A Hybrid Network for Maritime On-Board Communications

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***Abstract*—Current maritime on-board communications have to be enhanced for safety and security, where ubiquitous technologies can help, together with providing comfort and convenience to the crew and passengers. Employing wireless sensor networks on board is one recent practice of implementing ubiquitous technology for ships, where further study is needed because of the connectivity challenges. Meanwhile, it is important for an on-board communication system to be reliable and flexible for handling emergency situations. In this paper, we propose a solution of employing ubiquitous technology on ships in a way that both connectivity and emergency handling are examined. Two key aspects of this proposal are: 1) combine different on-board communication networks into a hybrid system, enabling the cooperation between them, 2) smoothly integrate these networks with a consideration of backward compatibility, ease of deployment and connection to shore via Internet. Simulations are used to support our choice between the separate networks and a hybrid one from comparing mainly the communication performance, and a combined integration approach is selected based on comprehensive analysis.**

I. Introduction

Communication is essential for maritime safety, security, integrated operations and for infotainment purposes. Communication of a ship can be categorized based on the route between source and destination, e.g., ship-to-shore, ship-to-ship and the on-board case. In this paper, we focus on maritime on-board communication which provides basic data for the other two types. User groups involved in the local communication include on-board equipment, cargo elements, crew and passengers. Communication between them are supported by the on-board infrastructures and services, such as a sensor network, a personnel tracking system and a wireless local area network (WLAN). Due to the harsh environment of ships for wireless communication and the cost consideration, current communication solutions on board are not satisfying. For example, most ship owners nowadays have only a monitoring system covering very essential equipment based on wired sensor networks, and a personnel tracking system is seldom in place. Internet connection via a WLAN on board is available merely in cruise ships and ferries. Safety and security can be much more enhanced if more intensive monitoring on a larger amount of user groups on board is achieved. Since deploying full-scale wired sensor networks on a ship leads to complexity and high costs, in [1], a Wireless Sensor Network (WSN) solution was proposed. After that, more papers [2] [3] have reported the experimental results of implementing WSN technology on ships. Although feasibility can be justified from the literature, real deployments still meet difficulties.

As we know that neither a wired or wireless solution of deploying sensor networks on board will function well alone, to combine their strengths together becomes an intuitive thought. This idea was implemented in [4] [5] for an energy-efficiency purpose. We apply it to the ship application mainly for tackling the connectivity challenges and for increasing system reliability. Therefore, in addition to wires, we also integrate the sensor network with other more established or to-be-established networks, such as a WiFi-based mesh network, the crew/passenger network, a personnel tracking system, and the global Internet. Reasons for involving human beings and Internet into the picture are explained as follows. Sensor monitoring systems on board are used for detecting abnormal operations, disordered equipment and for fire prevention. Rapid human response is usually required if any disorder or abnormality is detected. In this sense, it is preferable that crew carrying mobile devices around can participate in the monitoring process anytime and anywhere. On the other hand, it is desirable that crew-carried devices can perform mobile sensing and data collection as well, especially during system failures. If this on-board monitoring system can be seamlessly integrated with Internet, an ultimate goal of future maritime shipping - integrated operations for ships - will become feasible, where functions and personnel can be relocated from ship to shore based on efficient land-based control, remote maintenance, real-time surveillance and so on.

In order to test that the integrated hybrid on-board network will increase communication efficiency and system reliability, we use the ONE simulator [6] to evaluate some common scenarios, i.e., data collection in a monitoring sensor network, information dissemination for personnel tracking, and direct communication

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among people during emergencies. In addition, we investigate different methods of integrating WSNs with external networks, and present our selection based on thorough analysis considering both deployability and the particular maritime context. The remainder of this paper is structured as follows. In Section II, related work is discussed. Section III describes some application scenarios for using WSNs on ships. Section IV presents an integrated hybrid on-board network solution, together with a discussion about different integration approaches and our choice. Simulation and evaluation on the proposed hybrid network are presented in Section V. Finally, Section VI concludes this paper and points out directions for further work.

II. Related Work

Maritime communication is important in many aspects. One example is integrated operations for ships. The Norwegian Oil Industry Association has defined integrated operations in the oil and gas industry as "real time data onshore from offshore fields and new integrated work processes". An ultimate goal of integrated operations is to relocate personnel and functions from offshore to onshore, where communication plays a fundamental role. A traditional maritime communication solution can be described as a wired on-board monitoring system connected to a local area network which interacts with the Internet through satellites, shown in Fig.1.

