REA-6TiSCH: Reliable Emergency-Aware Communication Scheme for 6TiSCH Networks

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***Abstract*—From the perspective of the emerging Industrial Internet of Things (IIoT), the 6TiSCH working group has been created with the main goal to integrate the capabilities of the IEEE 802.15.4e time-slotted channel hopping (TSCH) with the IPv6 protocol stack. In order to support time-critical applications in IIoT, reliable real-time communication is a key requirement. Specifically, aperiodic critical traffic, such as emergency alarms, must be reliably delivered to the destination-oriented directed acyclic graph root within strict deadline bounds to avoid system failure or safety-critical situations. Currently, there is no mechanism defined in the 6TiSCH architecture for timely and reliably handling of such traffic and its prioritization over the noncritical one. In this article, we introduce REA-6TiSCH, a reliable emergency-aware communication scheme to support real-time communications of emergency alarms in 6TiSCH networks. In REA-6TiSCH, the aperiodic emergency traffic is opportunistically enabled to hijack transmission cells preassigned for the regular periodic traffic in the TSCH schedule. Moreover, we introduce a distributed optimization scheme to improve the probability that an emergency flow is delivered successfully within its deadline bound. To the best of our knowledge, this is the first approach to incorporate emergency alarms in 6TiSCH networks. We evaluate the performance of REA-6TiSCH through extensive simulations and the results show the effectiveness of our proposed method in handling emergency traffic compared to the Orchestra scheme. Additionally, we discuss the applicability of REA-6TiSCH and provide guidelines for real implementation in 6TiSCH networks.**

***Index Terms*—Industrial Internet of Things (IIoT), industrial wireless sensor networks (IWSNs), real time, time-critical applications.**

I. Introduction

INDUSTRIAL Internet of Things (IIoT) is a special branch of IoT that addresses connectivity and communications in industrial environments [1]. Industrial wireless sensor networks (IWSNs) constitute the major building block in the realization of the IIoT technology within process automation scenarios. Unlike consumer applications where cost is often the most important attribute, low delay and high reliability are key features for industrial applications [2]. In that aspect, the IEEE 802.15.4e standard implements time-slotted channel hopping (TSCH) that combines time-division multiple access (TDMA) along with multichannel and channel hopping capabilities to provide a deterministic delay for process automation scenarios [3]. The 6TiSCH group was created with the aim to enable IPv6 over the TSCH mode [4]. The routing protocol for low-power and lossy network (RPL) [5] organizes the 6TiSCH tree network in the form of a destination-oriented directed acyclic graph (DODAG). The nodes communicate following a common schedule which is composed of a matrix of cells, where each cell represents a pairwise assignment of a dedicated communication link between two nodes in a specific time slot on a given channel [6]. The proper functioning of the network in terms of reliability, delay, and network lifetime depends on that schedule. While the IEEE 802.15.4e TSCH mode defines the mechanism to execute the schedule, it does not define the policies to build and maintain the schedule, adapt the communication resources to the Quality-of-Service (QoS) requirements, and introduce service differentiation mechanism according to the criticality/importance of each traffic flow.

In time-critical applications, asynchronous safety-related traffic, such as emergency alarms, is triggered due to anomalies or hazards, e.g., risk of explosion. This type of traffic must be reliably delivered to the DODAG root within bounded deadlines to avoid system failures and outages that could create significant cost or even worse dangerous situations to human lives [7]. For instance, in oil refinery plants [8], the pressure within the piping system must be kept within pipe tolerances. If the pressure exceeds a certain limit, an emergency alarm is triggered to the controller to actuate either the shutoff valves or the pumps to avoid explosion. 6TiSCH offers the concept of Track to provide a deterministic path between the source and the destination for time-critical flows [9]. A Track consists of a set of reserved cells along a multihop path to guarantee delivery within specific bounded delay without the influence of other flows over the 6TiSCH network. However, critical emergency alarms are unpredictable and it is impractical to preassign a dedicated path for such traffic. In addition, this fixed assignment approach cannot guarantee immediate channel access for the critical traffic, instead it must wait until its reserved set of cells which may incur an extra delay. Another drawback is that most of the communication resources paired to Track will remain idle after the transmission of the time-critical traffic. Since such traffic occurs occasionally, the channel utilization will be reduced significantly. Currently,

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there are no specifications or recommendations of how Tracks are created, computed, and managed.

