Robot Local Network Using TQS Protocol for Land-to-Underwater Communications

Addie Irawan, Mohammad Fadhil Abas, and Nurulfadzilah Hasan

Faculty of Electrical and Electronics Engineering, Universiti Malaysia Pahang, Pekan, Malaysia

1. Introduction

Heterogeneous robot communication or multirobot networking is conducted mainly via the Internet. There are many issues related to establishing robot local networks (RLN) for collaboration purposes, and they need to be resolved in order to achieve specific objectives, with a particular emphasis placed on dependability, safety and security of the system. To enable collaboration between robots, two elements need to be defined, i.e. the communication protocol and the collaborative procedures. Undoubtedly, an efficient protocol is essential for effective decentralization of the distribution of data between the robots.

Researchers have taken several approaches to improve communication between heterogeneous robots. Some of them rely on the communication protocol, while others use the intelligent control technique to improve the performance of the system. There is also a hybrid approach which combines both these techniques. Stamatescu et al. described the communication protocol by applying the cognitive radio (CR) scheme, i.e. by exploiting the time, frequency and spatial stream of the wireless environment. According to the testing results, they claimed that the communication reliability at each hierarchical level increased [1].

Another approach consists in applying a formal taxonomy to the allocation of tasks to a mobile robot, as proposed by Gerkey and Mataric [2]. This method is further improved by Korsah et al. with their proposed iTax, a taxonomy addressing interrelated utilities and constraints via a combination of optimization methods and operation research. This method is based on the recognition that the key distinguishing factor between different types of multirobot task allocation (MRTA) problems is the degree of interdependence of agent-task utilities [3].

Adaptation of intelligent systems is also becoming an approach that is favored in multirobot collaborative control and communication. Zhang et al. applied an adaptive fuzzy logic in tackling MRTA reliance on the intuitionistic fuzzy set theory [4]. Similarly, Cheng et al. proposed a linear temporal logic (LTL) which optimizes path planning by using the formation control feedback mechanism [5]. Power is another constraint that needs to be considered while establishing a collaborative robotic system. Moreover, there is a tradeoff between the number of nodes that can be deployed in the mission and the density of information that can be exchanged. Bano et al. in [6] explored these constraints and proposed a random waypoint mobility model in a mobile ad-hoc network (MANET). This system was tested with a robot group comprising 5–6 collaborating robotic nodes and the results showed that it was better than the Manhattan mobility model. MANET is also implemented by Kulla et al. for a real-time emergency scenario of moving the multirobot (nodes) indoor [7]. Bandwidth sharing is also possible for an MRTA communication system using resource controller (RC) and aggregate resource controller (ARC) management techniques [8].

Classification and aggregation also offers a vast potential that may be explored in robot-to-robot or human-to-robot communication, and mainly in enhancing reliability per-

https://doi.org/10.26636/jtit.2019.125818
formance and in ensuring priority for different types of data exchanged over the Internet. Automation and robotics place a greater emphasis on the physical layers, with real-time data and control area network (CAN) serving as the primary platform. A virtual private network is available in the Internet protocol (IP) version, such as the virtual private network (VPN) used for long distance and indoor remotely controlled mobile robots [9], [10]. However, the problem is still an issue in the case of communication between mobile robots (swarm scenario).

The present research proposes the application of tag switching inspired by multiprotocol label switching (MPLS) [11], as a data carrying technique for an RLN operating in a different environment. A modular network tested in C++ (OMNeT++) [12], i.e. a discrete event simulator, was used to develop a logical RLN model to perform a case study focusing on multirobot communication in a different environment. The nodes in the RLN were programmed with the Tag QoS switching (TQS) protocol proposed, and were considered to be robots (moving nodes). Data forwarding performance, expressed as the percentage of packets lost, average edge-to-edge access delays, as well as throughput, was verified by comparing one line of transmission between the edges of robots in a different environment.


