Reliable and Power Confined Routing in Large and Densely Deployed 6TiSCH Mesh Networks

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***Abstract*—RPL, the de-facto standard for low power and lossy networks, forms multi-hop routing structures between network nodes and a single root. It intrinsically minimises the number of hops across the mesh, however this can result in large distances between adjacent forwarding nodes. Consequently, during forwarding operations, the received signal strength can be close to the receiver sensitivity threshold and result in frequent packet losses due to link fluctuations. RECLAIM, our proposed approach, overcomes this challenge by transmitting route-building messages at a reduced power level at first while switching back to the normal transmission power level during the actual data communication phase. This results in more reliable links per hop and ensures link budget above the receiver sensitivity threshold. This however creates more hops and a longer routing path in order to reach destination. Hence, RECLAIM further applies efficient and non-conflicting 6TiSCH scheduling method to coordinate those communication events in a non conflicting manner which do not collide or cause interference to each other, resolving the issue that has traditionally prevented this approach. Our detailed simulation shows that RECLAIM drops 60 times less packets than standard RPL, and achieves 99.9999% packet delivery ratio.**

***Index Terms*—6TiSCH; Routing; RPL; IEEE 802.15.4; Mesh Network; IoT;**

I. Introduction

Monitoring and control activities for industrial processes have traditionally been considered expensive, due to the vast number of sensors that must be installed, operated, and maintained; particularly when a wired network is required to facilitate communication. However, there have been significant advances in the field of Wireless Sensor Networks (WSNs) and Internet of Things (IoT), which offer the possibility of low-cost and highly flexible wireless networks. Yet while the use of wireless sensors is clearly advantageous to industrial monitoring scenarios, it is not without its challenges. Specifically, the presence of large metallic equipment and stringent reliability and security requirements result in harsh operating conditions for WSNs.

The 6TiSCH (IPv6 over time-synchronized Channel Hopping MAC) Internet Engineering Task Force (IETF) 6TiSCH standard [1], is considered by many to be the de-facto standard for industrial WSNs, and facilitates high reliability and low latency communication for IoT. However, routing in multi-hop mesh networks can be particularly challenging due to constrained devices, lossy radio links, intra-network interference, and the complexity of the multi-hop network topology.

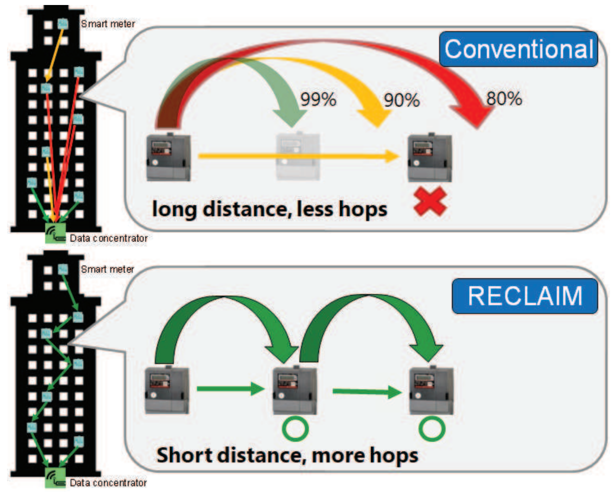


Fig. 1. Example of using RECLAIM in smart meter scenario.

As the hop count increases and nodes attempt to reach the sink via multiple relay devices, MAC contention and intra-network interference becomes very common. Consequently, the Routing Protocol for Low-Power and Lossy Networks (RPL) [2] has been adopted in the standard, which strives to create an optimized routing solution between the hop counts and other routing metrics such as Link Quality Index (LQI) or Expected Transmission Count (ETX).

