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Minimizing Route Overlap for Priority Data Delivery in Next Generation IoT Networks

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***Abstract*—With the advent of 5G and beyond communication technologies, the consumer IoT devices are evolving from current generation to next generation. The next generation IoT devices are capable of supporting multiple communication modes and performing more functions. During the migration phase, it is impractical to completely remove the deployed current generation devices. Accordingly, the next generation IoT networks will consist of the mixed current and next generation devices. To that end, how to efficiently route diverse data in next generation IoT networks needs to be addressed. This paper presents a two-topology routing architecture for next generation IoT networks, one topology for regular data delivery and another topology for priority data delivery. The priority routes are discovered to minimize route overlap. We evaluated our route discovery algorithms under varying network configurations. Compared with standard RPL baseline, the proposed routing algorithms can simultaneously reduce route overlap, route transmission time and route length.**

***Index Terms*—Next generation IoT networks, route overlap minimization, multi-mode communications.**

I. INTRODUCTION

The consumer IoT devices are evolving from current generation (G) to next G. The current G devices installed with less resources and perform simple function, e.g., support one communication mode and collect periodic data. On the other hand, the next G devices are equipped with more resources and can perform more functions, e.g., support multiple communication modes/protocols and collect both periodic and event based data. However, it is impractical to completely remove the deployed current G devices during this migration phase. To that end, the next G IoT networks will consist of the mixed current and next G devices. Take next G smart meter network for example, which will consist of current G regular meters and next G priority meters. The regular meters periodically collect and deliver metering data. However, the priority meters not only collect metering data but also sense power supply information, which is critical for power suppliers to make predictive maintenance and diagnose the cause of the abnormal events such as power outage and therefore, has higher priority than regular metering data. Accordingly, besides the metering data, the priority meters also need to efficiently deliver power supply information. Therefore, new routing architecture is needed to delivery heterogeneous data in next G IoT networks.

The routing has been extensively studied for many years. It is a high complexity problem consisting of route discovery and route scheduling. The route discovery can be NP-complete [1], e.g., maximizing throughput in multi-hop wireless network is proved to be NP-hard as a result of the wireless interference [2]. It has been also proved that both centralized and distributed route scheduling problems are NP-complete in 2D mesh topology [3], which indicates the complexity of the route scheduling problem.

Among many existing routing algorithms, there are well known classic route discovery protocols including Dijkstra's shortest path algorithm, dynamic source routing (DSR) and ad-hoc on-demand distance vector (AODV). The IPv6 Routing Protocol for Low-Power and Lossy Networks (RPL) [4] is a standard routing protocol designed for IoT networks. However, these routing protocols are designed for homogeneous networks without considering node heterogeneity and data heterogeneity, e.g., RPL does not distinguish router capability in routing topology construction and sends all uplink traffic to default parent. Accordingly, it is necessary to address routing challenges arising in next G IoT networks.

Route overlap is one of the issues to be addressed in next G IoT networks, especially for priority data delivery. Route overlap can significantly affect network performance. The overlapped routes can delay data delivery and cause data loss. To improve the reliability of data delivery, especially priority data delivery, route overlap needs to be minimized. Authors in [5] and [6] present algorithms to find K-shortest paths with limited overlap. Work [7] proposes an algorithm to compress routing tables. Paper [8] proposes the earliest-deadline-first scheduling and minimal-overlap shortest-path routing for real-time TSCH network. However, these routing schemes are developed for P2P routing and do not consider node heterogeneity as well.

This paper focuses on route discovery. We propose a two-topology MP2P routing architecture for next G IoT networks with one topology for regular data delivery and another topology for priority data delivery. The regular routes named as D-Routes are discovered for all nodes and the priority routes known as P-Routes are discovered for priority nodes only. We formulate P-Route discovery as optimization problem to minimize route overlap. The minimal overlap routes are further optimized with route transmission time and route length objectives.

II. RELATED WORKS

There are many routing protocols for various multi-hop networks. Dijkstra's algorithm is a distance based algorithm to find the shortest paths from one particular node to all other nodes in the graph. DSR and AODV are two reactive routing protocols for mobile ad-hoc networks. The difference is that DSR uses source routing and AODV employs routing table. The reactive routing protocols discover routes on demand and therefore, fit ah-hoc network well. RPL [4] is a proactive routing protocol that maintains information on all routes throughout the network and thus, fits stationary network well, especially when all nodes have data to deliver. RPL organizes nodes in a low-power and lossy network into a tree-like topology called Destination Oriented Directed Acyclic Graph (DODAG). RPL routing protocol has been extensively evaluated and enhanced in many works such as paper [9]. However, these classic routing protocols do not address issues such as route overlap, node capability and data heterogeneity.

