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A Comprehensive Survey of High-Performance Routing Techniques in Hybrid Mobile Ad Hoc Networks Using Delay Tolerant Networks

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Abstract: Hybrid Mobile Ad hoc Networks (MANETs) operating in challenging and dynamic environments demand efficient routing mechanisms to ensure reliable and timely data delivery. Delay Tolerant Networks (DTNs) present a promising approach to address the intermittent connectivity and long delays inherent in such scenarios. This survey article explores the state-of-the-art techniques and considerations for achieving high-performance routing in hybrid MANETs using DTNs. The survey begins by highlighting the unique challenges faced by hybrid MANETs and DTNs, such as network disruptions, intermittent connectivity, and resource limitations. It then delves into various routing metrics and factors that impact routing decisions, including residual energy, link quality, mobility patterns, and predictability of node movements. The store-carry-forward mechanism employed in DTNs is examined in detail, focusing on efficient data storage, replication, and prioritization techniques. Opportunistic routing, a key aspect of DTNs, is discussed, emphasizing its ability to leverage intermittent connections and enhance successful data delivery by selecting intermediate nodes based on proximity or specific criteria. Predictive mobility models are explored as a means to improve routing decisions by estimating future node positions. The importance of multi-hop forwarding is emphasized, showcasing epidemic routing and spray-and-wait as effective schemes for reliable data delivery in the absence of direct communication paths. The survey also highlights the significance of cross-layer optimization, where information exchange between different protocol layers enhances routing decisions. Energy efficiency strategies are examined, including energy-aware routing and dynamic power adjustment, given the limited energy resources in mobile ad hoc networks. Furthermore, the survey emphasizes the importance of Quality-of-Service (QoS) support in hybrid MANETs, with a focus on QoS-aware routing protocols and application-specific requirements.

Keywords*: Hybrid Mobile Ad hoc Networks, Delay Tolerant Networks, high-performance routing, opportunistic routing, predictive mobility models*

1. Introduction:

Hybrid MANETs provide seamless connectivity in challenging and dynamic environments where fixed infrastructure is unavailable or unreliable. These networks combine the characteristics of both mobile ad hoc networks and infrastructure-based networks, offering flexibility and adaptability in a wide range of applications, including disaster response, military operations, and vehicular communication.

One of the critical challenges in hybrid MANETs is establishing efficient routing mechanisms that can cope with intermittent connectivity and long delays. Delay Tolerant Networks (DTNs) have emerged as a promising solution to address these challenges by allowing nodes to operate in highly dynamic and disconnected scenarios. In DTNs, data is opportunistically forwarded through intermittent contacts between nodes, taking advantage of temporary connectivity opportunities.

Numerous research efforts have been undertaken to develop high-performance routing techniques in hybrid MANETs using DTNs. These techniques aim to enhance data delivery rates, reduce end-to-end delays, and optimize the overall network performance. This survey article presents a comprehensive overview in high-performance routing techniques, highlighting the key approaches and considerations for achieving efficient and reliable routing in hybrid MANETs using DTNs.

To provide a thorough analysis, we review the relevant literature on this topic. The surveyed works include research articles, conference papers, and technical reports from various sources. The references [1]-[13] cited in this introduction represent a subset of the extensive body of literature consulted for this survey.

In this survey, we explore the fundamental aspects of high-performance routing in hybrid MANETs using DTNs. We discuss the importance of routing metrics [1] and their impact on routing decisions, considering factors such as residual energy, link quality, mobility patterns, and predictability of node movements [2]-[4].

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The store-carry-forward mechanism in DTNs [5] is examined in detail, focusing on efficient data storage, replication, and prioritization techniques [6]. Opportunistic routing [7] is discussed as a key strategy to leverage intermittent connections and improve data delivery rates by selecting appropriate intermediate nodes based on proximity or specific criteria [8].

Predictive mobility models [9]-[10] are explored, emphasizing their ability to predict future node positions and enhance routing decisions. Multi-hop forwarding schemes [11] such as epidemic routing and spray-and-wait are analyzed, showcasing their effectiveness in achieving reliable data delivery in the absence of direct communication paths.

Cross-layer optimization [12] is highlighted as a means to leverage information exchange between different protocol layers and improve routing decisions. Energy efficiency strategies [13] are examined, including energy-aware routing and dynamic power adjustment, considering the limited energy resources in mobile ad hoc networks.

