ABSTRAK

Tingginya angka kecelakaan pelayaran nelayan Indonesia mendorong kebutuhan sistem komunikasi darurat antarkapal yang andal di perairan lepas pantai. Jaringan LoRa *Mesh multi-hop* menjadi kandidat yang menjanjikan karena berdaya rendah dan tidak bergantung pada infrastruktur terpusat, namun metode *routing* konvensional seperti *Greedy geographic routing* kerap gagal saat kondisi kanal memburuk atau topologi kapal bergeser secara dinamis. Penelitian ini merancang dan mengevaluasi algoritma *Q-learning* sebagai kebijakan pemilihan rute adaptif pada jaringan LoRa *Mesh* antarkapal nelayan. *Agent* dirancang dengan *state space* 28 dimensi yang merepresentasikan tujuh kategori RSSI dan empat zona jarak ke *shore station*, empat aksi semantik pemilihan *relay*, serta mekanisme *retry* per hop maksimum dua kali. Simulasi dijalankan menggunakan NS-3.41 pada tiga skenario kepadatan jaringan (15, 20, dan 25 kapal) dalam area perairan 20 km × 20 km, dengan total 6.000 episode pelatihan dan 3.000 *run* evaluasi per metode. Hasil menunjukkan bahwa *Q-learning* mencapai *Packet Delivery Ratio* (PDR) sebesar 79,88%, melampaui *Greedy geographic routing* yang sebesar 45,06%, atau meningkat 34,82 poin persentase (77,28%) dengan ukuran efek yang sangat besar (Cohen's d = 1,3698). Selain itu, *Q-learning* meningkatkan RSSI rata-rata sebesar 1,4873 dBm dan SNR sebesar 14,41%, serta meningkatkan *Path Reliability* dari 0,4512 menjadi 0,8947 (+98,30%) dengan ukuran efek yang sangat besar (Cohen's d = 2,3942). Sebagai konsekuensi, *hop count*, latensi *end-to-end*, *Time on air* (ToA), dan konsumsi energi total masing-masing meningkat sebesar 82,52%, 32,60%, 32,60%, dan 32,60% sebagai bentuk *trade-off*. Meskipun demikian, konsumsi energi per paket yang berhasil mencapai *shore station* justru 52,36% lebih rendah dibandingkan *Greedy geographic routing*. Uji *robustness* pada 14 kondisi operasional yang berbeda menunjukkan bahwa *Q-learning* secara konsisten memberikan performa yang lebih baik dengan nilai $p < 0,001$. Temuan ini menunjukkan bahwa pendekatan *Q-learning* berbasis RSSI layak diterapkan sebagai solusi *routing* adaptif untuk meningkatkan keandalan komunikasi darurat maritim pada jaringan LoRa *Mesh*.

Kata Kunci : *Greedy geographic routing* , Kapal Nelayan, Komunikasi Darurat, LoRa *Mesh*, *Q-learning*.

ABSTRACT

The high rate of fishing vessel accidents in Indonesia underscores the urgent need for reliable inter-vessel emergency communication systems in open-water environments. LoRa Mesh multi-hop networks present a promising solution due to their low power consumption and independence from centralized infrastructure; however, conventional routing methods such as Greedy geographic routing frequently fail under deteriorating channel conditions or dynamic network topology. This study designs and evaluates a Q-learning algorithm as an adaptive routing policy for LoRa Mesh networks among fishing vessels. The agent is built upon a 28-dimensional state space representing seven RSSI categories and four distance zones to the shore station, four semantic relay-selection actions, and a per-hop retry mechanism with a maximum of two attempts. Simulations were conducted using NS-3.41 across three network density scenarios (15, 20, and 25 vessels) within a 20 km × 20 km maritime area, comprising 6,000 training episodes and 3,000 evaluation runs per method. Results demonstrate that Q-learning achieves a Packet Delivery Ratio (PDR) of 79.88%, outperforming Greedy geographic routing at 45.06%, representing an absolute improvement of 34.82 percentage points (77.28%) with a very large effect size (Cohen's d = 1.3698). Furthermore, Q-learning improves the average RSSI by 1.49 dBm, increases SNR by 14.41%, and increases Path Reliability from 0.4512 to 0.8947 (+98.30%) with a very large effect size (Cohen's d = 2.3942). As a trade-off, hop count, end-to-end latency, Time on air (ToA), and total energy consumption increase by 82.52%, 32.60%, 32.60%, and 32.60%, respectively. Nevertheless, the energy consumed per successfully delivered packet is 52.36% lower than that of Greedy geographic routing. Robustness testing across 14 distinct operational conditions consistently confirms the superiority of Q-learning with $p < 0.001$. These findings demonstrate that an RSSI-based Q-learning approach is a viable adaptive routing solution for improving the reliability of maritime emergency communication systems over LoRa Mesh networks.

Keywords : Emergency Communication, Fishing Vessel, Greedy geographic routing , LoRa Mesh, Q-learning.