Papers [5] and [6] propose algorithms to find K-shortest paths from a source s to a target t in road networks with limited overlap. The k-shortest paths are (a) as short as possible and (b) sufficiently dissimilar based on a user-controlled similarity threshold. Authors formally proved that their multi-path algorithms are optimal in terms of complexity. However, the algorithms are designed for P2P routing without considering node heterogeneity. Work [7] presents an algorithm to compress routing tables with a minimal number of prefixes under the constraint that all the prefixes are not overlapped. This algorithm is proposed for the Internet backbone not for IoT networks. Authors in [8] propose the earliest-deadline-first scheduling and minimal-overlap shortest-path routing for real-time TSCH network, in which a greedy heuristic is applied to reduce overlap. Again, this paper considers P2P routing with one node type as well.

In terms of route overlap, the MP2P routing is different from P2P routing. In MP2P routing, the common destination node, i.e., data concentrator, is on all routes but does not transmit or relay data. Therefore, route overlap does not need to consider the common destination node. In P2P routing, a node can be the destination on one route but can also be the source on another route. Thus, all nodes on the routes need to be considered in route overlap. Therefore, we propose optimal routing algorithms to minimize route overlap for MP2P routing.

III. SYSTEM MODEL

This paper introduces a two-topology routing architecture to route both regular data and priority data in next G IoT networks, where nodes supporting one communication modulation scheme are called single-mode nodes and nodes supporting multiple communication modulation schemes are named as multi-mode nodes. The priority nodes and multi-mode nodes are considered as next G nodes and regular single-mode nodes are treated as current G nodes.

We consider a next G IoT network consisting of a data concentrator, a set of N regular data nodes named as D-Nodes and a set of M priority data nodes named as P-Nodes, where both D-Nodes and P-Nodes can be single-mode or multi-mode. The data concentrator is considered as a multi-mode node. The communications among single-mode nodes and between single-mode nodes and multi-mode nodes use low rate mode. The high rate mode can be only applied among multi-mode nodes. The deployment of D-Nodes and P-Nodes are random.

Fig.1 illustrates the proposed two-topology routing architecture, where node C is data concentrator, green nodes are P-Nodes, blue nodes are multi-mode D-Nodes and white nodes are single-mode D-Nodes, the thin dash lines represent low rate links, the thick dash lines represent high rate links, the red solid arrows are D-Routes for all nodes and the green solid arrows represent zero-overlap P-Routes for P-Nodes.

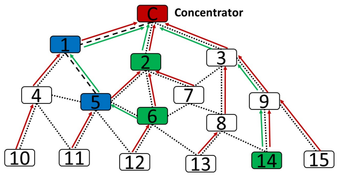

Fig. 1. Multi-Hop IoT Network Consisting of Heterogeneous Nodes

IV. DISTRIBUTED D-ROUTE DISCOVERY

We enhance RPL routing protocol for D-Route discovery. RPL uses the DODAG Information Object (DIO) message for upward route discovery and the Destination Advertisement Object (DAO) message for downward route construction. To fulfil P-Route discovery, each node also performs neighbor discovery during D-Route discovery. A node considers another node as a neighbor if it overhears the broadcasted DIO message from that node. Once D-Route discovery completes, each data node sends its neighbor information to data concentrator via a DAO message.

A. Carrying Communication Mode and Multi-Mode Link Count in DIO Message

The DIO message carries information that allows a node to learn DODAG configuration parameters for parent selection. In this paper, the communication mode (CM) and the multi-mode link count (MLC) are also included in DIO message with CM = 1 indicating single-mode and CM = 2 indicating multi-mode. Using CM parameter, the MLC metric can be computed to represent the number of multi-mode links along a route. At the data concentrator, CM is set to 2 and MLC is set to 0. During D-Route discovery process, a data node increases MLC by 1 if it is a multi-mode node and the DIO message transmitter is also a multi-mode node. Data nodes use RPL rank metric and MLC metric to select parents. If the ranks are same, a data node selects a route with the larger MLC since it consists of more high rate multi-mode links.

B. Carrying Accumulated Traffic Load in DAO Message

Traffic load can significantly impact network performance. However, it has been not well addressed in RPL routing protocol. In this paper, each data node includes its accumulated traffic load information into DAO message. In RPL protocol, a data node not only sends its own data but also relays its children's data to default parent. Therefore, the accumulated traffic load (ATL) at a data node n can be expressed as

$$ATL(n) = LD(n) + \sum_{k=1}^{n_c} ATL(c_k^n), \tag{1}$$

where $LD(n)$ is traffic load of node n, n_c is the number of children of node n and c_k^n $(k = 1, 2, ..., n_c)$ are the children. The ATL information is used in P-Route discovery.

