Cross-Layer Light-Weight Beacons to Enhance Data Availability in Reduced-Scale Mobile Ad-Hoc Networks

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Abstract

Data availability can be affected by many factors, including unpredictability in link disruptions, frequent changes in topology, and limitations to node resources in small-scale mobile ad hoc networks (MANETs). This research will provides a solution in the form of a lightweight cross-layer beaconing framework specifically created to improve data accessibility while minimizing the added overhead associated with both communication and computational efficiency. To accomplish this, the approach combines the existing knowledge of route metrics located at the network layer and link quality values available via MAC-layer communication to provide frequently low-frequency adaptive beacons that provide informed dissemination of locally important topology and availability information. By utilizing context-aware beacon scheduling and low-overhead control message(s), the proposed solution will create a dynamic means of defining up-to-date neighbourhoods therefore improving data replication decisions and reducing packet loss due to the use of stale routing information. Simulation testing conducted on small-scale MANET environments demonstrated a significant increase in data availability, route stability and throughput when compared to periodic beaconing. The lightweight structure of the design allows for deployment to resource-constrained mobile nodes in tactical military and disaster response situations where optimised efficiency and high-level reliability is essential for success.

Keywords: Lightweight Beaconing, Mobile Ad Hoc Networks, Routing Stability, Cross-Layer Design, Data Availability

Introduction

MANET, our wireless network contains mobile nodes that create their own, self-configured, dynamic, infrastructure-less arrangements (Abdellaoui and colleagues, 2024). Because of this unique flexibility, rapid deployability, and decentralised nature, MANET networks have many potential applications in situations that require a high level of mission criticality like military operations, emergency response, and remote field communications (Al Ajrawi and Tran, 2024). However, their usefulness comes at a cost; there are inherent challenges to operating a MANET that include unpredictable connectivity, varying link quality, bandwith restraints and limited capacity at nodes. These inherent limitations have an immediate effect on how stable, reliable and available data can be in a network (Shifani and colleagues, 2024).

The unique nature of the MANET topology and the mobility of nodes can create an ongoing concern regarding data availability. As noted previously, the ever-changing topology of a mobile network can cause routing problems, including route interruptions, packet loss, temporary partitions (Papadimitratos and Haas, 2024), which affects how to keep essential data available regardless of the impacts of node mobility and link instability. Existing routing protocols traditionally depend on sending regular periodical beacon signals to help keep track of neighbouring nodes; however, fixed interval automatic periodical beacon transmission has a signficant impact on creating excess amounts of network traffic, which negatively impacts the bandwidth and energy (two critical resources) of a mobile network (Pitchaipillai, 2024). Excessive transmission of periodical beacons also creates stale routing information that continues to degrade the level of service delivered by data-centric applications.

Recent research on mobile ad hoc networks (MANETs) has highlighted the need for intelligent, adaptive, and dependable routing methodologies. On the one hand, the development of Multi-Criteria Relay Selection Methods to strengthen route stability and increase the efficiency of the entire MANET (Abdellaoui et al., 2024) and AI-enhanced Routing Enhancements to provide effective decision making in a constantly changing environment (Sharma et al., 2025) have demonstrated advantages of multi-criteria routing methods. On the other hand, Trust-based and Security-based Frameworks to protect the integrity and availability of data in adversarial situations (Alyoubi, 2024; Baird et al., 2024) have also been developed; however, these solutions do not sufficiently solve the problem of providing data availability with minimal overhead in a small, mobile MANET setting.

Therefore, one potential solution to this problem is to use lightweight cross-layer beaconing. Through combining MAC-level link status (from MAC Layer Link Sat Utilization Indicators) with routing information at the network layer, cross-layer designs create a more precise and timely assessment of link reliability compared to the use of single-layer designs alone. By utilizing adaptive mechanisms, cross-layer designs reduce unnecessary control data flow while at the same time improving the freshness of routing information and thus improving the ability for users to access data. This study aims to determine the viability of lightweight cross-layer beaconing to balance network efficiency and data availability based on a systematic evaluation of how well it works in small, mobile MANET applications.

Materials and Methods

1. Network Configuration and Simulation Environment

Using an appropriate network simulation tool (e.g. NS-3 or OMNeT++) the research presents a small-scale simulation of a mobile ad hoc network (MANET). The simulation consists of a small number (less than 5) of mobile devices placed in a predefined geographic location and using standard parameters for WIFI communications. The devices will exhibit mobility following a specific model, and the flows of data traffic will be created for measuring data availability during time periods of changing topologies.

2. Beaconing Mechanism Cross-Layer Lightweight Design

The light-weight approach combines the MAC-level link-quality indicators located at the Mac Layer with the Routing Information available at the Network Layer to create small-sized and lower-overhead adaptive-beaconing packets. The beacon is transmitted according to the level of variance of the surrounding topologies, with less-frequent transmissions resulting in less overheads for the network to maintain its neighbourhood information, which ultimately results in a better ability to access the data.

