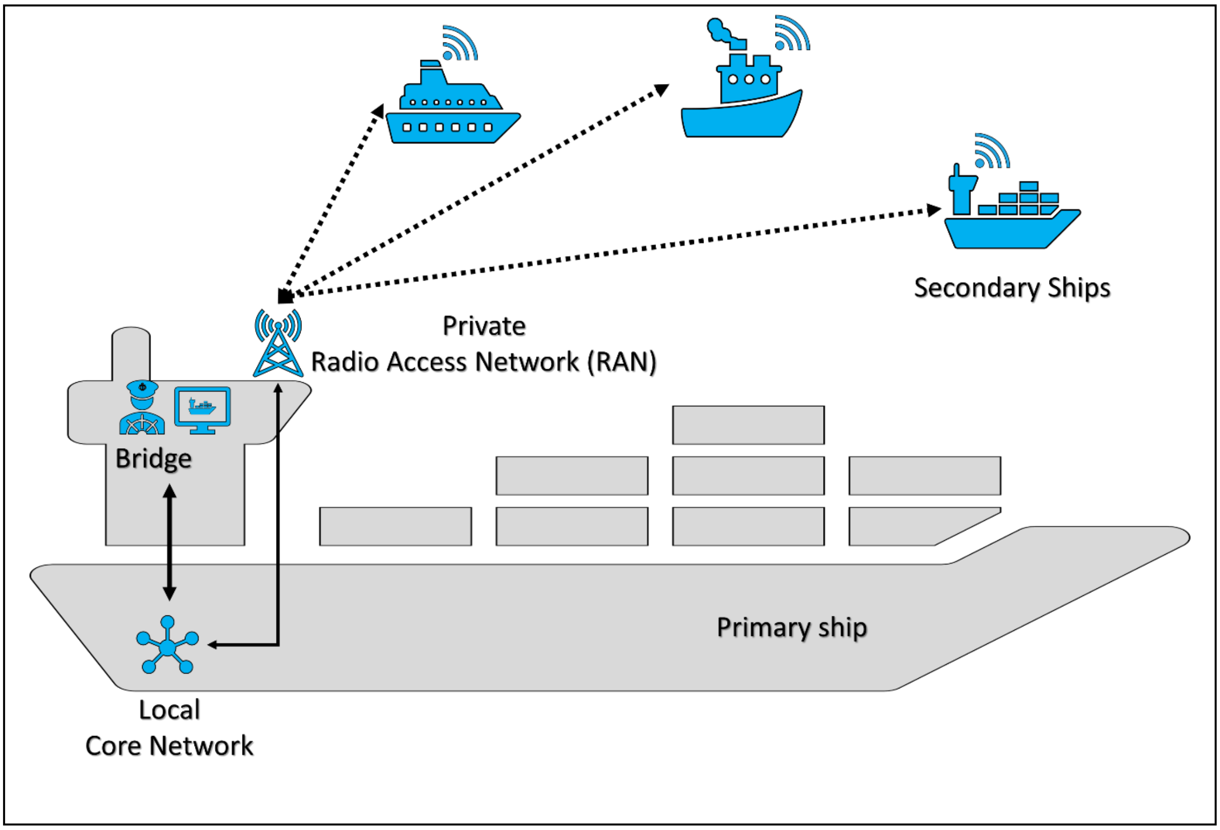

Figure 6. Ship-to-ship communication using a private 5G network

From a requirement perspective, using ship-to-ship communication for simultaneous operations and navigation in narrow channels and waterways will require a communication channel with high reliability and low latency. The operations require ships to exchange data related to position, orientation, heading, speed etc., but the bandwidth requirements can be considered low. From a 5G usage scenario perspective, 3.6 GHz eMBB is the preferred communication configuration. To get increased range, 700 MHz mMTC can be considered, as the data rates should still be sufficient for the envisioned applications.

5.3. Onboard communication

Unmanned and autonomous ships will have increased demands of sensors and instrumentation onboard the ships. In this regard, wireless communication can bring benefits such as simplified engineering and commissioning, reduced cabling, and increased flexibility. The usage areas for wireless communication onboard vessels are many, including:

- Sensor feeds for SCC operators (e.g. cameras, radar, LiDAR)
- Non-critical monitoring (e.g. wind, temperature, humidity, weather)
- Autonomous operation support (e.g. loading crane, mobile robots)
- Instrumentation for automation and control systems (e.g. sensors and actuators in machine room)

For onboard communication, a private 5G infrastructure is the only sensible architectural choice. The local Core Network can be connected to bridge systems, while one or more private RANs provide wireless coverage throughout the vessel. Since metallic structures block electromagnetic waves, multiple RANs may be required below decks, while a single RAN should be sufficient for above deck. An example of a private 5G network infrastructure for various applications onboard a ship is illustrated in Figure 7. Here, one RAN provides coverage for equipment on deck, while a separate RAN is installed for wireless communication for sensors and actuators in the machine/engine room.