V. CENTRALIZED P-ROUTE DISCOVERY

Once neighbor information is available, the data concentrator C can discover optimal P-Routes for the P-Nodes.

Let denote as $\mathbb{P} \overset{\text{def}}{=} \{p_1,p_2,...,p_M\}$ set of P-Nodes in the network and $R_{p_i} \overset{\text{def}}{=} (f_0^i = p_i, f_1^i, f_2^i, \ldots, f_{h_i}^i, C)$ a P-Route from P-Node p_i to data concentrator C ($i = 1,2,...,M$), then the set $\mathbb{F}_{p_i} \overset{\text{def}}{=} \{f_0^i = p_i, f_1^i, f_2^i, \ldots, f_{h_i}^i\}$ consists of nodes on the route R_{p_i} that transmit or forward data in priority data delivery process and therefore, is named as forward set of route R_{p_i} and nodes in $\mathbb{F}_{p_i}$ are referred to as forward nodes.

A. MP2P Route Overlap Definition and Calculation

There are different definitions for route overlap. Work [5] defines the link (edge) overlap as route overlap. However, this definition may undercount route overlap, e.g., in Fig.1, routes $(11,5,1,C)$ and $(12,5,2,C)$ overlap at node 5, but there is no link overlap on these two routes. Paper [8] defines route overlap as the sum of all individual node overlaps between any pair of the routes. This node based overlap definition for P2P routing may overcount the overlap of MP2P routes, e.g., aforementioned two routes have only one effective node overlap at node 5 since data concentrator C does not transmit data, yet this definition gives two overlaps, one at node 5 and another one at node C.

In this paper, we introduce a route overlap definition for MP2P routes, where data concentrator C is excluded in route overlap computation. The degree of route overlap (DRO) for routes $R_{p_1}, R_{p_2}, ..., R_{p_M}$ is defined as the sum of individual forward node overlaps by routes $R_{p_1}, R_{p_2}, ..., R_{p_M}$, i.e., total number of times routes $R_{p_1}, R_{p_2}, ..., R_{p_M}$ repeatedly pass through the forward nodes, e.g., aforementioned forward node 5 repeats once. To mathematically calculate the DRO, let denote as $Len(\cdot)$ the length of a route and $N_D(R_{p_1}, R_{p_2}, ..., R_{p_M})$ the total number of the distinct forward nodes on the routes $R_{p_1}, R_{p_2}, ..., R_{p_M}$. The DRO of the routes $R_{p_1}, R_{p_2}, ..., R_{p_M}$ can be calculated as

$$DRO(R_{p_1}, R_{p_2}, ..., R_{p_M}) = \sum_{i=1}^{M} Len(R_{p_i}) - N_D(R_{p_1}, R_{p_2}, ..., R_{p_M}). \tag{2}$$

B. Acyclic Route Discovery

A MP2P route $R_p = (f_0 = p,\ f_1,\ f_2,\ \ldots,\ f_h,\ C)$ is acyclic if it satisfies following conditions

1) $f_j \neq f_k \quad \forall j \neq k$,
2) $f_j \neq C$ for $j = 0, 1, \ldots, h$,
3) f_{j+1} is a neighbor of f_j for $j = 0, 1, ..., h-1$,
4) Node C is a neighbor of f_h, and
5) Only f_h is a neighbor of concentrator C.

Let denote as $\mathbb{R}_{p_i}$ the set of all acyclic routes for P-Node p_i. The data nodes that can directly communicate with concentrator C, i.e., the physical neighbors of node C, are called as direct link nodes and other data nodes are named as non-direct link nodes. We stress that direct link node may be different from 1-hop node because link reflects physical connectivity and hop represents logic connectivity. A 1-hop node is a direct link node but a direct link node may be not a 1-hop node. We denote as $\mathbb{N}_n$ the neighbor set of node n. For a direct link node $p_d \in \mathbb{N}_C$, only one acyclic route is constructed, i.e., $\mathbb{R}_{p_d} = \{(p_d, C)\}$. For a non-direct link node p_n, this paper proposes a recursive method to discover acyclic routes. The recursive method extends an acyclic sub-route hop-by-hop starting from source node p_n to data concentrator C. Before introducing recursive acyclic route discovery algorithm, we first define the end node.

