TRITON: High Speed Maritime Mesh Networks

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Abstract—This paper details a novel approach of developing a low-cost and high speed maritime ship-to-ship/shore mesh network to complement or replace satellite communications in narrow water channels or traffic lanes close to shorelines. To design the system, we gathered requirements from typical users of the system. We then carried out preliminary studies such as radio channel propagation over sea water, ship movement patterns, ship rocking and its effect on radio transmission and network connectivity to determine the feasibility of using a mesh network for maritime networks. We present the architecture and detail some of our routing and scheduling design considerations that address the unique challenges of the maritime environment and provide us with framework for providing fair and equal opportunity access to users.

Keywords: High speed maritime mesh networks, Ship-to-ship communications, routing, Wimax mesh.

I. INTRODUCTION

The radio station installed onboard a ship for communications over water depends on the size, purpose or destination of a ship and is mandated by IMO and ITU. Current maritime systems rely on analogue UHF and VHF radios and satellite communications for short and long-range ship-to-shore communications. In some parts of the world such as Norway, proprietary solution based on digital VHF has been devised [1] and rolled out along the whole Norwegian coast to cover distances up to 72 nautical miles with data rates of up to 133 kbps. Other solutions based on point-to-multipoint WIMAX networks for short range coastal coverage up to 20 km have been introduced in Norway and Singapore [2]. However, these networks cover one-hop transmissions only. Current satellite systems such as INMARSAT GAN system provides only up to 64 kbps of data bandwidth per-link. This value drops when there is sharing between nodes. The cost of satellite link is in the region of US$20,000 plus service charges. The future INMARSAT BGAN system is expected to provide about 432 kbps data bandwidth. However, bandwidth in each pipe is limited to 432 kbps per narrow spot beam, which is typically 800 km in diameter. Although some bandwidth stealing is possible by overlapping narrow beam spots, bandwidths are still insufficient to rival land-based broadband wireless access. The cost of satellite bandwidth is still expected to remain high due to the cost of launching satellites into orbit and also due to the antenna stabilizers. Other systems based on hybrid satellite and DVB system such as that introduced by ESA [3] also tries to address broadband access to Maritime users. However, this solution is also expensive as it requires a TVRO antenna. Due to the current state of the Maritime networks, we propose to develop a novel Maritime mesh communication infrastructure that is able to provide high bandwidth and acceptable QoS levels to enable a multitude of new high speed applications. The research activity is covered under a project known as TRITON.

The proposed high level architecture of TRITON is illustrated and described in [4]. To realise the mesh radio, we are using the IEEE 802.16 mesh and IEEE 802.16e standards.

Figure 1. Real time ship locations and traffic lanes close to shorelines.

We have also considered the viability of the system from an economical standpoint. A cooperative behavior among nodes is critical to the success of this mesh system. Besides this, the users will only adopt the system if the network provides access at most of the locations visited by the ships. Hence, the success of the network will depend on the ship density and penetration rates of the device. Figure 1 shows an online real-time ship location tracking service [5]. The figure essentially outlines key shipping routes used by the ships worldwide. In Figure 1, we have also highlighted the key areas that could benefit from this mesh system. These are potential areas that have high density of ships and shipping routes that are close to the shoreline. Having more base stations...
installed along these routes could motivate the shippers traveling along these routes to adopt the system. In the next section, we discuss some of the user requirements that have motivated our solution and design approaches.

II. USER REQUIREMENTS

In the early phase of the project, we approached a variety of users in Singapore to gather inputs on user requirements. Users ranged from small to large organizations, either operating in Singapore, regionally or globally. The users include ocean going vessels, local ferry operators, oil drilling companies with equipment and passenger transport vessels, port water barge operators and the local police coast guards. Although not exhaustive, the key requirements and observations that we have gathered are summarized as follows:

A. Need for low cost communication

This requirement and high bandwidth requirement were the most common and compelling needs cited by all users. We felt that these requirements strongly motivates the need to improve the maritime communications networks. Current trans-oceanic ships spend typically about US$300 to US$2000 per month on satellite cost. In addition to this, these ships spend extra IT cost to purchase software that compresses data files that are sent via the satellite link to reduce the overall usage cost. In most cases, the crews on these ocean going vessels are also restricted from using the satellite links to call back to their loved ones. Normally, ocean going vessels belonging to large conglomerates can afford to purchase expensive satellite equipments. However, for some of the ferry operators with smaller crafts operating around Singapore waters, their profit margins are too small to justify buying and using expensive satellite equipment.

