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ARTICLE TYPE

Operations, Administration and Maintenance (OAM) features for Reliable and Available Wireless (RAW) Networks

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Summary

Though the requirements are well defined and established, the adoption of radios for mission critical applications is lagging due to the fuzzy transmission characteristics of the wireless medium. To enable automation and safety applications, in particular for Machine-to-Machine traffic, strict reliability and availability demands must be met end-to-end. The Reliable and Available Wireless (RAW) Working Group (WG) aims specifically at enabling such guarantees by leveraging end-to-end Layer 3 services to compensate for the lossiness of the lower layers. In this letter, we present the Operation, Administration and Management (OAM) requirements to support industrial requirements. We detail first the operation challenge, the tools to verify that the network works properly, and to detect possibly faults. Then, we explain why we need to administrate the network to know in real time the state and the resources provisioned. Finally, we detail the mechanisms to make the network reliable and fault-tolerant.

KEYWORDS:
Industrial Internet of Things; IIoT; IoT; LLNs; Reliable and Available Wireless; RAW; Operations, Administration and Maintenance; OAM; Standardization; IETF

1 | INTRODUCTION

The wireless medium is becoming more and more essential for critical applications. However, radio transmissions are known to be lossy, contrary to the transmissions in wired networks. Thus, controlling the congestion remains insufficient to provide high reliability. Even worse, radio link quality is time and space dependent[1,2]. Thus, we expect to propose operations at the IP layer able to enable high reliability on top of these unreliable networks[3]. To provide Quality of Service (QoS) along a multi-hop path that is composed of wired and wireless technologies, additional methods required to be considered to leverage the specific properties of wireless medium.

The newly-formed Reliable and Available Wireless (RAW) Working Group (WG) in the IETF extends Deterministic Networks (DetNet) WG to approach end-to-end deterministic performances over a network that comprises wireless segments. RAW must provision sufficient radio resources to provide high reliability, *e.g.*, in terms of packet delivery ratio within delay constraints, and high availability, *e.g.*, bounded number of consecutive losses. The capability to schedule the wireless transmissions appears critical to ensure a bounded latency; it is required not only to support the computation of the end-to-end schedule, but also to control the co-channel interference within the limits of a given technology and associated spectrum. In order to ensure delivery at all times, and yet avoid the overuse of constrained resources such as bandwidth and battery, RAW methods must dynamically monitor the network infrastructure and maintain the optimal amount of logical resources for each application[4].

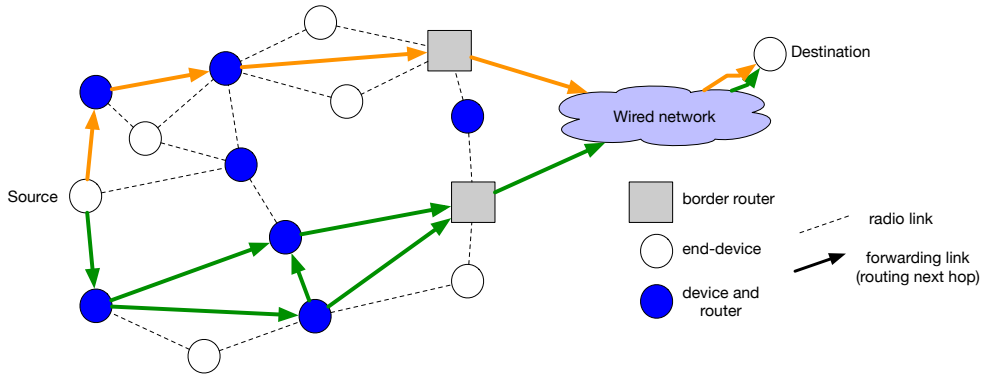

FIGURE 1 Network Infrastructure of a typical Industrial Low-Power Network.