Algorithm 1: Acyclic Route Discovery

```
Input: P-Node $p_n$ and its neighbor set $\mathbb{N}_{p_n}$;
Initialize route set: $\mathbb{R}_{p_n} = \{(p_n,n_1),(p_n,n_2),...,(p_n,n_h)\}$;
Define $\mathbb{Z}^+$ as candidate set of the acyclic route ID;
Assign $i$ as ID of sub-route $(p_n,n_1)$ (i = 1, 2, ..., h);
for $i$ = 1, 2, ..., $h$ do
    Recursively extend sub-route $(p_n,n_i)$ via Algorithm 2;
end
Output: Acyclic route set $\mathbb{R}_{p_n}$
```

Definition 1. *An end node is a data node from which the extension of an acyclic sub-route ends, i.e., the sub-route cannot be extended without cycle.*

End node is different from leaf node. An end node is a leaf node, but a leaf node is not necessarily an end node. The end node decision depends on the sub-route to be extended. A node can be an end node for one sub-route extension, but it may be not an end node for another sub-route extension. In Fig.1, to extend sub-route (10,4), node 11 is not an end node, but to extend sub-route (4,5), node 11 is an end node.

Mathematically, to extend a sub-route $R_{p_n}^s = (f_0 = p_n, f_1, f_2, \ldots, f_k)$, node f_k is an end node if and only if $\mathbb{N}_{f_k} \setminus \mathbb{F}_{p_n}^s = \emptyset$, where $\mathbb{F}_{p_n}^s \overset{\text{def}}{=} \{f_0 = p_n, f_1, f_2, \ldots, f_k\}$. Accordingly, at the hop k, the extension of the sub-route $R_{p_n}^s$ (1) completes if f_k is a direct link node or (2) ends if f_k is an end node or (3) continues otherwise. The set $\mathbb{N}_{f_k} \setminus \mathbb{F}_{p_n}^s$ is named as extendable set of node f_k for the sub-route $R_{p_n}^s$.

For a non-direct link node p_n, let $\mathbb{N}_{p_n} = \{n_1, n_2, ..., n_h\}$, then Algorithms 1 and 2 describe the recursive acyclic route discovery. The introduction of route length threshold L_{max} is based on the rationale that although minimal overlap routes are desired, the very long routes are not preferred.

C. Minimal Overlap P-Route Discovery

It is not always possible to discover zero-overlap P-Routes, e.g., for more than 3 P-Nodes in Fig.1. Our objective is to minimize the route overlap. Once acyclic routes for P-Nodes are discovered, the next step is to find the acyclic routes that minimizes the DRO. This problem can be formulated as an optimization problem, i.e., find routes $R_{p_1}^o \in \mathbb{R}_{p_1}, R_{p_2}^o \in \mathbb{R}_{p_2}, ..., R_{p_M}^o \in \mathbb{R}_{p_M}$ for P-Nodes $p_1, p_2, ..., p_M$, respectively, such that

$$DRO(R_{p_1}^o, R_{p_2}^o, ..., R_{p_M}^o) = \min_{R_{p_1} \in \mathbb{R}_{p_1}, R_{p_2} \in \mathbb{R}_{p_2}, ..., R_{p_M} \in \mathbb{R}_{p_M}} DRO(R_{p_1}, R_{p_2}, ..., R_{p_M}). \tag{3}$$

It can be seen that the $DRO(R_{p_1}^o, R_{p_2}^o, ..., R_{p_M}^o) = 0$ provides an ideal solution, i.e., all routes do not overlap.

The Problem (3) is a non-linear optimization problem that can be intractable to solve, especially for large and dense networks with large number of acyclic routes. In fact, the Problem (3) belongs to combinatorial optimization problem and is weakly NP-Hard [5].

We propose a greedy heuristic method to solve the Problem (3). Our method is described in Algorithm 3, where

Algorithm 2: Recursive Acyclic Route Extension

```
Input 1: P-Node $p_n$ and its acyclic route set $\mathbb{R}_{p_n}$;
Input 2: Sub-route $R^s_{p_n} = (f_0, f_1, ..., f_k)$ and its ID $i$;
Input 3: Neighbor sets of all nodes in the network;
Input 4: Route length threshold $L_{max}$;
if $Len(R^s_{p_n}) > L_{max}$ then
    Remove route $R^s_{p_n}$ from route set $\mathbb{R}_{p_n}$;
    Replace the largest assigned route ID with $i$;
else
    if Node $f_k$ is a direct link node then
        Complete sub-route $R^s_{p_n}$ extension as $R^i_{p_n} = (R^s_{p_n}, C)$;
    else if Node $f_k$ is an end node, i.e., $\mathbb{N}_{R_n} \setminus \mathbb{F}^s_{p_n} = \emptyset$ then
        Remove sub-route $R^s_{p_n}$ from set $\mathbb{R}_{p_n}$;
        Replace the largest assigned route ID with $i$;
    else
        Let extendable set $\mathbb{N}_{f_k} \setminus \mathbb{F}^s_{p_n} = \{k_1, k_2, ..., k_e\}$;
        for j=1,2, ..., e do
            if j = 1 then
                Recursively extend sub-route $(R^s_{p_n}, k_1)$;
            else
                Assign the smallest available route ID to the
                 sub-route $(R^s_{p_n}, k_j)$;
                Add new sub-route $(R^s_{p_n}, k_j)$ into route set $\mathbb{R}_{p_n}$;
                Recursively extend sub-route $(R^s_{p_n}, k_j)$;
        end
Output: Updated acyclic route set $\mathbb{R}_{p_n}$
```