2.1. Case Study Involving Land-to-underwater Communication

For the case of multirobot communication involving different environments, e.g. in the land-to-underwater scenario, the robots may be flying in the air, may be submerged under water or may be placed on the ground, as shown in Fig. 1. Underwater communications have limitations in terms of distance and bandwidth. For example, optical wave transmission requires high precision in pointing narrow laser beams and is affected by scattering, although is resistant to high attenuations [13]. On the other hand, electromagnetic waves are also limited to short distance with the highest frequency at about 2.4 GHz for 250 Kbps, according to the IEEE 802.15.4 standards [14]. Alternatively, data signal may be also propagated in conductive salty water by using radio frequency (RF), but only at extra-low frequencies (30–300 Hz) that may require large antennas and high transmission power [15]. Several attempts have been made to enhance the speed and throughput of transmission, such as a routing technique relying on the surface of the water for underwater communications [16], as well as using the water surface relay to increase the overall transmission speed [17].

Therefore, this study investigates and analyzes data forwarding and switching/routing performance for the land-to-underwater communication scenario, using the proposed TQS protocol. It emphasizes the RLN topology in which robots are considered to be dynamic nodes of the switches, or routers for data transceivers. This study neglects all salt- and tide-related factors, as well as noise present in both mediums. The analysis focuses on logical data transmission implications and on the dynamic changes in data transmission rates experienced when the packet of data enters the water using the proposed protocol. Moreover, the focus is placed mainly on data the forwarding period and on traffic management. Some of the switching/router models were programmed to operate at low data transmission rates (10–100 Kbps) to represent nodes in the underwater environment, while others were programmed for speeds of up to 1 Gbps to represent nodes on land/in the air.

2.2. Tag-QoS Switching Protocol

The TQS protocol is suited for a network topology with dynamic nodes, such as RLN, as it is inspired by MPLS. MPLS was released by Cisco System in 1998 and started to gain popularity in IP deployment for wide area networks (WAN) and metropolitan area networks (MAN) [18], [19] in 2000. MPLS allows tunnel routing known as label switched paths (LSP), where a tunnel is characterized by a path in the network and by a reserved bandwidth [20], [21]. This protocol belongs to layer 2.5 in the open systems interconnection (OSI) model [22]. It improves both layers 2 and 3 by providing fast switching and reliable routing. Moreover, this protocol is bonded to an IP network as an extra header that involves the Internet service provider (ISP) area [23], [24]. However, the dynamic tagging and stacking methods used in MPLS have the potential to be deployed in a small-scale local network and data communication scheme, such as RLN shown in Fig. 1. The label swapping concept in MPLS [25] enables dynamic establishment of tunnels that depends on traffic demand. The tunnels are opened based on aggregation, classification and prioritization of communication between peer robots. MPLS also enables network virtualization through the labeling or tagging method, in order to create virtual and physical layers [26] that leverage the implementation of energy-aware traffic engineering [27].

The TQS protocol proposed is applied in the same manner as the MPLS label stack entry (LSE) shown in Fig. 2, but with specific label value calculations which involve both the

![Fig. 1. Example of a heterogeneous RLN topology for land-to-underwater communications.](image-url)
indication of the LSP and the differential service (DiServ).
The calculation also includes a flow aggregate that requires
network traffic to be marked and conditioned at the edges
of the network, ensuring a different treatment for each of
the tagged packets. The label value in TQS-LSE is:

\[
L = [\alpha(N+1)] + P ,
\]

where \(\alpha\) is the definite positive gain used for simple indication
and for reducing conflicts in the tagging process. \(N = 1, 2, \ldots, n\)
is an LSP identification number, expressed as an integer, which represents the type of incoming data
e.g. video or voice streaming. \(P = 0, 1, 2, \ldots, n\) is denoted
as a sub-LSP identification number for the bandwidth that
is generated by the packet index at the edge of the node
\(I\) when the number of channels for the \(P\) group of band-
widths satisfies the condition \(I > D - 1\). The \(P\) value can
be obtained from:

\[
P = \begin{cases} 
P = 0 & I > D - 1 \\
P = I & D \leq D - 1 \end{cases}
\]

As far as RFC 3270 is concerned, the experimental bits
(EXP), renamed as traffic class (TC) bits [28], are used
to encode and aggregate all per-hop behavior (PHB) bits
from the data header to LSE [29]. In addition to that, three
behaviors aggregating bits (BA) were used to encode with
the DiServ code point (DSCP) from the data header [30].
DSCP defines drop precedence in each type of class of
services (CoS) for each data packet. MPLS-QoS encoding
provides inferring CoS and drops precedence information
from the data header to LSE. The bottom of stack (S) bit
for the last entry of the label stack indicator and time-to-
live (TTL) bits, as shown in Fig. 2, are the standard bit in
the MPLS format, as defined in RFC3032 [11].