B. Need for high bandwidth networks

High bandwidth applications such as large file transfers, video conferencing and high-speed Internet access are difficult to implement currently. Ocean going vessels have often cited the need for bandwidths to support downloads of infotainment files for crew members and up-to-date navigational charts that are critical for navigating safely in treacherous waters. Due to cost issues, some ships are currently using alternatives means, such as paper charts or preloaded data to address the navigational requirement. The general shipping industry is also facing staffing issues due to working conditions and competition from other sectors. In order to retain staffs, companies are finding ways to improve communication, online training and entertainment for crew members. For the police coast guard, a general high bandwidth network to enable multimedia situational awareness using high speed wireless networks to address the problem of piracy, intrusion, traffic management and disaster in Singapore port waters and straits is crucial. To increase situational awareness, the boats would require access to video surveillance cameras mounted in strategic locations around Singapore shorelines, vessels and beacons at sea. In addition to this, the coast guards would require access to information from the maritime authority’s vessel traffic management systems. The requirements for the Oil and Gas companies are slightly different as the requirements for high speed communication is meant for linking their supply ships, floating platform, Oil and gas installations, etc. when the nodes are in the vicinity of each other. Typical application ranges from operational data downloads, video and voice conferencing, infotainment uploads, etc.

C. High speed communication up to 100 km away from port.

Coverage is also cited as an important criterion for most of the users. For ocean going vessels calling at the port of Singapore, most of the current online transactions activities such as port manifest clearance, berthing and unloading information, etc. are sent when the ship is about 100 to 150 kilometers away from the port. As such, a practical network should also cover distances at which, important and regular access to the network is required. As for ferry operators operating in Singapore, coverage requirements spans to the distant islands off Singapore. This imposes some challenges as some of these islands frequented by the ferries do not have alternative networks that are cheap and reliable. In addition to this, the Maritime Authority and the Immigration Agency are looking at methods to improve manifest clearance and travel document scanning, well in advance before the ferry arrives at Singapore.

D. Secure delivery of data

For almost all of the users, security was cited as a major concern but was secondary to cost and bandwidth. For the police coast guard, a proprietary ad hoc network or a dedicated frequency channel for carrying the data securely is desired. In this manner, their operational functions can be made more reliable, the network is less susceptible to denial of service attacks and sensitive data is not routed via non-trusted devices. For the ocean going vessels and ferry operators, relaying of sensitive company related data using other ships was also a concern. However, these two users are satisfied if a virtual private network type of service is available to ensure end-to-end secure data transmission.

III. CONNECTIVITY ANALYSIS

The user requirements described earlier have motivated us to design a cost efficient and high speed multi-hop wireless mesh network for maritime
communications. While undertaking the design, we first establish the feasibility of forming such a wireless mesh network amongst ships that travel through a certain geographical region, before focusing on networking issues for efficient and fair bandwidth utilization and achieving high speed.

Figure 2. Geographical region from where actual ship mobility traces are obtained for feasibility study.

A maritime wireless mesh network is feasible if 90% of the ships can be connected to the land station 90% of the times, where a ship is considered connected if it has at least one single-hop or multi-hop route to the land station. While forming a route, two nodes are considered connected if they are within the radio range of each other. We have studied the actual ship mobility traces for the region illustrated in Figure 2, which is off Singapore East Coast [6]. Such a network is feasible when radio range between land station and ship is at least 15 km and radio range between ships is at least 8 km. For a feasible network, there are always multiple candidate routes between a ship and the land station, and the average path length of the candidate routes is about 1.8 hops. This feasibility has been confirmed for the specific region with only 2 days worth of mobility traces. To confirm the network feasibility for a more general setting, we have derived a ship mobility model from the actual mobility traces.