Algorithm 3: Minimal Overlap Route Greedy Search

```
Input 1: P-Node set $\mathbb{P}$;
Input 2: All acyclic route sets $\mathbb{R}_{p_1}, \mathbb{R}_{p_2}, ..., \mathbb{R}_{p_M}$;
Initialize degree of route overlap: $DRO = \infty$;
Initialize minimal overlap route ID set: $\mathbb{I}^{ove}_{min} = \emptyset$;
Initialize number of minimal overlap routes: $NoMOR = 0$;
for i = 1, 2, ..., M do
    Label routes in $\mathbb{R}_{p_i}$ as $R^{I_i}_{p_i}$ ($I_i$ = 1, 2, ..., $|\mathbb{R}_{p_i}|$);
end
for Each combination of $\{I_1, I_2, ..., I_M\}$ do
    Compute $DRO_{temp}$ = DRO($R^{I_1}_{p_1}, R^{I_2}_{p_2}, ..., R^{I_M}_{p_M}$) via Eq.(2);
    if $DRO_{temp} < DRO$ then
        DRO = $DRO_{temp}$;
        Empty ID set $\mathbb{I}^{ove}_{min} = \emptyset$ and set $NoMOR = 1$;
        Add combination $\{I_1, I_2, ..., I_M\}$ into ID set $\mathbb{I}^{ove}_{min}$;
    else if $DRO_{temp} = DRO$ then
        Increase $NoMOR$ by 1;
        Add combination $\{I_1, I_2, ..., I_M\}$ into ID set $\mathbb{I}^{ove}_{min}$;
end
Output: Minimal overlap route ID set $\mathbb{I}^{ove}_{min}$
```

$\mathbb{I}^{ove}_{min}$ denotes set of the minimal overlap route IDs. The route length threshold L_{max} impacts complexity of the algorithm.

VI. OBJECTIVE BASED ROUTE OPTIMIZATION

The Problem (3) can be a multi-solution problem, e.g., in Fig.1, routes (2,C), (6,5,1C), (14,9,3,C) and routes (2,C), (6,5,4,1,C), (14,8,3,C) are two sets of the routes with zero overlap. Therefore, we can find subset of the minimal overlap routes to further optimize other metrics such as route transmission time and route length. We stress that in networks without multi-mode node, the minimal length routes may give the minimal transmission time. However, in the presence of multi-mode node, these two objectives may produce different solutions.

A. Minimal Transmission Time Routes

The route transmission time (RTT) is a metric to compute data transmission time along a route. For a route $R_p = (f_0 = p, f_1, ..., f_h, C)$, assume r_0, r_1, …, r_h are the highest link transmission rates for links $[f_0 = p \to f_1]$, $[f_1 \to f_2]$, ..., $[f_h \to C]$, respectively. Then RTT of route R_p is computed as

$$RTT(R_p) = \sum_{i=0}^{h} \frac{ETX(f_i) * ATL(f_i)}{r_i}, \tag{4}$$

where $ETX(f_i)$ is the expected transmission count at node f_i $(i = 0, 1, 2, ..., h)$. For a set of minimal overlap routes identified by $\{I_1, I_2, ..., I_M\} \in \mathbb{I}^{ove}_{min}$, total RTT is given by

$$RTT(R^{I_1}_{p_1}, R^{I_2}_{p_2}, ..., R^{I_M}_{p_M}) = \sum_{k=1}^{M} RTT(R^{I_k}_{p_k}). \tag{5}$$

Our objective is to find a set of the minimal overlap routes $R^{ot}_{p_1}, R^{ot}_{p_2}, ..., R^{ot}_{p_M}$ that minimize the total RTT:

$$\begin{aligned} RTT(R^{ot}_{p_1}, R^{ot}_{p_2}, ..., R^{ot}_{p_M}) &= \\ \min_{\{I_1, I_2, ..., I_M\} \in \mathbb{I}^{ove}_{min}} & RTT(R^{I_1}_{p_1}, R^{I_2}_{p_2}, ..., R^{I_M}_{p_M}). \end{aligned} \tag{6}$$