For this purpose, we need traceability, that belongs to Operations, Administration and Maintenance (OAM). We need to provide a toolset for fault detection and isolation, and for performance measurement. These OAM tools[5] have to be tailored for the Low-power Lossy Network (LLN) world[6]. We propose here to detail the requirements of the OAM features recommended to construct a predictable communication infrastructure on top of a collection of wireless segments. We describe the benefits, problems, and trade-offs for using OAM in wireless networks to provide availability and predictability[7].

2 | PROBLEM STATEMENT

RAW aims at making the communications more reliable and predictable over wireless network infrastructure. Most critical applications need to respect Service Level Objectives (SLO), defined in an end-to-end manner. Typically, an application needs a minimum reliability and a maximum latency to work properly.

We consider a typical scenario as illustrated in Fig. 1, where a wireless network is connected to a wired network via two different border routers. A source node needs to send a collection of packets (*i.e.*, a data flow) to a destination. Since packets may be lost inside the radio network, the infrastructure selects multiple independent paths. Considering then for instance a broken link or external interference over one path, multiple different paths are established to forward the data flow to the final destination. Indeed, we have several flows (pairs of source / destination) in the heterogeneous network, that respect strict reliability and delay constraints.

In this letter, we aim at defining the OAM[8] operations that a RAW network must support:

- Operations correspond to the mechanisms to set-up to maintain the network operational. This part is also in charge of monitoring the network to identify possibly faults;
- Administration quantifies the resource that have already been allocated in the network;
- Maintenance focuses on repairing the network. This repair may be triggered after a fault has been detected, or preventively.

An OAM framework is required in RAW networks to maintain a real-time status of the network infrastructure. Thus, we can verify in real time that the SLOs are respected. Furthermore, to respect strict guarantees, RAW relies on an orchestrator (*e.g.*, SDN controller) which will be responsible to schedule the transmissions in the deployed network. Thus, resources have to be provisioned a priori to handle any defect. OAM represents the core of the over provisioning process, and maintains the network operational by updating the schedule dynamically.

What makes RAW so specific is that the network infrastructure is based on heterogeneous technologies. We must gather enough information from the link layer to take the right decisions at the IP layer (*e.g.*, packet replication, alternative paths). To make the network predictable, we must be able to capture these characteristics in real-time.

3 | OPERATION FOR RAW NETWORKS

Radio resource allocation protocols have received much attention (*e.g.*, 6P[9]). However, we still need tools to make diagnostics, and to verify the network behavior. Hereafter, we detail the operations that a RAW network must support.

3.1 | Connectivity Verification

In classical networks, ping packets help to verify that two end-hosts are well connected, *i.e.*, a route exists in both directions. In RAW networks, resources are reserved per data flow to guarantee flow isolation properties. For the same reason, the control and data packets may not follow the same path. Thus, the ping packets must be labeled in the same way as the data packets of the flow to monitor. Moreover, ping packets should not “disturb" the actual data traffic. Thus, it is of primary importance to piggyback control information inside the data flows, instead of generating additional control packets.

Existing tools like traceroute help to identify the list of routers in the route. However, the network infrastructure provisions redundant resources for each flow, so that any fault can be handled without violating any SLA. Therefore, this means that multipath routing is the rule[10]. Thus, to correctly identify unexpected behaviors, we have to implement per route tracing tools. All the possible paths between two maintenance endpoints should be retrieved. More importantly, the network infrastructure has to be able to reconstruct a priori the paths followed by a specific data packet. It might be that only one path is faulty, in such scenario the network infrastructure has to be able to identify the misbehaving subpart along the path.

3.2 | Fault Detection and Identification

We need mechanisms able to detect faults, before they impact the network performance. By fault, we mean that the network has deviated from its expected behavior, so that it jeopardizes possibly its behavior.

In Low-power Lossy Networks (LLNs), we propose a two-steps process:

1. Fault **detection**: a misbehavior has been detected. For instance, the end-to-end reliability of a specific flow has decreased, or a buffer overflow occurred. While these events are the results of a fault, the infrastructure is not aware of the **cause**.