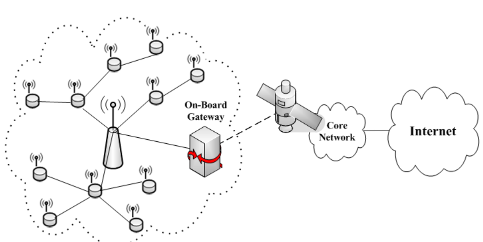

Fig. 1. The Traditional Maritime Communication Approach.

In papers [7] and [8], the ship-to-shore communication has been explored further by using multiple wireless access networks. Vertical handover among these networks based on the IEEE 802.21 standard is described in paper [7], and a supplementary capability of Delay Tolerant Networking (DTN) targeting at challenged satellite communication is depicted in paper [8]. From Fig.2, we get a basic idea of how to enhance maritime communication from the ship-to-shore part.

In this paper, we move our focus from ship-to-shore communication to the on-board case. A current popular suggestion of improving communication on board is to utilize the WSN technology. WSNs are distributed systems, consisting of low-power devices with integrated computation, sensing and wireless communications. This

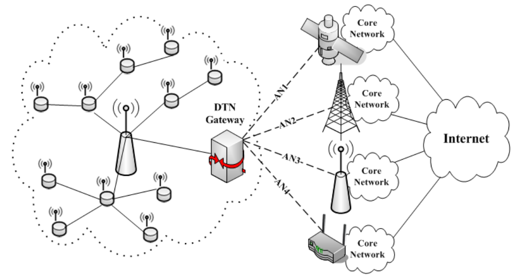

Fig. 2. Improved Ship-to-Shore Maritime Communication.

integrated characteristic has popularized WSNs in a wide range of applications including operation monitoring, object tracking and detection. Different wireless communication technologies such as WiFi, Zigbee, and Bluebooth have been exploited for the construction of an efficient WSN. Due to resource constraints of a sensor node and the inherent feature of wireless communication, energy consumption and the connectivity problem are two major issues in WSNs and have attracted a lot of research work. In [9], a hybrid wired and wireless sensor network was adopted for energy efficiency. The used wires were acting as short cuts to bring down the average hop count, therefore reducing the energy dissipation per node and the energy consumption of the whole network. Compared with their work, we focus on addressing the connectivity problem when deploying WSNs on ships caused by steels and aluminium materials. Apart from energy efficiency, wires placed in some specific parts of the ship will function as connectors within an on-board WSN.

Connectivity problems in other traditional WSNs, such as a habitat monitoring system, are often introduced by mobility of the nodes and low node density. Therefore, increasing node density is one way to achieve connectivity, which is, however, not recommended in most cases due to the high cost. Deploying extra communication infrastructures like a base station is another way, e.g., integrating WSNs with a Wireless Mesh Network (WMN) for Internet connectivity, where the WMN acts as a wireless backbone. It is argued in paper [10] that a WMN should be used not only as the backbone but also for sensor node to sensor node communication. This deep-level interconnection applies to the situation on ships as well. However, the paper only considers the combination of WSNs with WMNs, in which, mesh nodes usually support limited or no mobility. We also add mobile nodes into the hybrid on-board network, because taking advantage of the mobility of some specific nodes is an efficient way to achieve connectivity in WSNs. These nodes are called data mules/ferries [11], and they have been well studied in the terrestrial WSNs scenarios but not in a ship environment. In this paper, we make use of both communication infrastructures and the crew carrying mobile devices with random or intentional mobility, to build an integrated hybrid sensor network on board. Communication infrastructures in the form of wires and WMNs are used here as an on-board core network, to address connectivity challenges, to reduce energy consumption and to avoid inefficient data routing. Introduction of the crew network consisting of mobile devices is a redundancy solution, aiming at the network reliability and robustness. Mobile devices behave as normal sensors under failure situations and as control centres when abnormality is detected, or they can function merely as relays.