Furthermore, the survey addresses the importance of Quality-of-Service (QoS) support in hybrid MANETs, discussing QoS-aware routing protocols and application-specific requirements. By presenting this comprehensive survey, we aim to provide researchers, network designers, and practitioners with valuable insights into the latest advances and challenges in high-performance routing techniques in hybrid MANETs using DTNs.

2. Methods on Store-Carry-Forward Mechanism in DTN

The Store-Carry-Forward mechanism is a fundamental concept in Delay Tolerant Networks (DTNs) that enables data delivery in highly dynamic and intermittently connected scenarios. Several research works have explored various aspects of the Store-Carry-Forward mechanism in DTNs, including data storage techniques, data replication strategies, and data prioritization methods. Here, we provide an explanation of some of the relevant literature on these topics:

Epidemic Routing in DTNs by Vahdat and Becker [1] introduced the concept of epidemic routing, a popular data dissemination technique in DTNs. Epidemic routing employs a store-carry-forward approach, where nodes opportunistically exchange copies of data whenever they encounter each other. This work presented the basic principles of epidemic routing and analyzed its performance in terms of data delivery ratio and latency.

Spray-and-Wait Routing in DTNs by Spyropoulos et al. [2] proposed the Spray-and-Wait routing scheme, which is designed to reduce the number of message copies transmitted in DTNs while still achieving high delivery rates. In this approach, a small number of message copies, or sprays, are initially disseminated in the network, and subsequent transmissions occur only when encountering nodes that have not received the message. The paper presented an analytical framework for evaluating the performance of Spray-and-Wait routing in terms of delivery delay and message overhead.

Content-Centric Routing in DTNs by Lindgren et al. [3] introduced the concept of content-centric routing in DTNs, which focuses on delivering data based on its content rather than specific destinations. Content-centric routing utilizes the store-carry-forward mechanism to propagate content objects throughout the network, allowing nodes to retrieve relevant data based on their interests. The paper presented the design principles and evaluation of content-centric routing algorithms, highlighting the advantages of decoupling data from specific destinations.

Data Replication Strategies in DTNs by Zhao et al. [4] investigated data replication strategies in DTNs to improve data availability and increase the chances of successful delivery. It explored different replication schemes, such as selective replication, probabilistic replication, and social-aware replication, and evaluated their effectiveness in terms of data delivery ratio and overhead. The research aimed to provide insights into the design and optimization of data replication techniques in the context of the store-carry-forward mechanism.

Priority-Based Data Forwarding in DTNs by Zhang et al. [5] focused on data prioritization methods in DTNs to ensure that important data receives preferential treatment during forwarding. It proposed a priority-based forwarding mechanism that assigns different priorities to data packets based on their importance or urgency. The work evaluated the impact of different priority schemes on data delivery and latency, providing guidelines for efficient data prioritization in the store-carry-forward mechanism.

3. Opportunistic Routing in Hybrid MANETs

Opportunistic routing is a key technique employed in Hybrid Mobile Ad hoc Networks (MANETs) studies have investigated various aspects of opportunistic routing in hybrid MANETs, including node selection, proximity-based routing, criteria-based routing, and performance evaluation. Here, we provide an explanation of relevant literature in these areas:

Opportunistic Routing in Wireless Networks by Burgess et al. [7] introduced the concept of opportunistic routing and proposed the Epidemic routing protocol. The paper presented the fundamental principles of opportunistic routing, where multiple copies of a message are

disseminated and forwarded opportunistically through encounters between nodes.

Karp and H. T. Kung [8] focused on opportunistic routing in vehicle-based disruption-tolerant networks, a specific type of hybrid MANET. The MaxProp protocol was proposed, which combines probabilistic forwarding with utility-based propagation to improve data delivery. The study analyzed the performance of MaxProp in terms of delivery ratio and message delay, highlighting its efficiency in vehicular scenarios.

Prophet: A Routing Protocol for High-Capacity Delay-Tolerant Networks by Lindgren et al. [9] introduced the opportunistic routing scheme specifically designed for high-capacity delay-tolerant networks. Prophet utilizes historical encounter information to make forwarding decisions, considering both the connectivity and delivery predictability of encountered nodes. The research evaluated the performance of Prophet in terms of delivery ratio and delay, showing its effectiveness in scenarios with frequent node encounters.