Most practical networks built on RPL optimize for fewer hops in order to reduce routing complexity, MAC contention, and potential interference. However, this also increases the average communication distance and hence compromises on the link quality per hop. Despite considerable research effort, there remain situations where RPL can't achieve the high reliability required by industrial networks. A new approach to routing across a multi-hop mesh network is needed. In a time-synchronized 6TiSCH network, all communications can be scheduled and coordinated in a non-conflicting manner, and parallel transmissions on different channels can be scheduled without self-interference. We therefore propose RECLAIM (REliable and power Confined routing in Large and Densely deployed 6TiSCH Mesh networks), illustrated in the example scenario in Figure 1 and underpinned by two key concepts:

1) Confine the transmission power when forming the mesh topology, for a greater number of short distance hops.

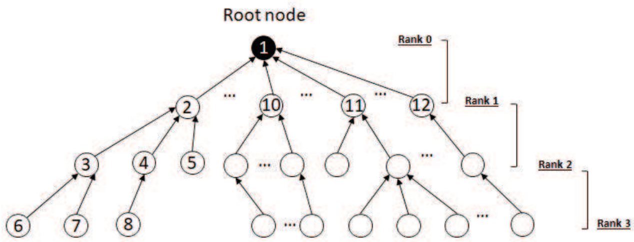


Fig. 2. Example of DODAG graph and tree topology formed by RPL.

2) Increase the transmission power for application data, taking advantage of the enhanced link quality.

The rest of the paper is organized as follows. Section II provides the background and related work. We present the proposed RECLAIM algorithm in Section III. Simulation results are illustrated in Section V. The paper finally concludes in Section VI summarizing the key findings and future work.

II. Background and Related Work

A. Mesh topology and RPL routing

Unlike wired networks, where the routing topology is imposed by the physical wires, low power and lossy networks do not typically have predefined topologies. As a result, the RPL routing protocol must discover links and maintain the topology. RPL builds this routing topology as a tree-like Destination-Orientated Directed Acyclic Graph (DODAG), as shown in Figure 2, which is optimised for communications to and from a single root node. Each edge of the DODAG represents a communication link between two nodes, which are configured in a parent-child relationship. RPL defines three control messages topology formation:

- **DAG Information Objection (DIO):** carries information on the RPL topology, allowing nodes to learn configuration parameters and select a parent from the DODAG.
- **DAG Information Solicitation (DIS):** used to perform neighbor discovery and solicit DIO messages from a neighboring node.
- **Destination Advertisement Object (DAO):** used to propagate destination information upwards along the edges of the DODAG towards the root node.

DODAG construction is initiated by a DIO control message broadcast from the root. Nodes receiving this message can choose to join the DODAG by adding the sender to its parent list, and computing its rank relative to the parent node based on an objective function such as Minimum Rank Objective Function (MRHOF) and Objective Function Zero (OF0) [2].

$$Rank(nodeID) = Rank(ParentID) + Rank_{increase} \quad (1)$$

$$Rank_{increase} = (R_f \times S_p + S_r) \times MinHopRankInc \quad (2)$$

Equations 1 & 2 briefly outline OF0: the constant $MinHopRankInc$ corresponds to the minimum rank increase imposed for a hop in the DODAG; R_f is a configurable value known as the *rank factor*, which is used to multiply the effect of the link property parameter on the rank increase computation; S_p is a computed value, based on the link properties with a neighbouring node, and is known as the *step of rank*; and S_r is a configurable value known as the *stretch of rank*, indicating a maximum augmentation to S_p. In common practice S_r is set to one, meaning that a node with a greater number of hops could result in a higher rank value, and therefore be less likely to be chosen as the preferred parent. As a result, a shorter path comprising of a smaller number of hops, but with poorer link property metrics, could be chosen over a longer path with a greater number of hops but with better link property metrics.

B. Power Control Aware Routing in Mesh Networks

To reduce interference and MAC contention, power control aware routing protocols for ad-hoc mesh networks ask the question: what is the optimal common power level under a shared wireless medium? Excessively high transmission power may cause interference, while lower power levels will result in fewer links but may partition the network. Notably, COMPOW [3] is a proactive centralized routing protocol that uses different transmission powers to create multiple routing trees. A minimum possible common power level is chosen for data communication, whilst ensuring network connectivity. COMPOW aims to achieve full network connectivity while reducing intra-network contention and interference. OPC-OR proposed in [4], is designed to make a compromise between the enhancement of overall network performance and the decrease of the total energy consumption. Finally, as far as the authors aware, most of the existing work in this domain apply the same transmission power for both signalling messages forming the network as well as the actual data messages, which is a different case for RECLAIM.