   A device that detects a fault has to trigger an alarm;

2. Fault **identification** comes after the fault detection. After an alarm has been reported, the infrastructure has then to identify the causes of this deviation. For instance, the end-to-end reliability for a collection of data flows may decrease because of external interference along the path.

   Typically, the level of monitoring increases to obtain more accurate information to identify the cause.

LLNs are specific, and make the fault detection and identification harder. Because of the energy-efficiency, we have to limit the volume of monitoring information since every bit consumes energy. Besides, the bandwidth is also significantly lower than in wired networks. In scheduled networks, we have to dedicate radio resources for the control traffic. Thus, localized and centralized mechanisms have to be combined together.

4 | ADMINISTRATION FOR RAW NETWORKS

To take proper decisions, the network infrastructure has to be aware precisely of the *state* of each device and flow. This state helps the network to accept (or not) a novel flow (call admission), to reconfigure the network to reduce the energy consumption or to keep on respecting SLA contracts[11].

4.1 | Key Performance Indicators

Most Service Level Agreement (SLA) contracts mention end-to-end Key Performance Indicators (KPI), for each data flow. The end-to-end reliability is of primary importance, since most industrial applications stop working when large number of packets are lost. The reliability KPI is often expressed at the application level, while the packets may be fragmented. Thus, reliability constraints per fragment are even higher to be able to reassembly the packets at the destination.

The end-to-end delay is also particularly sensitive: after a given deadline, the packet becomes obsolete and does not need to be delivered. Typically, control command applications[12] are interactive, and need to react in real time after having received physical measurements.

Thus, we need a per-flow monitoring approach, and we have to measure the SLA for each virtual circuit.

4.2 | Individual Performance Metrics

Administrators of mission-critical networks need to know in real-time the performance of the network infrastructure. Thus, the we need to measure the link quality to provision enough resources for the flows forwarded through such link. Many link quality metrics exist in the literature, from the Packet Delivery Ratio (link-level) to RSSI, LQI and SNR (PHY level).

The link quality should be monitored i) per channel, ii) per neighbor, iii) per flow, iv) per scheduled transmission. Indeed, counter-measures deeply depend on the phenomena which impacts the reliability. For instance, a low link quality for a specific channel may come from external interference, while a low packet delivery ratio for a given transmission opportunity may denote a collision in the schedule.

Furthermore, we have to collect also network-layer statistics. The buffer occupancy denotes the congestion along the path, and should be sufficiently low to buffer the packets when a fault occurs. Besides, a high buffer occupancy implies also a larger medium access delay, which may jeopardize the respect of the end-to-end SLAs.

4.3 | Worst-case Metrics

Since low-power lossy networks exhibit time-dependent characteristics, we need to predict the future performances. Thus, we have to pay attention on the measurement method. A Window Mean Exponential Weighted Moving Average (WME-WMA) is very common to obtain smoothed values for stochastic metrics. However, the estimator has to be sufficiently reactive to detect anomalies.

Since wireless networks are known to be lossy, we have have to implement strategies to improve the reliability on top of unreliable links. Hybrid Automatic Repeat reQuest (ARQ) has typically to enable retransmissions based on the end-to-end reliability and latency requirements. To take correct decisions, the controller requires to be aware of the distribution of packet losses for each flow, and for each hop of the paths. In other words, average end-to-end statistics are not enough. They must allow the controller to predict the worst-case.

4.4 | Energy Efficient Collect

RAW targets also low-power wireless networks, where energy represents a key constraint. Thus, we have to take care of the energy and bandwidth consumption.

A first technique consists in piggybacking control packets in data packets. Indeed, inserting additional bits in an existing packet is often much less expensive as transmitting another dedicated control packet. The transmitter may buffer control packets and piggyback them in data packets if the combination does not exceeds the Maximum Transmission Unit (MTU)[13]. Alternatively, we may create additional flags/fields for retrieving control information. Typically, path inference tools[14] insert additional information in the headers so that the destination can identify the path followed by a given packet. With multipath routing in scheduled networks, some mechanisms help to reduce the volume of information to include in the headers[15][16].