B. Minimal Length Routes

For a set of minimal overlap routes identified by $\{I_1, I_2, ..., I_M\} \in \mathbb{I}^{ove}_{min}$, total route length is expressed as

$$Len(R^{I_1}_{p_1}, R^{I_2}_{p_2}, ..., R^{I_M}_{p_M}) = \sum_{k=1}^{M} Len(R^{I_k}_{p_k}). \tag{7}$$

Our objective is to find routes $R^{oh}_{p_1}, R^{oh}_{p_2}, ..., R^{oh}_{p_K}$ that minimize total route length:

$$\begin{aligned} Len(R^{oh}_{p_1}, R^{oh}_{p_2}, ..., R^{oh}_{p_M}) &= \\ \min_{\{I_1, I_2, ..., I_{I_M}\} \in \mathbb{I}^{ove}_{min}} & Len(R^{I_1}_{p_1}, R^{I_2}_{p_2}, ..., R^{I_M}_{p_M}). \end{aligned} \tag{8}$$

VII. PERFORMANCE EVALUATION

The D-Routes are RPL based routes and the performance of RPL routes have been extensively assessed by many works such as paper [10]. This paper focuses on evaluation of the proposed P-Routes. The brute force method is applied to solve Problems (6) and (8).

A. Simulation Settings

We use NS3 simulator with IEEE 802.15.4g communication protocol in 920 MHz band with 200 kHz channel. The PHY data rate for single-mode nodes is set to 100 $kbps$ and the high PHY data rate for multi-mode nodes is set to 800 $kbps$. The measured communication range in NS3 simulator is up to 230 $meters$. In the simulation, each P-Node delivers a priority packet of 100 bytes to the data concentrator C. We simulated varying network configurations with different number of P-Nodes. The route length threshold L_{max} is set to 20. We placed data concentrator C at the corner and center of node deployment area. The corner placement is to show how routing algorithms perform with less non-overlap options. On the other hand, the center placement aims to reveal the performance of routing algorithms with more non-overlap options.

We evaluated the proposed P-Route discovery algorithms in three aspects: (i) route overlap, (ii) data transmission time and (iii) route length. We used the standard RPL protocol as the baseline for performance comparison.

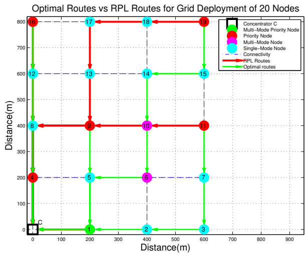

Fig. 2. Grid Deployment of 20 Nodes with Concentrator at Corner

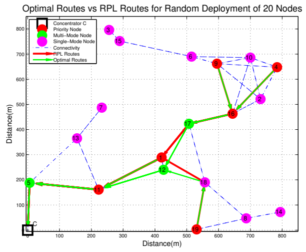

Fig. 3. Random Deployment of 20 Nodes with Concentrator at Corner

B. Grid and Random Deployment of 20 Nodes

In 20 node simulations, nodes $1,4,9,11,16$ and 19 are randomly selected as P-Nodes.

In grid node deployment, 19 data nodes are deployed in a $600\,meter \times 800\,meter$ rectangle with $200\,meter$ grid distance as shown in Fig.2. Nodes $1,6$ and 10 are multi-mode nodes and the rest of nodes are single-mode nodes. As a result, node 1 is a multi-mode priority node. The RPL routes overlap 9 times with total 21 hops and $161\,ms$ transmission time. On the other hand, the minimal overlap routes have 5 overlaps (44% route overlap reduction) with $21-23$ hops. Fig.2 shows one set of minimal overlap routes with minimal transmission time of $133\,ms$ and 21 hops. Optimal routes take advantage of high rate links $[1 \rightarrow C]$ and $[10 \rightarrow 6]$ to reduce transmission time by $28\,ms$ (17%) while maintaining same route length.

In random node deployment, 19 data nodes are randomly deployed in a $800\,meter \times 800\,meter$ square as shown in Fig.3. Nodes $5,12$ and 17 are multi-mode nodes and the rest of data nodes are single-mode nodes. The RPL routes overlap 18 times with total 27 hops and $174\,ms$ transmission time. On the other hand, the minimal overlap routes have 17 overlaps (6% route overlap reduction) with $27-32$ hops. Fig.3 shows one set of minimal overlap routes with minimal transmission time of $153\,ms$ and 27 hops. Once again, the optimal routes utilize high rate links $[17 \rightarrow 12]$ to reduce transmission time by $21\,ms$ (12%) while maintaining same route length.

These results reveal the impact of multi-mode nodes on route transmission time.