C. A New Approach to Mesh Routing

It has been proven that CSMA contention based methods don't scale as the number of communications increases [5]. Conventional RPL networks therefore favour paths comprising of fewer hops when forming a routing topology. This is advantageous when common wireless channel is used for the entire network, as having more hops results in greater contention for radio resources and a further chance of intra-network interference. However, as the network grows the chance of contention increases, and the network can suffer from reduced reliability and increased latency.

Unlike other Low Power and Lossy Networks (LLNs), time-synchronized 6TiSCH networks can be scheduled and coordinated in a non-conflicting manner. In light of this, many of the original objectives of RPL are no longer applicable, namely, the desire to reduce the number of hops in order to reduce channel contention. We consequently propose RECLAIM, compared against both RPL and COMPOW in Table I, with the aim of minimising the end-to-end packet loss rate to achieve high reliability:

TABLE I
COMPARISONS WITH THE STATE OF THE ART.

	Type	Complexity	Power Control	Link Quality	High Reliability	Aim
RPL [2]	Distributed	Low	×	✓	×	$<$ hops + $<$ contention
COMPOW [3]	Centralized	High	✓	×	×	$< T_x$ Power + $<$ contention
OPC-OR [4]	Centralized	High	✓	✓	×	$< T_x$ Power + $<$ Energy
RECLAIM	Distributed	Low	✓	✓	✓	$<$ range + $>$ hops + $> T_x$ power for data

1) Prioritise bi-directional link reliability along a routing path, and select the most reliable path based on the proposed Priority Routing Index (PRI) index. This is a trade-off against possible greater hops between a node and the DODAG root, which can be solved in upper layers with optimized 6TiSCH scheduling.
2) Use reduced power to form the routing topology, whilst use full power for actual data transmissions to ensure communication reliability.
3) RECLAIM does not require the geographical distance information among nodes. Rather, it utilizes both PRI and RPL ranking to avoid communication loops.

III. Proposed RECLAIM Solution

RECLAIM is a reactive routing protocol based on RPL, but with a different focus. Compared with RPL, a path composed of several short hops is preferred over a path formed with fewer hops but a greater distance at each link: with the aim of creating the most reliable routing path. It contains two main stages:

- **Stage 1 - Signalling:** firstly, power confined signalling is used to search for a path consisting of shorter distance hops, whilst normal RPL signalling ensures connectivity.
- **Stage 2 - Data Communication:** higher T_x power is used for the actual data communication phase, with upper 6TOP layer and scheduling used to coordinate communication as well as avoid interference and collisions.

Signalling in RECLAIM follows similar steps in RPL: where DIO, DAO and DIS messages are used to form a routing tree. However, RECLAIM allows different power levels to be used during the joining process to ensure reliable, short distance hops in the routing tree. Once a node formally joins the network, a predefined higher transmission power level is set for other communication events, such as scheduling, data communication and other non-routing related signalling. For simplicity, two T_x power levels are used in the example discussed below:

- Messages transmitted with the maximum power level, M_f (i.e DIO_f, DAO_f, and DIS_f).
- Messages transmitted at a lower power level, M_r (i.e. DIO_r, DAO_r, and DIS_r).

A Priority Routing Index (PRI) is proposed that can be added to the RPL routing header of the M_f and M_r messages, the value of which can be computed as:

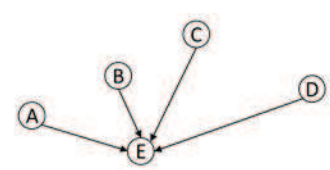
$$PRI(new) = PRI(received) + X \tag{3}$$

$$where, X = \begin{cases} 1 & when\ M_f\ is\ sent \\ 0 & when\ M_r\ is\ sent \end{cases} \tag{4}$$

In case of N different transmit power levels, N different values of X can be applied. In general, the values of X will increase with the transmit power level of the message such that a high power DIO message will have a higher PRI value than a low power message transmitted by the same node.