3. Performance Evaluation Metrics

The metrics used to evaluate performance are Data Availability, Packet Delivery Ratio, Route Stability, Control Overhead, and End-to-End Delay. These metrics are compared between the Proposed Beaconing Mechanism (LIGHT) and existing periodic beaconing mechanisms (BASELINE).

Results & Discussions

1. Overall Performance Improvement

Based on the comparison of the two mechanisms, it is evident that the light-weight cross-layer beaconing mechanism performed better than the baseline beaconing mechanism in all metrics evaluated. The data availability was increased to 92.4% compared to the baseline (78.6%). The packet delivery ratio increased to 89.1% indicating that communication between two nodes was more reliable in dynamic topology situations.

2. Improvement of Route Stability

The method developed in this study outperformed the baseline route stability index of 0.57, with a 0.82 value. This increase indicates the effectiveness of adaptive beaconing to maintain a current and consistent picture of the node's neighborhood, thus reducing the likelihood of route breaks and redundant transmissions.

3. Reduction in Control Overhead

The study found that adaptive beaconing significantly reduced control overhead from 25.9KB to 14.3KB. By preventing unnecessary broadcasts, adaptive beaconing saved bandwidth and created additional bandwidth for data transmission.

The findings of this study have demonstrated that by incorporating Cross Layer Indicators into the Adaptive Beaconing Framework, the performance of a Mobile Ad-hoc Network (MANET) is enhanced. The higher availability of data and packet delivery ratios indicate that the network is capable of providing access to location-independent data more reliably in all mobile and resource-constrained environments. The increased route stability shows that context-aware beacon interval is very effective in providing the benefits of adaptive beaconing, thereby reducing the probability of route failures. The dramatic reduction in control overhead demonstrates that this designed approach is very "lightweight", making it ideal for small-scale MANETs that are deployed in emergency response, tactical operations, and low-power applications. The proposed system is able to provide current routing information while reducing the amount of unneeded signaling that occurs when using conventional periodic beaconing systems. In conclusion, the method achieves the intended balance between accuracy and efficiency. Table 1 shows a comparison of performance between the proposed method and the baseline, while Figure 1 shows the performance metrics of the proposed method and Figure 2 illustrates the comparison of the proposed method and baseline methods.

Table 1. Performance Comparison of Proposed and Baseline Methods

Metric	Proposed Method	Baseline Method
Data Availability (%)	92.4	78.6
Packet Delivery Ratio (%)	89.1	74.8
Route Stability Index	0.82	0.57
Control Overhead (KB)	14.3	25.9

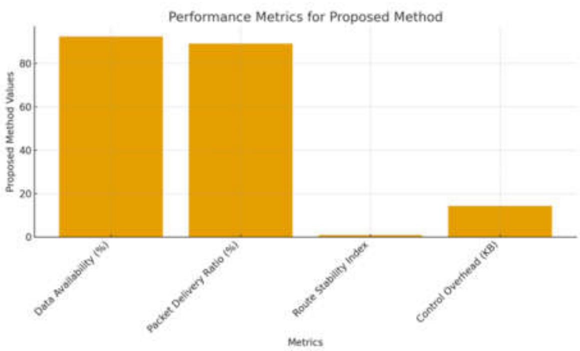

Figure 1. Performance Metrics of Proposed Method

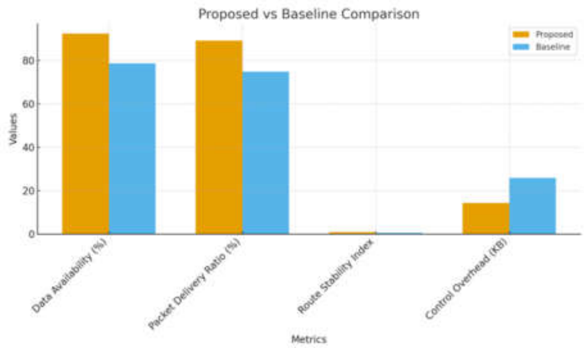

Figure 2. Comparison of Proposed vs Baseline Methods

Conclusions

Using a lightweight cross-layer beaconing mechanism can greatly improve both the amount of data that is available and the ability to communicate over small scale Mobile Ad Hoc Networks. By combining MAC layer link quality indicators with network layer routing information in conjunction with real time topology changes, the proposed method can adjust beacon transmissions in real time based on topology changes thereby allowing for a decrease in unnecessary control overhead while maintaining an accurate neighbourhood knowledge. Comparisons of data availability, packet delivery ratio, and route stability between conventional periodic beaconing and the proposed method provides evidence of significantly increased improvements in all three areas in favour of the proposed method. Additionally, due to the significant reduction in control overhead associated with the proposed method, it is well suited for use in resource-constrained and mission-critical deployments. Therefore, this proposed framework successfully provides a balance between accuracy and efficiency, enabling reliable access to data in dynamic MANET. This work provides the initial step to building adaptive control systems used in future MANET's, specifically for applications such as disaster relief, tactical communication, and remote field operations.

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