Although networks integration, such as using WLAN and WPAN, together with WSNs on ships, is recommended in paper [2], for the adaptation to various environmental conditions, the paper does not specify how to integrate a sensor network with other, e.g., well-known TCP/IP networks. Integrating a WSN with external TCP/IP networks is not a trivial job. Numerous work has been dedicated to this. Basically there are three types of integration, a proxy-based solution, a DTN approach, and directly using TCP/IP stack in sensor nodes. Implementing a specific proxy gateway [12] [13] between a sensor network and an external network is the most common way of doing integration, because of its no need of changing existing sensor networks or the external one. A DTN [14] architecture expands the proxy method by deploying a common Bundle layer as an overlay covering both TCP/IP network and non-TCP/IP network protocol stacks. Based on these overlay nodes, late address binding can be achieved independence of the underlying bearer protocols and addressing schemes. Directly running the TCP/IP protocol stack in the sensor network had been long argued as non-realistic until the micro IP (uIP) implementation [15]. After that, tremendous work has started following this direction, such as Tiny TCP/IP [16] and 6LoWPAN [17] related solutions. In paper [18], a complete IPv6/6LoWPAN stack for low-power wireless networks was presented. We make a comparison between these three methods from a deployment point of view, see Fig.3.

While implementing TCP/IP in sensor networks is considered as the ideal way of interconnecting sensor networks with TCP/IP networks seamlessly, and to unite all kinds of different sensor networks themselves, proxy-based approaches are the most realistic way to pursue integration because of their backward compatibility. Nevertheless, a specific proxy gateway only solves the problem of interconnecting a certain type of sensor networks with others and it is not a generic architectural approach. Therefore, in this paper, we make a combination of these three methods, in order to aggregate their strengths and to proceed integration smoothly. For example, the TCP/IP stack will be utilized in future deployed sensor networks; proxy gateways are added to existing non-TCP/IP sensor networks, and the DTN overlay architecture functions as a mediator when combining these two methods.

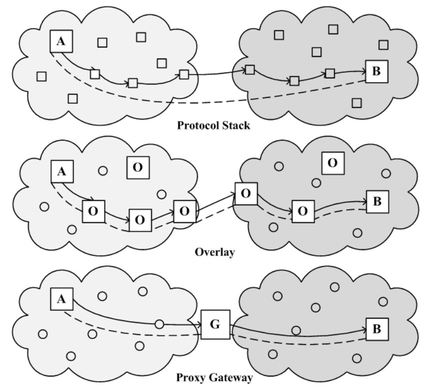

Fig. 3. Three Different Integration Methods.

III. Maritime On-Board Communication Scenarios

1) For monitoring abnormal operation or disorder of equipment: A ship has many types of equipment on board, and they are closely related to each other. A failure of any equipment may cause problems to other equipment or the main engine system, leading to abnormalities in the ship's operation. Therefore, it is important to monitor equipment as much as possible to reduce the risk of structural or engine failures. The current means of monitoring ship equipment are based on wired sensor networks, and the sensed data is collected and transmitted to the control server in the engine room in real time. Due to the high cost of cabling and the complexity of deploying a large wired sensor network on board, many ships today have a monitoring system only for their essential equipment [2], and the WSN technology has been proposed to improve this situation.

2) For environmental measurements: Crew and passengers wish to have better lives on ships, provided by ensured comfort living conditions, such as automatically controlled temperature, humidity, and similar environmental factors. Above comfort, safety on board has to be continuously guaranteed. External help is not easy to obtain if any crisis occurs on ships, e.g., fires and explosions. Therefore, it is of high significance to prevent emergency situations from happening by assessing their possibilities of occurring before their actual occurrences. This can be achieved by real-time environmental monitoring of dangerous areas and suspected containers or cargoes (for cargo ships). WSN technology is recommended here for monitoring areas like walls or above the ceiling or for a large amount of cargo containers.

Optimization is necessary for efficient communication under complex structures inside ships, before any real implementation.

3) For personnel tracking and locating: Surveillance of the positions and movements of crew on board is a requirement for safety and efficient operations. It is especially important when crew members are sent to dangerous areas for maintenance or other tasks. The surveillance of passengers can help alarm them when they are close to a dangerous zone, or for counting passengers while they pass from one deck or territory of the ship to another. The most well-known ubiquitous technology that is currently in use for tracking personnel consists of Radio Frequency Identification (RFID) tags and readers. Cost is high for a RFID-based monitoring system being installed independently on shipboard, especially if the accuracy requirement is high. It is also not easy to reliably recognize an RFID tag carried by a highly mobile entity, and the equipment cannot last long in harsh environments. Therefore, if a personnel monitoring system can be based on the WSN technology and be integrated with other existing data networks, the communication efficiency and reliability will be increased at no extra cost. Meanwhile, considering the fast development of modern mobile devices, in the foreseeable future, a personnel tracking system will be able to employ personal mobile devices directly. It is more convenient to deploy such a system than an independent RFID-based one, and useful for emergency situations, where crew and passengers can self organize into a mobile ad-hoc or purely opportunistic network for information dissemination.