When forming the tree routing topology, both M_r and M_f messages will be sent following an optimized pattern. We pose a simple scenario to help convey this idea, with M_r messages and M_f messages to be sent out periodically, starting from the root node.

When a node receives a DIO, the PRI value would be updated based on whether the received message is a M_r or M_f. If node receives both M_r and M_f DIO messages from its neighbors, the parent node with the smallest PRI value is preferred, meaning there are fewer long distance hops along the path. When a node determines its preferred parent and selects it as its next hop relay, the RPL ranking is calculated using an objective function (e.g. OF0) and link metrics (e.g. ETX). Therefore, in case messages containing the same value of PRI are received, the RPL rank is subsequently used to decide the best routing candidate. While switching parent, separate DAO messages are needed with different power level settings to the old and new parents in order to complete the switch.



Parent ID	PRI	RPL rank	Preference
A	0	300	1
B	0	400	2
C	2	200	4
D	1	300	3

Fig. 3. Example of parent choice based on PRI and RPL ranks.

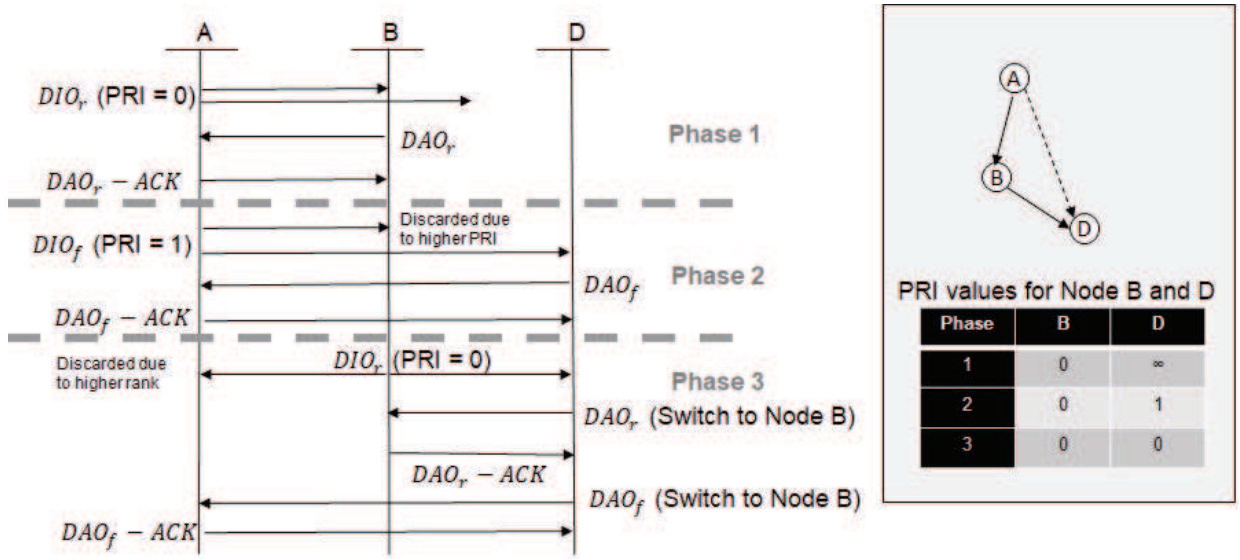


Fig. 4. Example of RECLAIM signalling.

RECLAIM maintains both PRI value and normal RPL ranks during the parent selection process. However, the PRI value has a higher priority. Only when the same PRI value is obtained will the RPL rank be further used to determine the parent node. An example is provided in Figure 3, where Node E receives DIO messages from its neighbouring nodes: A, B, C, and D. A and B have higher priority as they have a smaller value of PRI, and A is eventually selected as it has a lower RPL rank compared with B.