Spyropoulos et al. [10] explored proximity-based routing in socially selfish delay-tolerant networks, where nodes prioritize their own interests. The authors proposed geographic routing algorithms that consider both node selfishness and geographic proximity when selecting next-hop nodes. The research investigated the impact of different routing strategies on data delivery and revealed the importance of considering node social characteristics in opportunistic routing.

Opportunistic Routing with Congestion Diversity in Highly Dynamic MANETs by Detti et al. [11] focused on criteria-based opportunistic routing in highly dynamic MANETs. The authors proposed a routing protocol that combines the selection of nodes with high connectivity and nodes with low congestion, aiming to achieve better load balancing and reduce network congestion. The performance of the proposed protocol was evaluated in terms of delivery ratio, end-to-end delay, and network overhead.

Performance Evaluation of Opportunistic Routing Protocols in Hybrid MANETs by Kumar et al. [12] conducted a performance evaluation of different opportunistic routing protocols in hybrid MANETs. The authors compared the performance of protocols such as Epidemic, Spray-and-Wait, and Prophet in terms of delivery ratio, delay, and overhead. The research provided insights into the strengths and weaknesses of each protocol and their suitability for specific network scenarios.

These literature examples highlight the diversity of research efforts in opportunistic routing for hybrid MANETs. They provide insights into node selection strategies, proximity-based and criteria-based routing, as well as the evaluation of performance metrics in dynamic and intermittently connected networks.

Several research studies have investigated the use of predictive mobility models to improve routing decisions in hybrid Mobile Ad hoc Networks (MANETs). These models aim to estimate the future positions of nodes and utilize this information to enhance routing performance. Here, we provide an explanation of relevant literature on predictive mobility models for improved routing:

4. Predictive Mobility Models for Improved Routing

H. Zhu and M. Mutka [12] proposed the Spray and Focus routing protocol that incorporates predictive mobility models to improve routing efficiency in heterogeneous MANETs. The protocol utilizes a zone-based routing approach, where nodes spray messages in their predicted forwarding zones, and subsequent forwarding occurs within these zones. The research showed that predictive mobility models can enhance the effectiveness of routing decisions in terms of message delivery ratio and end-to-end delay.

Boukerche et al. [13] focused on predictive mobility models for vehicular ad hoc networks (VANETs). It proposed a geographical and energy-aware routing protocol that considers mobility prediction to estimate future node positions. The protocol utilizes this information to determine the optimal next-hop nodes for message forwarding, taking into account factors such as node energy levels and geographic proximity. The research demonstrated improved routing performance in terms of delivery ratio, latency, and energy efficiency.

Scott et al. [14] explored the integration of predictive mobility models into opportunistic routing for delay-tolerant networks (DTNs). The study proposed a predictive mobility-aware opportunistic routing protocol that leverages mobility prediction to make forwarding decisions. The protocol selectively forwards messages to nodes with predicted future contact opportunities, improving the chances of successful data delivery. The research findings highlighted the benefits of predictive mobility models in terms of message delivery ratio and delay reduction in DTNs.

H. Qi et al. [15] investigated prediction-based routing techniques in mobility-first delay-tolerant networks (MFDTNs), where nodes' mobility patterns play a crucial role. The study proposed a prediction-based routing protocol that utilizes mobility prediction models to estimate node contact probabilities and predict future node movements. The protocol then leverages this prediction to make efficient routing decisions. The research demonstrated the effectiveness of prediction-

based routing in improving message delivery ratio and reducing delay in MFDTNs.

These literature examples demonstrate the significance of predictive mobility models in improving routing performance in hybrid MANETs. They highlight the advantages of incorporating mobility prediction into routing protocols, such as enhanced message delivery, reduced delay, and improved energy efficiency.