IV. Integration into a Hybrid On-Board Communication Network

A. A Hybrid On-Board Network

In the previous section, we listed some common scenarios of implementing ubiquitous technology on board a ship for local communications. We focused on the WSN technology. Since the network performance of a WSN on board depends strongly on the deployment of sensor nodes in real environments, which varies from ship to ship, it is preferable that more general optimization technologies can be applied, before any real-life implementation. Our method is to increase communication efficiency and system reliability by increasing system diversity from integrating different strategies, e.g., involving communication infrastructures (wires and WiFi nodes) and taking advantage of mobility of some specific nodes (crew carrying mobile devices). This way, a hybrid on-board sensor network, see Fig.4, is formed including wireless sensor nodes, wired sensor nodes, mobile nodes and WiFi nodes. This hybrid network can be used to cover all scenarios mentioned earlier.

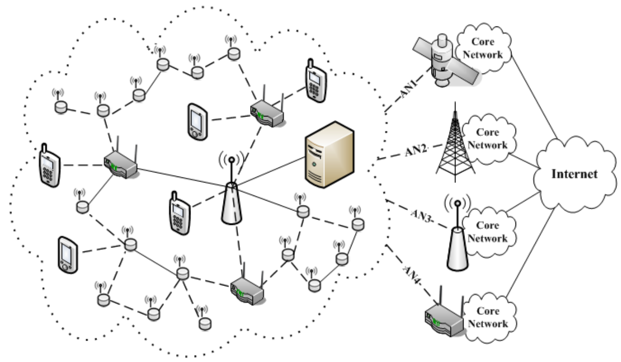

Fig. 4. The Future Maritime Communication Approach.

For a monitoring process to work, a sensor network needs to be connected to a central entity that can access and analyse the data. In our hybrid network (Fig.4), the sensor network is connected to multiple monitoring entities via multiple means, upon a WiFi-based network which directly attaches to an on-board control center, connecting to mobile devices carried by crew members which can behave as control points themselves, and to the global Internet through ship-to-shore communications. We explain this integrated on-board network in more detail by using following three individual networks.

(1): Fig.5 shows a basic WSN with focusing on the communication infrastructure support from wires.

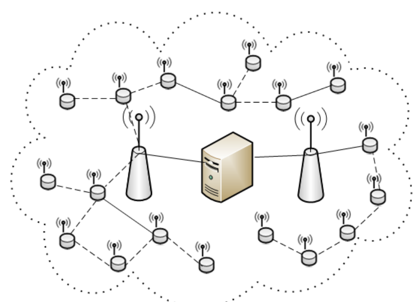

Fig. 5. A Basic Sensor Network.

Communication technology within this network includes wired transmission, ZigBee and/or Bluetooth and/or WiFi short-range transmission. A sensor node in the figure can be a source of data, an intermediate node to forward data or a sink node for collecting data. Data is delivered between a sensor and a sink based on either single-hop or multi-hop routing. After the initial deployment, this network is supposed to be fully connected and the data is transmitted in real time, whereas the reliability is probably low and there may be unanticipated disturbances or interferences in the future. The main purpose of this sensor network is to monitor abnormal operation, disorder of equipment and for the environmental measurements.

(2): Fig.6 shows a WiFi-based WMN that runs as a core network connecting on-board user groups to the on-board control center. Mesh nodes in a legacy WMN case, behave as a wireless backbone to extend network coverage, e.g., connecting an edge sensor network to the Internet via a sink. In our case, we seamlessly integrate these mesh nodes with the on-board WSNs by adding the sensor node capability to them. This way, a mesh node will have a twofold role: 1) as a powerful relay node to deliver large amounts of data between sensor nodes and 2) as an access point being contacted by any WiFi devices. Seamless integration is introduced also because of situations such that data from sensors is needed by a nearby crew member carrying a smartphone. The only possible path in a traditional WSN is through the control server in the engine room, which leads to very inefficient data routing. If the mesh core network is interconnected with the sensor network seamlessly, data can be obtained efficiently via nearby mesh nodes. We go a step further in this direction by expecting that future mobile devices will be able to contact sensor nodes directly even without the help from an on-board core network, which will be explained in the next paragraph.