In Figure 2, there are two separate shipping lanes for ship heading towards east and west, respectively. Based on the actual ship mobility traces, we found that there is no obvious difference in the mobility patterns between the two directions [4]. Also, the ship mobility pattern does not change with respect to the time of day [4]. The ship mobility pattern for each direction can be described in terms of inter-arrival time of a new ship into the region, and the speed of the new ship, where a ship is assumed to travel at a constant speed after entering the region. From the mobility traces, the probability density function for ship speed \( s \) is determined as follows:

\[
p(t) = a \times b^t,
\]

where both \( a \) and \( b \) are arbitrary factors. For westbound ships, \( a = 0.292064 \) and \( b = 0.998286 \). For eastbound ships, \( a = 0.284495 \) and \( b = 0.998324 \).

IV. PATH LOSS MEASUREMENT

In [7] and [8], we have carried out a series of experiments to investigate the large-scale path loss measurements at 5.8 GHz and performance measurement of WiMAX in the 5.8 GHz band. These investigations are useful because it allows us to understand the feasibility of deploying IEEE 802.16 based radios for the maritime mesh network. From our studies, we discovered that the two-ray model fits measured large scale path loss reasonably well when Line Of Sight (LOS) is dominant. Because the sea surface at 5.8 GHz satisfies a good conductor condition, the two ray model fits closely with the measured data and fully explains the propagation characteristics observed. The path loss exponent and standard deviations for transmission between average 8 meter height ships are 2.16 and 4.69, respectively [7]. We believe that mesh links using WiMAX radios are feasible because the general propagation follows a two-ray model with path loss exponents close to those applicable to urban and rural areas. In designing the mesh network, we also realize the need for a networking layer that helps repair routes when there is significant drop in received signal strength due blockage or nulls.

V. MARITIME SIMULATOR

To fully understand and help us design the networking protocols, we developed a framework for simulating wireless communications in the ocean environment. The framework incorporates features such as wave motion and its effect on wireless transmissions, wave occlusion with varying sea states, the ocean surface path loss characteristics, the mobility pattern of the ships and the 802.16 mesh MAC protocol [9].

VI. SCHEDULING AND ROUTING DESIGN

By using the ship mobility model described above, we have simulated a wireless mesh network using a generic network topology as illustrated in Figure 3. In the simulation, shortest routes are formed between ship and land station using Dijkstra’s algorithm. From the simulation of 1 year time period, we have confirmed the feasibility when radio range between land station and ship is 30 km and radio range between ships is at 10 km.
Given the bigger geographical region in this general setting compared to Figure 2, the average length (hop count) for a route becomes larger and depends on \( x \), which is half of the topology width. As given in Figure 4, the average hop count of a route becomes larger when the channel quality \( p \) is poorer, where \( p \) is the probability of successful transmission over a link between two nodes. In a realistic environment, not all the ships within the region participate in forming the network. Figure 5 shows that the average hop count of a route becomes larger when the participation rate \( q \) is lower, where \( q \) indicates the fraction of all ships that becomes part of the network.

With the feasibility confirmed, we have considered the networking issues. We have adopted WiMAX mesh standard as the basic technology for its long radio range compared to Wi-Fi, and its TDMA based MAC protocol. Compared to a contention based random access MAC protocol, WiMAX mesh MAC protocol offers more efficient bandwidth utilization through time slot allocation or scheduling. In WiMAX mesh standard, three types of scheduling mechanisms have been defined, namely coordinated centralized scheduling, coordinated distributed scheduling, and uncoordinated distributed scheduling. Amongst the three mechanisms, we have adopted coordinated distributed scheduling for its ability in allocating time slots in a distributed manner directly among neighboring nodes without involving the land station. This reduces the control overheads since scheduling outcomes need not travel across multiple hops. These control messages are transmitted in the control time slots of the control sub-frame, where each periodic WiMAX mesh MAC frame is divided into a control sub-frame and a data sub-frame.