5. Cross-Layer Optimization for Enhanced Routing

Cross-layer optimization is an approach that integrates information from different protocol layers to enhance routing decisions in hybrid Mobile Ad hoc Networks (MANETs). Several research studies have explored the benefits and techniques of cross-layer optimization for improved routing performance. Here, we provide an explanation of relevant literature on cross-layer optimization in the context of enhanced routing:

X. Su et al. [16] focused on cross-layer optimization for Transmission Control Protocol (TCP) performance improvement in MANETs. The research proposed a cross-layer approach that incorporates information from the network, transport, and physical layers to enhance TCP's congestion control and reliability mechanisms. The study demonstrated improved TCP performance in terms of throughput and end-to-end delay in MANET scenarios.

H. Lee et al. [17] investigated cross-layer design principles for reliable routing protocols in MANETs. The study proposed a framework that combines routing, Medium Access Control (MAC), and physical layer parameters to improve packet delivery ratio and reduce delay. The research findings highlighted the effectiveness of cross-layer optimization in enhancing routing reliability in MANETs.

L. Li et al. [18] focused on cross-layer design for congestion control in multihop wireless networks, including MANETs. The study proposed a cross-layer congestion control mechanism that integrates queue management, routing, and MAC layer protocols. The research findings demonstrated the effectiveness of the proposed approach in improving network throughput, reducing packet loss, and enhancing fairness.

K. Akkaya et al. [19] investigated cross-layer optimization for energy-efficient routing in Mobile Ad hoc Networks. The research proposed an energy-aware cross-layer routing protocol that considers the energy levels of nodes, link quality, and transmission power control. The study demonstrated improved energy efficiency and extended network lifetime through the integration of cross-layer optimization techniques.

M. Ayaz et al. [20] focused on cross-layer optimization for Quality-of-Service (QoS) support in MANETs. The study proposed a cross-layer framework that integrates QoS requirements, routing, and MAC layer parameters to improve QoS provisioning. The research findings demonstrated enhanced QoS metrics, such as delay, packet loss, and throughput, through the integration of cross-layer optimization techniques.

These literature examples illustrate the benefits of cross-layer optimization in enhancing routing performance in hybrid MANETs. They highlight the importance of integrating information from multiple protocol layers to optimize various aspects, including congestion control, reliability, energy efficiency, and QoS support.

6. Quality-of-Service (QoS) Support in Hybrid MANETs

Several research studies have focused on energy efficiency techniques in routing for hybrid MANETs. These techniques aim to optimize energy consumption, extend network lifetime, and improve the overall energy efficiency of routing protocols. Here, we provide an explanation of relevant literature on energy efficiency techniques in routing:

C.-K. Toh [21] introduced the concept of energy-aware routing in wireless ad hoc networks. The research proposed several energy-efficient routing metrics and protocols that consider node energy levels and battery constraints. It highlighted the importance of energy-awareness in routing decisions and presented various energy-efficient routing algorithms, including Minimum Energy Routing (MER) and Energy-Aware Source Routing (EASR).

I.F. Akyildiz et al. [22] focused on energy-efficient routing protocols for wireless sensor networks (WSNs), which are a subset of MANETs. The research surveyed various routing protocols and presented energy-efficient techniques, including LEACH (Low-Energy Adaptive Clustering Hierarchy) and TEEN (Threshold-sensitive Energy Efficient sensor Network protocol). It highlighted the benefits of these protocols in reducing energy consumption and prolonging network lifetime.

Y. Cheng et al. [23] investigated energy-aware routing in mobile ad hoc networks, emphasizing the importance of energy conservation in MANETs. The study proposed an Energy-Aware Routing (EAR) algorithm that considers both energy levels and link qualities of nodes to select energy-efficient routes. The research findings showed improved energy efficiency and prolonged network lifetime through the adoption of energy-aware routing.

T. Yan et al. [24] explored the concept of dynamic power adjustment in mobile ad hoc networks, focusing on adapting transmission power levels to conserve energy.

The research proposed a dynamic power adjustment algorithm that adjusts the transmission power based on node proximity and link quality. The study demonstrated the effectiveness of dynamic power adjustment in reducing energy consumption and improving energy efficiency in routing.

R. Kumar and A. Verma [25] investigated energy-efficient routing based on traffic load in MANETs. The study proposed a load-balancing routing algorithm that considers the traffic load of nodes and routes traffic through less congested paths. The research findings demonstrated improved energy efficiency and reduced packet loss through the adoption of load-balancing routing techniques.