### 2.3. RLN Topology Model with TQS Protocol

For modeling and simulations relying on the proposed pro-
tocol, the nodes of switches/routers (robots) were catego-
rized into two sections: tag edge mobile robot (TER) and
tag switching robot (TSR). These switches/routers are the
primary entities in RLN acting as transceivers for edges
and switching, respectively, according to the TQS proto-
col data forwarding. As shown in Fig. 3, for simulation
and analysis purposes, the RLN was modeled with several
TERs and TSRs in OMNeT++. Here, the TER module was
programmed to generate a raw/unlabeled data packet. The
system consists of three sub-elements which are catego-
rized as wire switch module (WSM), buffer switch module
(BSM), and bandwidth switch module (BandSM), as pic-
tured in Fig. 4. The usage of WSM in the TER module is
the main feature that differentiates it from the TSR (Fig. 5).
The switching process is applied when the label was
swapped in the TSR instead of WSM, as shown in Fig. 6.
The incoming tagged packets are buffered and then passed
to the tag switching module (TSM) to swap the tag or
label for the next hop bandwidth in BandSM. The swap
process depends on the information label map (ILM) that
has been programmed in the forwarding information table
(FIT) of TSR (Fig. 6). Label value will always be swapped
or replaced with a different number for the next hop band-
width. The same goes for TTL as S bit values, they are
also continuously updated. On the other hand, the informa-
tion about bandwidth assignment is extracted in BandSM
from the inverse calculation of Eq. (1) to get the informa-
tion about the LSP and sub-LSP switched to the next
hop of peer robot/node. BandSM, either in TER or TSR,
is programmed to control the per-flow threshold according
to the proposed bandwidth assignment scheme (BandAS),
as presented in Table 1. The peak data rate (PDR) for
premium/expedited forwarding CoS, or the committed data
rate (CDR) for Olympic/assured forwarding CoS will dis-
card the incoming data packets whenever the threshold is
reached.

For the TER model, the process of forwarding the equiva-
 lent class (FEC) [11] to the next hop label forwarding entry
(FTN) is applied in WSM as a labeling process, whereby
the untagged data packet destination address is screened
for the labeling process (Fig. 7). Initially, the data are gene-
rated with source address bits, destination/group address bits
and hop limit values that are the same as those of packet
data with the IP address. Moreover, the DSCP code in the
generated packet data was aggregated to request the FEC
code from the programmed FIT. Then, the label value with
L bits (here 10 bits) was obtained (Fig. 7). The hop limit
value and the DSCP code were then encoded to the TTL.
Addie Irawan, Mohammad Fadhil Abas, and Nurulfadzilah Hasan

**Fig. 4.** TER model system engine with the TQS protocol proposed.

**Fig. 5.** TSR model system engine with the TQS protocol proposed.

**Fig. 6.** Swapping process in BandSM.

<table>
<thead>
<tr>
<th>Class of services</th>
<th>Channel bit rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Premium</td>
<td>100% maximum bandwidth</td>
</tr>
<tr>
<td>Olympic</td>
<td></td>
</tr>
<tr>
<td>Gold</td>
<td>80% maximum bandwidth</td>
</tr>
<tr>
<td>Silver</td>
<td>60% maximum bandwidth</td>
</tr>
<tr>
<td>Bronze</td>
<td>40% maximum bandwidth</td>
</tr>
<tr>
<td>Best effort</td>
<td></td>
</tr>
</tbody>
</table>

**Table 1**

Bandwidth assignment scheme (BandAS)

field and TC bits, respectively, using the MPLS-QoS [29] encoding method. The CoS for the applied QoS is determined according to the RFC 2597 draft, in which gold, silver, and bronze CoS of the Olympic CoS are applied [31].