RECLAIM signalling steps are illustrated in Figure 4. The root node (A) first sends out the DIO_r message with reduced power level. A child node (B) receives the message and replies with a DAO_r to join the network. Upon successful reception of the DAO_r message, Node A unicasts a $DAO_r - ACK$ message to B, to confirm the join process. Node D doesn't receive this message due to the lossy link between A and D. However, it later receives the DIO_f message with full power sent from A. The PRI value is, however, increased by 1 due to full power transmission. As before, the process is repeated and D joins the network with A as its next hop node. Node B also receives the DIO_f message from A, due to a larger PRI value, however it simply discards this message with no further action. Later, during phase 3, B also broadcasts a DIO_r message with reduced power to its neighbouring nodes. This time, since the link between nodes B and D is in good condition, D successfully receives the message. The newly received DIO_r has a lower PRI value compared with its previous stored value during phase 2. Node D decides to elect B as its next hop parent rather than A. Two notification DAO messages are then sent to complete the switch process.

Figure 5 shows an annotated example of multi-hop parent node selection process, where a solid arrow represents a communication link through which a reduced power message from M_r messages can be received, and a dashed line represents a communication link through which only a high power message from the M_f messages can be received. In order to determine the routing topology it is first necessary to consider the PRI values in the received DIO messages and secondly, if required, the resulting rank from selecting either of the neighbouring nodes as the parent.

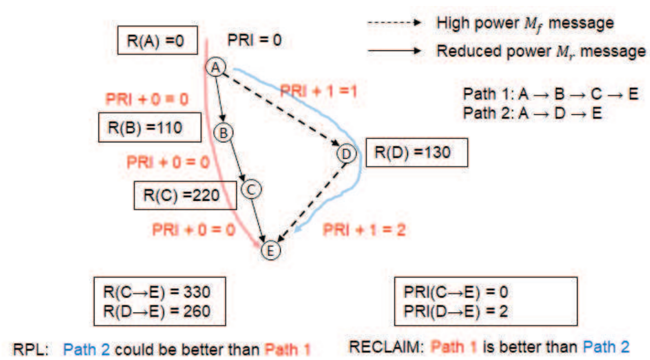


Fig. 5. Example of RECLAIM multi-hop path selection.

Path 1 comprises a route from $A - B - C - E$, and can be traversed using only reduced power messages. The PRI value, calculated in accordance with (3) & (4) and contained within the DIO message transmitted by node C, is 0, as each hop of Path 1 adds 0 to the received PRI value. Conversely, Path 2 is formed of two links through which only high power messages M_f can be received. This could be due to a number of reasons, for example large distance between nodes A, D and E. Since Path 2 can only be traversed using full power messages, the PRI value contained within the DIO packet transmitted by Node D is 2. Although the RPL ranking of Node C, R(C), is greater than R(D), in accordance with the method of parent node selection discussed above, Node C is selected as the