Another challenging issue in that aspect is that even with using the deterministic Track communications, transmission failures for critical traffic are inevitable due to the harsh channel conditions in the industrial environment, which involves moving objects, multipath fading, and electromagnetic interference [7]. In 6TiSCH networks, transmission failures are mitigated by retransmission of failed packets if no acknowledgment is received within a predefined time-out. Retransmissions are carried out through shared slots that follow the carrier sense multiple access with collision avoidance (CSMA/CA) channel access scheme with exponential backoff [3], which is an inefficient approach for time-critical applications in terms of reliability and timely delivery of already delayed traffic [15]. Nodes with failed transmissions attempt to retransmit their packets until receiving an acknowledgment or a retransmission limit are reached. The retransmission limit is set as a fixed value for all nodes along a delivery path. If the number of retransmissions exceeds this value, the packet is dropped (the default limit is 3 [3]).

Fixing the retransmission limit is an inflexible approach for time-critical applications because of the following. This limit can be low; that is, the packet may be dropped even if there is still adequate time for more retries before its corresponding deadline bound. On the other hand, the limit may also be too high, where a node tries to retransmit an out-of-date packet, i.e., useless information, to the DODAG root, which is a waste to the communication resources. Moreover, if a retransmission attempt fails for some reason, an exponential backoff mechanism is initiated; that is, the next retransmission attempt is deferred for some slots [3]. This may lead to run out of the available shared slots in the same superframe, especially for applications with a high refresh rate. Additionally, both critical and noncritical data equally contend for retransmissions within the set of shared slots, where there is no service differentiation mechanism provided to ensure that critical packets gain higher priority for channel access. Therefore, providing reliable real-time communication in 6TiSCH networks is a key challenge to support industrial applications with time-critical constraints.

In this article, we focus on time-critical applications within IIoT and propose REA-6TiSCH, a reliable emergency-aware communication scheme for 6TiSCH networks. Our main contributions can be summarized as follows.

1) We first introduce a priority-based channel access method to incorporate the unpredictable emergency alarms in 6TiSCH networks with low delay communication. The proposed mechanism enables the generated emergency alarm to opportunistically hijack TSCH cells assigned for the periodic regular traffic in a nonconflicting manner.
2) Furthermore, to improve the transmission reliability, we introduce a distributed optimization algorithm to set the proper retransmission limit to improve the probability that an emergency flow is delivered successfully along its predefined path within its deadline bound.
3) We evaluate the performance of REA-6TiSCH through extensive simulations to demonstrate its effectiveness, and the results show that REA-6TiSCH can reliably handle the on-time delivery of emergency alarms in 6TiSCH networks compared to the Orchestra scheme at the expense of insignificant deferring ratio of the regular traffic.
4) In addition, we discuss the practical applicability of the proposed method and provide guidelines for the implementation in 6TiSCH networks.

The remainder of this article is organized as follows. Section II discusses the related work. Section III describes the proposed REA-6TiSCH scheme. A theoretical analysis of REA-6TiSCH is conducted in Section IV, followed by performance evaluations in Section V. Section VI presents the challenges of REA-6TiSCH implementation in real networks. Finally, conclusions and directions for future work are presented in Section VII.

II. Related Work

Several research works have been proposed in the literature to develop efficient scheduling solutions for 6TiSCH networks [10]–[14]. However, these works are not explicitly designed to handle the transmission of aperiodic emergency traffic in a reliable and real-time manner. In that context, a set of protocols has been introduced to improve the reliability and real-time performance of IWSNs [15]–[21].