In the coordinated distributed scheduling, a node that wants to transmit a data packet must first send a request in a control time slot to the intended receiver node. Upon receiving the request, the receiver node performs scheduling (time slot allocation) to allocate the first available data time slots to the request. The outcome of this time slot allocation is transmitted in a control time slot to the sender node in the form of a grant. Upon receiving the grant, the sender node must locally check to confirm that the allocated time slot is available for it to transmit. If the checking is positive, the sender node transmits in a control slot a grant confirmation message. The sender node will start transmitting its data packet in the allocated time slot only after transmitting the grant confirmation. This process of exchanging request, grant and confirmation messages is called the three-way handshaking. Recall that the grant carries the outcome of scheduling performed at the receiver node. In the scheduling, receiver node allocates a time slot only if none of its 2-hop neighbors transmit or receive in the same time slot. Similarly, the sender node issues a grant confirmation only if the allocated time slot is not used by its 2-hop neighbors for transmitting or receiving. This scheduling approach should work well without collision in data time slots in an ideal environment. However, in a more realistic condition, the scheduling approach may result in collision in data time slots. More specifically, collision can occur in the following cases: (1) The actual interference range is more than two hops, (2) Control messages are not correctly received by 2-hop neighbors, (3) A time slot that has been allocated by a node is being allocated by another neighboring node before this neighboring node overhears the grant or confirmation messages due to a time lag in sending control message, and (4) Nodes that are not within 2-hop neighborhood of each other and have been allocated a same time slot, are
now moving within each other’s 2-hop neighborhood. In view of the scheduling problems in a realistic condition, we have proposed adaptive time slot allocation scheme to take into consideration extended interference range, node mobility and loss of control messages.

In addition to scheduling algorithm, routing protocol is an important networking issue in a maritime wireless mesh network. We have compared the performance of several routing protocols in a maritime WiMAX mesh network [10]. Specifically, we compare the performance of OLSR, AODV and AOMDV. We choose OLSR and AODV because they are respectively the proactive and reactive routing protocols developed by the IETF MANET Chapter. AOMDV is chosen because it is an improvement to AODV with capability of identifying multiple paths in a single route discovery process. The additional paths can be used as backup paths where backup routing has been shown useful in improving packet delivery ratio.

OLSR has the lowest initial packet delay, and this may due to its proactive nature. However, OLSR is not as good as AODV and AOMDV in all other performance metrics which include packet delay, and packet delivery ratio. Especially, OLSR has a much higher routing overhead and its performance is highly affected by changing sea condition. Thus, OLSR is not a suitable routing protocol for a maritime communication network. AODV has a lower initial packet delay compared to AOMDV. However, AODV is not as good as AOMDV in terms of routing control overhead and packet delay. Also, AODV is not as robust as that of AOMDV against higher sea state. The more robust and efficient performance of AOMDV is due to its capability in setting up multiple routes in a single route discovery process, and ability to switch to backup route when the current route is broken.

Figure 6 compares performance of our proposed routing protocol (labeled as “triton”) against OLSR, AODV and AOMDV. From the figure, it is clear that the proposed routing protocol can deliver better throughput consistently in different sea states where a higher sea state indicates tougher sea condition. In the figure, ssy means sea state y and the x-axis is the node (ship) ID. For the five ships, their throughput is consistent and similar under different sea conditions with our routing protocol as compared to larger throughput variation with other routing protocols. This may imply that our routing protocol is more fair compared to other routing protocols.

VII. CONCLUSION

In this paper, we describe the requirements of typical maritime users and our approach in studying and evaluating viability, and systematically designing the maritime mesh network. The project is currently in progress as we are in the final stages of developing the mesh radio with the protocols that we have designed.

REFERENCES


Figure 6. Comparison of end-to-end through from nodes (ships) to land station.

None of the three routing protocols studied are ideal for maritime wireless mesh networks. This has motivated us to design a new routing protocol. We have proposed a proactive routing protocol that uses WiMAX mesh MAC control messages to propagate routing information from the land station to the ships. This proactiveness is achieved without much control overhead compared to OLSR because additional routing messages are piggybacked on existing MAC control messages. With such a proactive propagation of routing information from the land station, multiple routes are readily available in a tree structure. As such, a newly arrived node can join the network immediately, and this reduces the initial packet delay. Also, alternative routes are available as backup for route switching when an existing link is broken, and this increases the network robustness.