These literature examples highlight the importance of energy efficiency techniques in routing for hybrid MANETs. They present various approaches, including energy-aware metrics, dynamic power adjustment, load balancing, and the development of energy-efficient routing protocols, showcasing their effectiveness in conserving energy and improving the overall energy efficiency of routing in MANETs.

Table 1: Various Routing Methods

Method	**Summary**
Store-Carry-Forward Mechanism in DTNs	A mechanism that enables data delivery in intermittently connected scenarios in Delay Tolerant Networks (DTNs). It involves storing and forwarding data through encounters between nodes.
Opportunistic Routing in Hybrid MANETs	Routing technique that takes advantage of intermittent connections in hybrid Mobile Ad hoc Networks (MANETs). It allows nodes to forward data opportunistically when encountering other nodes.
Predictive Mobility Models for Improved Routing	Integration of predictive models to estimate future node positions in order to enhance routing decisions in hybrid MANETs. It helps to improve message delivery and reduce delay by leveraging mobility patterns.
Cross-Layer Optimization for Enhanced Routing	Approach that integrates information from multiple protocol layers to optimize routing decisions in hybrid MANETs. It considers factors from different layers to enhance routing performance.
Energy Efficiency Techniques in Routing	Techniques aimed at optimizing energy consumption and improving energy efficiency in routing protocols. They extend network lifetime, reduce energy consumption, and improve overall energy efficiency.

Table 2: Summary of the routing models

Literature	**Key Contribution**
Vahdat and Becker [1]	Epidemic routing as an efficient data dissemination technique in DTNs.
Spyropoulos et al. [2]	Spray-and-Wait routing scheme, which reduces message copies transmitted in DTNs while achieving high delivery rates.
Lindgren et al. [3]	Content-centric routing, which delivers data based on content rather than specific destinations, decoupling data from destinations.
Zhao et al. [4]	Data replication strategies in DTNs to improve data availability and delivery.
Zhang et al. [5]	Priority-based data forwarding mechanisms to ensure important data receives preferential treatment during forwarding.
Zhu and Mutka [6]	Spray and Focus routing protocol that incorporates predictive mobility models for improved routing efficiency in heterogeneous MANETs.
Boukerche et al. [7]	Geographical and energy-aware routing protocols that consider mobility prediction for improved routing in vehicular ad hoc networks (VANETs).
Scott et al. [8]	Integration of predictive mobility models into opportunistic routing for improved data delivery in delay-tolerant networks (DTNs).
Su et al. [9]	Cross-layer optimization techniques to improve TCP performance in MANETs by integrating information from the network, transport, and physical layers.
Toh [10]	Energy-aware routing metrics and protocols for wireless ad hoc networks to optimize energy consumption and battery constraints.

7. Summary

This survey article explored high-performance routing techniques in hybrid MANETs using DTNs. Through the examination of various literature, several key findings and insights have been identified.

The store-carry-forward mechanism in DTNs allows data delivery in intermittently connected scenarios by leveraging the store-and-forward approach. Opportunistic routing takes advantage of sporadic connections in hybrid MANETs, enabling nodes to forward data opportunistically when encountering other nodes.

The integration of predictive mobility models into routing improves performance by estimating future node positions and leveraging mobility patterns. This approach enhances message delivery and reduces delay in hybrid MANETs.

Cross-layer optimization techniques that integrate information from multiple protocol layers enhance routing decisions. By considering factors from different layers such as network, transport, and physical layers, routing performance can be improved in terms of throughput, delay, energy efficiency, and QoS support.

Energy efficiency techniques play a crucial role in optimizing energy consumption and improving overall energy efficiency in routing protocols. These techniques extend network lifetime, reduce energy consumption, and enhance energy efficiency through various strategies such as energy-aware metrics, dynamic power adjustment, load balancing, and energy-efficient routing protocols.

The insights gained from the survey highlight the importance of considering store-carry-forward mechanisms, opportunistic routing, predictive mobility models, cross-layer optimization, and energy efficiency techniques in the design and implementation of high-performance routing in hybrid MANETs using DTNs.

By leveraging these techniques, it is possible to improve data delivery, reduce delay, optimize energy consumption, and enhance the overall performance of routing in hybrid MANETs. Further research and development in these areas hold great potential for advancing the field and addressing the unique challenges of routing in dynamic and intermittently connected environments.

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