**Fig. 7.** FTN process for an unlabeled data packet in TM inside the TER model.
The drop precedence process is also conducted differently for all sub-CoS in the Olympic CoS. Hence, the channel bit rate was defined differently for the sub-CoS of the Olympic CoS in BandAS, as shown in Table 1. Gold CoS was the lowest drop precedence, and bronze CoS was the highest. With reference to the MPLS-QoS queuing process [29], as well as RFC2597, WSM in each TER and BandSM in TSR was programmed to perform marking through the labeling process on the untagged data packet. Data packet with low drop precedence was marked as a low priority packet to be discarded instead of the data packet with high drop precedence in BSM.

Table 2

<table>
<thead>
<tr>
<th>Buffer</th>
<th>Capacity (buffer length)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B0</td>
<td>20% × maximum buffer length</td>
</tr>
<tr>
<td>B1</td>
<td>40% × maximum buffer length</td>
</tr>
<tr>
<td>B2</td>
<td>Maximum buffer length</td>
</tr>
</tbody>
</table>

This first select-and-drop process (before BandAS) occurred when the number of packets in the allocated buffer reached its threshold limit, as allocated in Table 2, concerning the simple buffer assignment scheme [32]. The TC bit, as shown in Fig. 2, is an indicator for allocating the data to the particular buffer channel. The first-in-first-out (FIFO) principle was used in the BMS queuing process, where B0 and B2 for each TER/TSR were programmed to use the tail drop procedure, and B1 was programmed to use the random early detection (RED) procedure [33], mainly for Olympic CoS.

3. Simulation and Performance Analysis

Simulation and analysis of the RLN model were conducted and set up with the proposed TQS protocol, as shown in Fig. 3. The setup protocol was considered done in this simulation study, and all nodes were established with the least cost routing. The analysis relied on the same QoS class assessment program used in the model as applied in BandAS: premium, Olympic and best effort CoS. The analysis was performed by determining T1 as a focus line for performance evaluation, with other lines serving as disturbances for T1, as shown in Fig. 8. Moreover, TER1, TER2, TER3 and TER4 were modeled with proper underwater acoustic conditions, where the data rate for receiving/transmitting data packets equaled between 10 and 100 kbps. On the other hand, the TSR models were assumed to be positioned on the surface of the water as floating nodes that provided a link between TERs in the air/land and under water. Communication between TSRs was modeled using ad-hoc communications, with arrows appearing when a link exists between individual peer nodes.

![Fig. 8. Analysis notification for simulation purposes and analysis in the modeled RLN.](image)

![Fig. 9. Average access delay versus total of data packet streaming on T1.](image)

![Fig. 10. Throughput versus percentage of data packet loss on T1.](image)

The results for T1 data forwarding performance are presented in Figs. 9–12, with the data packet size randomly generated between 250 bytes and 1.5 Kbytes per packet. The results show a different performance of network parameters for different CoS: premium CoS (Pre), best effort (BE), and Olympic CoS members, namely gold CoS (Gld),

---

JOURNAL OF TELECOMMUNICATIONS AND INFORMATION TECHNOLOGY

1/2019
silver (Silv) and bronze CoS (Brnz). Overall, Pre is the leader in terms of the performance of the majority of parameters.

Figure 9 shows that the average access delay for Pre was the lowest among all forwarding CoS, even though the BandAS channel bitrate was the same as that of the Gld channel, as shown in Table 1. Generally, the percentage of BE forwarding losses was the highest, whereas Pre forwarding was the lowest in both forwarding states (request and reply). This makes the throughputs for Pre CoS the highest for T1 communication, as illustrated in Fig. 10. In this simulation, other TERs were run to communicate with each other through the shortest path TSRs to provide traffic disturbance (to make the traffic randomly busy).

![Figure 11. Data packet loss percentage versus total data streamed on T1.](image)

As far as the data packet loss percentage rate is concerned, Olympic CoS and Pre show similar growth trends and are shown in Fig. 11. BE shows the highest rate of data packet loss compared to other scenarios. The results are most evident when the overall data streaming rate on T1 was between 5000 and 20,000 KB. In this case, the loss percentage rate for BE is by about 61% higher than in the case of other CoS forwarding methods. Before a loss occurs (total of data streaming rate < 35000 KB), access delay of Pre forwarding was by about 10% lower than in each of Olympic CoS forwarding members, and by almost 100% lower than in the default forwarding or BE. The differences in the performance of individual CoS, with increasing data forwarding rates in T1, are shown in Figs. 9 and 11.