C. Random Square Deployment of 50 Nodes

In the simulations, 49 data nodes are randomly deployed in a $1200\,meter \times 1200\,meter$ square with the data concentrator C being deployed at the corner and center, respectively. There is no multi-mode node. We intentionally select P-Nodes to be far away from the data concentrator C to show the trade off between route overlap and route transmission time without multi-mode node.

When the data concentrater C is placed at the corner as shown in Fig.4, nodes $6,10$ and 11 are selected as P-Nodes. The RPL routes overlap 9 times with total 30 hops and $240\,ms$ transmission time. The minimal overlap routes have 6 overlaps with $34-45$ hops. Fig.4 shows one set of minimal overlap routes with 34 hops and $272\,ms$ transmission time. For P-Node 10, RPL route takes shorter lower branch but optimal route takes longer upper branch to reduce overlap. As a result, the optimal routes reduce 3 (33%) route overlaps, but increase route length by 4 hops (13%) and transmission time by $32\,ms$ (13%). Two unidirectional links are detected, $[11 \rightarrow 24]$ and $[29 \rightarrow 17]$, which can be caused by the physical communication capability or packet loss during neighbor discovery. Route discovery must avoid unidirectional links.

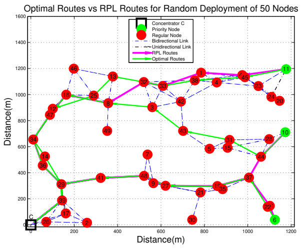

Fig. 4. Random Deployment of 50 Nodes with Concentrator at Corner

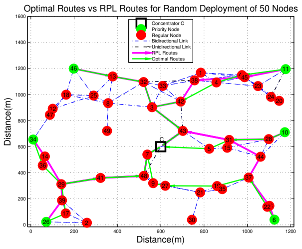

Fig. 5. Random Deployment of 50 Nodes with Concentrator at Center

When the data concentrater C is placed at the center as shown in Fig.5, nodes 6, 10, 11, 26, 34 and 46 are selected as P-Nodes. The RPL routes overlap 9 times with total 33 hops and $264\,ms$ transmission time. The minimal overlap routes have 6 overlaps with $34-50$ hops. Fig.5 shows one set of minimal overlap routes with 34 hops and $272\,ms$ transmission time. Accordingly, the optimal routes reduce 3 (33%) route overlaps but increase route length by 1 hop (3%) and transmission time by $8\,ms$ (3%). There are four unidirectional links in this case, $[11 \rightarrow 24]$, $[48 \rightarrow C]$, $[32 \rightarrow 38]$ and $[43 \rightarrow 42]$.

These simulations reveal that without multi-mode node, route overlap reduction can increase route transmission time and route length.

D. Grid and Random Circular Deployment of 50 Nodes

For these two deployments, we randomly selected nodes $6,10,11,48,23,37,34,45,38$ and 24 as potential P-Nodes.

For grid node deployment, we placed data concentrator C at the corner and 49 data nodes in a $1200\,meter \times 1400\,meter$ rectangle with $200\,meter$ grid distance as shown in Fig.6. A diagonal high rate path is configured from node 48 to the data concentrator C with blue color. The performance comparison between RPL routes and optimal routes is shown in Fig.7, where 1 P-Node indicates that node 6 is only P-Node, 2 P-Nodes indicates that nodes 6 and 10 are only P-Nodes, so on and so forth. Fig.6 shows the routes for 10 P-Nodes. The optimal routes outperform the RPL routes in terms of route overlap and transmission time. In particular, the optimal routes reduce route overlap from 3 to 0 (100%) for 3 P-Nodes and reduce transmission time from $500\,ms$ to $290\,ms$ (42%) for 9 P-Nodes. However, the optimal routes increase route length for 3-5 P-Nodes, e.g., from 15 hops to 17 hops (13%) for 3 P-Nodes. These results shows that with the help of multi-mode node, the longer optimal routes can have shorter transmission time.

For circular node deployment, the data concentrator C is placed at the center and 49 data nodes are randomly deployed in a circle with radius of $500\,meters$ as shown in Fig.8. There is no multi-mode node in this setting. This deployment aims to provide more opportunities for non-overlap route discovery. The neighbor discovery shows that the data concentrator C has 15 physical neighbors.