Using a private 5G network for onboard communication will be subject to similar regulatory challenges as described in the previous section on ship-to-ship communication since regulations by national authorities reserves frequencies on either a national level (for the telecom operators), or on a regional/local level for private 5G networks within a *geographically limited area*. The open issue on how to regulate frequency allocations for a mobile RAN must thus be solved before onboard communication using 5G becomes a reality.

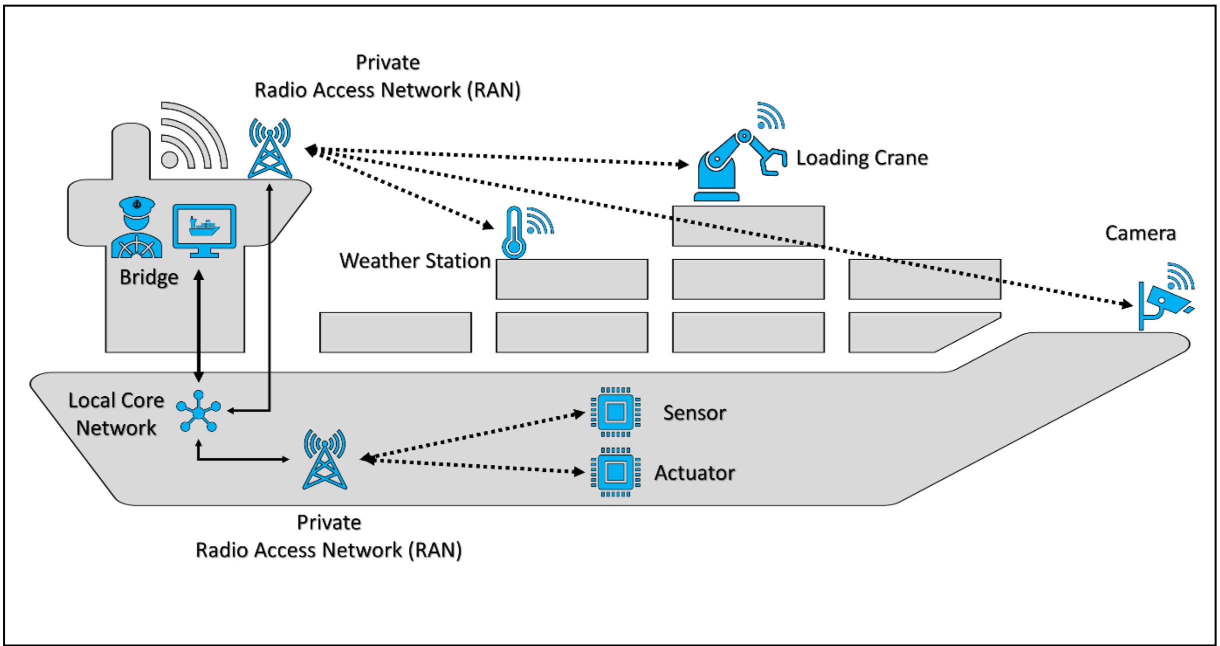

Figure 7. Using a private 5G network for onboard communication

The requirements for onboard communication vary depending on the usage area, and in this setting the flexible nature of 5G networks can be used in its entirety. eMBB with its high data rate can handle video, radar, and LiDAR streams, URLLC with high reliability and low latency is capable of supporting machine room closed-loop control and operation of autonomous cranes and robots, while mMTC can be used for non-critical monitoring where long battery life is desirable.

6. Conclusions

This paper has introduced target technical capabilities and novelties with 5G, the next generation mobile network technologies. Furthermore, the potential applicability of 5G within ship-to-shore, ship- to-ship and onboard communication has been analyzed, with the conclusion that 5G should be capable of addressing a large set of use cases and applications within the maritime domain. In addition, the possibility of having one technological framework for a multitude of applications is on its own a great benefit, especially compared to today's situation where maritime technology and solution providers have to provide equipment and support for close to one hundred different wired and wireless communication protocols.

At the time of writing, the main challenge with 5G is related to frequency regulations for private 5G networks. For onboard communication and many scenarios with ship-to-ship communication using national infrastructure is not feasible, and the only practical solution is to establish a private 5G network on the ship. However, the regulatory challenge related to frequency allocation for a mobile RAN must be addressed by the authorities. This is further complicated for ships in international traffic, which will encounter regulatory issues in many countries.

In addition to exploration of regulatory possibilities, a more thorough analysis and study of concrete business models and their requirements for various maritime 5G applications are a natural next step for further research.

Acknowledgments

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