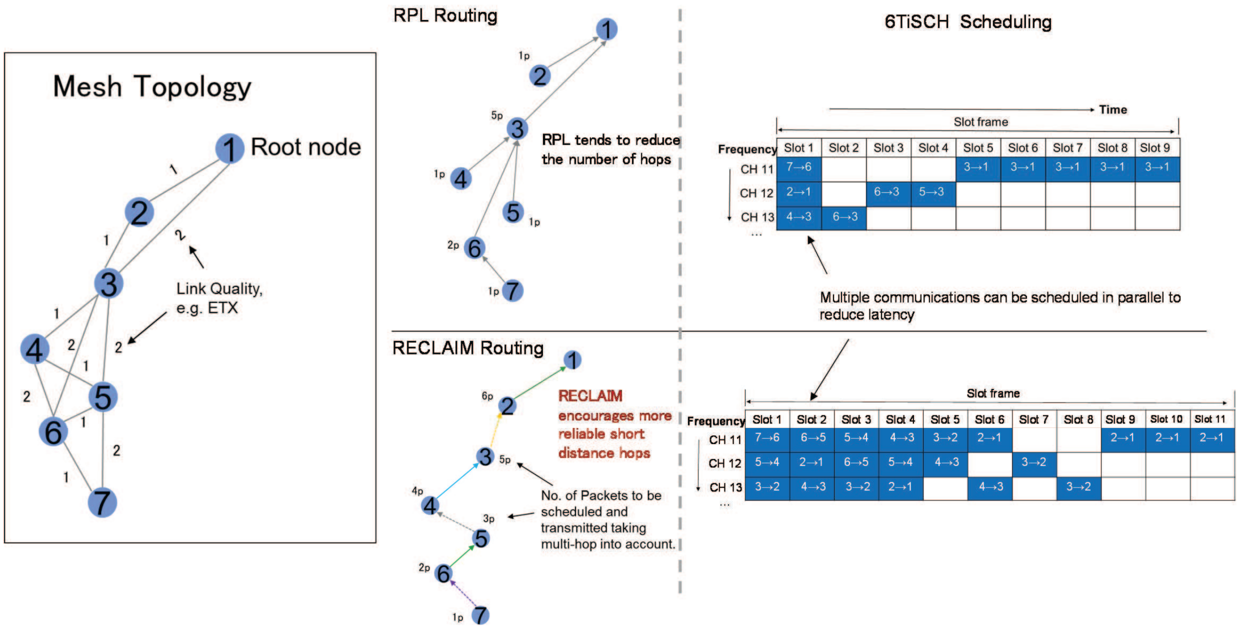


Fig. 6. Example of 6TiSCH scheduling on top of RPL and RECLAIM.

parent node for Node *E*, and RECLAIM forms Path 1 rather than Path 2.

IV. 6TiSCH Scheduling on top of RECLAIM

6TiSCH offers highly reliable, low latency communications through efficient and deterministic allocation of radio resources in the mesh. To achieve this, a scheduler orchestrates communication over individual links in an optimized and non-conflicting manner. In the time domain the schedule operates in a Time Division Multiple Access (TDMA) manner, whereas in the frequency domain it divides the wireless spectrum into multiple channels. The scheduling period is referred to as a *slot-frame*, which repeats over time. A schedule is formed by assigning *timeslot* and channel offsets to each communication link, and specifying which node should transmit or receive data to/from its scheduled counterpart within a *slot-frame*. Channel-hopping is also adopted, where communication links hop over a set of available channels in a pseudo-random pattern among *slot-frames*, mitigating the effect of narrow-band interference and multi-path fading.

Figure 6 illustrates the operation of 6TiSCH scheduling on top of RPL and RECLAIM. A tree topology is firstly formed, and by further adopting 6TiSCH scheduling algorithms such as [6] all communication links can be scheduled and coordinated in a non-conflicting manner. The tables shown on the right of Figure 6 are the schedules that are built, based on network routing trees created by RPL and RECLAIM respectively. To avoid self-interference, parallel communications can be scheduled by assigning them on different channels. While advanced 6TiSCH scheduling solutions are out of the scope of this paper, more details can be found in a number of existing works [6]–[11]. It should be noted that, in order to avoid interference during stage 2 high power data communication, the channel reuse consideration for the scheduling algorithm has to be carefully considered, e.g. it is only possible to reuse the same channel for least K hops, where K should be larger than i.e. 5 rather than a typical setting of 3.

V. Simulation Evaluation

In this paper we evaluate the RECLAIM algorithm, via simulation, in a network with 1000 nodes per root: representative of the targeted smart meter applications in urban cities, with large-scale and dense deployment. All nodes are uniformly distributed, with the root node located at the centre of the network. The IEEE 802.15.4g based physical layer with Sub-GHz radio is assumed, and a Rayleigh fading model is adopted for urban environments. It is further assumed that there is a periodic traffic pattern, and the distributed 6TiSCH scheduling algorithm [6] is applied on top of the IETF RPL protocol and proposed RECLAIM solution in order to achieve a fair comparison.