5 | MAINTENANCE FOR RAW NETWORKS

While the administration and operation features aim to provide the state of the network, and to detect faults, the maintenance aims to reconfigure the network to be able to respect the SLA.

5.1 | Fault Tolerance

To be fault-tolerant, several paths can be reserved between two maintenance endpoints. They must be Node-Disjoint and avoid Shared-Risk Link Groups (SRLG), in order to guarantee that a single problem cannot interrupt the communication. In wireless,

TABLE 1 OAM features and their specificities in RAW networks

Feature	Mechanisms and Challenges
Operation	Each flow has its own dedicated ressources to monitor and to check, and multipath routing is the rule; Faults are very common in wireless networks (external interference, obstacle); Identifying the faults requires to collect and aggregate different metrics / events.
Administration	Metrics have to be monitored per flow, and also per radio ressource (*e.g.*, radio channel); We need to identify worst case metrics, and thus to know their distribution; Energy is the key for autonomous devices, and the volume of information to collect must be limited.
Management	We have a trade-off between resource badly used by the network, and the cost to reconfigure the network; The network must be able to detect and predict the evolution, with an efficient over-provisioning scheme.

avoiding SRLG means employing as much diversity as possible, including channel diversity, time diversity, code diversity, and possibly different PHY techniques (e.g., narrowband vs; spread spectrum) to defeat the various interferences that after the medium. In Fig. 1, the green and orange paths pass through different routing devices, and border routers.

When multiple paths are reserved between two maintenance endpoints, they may decide to replicate the packets to introduce redundancy, and thus to alleviate transmission errors and collisions [17]. In Fig. 1, the green set of paths on the right of the figure are meshed, so that packets are replicated among all these links. Such technique is particularly efficient to deliver data packets even if the links are very unreliable [16].

5.2 | Reconfiguration

A wireless network exhibits time-variable characteristics, that may come from *e.g.*, obstacles, external interference, devices running out of energy. In these conditions, we must implement self-healing and self-optimization mechanisms. The network must continuously retrieve the state of the network, to judge about the relevance of a reconfiguration Reconfiguration may only be triggered if the gain is significant, and we need to quantify:

the cost of the sub-optimality: resources may not be used optimally (*e.g.*, a better path exists);

the reconfiguration cost: the controller needs to trigger some reconfigurations. For this transient period, resources may be twice reserved, and control packets have to be transmitted.

Since RAW expects to support real-time flows, we have to support soft-reconfiguration, where the novel ressources are reserved before the ancient ones are released. Some mechanisms have to be proposed so that packets are forwarded through the novel track only when the resources are ready to be used, while maintaining the global state consistent (no packet re-ordering, replication, etc.)

5.3 | Efficient Provisioning

Because the QoS criteria associated to a path may degrade, the network has to provision additional resources along the path. We need to provide mechanisms to patch a schedule (changing the channel to use, allocating more timeslots, changing the path, etc.).

Based on the information retrieved through the administration feature, the network must be able to predict the evolution. If the network is also able to quantify a priori the impact of one reconfiguration, it is also able to trigger a change to optimize the cost (*e.g.*, energy, bandwidth).

6 | CONCLUSIONS

In this letter, we presented the Operation, Administration and Management (OAM) features to enable wireless infrastructure to support critical applications. We regrouped in Table 1 the challenges specific to RAW networks. We need to provide OAM mechanisms to be able to provision enough ressources in order to respect reliability and delay guarantees.

In the future, we expect to implement all the mechanisms presented here to assess their performance in vivo. We need also to define standardized methods to measure each of the metrics described here. We have to define efficient mechanisms based on lossless compression techniques to reduce the volume of control packets to maintain an accurate view of the infrastructure.

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