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ODeSe: Amélioration de l'efficacité du réseau grâce aux multi-trajets dans RPL

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Lorsqu'un algorithme de routage multi-chemins est utilisé dans un réseau d'objets fonctionnant avec le protocole de routage RPL, la sélection des parents d'un noeud est critique pour garantir à la fois fiabilité et efficacité énergétique. Cet article présente l'algorithme de sélection de parents à la demande nommé ODeSe, qui cherchera à minimiser le nombre de relais des couches supérieures. Comparé aux algorithmes d'ancêtre commun ou de chemin unique, ODeSe atteint un taux de livraison de paquets plus élevé tout en réduisant considérablement la consommation d'énergie en limitant les transmissions redondantes.

Mots-clefs : Internet of Things, Low-power and Lossy Networks, RPL, Multipath, Routing Protocols

1 Introduction

Reliable communication in Low-power and Lossy Networks (LLNs) is crucial for Industrial Internet of Things (IoT) applications. Single-path routing in the IPv6 Routing Protocol for Low-Power and Lossy Networks (RPL) often fails to meet the required reliability [MK24]. Multipath routing, enhanced by the Packet Automatic Repeat reQuest, Replication and Elimination, and Overhearing (PAREO) functions [KPJ⁺20], provides greater reliability through redundancy while managing network resources effectively [MKL17]. In this context, we propose the On-Demand Selection (ODeSe) algorithm that improves multipath routing by selecting relays that share the same upper relays towards the root to enhance reliability and reduce flooding.

2 Technical Background

2.1 Routing Protocol: RPL

RPL is a widely adopted proactive distance-vector standardised routing protocol designed to address the unique requirements of LLNs [WTB⁺12]. RPL builds a Destination Oriented Directed Acyclic Graph (DODAG) to provide a single-path between source nodes and the destination DODAG Root node. In the default design of RPL, each node forwards packets to a chosen neighbour towards the root, which is called its parent node or Preferred Parent (PP), thus using a single-path. If any packet forwarding fails along the path, the sender relay node may attempt retransmissions to its parent. This behaviour introduces unpredictable and unbounded delays, especially if links are prone to failure or congestion. As a result, the single-path configuration often falls short of meeting deterministic properties such as low packet error rate, bounded consecutive losses, and bounded end-to-end latency.

2.2 Multipath RPL with the PAREO functions

The concept of multipath RPL has emerged to overcome these limitations and improve the network's end-to-end reliability and latency. Multipath RPL extends the capabilities of traditional RPL by enabling the selection of an Alternative Parent (AP), which is the second PP. By using multiple parents, a node may duplicate packets to several upward relays to provide redundancy. However, this requires a careful selection

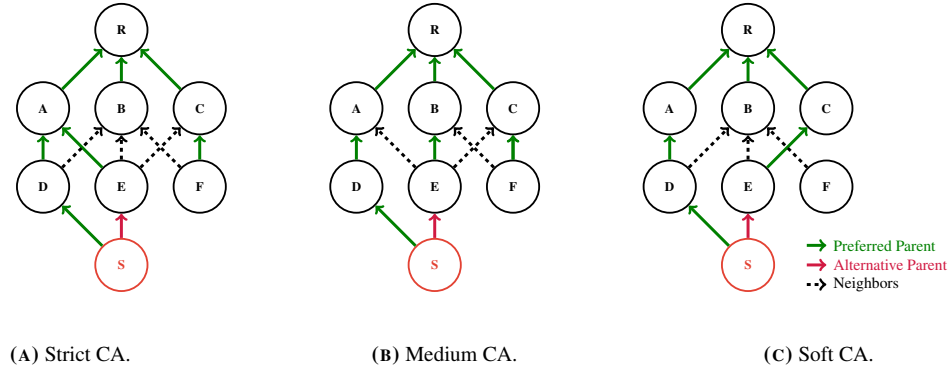


FIGURE 1: Algorithms for selecting an AP by using a Common Ancestor.

of the upward relays (PP, AP) to prevent network flooding or excessive resource consumption. The PAREO functions address this challenge by providing the following set of functions:

- Automatic Repeat reQuest (ARQ): This function detects failed transmissions and initiates retransmissions. ARQ relies on acknowledgements to confirm successful delivery.
- Packet Replication and Elimination (PRE): Packet replication improves reliability by replicating packets across multiple paths, ensuring that at least one copy reaches its destination. The packet elimination function prevents redundant packets from propagating through the network, and thus, it discards the duplicated packets.
- Overhearing: This function leverages the broadcast nature of wireless networks, enabling nodes to promiscuously listen to transmissions not directly addressed to them. Overhearing increases the chances of packet reception, particularly in dense network topologies, while avoiding acknowledgement collisions by targeting only unicast recipients.