TABLE II
Network and scheduling comparison illustrated in Fig.7

	Max Hops	Scheduled Communications (cells)	Schedule Length (timeslots)
RPL	7	6972	1998
RECLAIM	14	13068	2010

Figure 7 graphically compares the network topologies formed by RECLAIM and RPL respectively. The color bar indicates link quality ranging from $[\ 70\% \sim 99\%\ ]$ of average successful reception ratio, where green represents high reliability link, while red indicates poor connections. Figure 7a

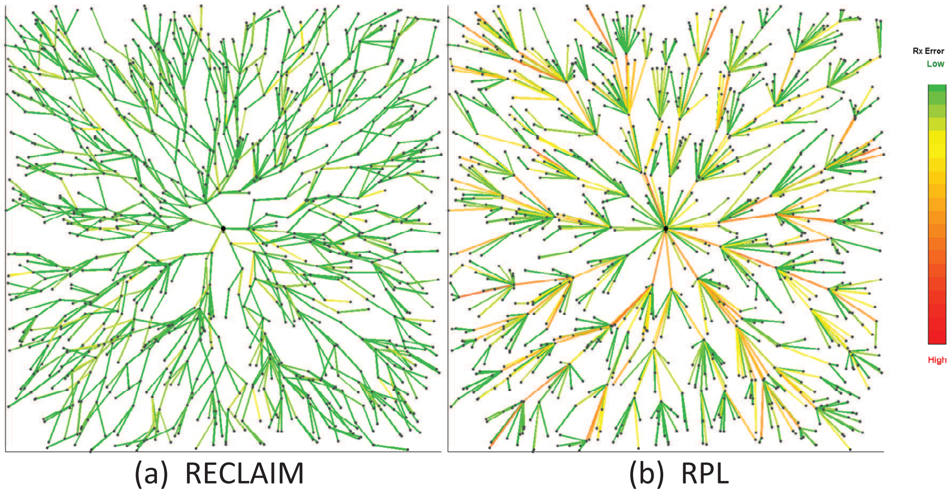


Fig. 7. Comparison of network topology by adopting RECLAIM or RPL.

shows that RECLAIM creates more hops, where the maximum number of hops for a leaf node to reach the root node at the centre is 14, whereas 7a shows that RPL creates a maximum of 7. However, it can be clearly observed that the topology formed by RPL involves a considerable number of low quality communication links. In contrast, RECLAIM encourages more reliable, shorter distance hops between a node and the root node. As a result, RECLAIM packet drop rate is less than 60 times that of RPL. Notably, the total schedule latency is only increased by less than 0.6% since the 6TiSCH scheduling algorithm schedules non-interfering parallel communications, as previously shown in Figure 6. However, there is a trade-off. The 6TiSCH algorithm has to schedule 13068 communication events (*slot-frame* cells) using RECLAIM, as opposed to 6972 events when using standard RPL. It is therefore possible that RECLAIM could impose high scheduling complexity when adopting centralized scheduling solution such as [8], in which algorithm complexity may grow exponentially with the number of cells. However, the use of decentralized scheduling algorithms such as [6] or [7] can effectively solve this issue.

TABLE III
PACKET DELIVERY STATISTICS V.S. MAC RETRANSMISSIONS

RT_x No.	Total T_x	RPL		RECLAIM	
		R_x	Dropped	R_x	Dropped
1	1581903	1013162	568741	1572411	9492
2	1598602	1514195	84407	1598282	310
3	1343503	1325432	18071	1343489	14
4	1034233	1034231	3102	1034231	2
5	1287845	1287149	696	1287844	1

We further monitored all packets drop events during simulation, by varying the MAC retransmission (RT_x) settings from 1 to 5. As the MAC RT_x increases fewer packets are dropped for both RPL and RECLAIM, as shown in Table III. Although RPL enjoys decent Packet Delivery Ratios (PDR) of $> 99.9\%$ when the MAC RT_x is increased to 5 (as shown in Figure 8),