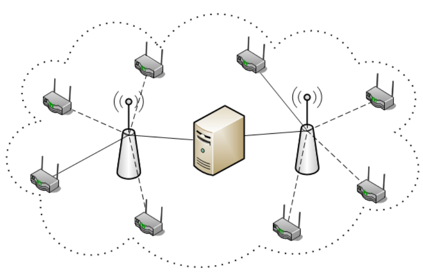

Fig. 6. A Mesh Core Network.

(3): Fig.7 shows an opportunistic P2P communication network formed by crew members and passengers. Modern mobile devices with WiFi direct, Bluetooth, or other communication technologies can be used for network construction. The network has an opportunistic networking capability [14], which means that data delivery can be carried out in a store-and-forward manner among opportunistic encountered nodes. Therefore, data transmission in this network is not based on real time but has possibly some delays. Such a network is useful in many circumstances, e.g., for personnel tracking, for cargo monitoring and for direct communication among passengers. If this network can be seamlessly integrated into the previous two networks, crew members with random or intentional mobility will be able to assist on-board sensing and equipment monitoring anytime and anywhere. A crew-passenger tracking system will be able to use mobile devices directly and cooperate with encountered sensor nodes or mesh infrastructure nodes. Direct communication requirements from crew and passengers can be satisfied, which is very useful for emergencies, e.g., when facing with communication infrastructure damages. Furthermore, the ship-to-shore communication attachment with the Internet is no longer a single point upon an on-board gateway, but many points through different mobile devices. This crew (passenger) network and the previous mesh core network are self-organizing networks, which facilitates fast built-up processes and changeability handling. Therefore, we can deploy them in a flexible and incremental manner according to different ship interiors and different user requirements.

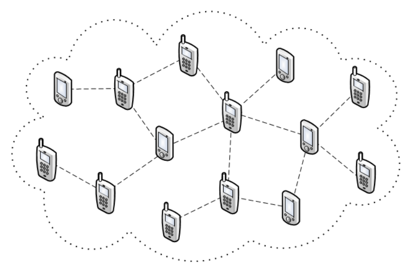

Fig. 7. A P2P Crew/Passenger Network.

B. An Integration Roadmap

An integrated hybrid network on board shall have increased system reliability and better network performance, which we will test in the simulation section. But before that, it is necessary to answer the question of how to integrate different networks. Given that the TCP/IP protocol suite is the de-facto networking standard both for the global Internet and for local-area networks, integration between sensor networks and the TCP/IP world is of major importance. As mentioned in related work, there are basically three approaches, and we make a comparison between them under the maritime context.

A proxy-based integration architecture relies on sink nodes to provide protocol bridging between the sensor network and the external one, which can be implemented by executing either protocols translation or stack virtualization on mesh nodes on board. It has the advantage of keeping specialized sensor nodes with almost no disturbances to the network. Therefore, a proxy-based architecture is very suitable for already deployed on-board sensor systems with dedicated protocols. As the development of hardware and software technologies, a sensor node will have more resources and more powerful computing capability. At the same time, most mobile devices in the future will have global unique IPv6 addresses and the Internet shall provide transparent pervasive accessibility and mobility to users. Therefore, from a long-term point of view, implementing TCP/IP in sensor networks is an ideal way of interconnecting sensor networks with others [16]. It is also the trend of integrated operations for ships, which requires seamless interactions between on-board equipment, devices and the on-shore control centres. Since existing TCP/IP architectures can not flexibly handle the case of different resource conditions of sensor nodes, and mobility support is lacking, they must be integrated into a larger architecture, e.g., the DTN architecture. A DTN-based integration architecture is similar to the proxy-based approach, but provides general mechanisms and an interface that can be used for more occasions. With a DTN architecture, it becomes easy to integrate different heterogeneous wireless networks from deploying a common DTN Bundle Layer into their protocol stacks. Deploying a Bundle layer into existing protocol stacks involves activities towards both the lower and application layer. Therefore, in our case, we allow the network to have a DTN networking capability gradually, e.g., first the on-board proxy gateways, then the mobile devices carried by crew, then more infrastructure nodes, and then specific sensor nodes. Besides the architectural support for integration, DTN also provides a set of features which can be used to overcome issues within problematic communication environments, i.e., the maritime communication. We can explain this from the following two aspects:

- *First, a local on-board WSN meets a lot connectivity challenges because of the materials and the structure used for building a ship. Participation from the crew and passengers carrying mobile devices, supported with the DTN networking capability, can help mitigate the communication problem and increase the system reliability.*
- *Second, it is anticipated that on-board networks will be connected to Internet via the ship-to-shore communication, and most of the time, ship-to-shore communication has to rely on challenged satellite networks. DTN is recommended to be used in this context [19], and it enables user preferred data migration from satellite to other terrestrial networks as well [8].*

Therefore, we suggest an integration roadmap for maritime scenarios based on a combination of different methods using the DTN networking architecture as a transition phase, see Fig.8. Future on-board WSNs can be deployed based on the TCP/IP protocol stack, and they communicate with an on-board DTN gateway using local area networks. The DTN gateway will transmit the gathered information over the global Internet at places where it obtains preferred Internet access, e.g., WiFi at ports. This on-board DTN gateway is either a static server or a mobile device carried by a crew member. Thanks to the special position of a proxy gateway, it

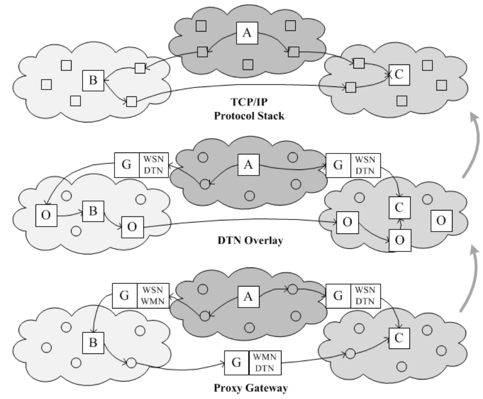

Fig. 8. The Integration Roadmap.

can be placed where traditional sensor networks exist with dedicated protocols, or where the sensor resources are extremely constrained and performance requirements are high, by running some specific code on it [20].

V. Simulation and Evaluation

Different ships often have different interiors and inner structures based on the owner's initial requirements, and these initial designs can change with time. Since communication within a WSN depends heavily on the actual environment, it is not trivial to generally simulate the connectivity challenge of deploying WSNs on ships. However, as a connectivity problem of a WSN can be caused not only by the actual surroundings, but also by mobility of the sensor nodes, we can simulate the connectivity challenge of deploying WSNs on board by adding random mobility to the nodes. This way, simulation is used to support our arguments from a more general perspective. The primary input parameters for the simulation are: the node density, the mobility model and the routing protocol. We use node density as an input variable and set random walk mobility to all nodes. Routing protocols are chosen according to the scenarios. Usually delivery rate and delivery delay are two main output parameters for the evaluation. Since we simulate the connectivity challenge by adding mobility to all nodes and data is based on a hop-by-hop non-real-time delivery, the delay parameter will lose its original value. It can be assumed that the real-life sensor network implementation is mostly real-time data transmission, and crew assisted data delivery is a redundancy solution which can tolerate some delays. Other scenarios such as the personnel tracking, cargo monitoring and direct communication among people are delay-tolerant applications. Therefore, we compare only the delivery rates collected from the simulation which is executed in three cases.

Case 1 is a scenario of WSNs on board for monitoring abnormal operation or disorder of equipment, and for environmental measurements. A pure WSN on board is simulated as a mobile network with all nodes having the same characteristics, whereas the proposed hybrid network can behave as including some special nodes. Special infrastructure nodes have much larger transmission ranges and higher transmission speeds. Other special crew nodes will have higher mobility, added by the human walking speed. Regarding the routing protocol to be used in this network, we exploit the first-contact protocol from the ONE simulator, routing only a single copy of data to simulate the real-time ad-hoc data transmission in a discrete manner. Similarly, as all nodes have been configured with random mobility, a geographically fixed control center will not exist. Therefore, it is not necessary to have one single destination in the network for the data collection scenario, as long as the messages are unicast-based. Fig.9 shows simulation results on the delivery ratio of data transmission in a pure WSN, a WSN with infrastructure nodes and the one with both infrastructure and crew nodes support. We can see that the higher node density, the higher delivery probability for all three networks. But if the node density is low, which represents the connectivity challenges aboard ships, roles played by communication infrastructures and the crew nodes are apparent.