Each function can work either independently or together. Each addresses a particular issue, contributes to enhanced network end-to-end reliability, and helps reduce latency. However, they must be paired with an efficient parent selection mechanism to optimise resource utilisation and prevent unintended flooding.

2.3 Common Ancestor (CA) Algorithms

Numerous methods exist to implement the PRE function on the source and intermediate nodes. We have identified a family of algorithms that generate a braided routing pattern with advantageous properties. This section presents parent selection algorithms based on a braided pattern, utilising two routing paths [JKPM21]. All three CA algorithms are illustrated in Figure 1.

- Strict CA: In the Strict CA algorithm, node k selects a candidate parent node c as an AP only if $PP(c)$ matches the $PP(PP(k))$ (the preferred grandparent) of node k .
- Medium CA: Using the Medium CA algorithm, node k selects a candidate parent node c as an AP only if the $PS(c)$ includes the $PP(PP(k))$.
- Soft CA: Finally, the least restrictive method, using the Soft CA algorithm, node k selects a candidate parent node c as an AP if there is any overlap between the $PS(c)$ and the $PS(PP)$, i.e., $PS(PP(k)) \cap PS(c) \neq \emptyset$.

3 ODeSe Algorithm

While improving reliability, the CA algorithms present remarkable challenges. Strict CA's rigid selection criteria can fail to provide an AP in certain topologies, affecting reliability. On the other hand, Medium and Soft CA can lead to excessive flooding due to their relaxed selection criteria, undermining energy efficiency and increasing network congestion. These limitations underscore the need for a more adaptive algorithm that balances network end-to-end reliability and bounded latency with efficient resource management.

ODeSe addresses the limitations of CA algorithms by introducing a two-hop parent selection strategy. Unlike CA algorithms, ODeSe determines the PP and AP for the current hop and assigns these parents for

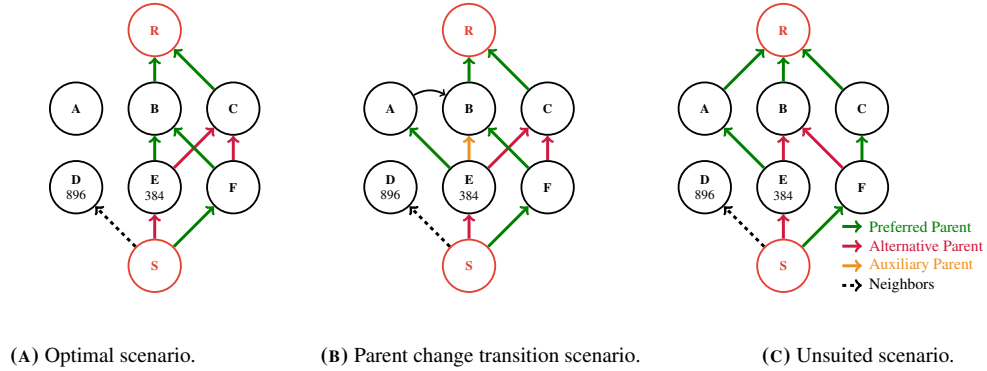


FIGURE 2: ODeSe functions for parent selection.

the next hop, enabling tighter control over packet flooding and energy consumption.

The primary distinction between ODeSe and CA algorithms lies in the fact that ODeSe will try to narrow the path. Nodes at the same layer (i.e., the same number of hops away with respect to the DODAG Root) in the DODAG select the same set of relay parents, ensuring consistent multipath routing. ODeSe requires that candidate PPs at the same distance in the network hierarchy share the same PP to achieve this. If this condition is not met, ODeSe dynamically adjusts parent assignments to meet these requirements.

In the ideal case, illustrated in Figure 2a, nodes E and F both select B as their PP, allowing C to serve as their AP. This configuration ensures efficient alignment of multipath routes. However, if nodes initially choose different PPs, ODeSe introduces auxiliary adjustments to align parent sets. For instance, as shown in Figure 2b, node E may temporarily switch its PP from A to B to maintain multipath consistency without altering the RPL structure. ODeSe falls back to the Soft CA approach if no suitable adjustment can be made, as depicted in Figure 2c. This ensures that reliability is preserved even when strict relay alignment is not achievable. By implementing two-hop forwarding control, ODeSe limits unnecessary flooding, reduces redundant packet propagation, and conserves energy while achieving similar reliability results.