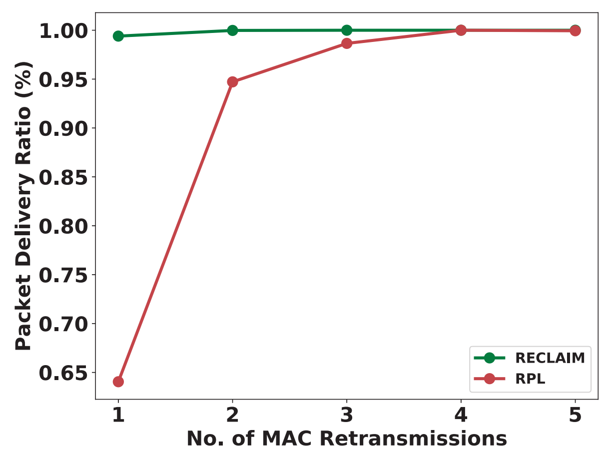


Fig. 8. Packet Delivery Ratio (PDR) vs number of MAC retransmissions.

it still continues to drop a considerable number of packets. In stark contrast, at MAC RT_x 5, RECLAIM manages to drop only 1 packet in over a million: a PDR of over 99.9999%. This is significant, as while retransmissions may be necessary to communicate a packet reliably, they can introduce significant delays and cause unnecessary congestion in the network due to buffering.

Total energy consumption is compared in Figure 9. RECLAIM consumes almost twice the amount of energy spent on normal communication events in comparison to RPL, stemming from the fact that it has effectively double the amount of scheduled communication events. However, while the energy spent on MAC RT_x is almost negligible for RECLAIM, RPL further wastes considerable energy on these events due to heavy losses on poorer links. Overall, RECLAIM spends around 25% more total energy, however it drops 60 times less packets compared that of RPL. Hence, it grealty enhances communication reliability and we argue that RECLAIM + 6TiSCH is ideally suited to industrial applications where

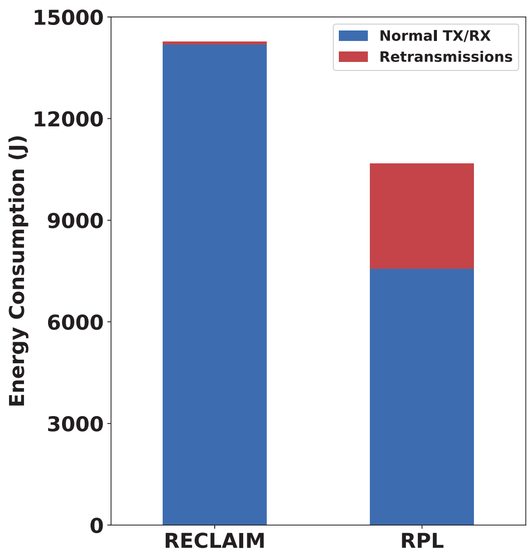


Fig. 9. Comparison of total energy spent on normal communication and retransmission events. MAC retransmissions are sets to 3.

communication reliability (PDR $>$ 99.999%) is generally the key requirement when trading off against low energy consumption.

VI. Conclusions and Future Work

For conventional routing protocols such as RPL, a shorter path comprising a smaller number of hops will generally be preferred over a longer path with a greater number of hops. This is due to the fact that it advantageous in situations where MAC contention affects communication reliability as a dominant. However, in light of the scheduling approaches adopted in 6TiSCH, the proposed RECLAIM solution aims to create a path formed of multiple high-reliability hops, in order to alleviate MAC contention and intra-network interference. Despite RECLAIM consumes 25% more energy and increases end-to-end lantecy by 1% compred with RPL, the overall reliability in terms of PDR is significantly improved by dropping 60 times less packets. This paves the way to for realizing wireless monitoring for indurial applications where the reliability requirement often $>$ 99.999%. We plan to further evaluate RECLAIM as a standards-compliant extension of RPL through an implementation on the low-power Contiki-NG operating system [12] for low-power devices.

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