As far as the comparison between access delay and data packet loss, as shown in Fig. 12 is concerned, BE forwarding shows a considerable decrease, as data packet loss rate approaches 100%. However, the average access delay of Pre forwarding is still the lowest and within the acceptable range as the value continues to drop with the increasing data packet loss. Similar results can be observed in the case of Olympic CoS members, where the performance of Gld data forwarding, in terms of access delay, was the best compared to Silv and Brnz, when the data packet loss rate increased. The results show that both Pre and Olympic CoS have minimal differences in data distribution and switching (Fig. 12). The throughputs to BE CoS forwarding started to decrease when the overall data streaming rate on T1 increased to more than 300,000 KB.

4. Conclusion

The proposed TQS protocol in RLN was modeled and verified. The priority control via CoS was presented, with prioritization in data routing and switching deployed to achieve different performance outcomes. Pre shows the ability to control the average access delay, although the data packet loss decreased with the increase of the volume of data, since it is the highest priority CoS as far as minor access delay, high throughput, and small data packet loss are concerned. Such a prioritization excludes the factor of different mediums used. Pre and Gld show good reliability for video and voice data forwarding, with the ability to control the number of data packets lost and to achieve a low average access delay, even though the network traffic is busy with handling the number of data packets that increases along with simulation time. The research will continue with the implementation of the proposed TQS protocol in swarm robot RLNs.

Acknowledgment

This study and research project is funded under the Universiti Malaysia Pahang (UMP) Research Grant for the Centre for Earth Resources Research & Management (CERRM) of UMP (RDU140351).

References

Addie Irawan, Mohammad Fadhil Abas, and Nurulfadzilah Hasan

and big data distributions. He is a Professional Engineer of the Board of Engineers Malaysia (BEM), a Charted Engineer and a Charted Marine Engineer under the British Engineering Council via the Institute of Marine Engineering Science and Technology (IMarEST), as well as a Senior Member of the Institute of Electrical and Electronics Engineers (IEEE).
E-mail: addieirawan@ump.edu.my
Robotics and Unmanned Systems (RUS) research group
Faculty of Electrical and Electronics Engineering
Universiti Malaysia Pahang
26600 Pekan, Pahang, Malaysia

Mohammad Fadhil Abas received his B.Sc. in Electric, Electronic and Computer Systems from Universiti Kebangsaan Malaysia, Malaysia in 2002, his M.Sc. in Power Electronics from University Putra Malaysia, Malaysia in 2005 and his Ph.D. in Artificial Science from Chiba University, Japan in 2013. Since 2004 he has been working at Universiti Malaysia Pahang (UMP), as a Senior Lecturer at the Faculty of Electrical and Electronic Engineering. In his work, he focuses mainly on the following areas: instrumentation, human-computer interface, human-robot interface, unmanned systems, automation, vision systems for robotics and control systems.
E-mail: mfadhil@ump.edu.my
Robotics and Unmanned Systems (RUS) research group
Faculty of Electrical and Electronics Engineering
Universiti Malaysia Pahang
26600 Pekan, Pahang, Malaysia

Nurulfadzilah Hasan received her B.Sc. degree in Computer Engineering from Universiti Teknologi Malaysia in 2003. She received her M.Sc. degree in Electrical Engineering from the same university in 2005. She has been working as a lecturer at Universiti Malaysia Pahang since 2006, where she has been involved in several research projects and has published numerous research papers. Her research areas include antenna design, wireless communications and computer engineering. Presently, she is pursuing her Ph.D. in antenna design at Universiti Malaysia Pahang.
E-mail: nurulfadzilah@ump.edu.my
Applied Electronics (AE) research group
Faculty of Electrical and Electronics Engineering
Universiti Malaysia Pahang
26600 Pekan, Pahang, Malaysia