4 Performance Evaluation

We evaluate the performance of ODeSe against the CA algorithms and single-path RPL with various retransmission attempts under a network scenario with 50% link quality, five hops, and a parent set of 6 nodes per layer in a 32-node topology.

In low link-quality conditions, as shown in Figure 3a, multipath routing (with any PRE base algorithms) shows a better packet delivery ratio than single-path algorithms. In such conditions, single-path RPL relies on retransmissions to mitigate poor link quality, leading to reduced reliability compared to multipath approaches. If we focus on multipath algorithms, we see that Strict CA provides a lower packet delivery ratio due to its rigid selection policy, which often fails to find APs. Medium and Soft CAs improve reliability by relaxing the parent selection criteria, which eventually will introduce flooding.

On the other hand, ODeSe achieves a Packet Delivery Rate (PDR) of 99.14% while maintaining efficient parent selection that reduces the number of copies in the network while still providing high reliability. By aligning parent sets across nodes in the same layer and implementing dynamic adjustments, ODeSe outperforms Strict CA and Medium CA and achieves end-to-end network reliability comparable to Soft CA without excessive flooding.

The energy consumption of each algorithm is derived using the duty cycle of the Zolertia Z1 mote's CC2420 radio module. Energy costs are calculated considering transmission, reception, and idle power states with the following parameters: $P_{TX} = 52.2mW$, $P_{RX} = 56.4mW$, and $P_{Idle} = 1.28mW$. As shown in Figure 3b, CA algorithms exhibit the highest energy consumption among the multipath approaches due to uncontrolled flooding. In contrast, ODeSe demonstrates better energy efficiency by concentrating alternative paths near the main path and reducing unnecessary transmissions.

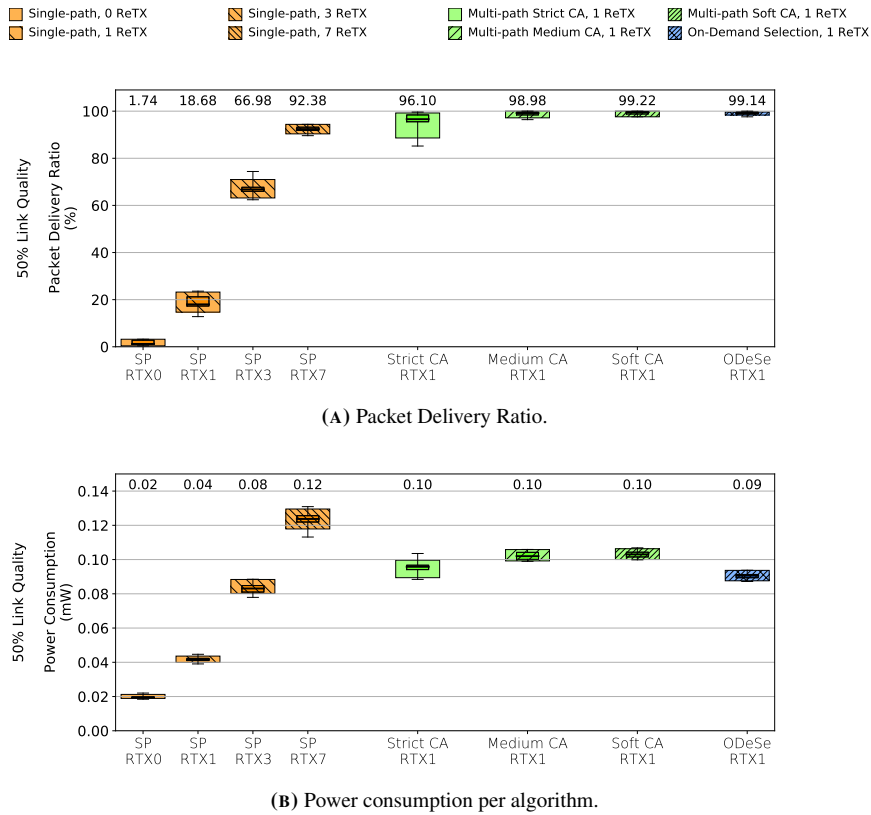


FIGURE 3: Performance evaluation results with 50% radio link quality.

5 Conclusions

In this work, we have presented and evaluated the performance of the multipath RPL ODeSe algorithm. We compared this new algorithm against single-path and multipath RPL strategies under challenging link quality conditions. Our performance evaluation results demonstrate that ODeSe better addresses the trade-off between PDR and energy efficiency, making it a promising solution for industrial IoT applications.

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