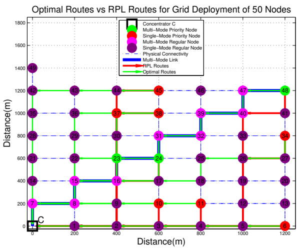

Fig. 6. 50 Nodes with Grid Deployment

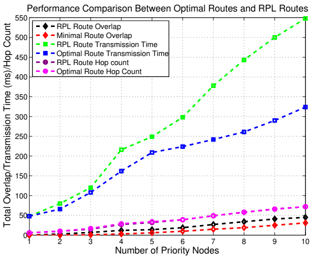

Fig. 7. Optimal Routes and RPL Routes Performance Comparison

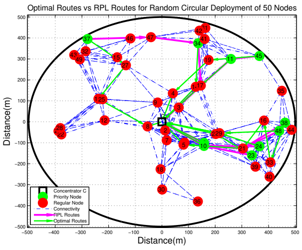

Fig. 8. 50 Nodes with Random Circular Deployment

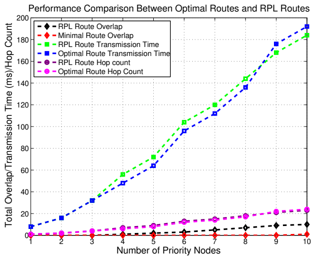

Fig. 9. Optimal Routes and RPL Routes Performance Comparison

Theoretically, we can discover non-overlap routes for 15 P-Nodes. However, due to random node deployment, 6 of 10 P-Nodes are deployed at the southeast branch. As a result, the optimal routes have 1 overlap for 10 P-Nodes as shown in Fig.9. On the other hand, the RPL route overlap starts from 4 P-Nodes with 1 overlap and increases to 10 overlaps for 10 P-Nodes. Accordingly, the optimal routes reduce 100% of route overlap for 4-9 P-Nodes and reduce 90% route overlap for 10 P-Nodes. The route length is same for 1-3 P-Nodes, i.e., 1, 2 and 4 hops, respectively. The optimal routes reduce route hops from 7 to 6 (14%), 9 to 8 (11%), 13 to 12 (8%), 15 to 14 (7%) and 18 to 17 (6%) for 4-8 P-Nodes respectively and however, increase route hops from 21 to 22 (5%) and 23 to 24 (4%) for 9-10 P-Nodes, respectively. The transmission time equals to 8 × route length (*ms*) since there is no multi-mode node and no re-transmission was performed in the simulation, i.e., ETX = 1 in Eq.(4). In particular, these results show that without multi-mode node, the optimal routes can simultaneously reduce route overlap, transmission time and route length for 4-8 P-Nodes.

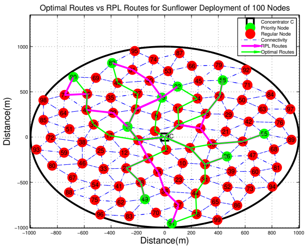

Fig. 10. 100 Nodes with Sunflower Deployment

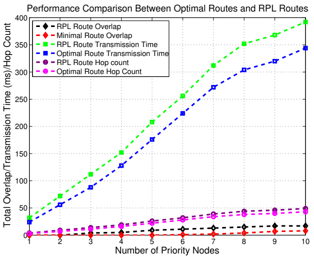

Fig. 11. Optimal Routes and RPL Routes Performance Comparison

E. Sunflower Deployment of 100 Nodes

The data concentrator C is placed at the center and the Sunflower algorithm is applied to deploy 99 data nodes in a circle with radius of 1000 *meters* as shown in Fig.10. Nodes 19, 55, 32, 49, 82, 91, 90, 58, 9 and 26 are randomly selected as potential P-Nodes. There is no multi-mode node in this setting. The optimal routes outperform the RPL routes in terms of overlap, route length and transmission time. The RPL routes overlap 0, 0, 4, 5, 9, 11, 13, 15, 17 and 17 times, respectively. The optimal routes overlap 0, 0, 0, 0, 0, 1, 2, 4, 7 and 8 times, respectively. The RPL route lengths are 4, 9, 14, 19, 26, 32, 39, 44, 46 and 49 hops, respectively. The optimal route lengths are 3, 7, 11, 16, 22, 28, 34, 38, 40 and 43 hops, respectively. Again, the transmission time is 8 × route length (*ms*). These results are shown in Fig.11. In particular, the optimal routes simultaneously reduce 100% route overlap, 21% route length and 21% transmission time for 3 P-Nodes.

VIII. CONCLUSION

The consumer IoT devices are evolving from the current generation to the next generation. Although the next generation devices are more capable than the current generation devices, it is impractical to remove the deployed current generation devices. As a result, the next generation IoT networks will consist of the mixed current generation and next generation nodes. The next generation IoT networks are expected to efficiently deliver heterogeneous data with different priorities by fully utilizing multi-mode communication capability of the next generation nodes. However, how to route heterogeneous data in next generation IoT networks is not well addressed. This paper proposes a two-topology routing architecture to deliver regular data and priority data in next generation IoT networks. Compared with standard RPL baseline, the proposed optimal routes can simultaneously reduce up to 100% route overlap, 21% transmission time and 21% route length.

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