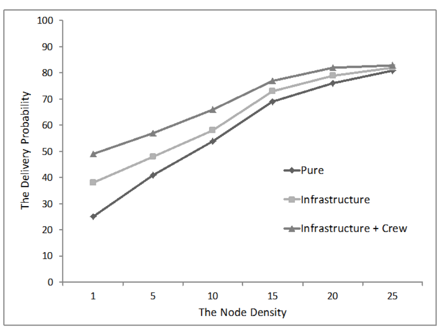

Fig. 9. For the Basic Sensor Network Scenario.

Case 2 is for the personnel monitoring. A traditional personnel monitoring system that uses RFID tags and PDA readers can be considered as a mobile network with low involvement of communication infrastructures. Personnel's coordinates are only available when they pass places where tag readers are installed. As the fast development of modern smartphones, e.g., being conjunction with RFID devices, future personnel tracking will be able to use personal devices directly. It is also possible for a future on-board personnel monitoring system to be integrated with other data networks due to the simultaneous location and data transmission capability of modern ubiquitous technologies. We can simulate the future integrated personnel monitoring system as the network having a much higher node density; data can be routed in an epidemic manner under critical conditions and message copies are reduced in a normal tracking case. Senders and receivers are personnel nodes which have higher moving speeds but an overall lower density, compared with message senders and receivers in case 1, but the density of the relay nodes is much higher. From

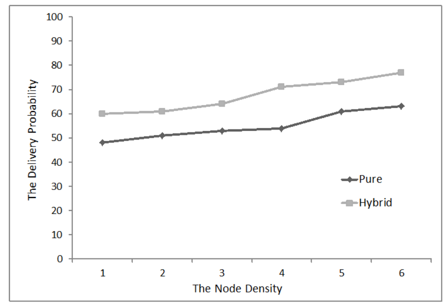

Fig. 10. For the Personnel Monitoring Scenario.

the simulation results shown in Fig.10, we see that a future hybrid personnel tracking system behaves better than a pure one in terms of successful message delivery upon different node density settings.

Case 3 simulates a situation where direct communication among the crew or passengers are required. Direct communication can happen frequently in the daily life for an entertainment purpose. It is useful for the personnel tracking, and it can be very critical in emergency situations. Therefore, it will be necessary for the on-board network to enable direct communications, supported by a DTN networking feature. A traditional on-board network without a DTN networking support will not function well if the communication infrastructures are damaged, which can be simulated by only a direct-delivery routing protocol being available. The hybrid DTN-based network can be treated as supporting a flooding-based routing mechanism, e.g., the spray-and-wait routing protocol. Results shown in Fig.11 tell us that if the node density is high, such as in passenger ships, an on-board network with the DTN networking feature will function better for direct communication situations.

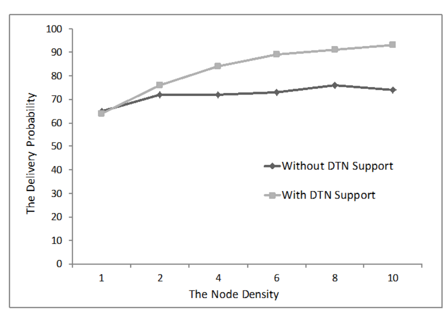

Fig. 11. For Direct Communication and Emergencies.

VI. Conclusion and Future work

In this paper, we explained the reasons for applying ubiquitous technology particularly the wireless sensor network to a ship environment and the challenges of doing so. A hybrid on-board network which consists of diverse communication systems was introduced to address the challenges and to handle emergency situations. We investigated different means of integrating wireless sensor networks with the TCP/IP world due to its popularity. From thorough analysis, we suggested a gradual integration roadmap for the ship application, based on a combination of three popular methods, using DTN overlay architecture as a transitional step to achieve the final seamless integration. We also implemented simulation to prove that the hybrid network can provide better communication performance and increased reliability than separate systems, when faced with connectivity challenges or infrastructure damages. However, future testing and implementation are needed especially in following directions:

- Develop DTN applications for maritime scenarios, such as data collection within on-board WSNs, smartphone-based personnel tracking and direct communication among crew and passengers
- Provide a common standard middleware layer to facilitate the communication between different DTN applications and the underlying data transmission, to further enable future application development

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