Farag *et al.* [15] proposed SS-MAC, a slot stealing MAC protocol to enable deterministic channel access for emergency alarms in IWSNs through the deadline-aware scheduling mechanism. A novel MAC protocol, named WirArb, has been proposed in [16] mimicking the behavior of CAN bus to guarantee real-time performance. WirArb combines PHY layer and MAC layer to perform frequency arbitration in order to decide priorities and in turn decide the order of channel access. SS-MAC and WirArb consider error-free channel, i.e., a successful data delivery from the first attempt, however, in an industrial setting, erroneous channel is inevitable. A PriorityMAC protocol was introduced in [17] to enable prioritized transmission and retransmission of critical traffic by hijacking time slots assigned for noncritical traffic. However, PriorityMAC considers a fixed retransmissions limit, after which the critical packet is dropped. In addition, all the aforementioned works are only applicable in star networks, which is not the case of 6TiSCH networks.

Yang *et al.* [18] proposed a novel framework to enable safety-critical applications in IWSNs. In the proposed solution, the radio resources are optimized to reduce the bandwidth requirement of the wireless system and obtain a short system response time when an emergency event occurs. Li *et al.* [19] presented a real-time protocol to incorporate emergency alarms in multihop wireless process control scenarios by allowing emergency alarms and regular flows to be scheduled in the same dedicated time slots. To enable reliable communication for emergency alarms, redundant retransmission attempts are scheduled in dedicated and shared slots.

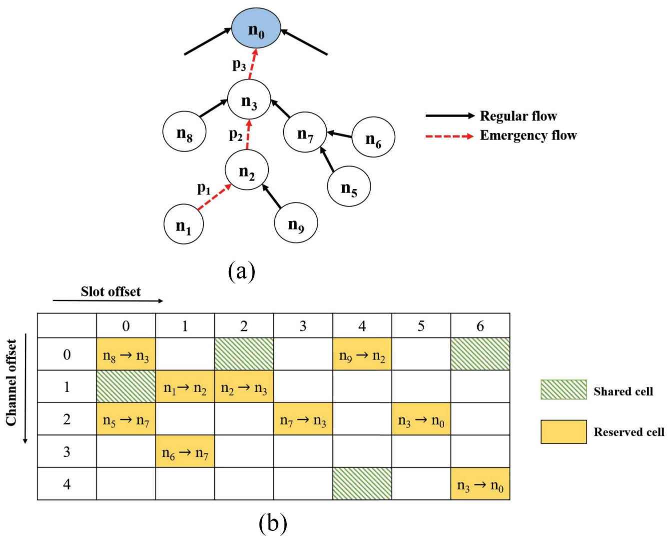


Fig. 1. (a) Network architecture. (b) Possible link schedule.

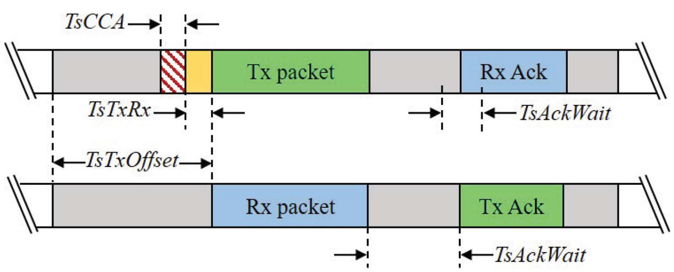


Fig. 2. Slot timing.

A novel slot scheduling was proposed in [20] to enhance the retransmission efficiency in shared time slots through embedding multiple clear channel assessment (CCA) subslots in each shared slot. GinMAC protocol was introduced in [21] to enable predictable and reliable communications for time-critical applications. Based on predeployment measurements of the worst case link reliability, a number of retransmission time slots are included at the end of each superframe. Besides the limited scalability, the adopted approach in GinMAC could lead to several retransmission slots to be left unused or even violating the delay bound when the superframe would become too long. Despite their effectiveness to improve transmission reliability, none of the above works consider the timely delivery of unpredictable emergency alarms.

III. Proposed REA-6TiSCH Scheme

A. Network Model

We consider an industrial application, where the 6TiSCH network has formed a tree routing topology by the RPL as shown in Fig. 1(a). Each child node forward its data up to the sink node, referred to as DODAG root, via its preferred parent. The communication in the network is modeled as an oriented graph $G = (V, E)$, where $V = \{n_i : 1 \leq i \leq N\}$ is the set of all nodes and E is the set of edges representing the communication links between nodes. The sensor data are gathered through a tree structure $G_T = (V_T, E_T)$ rooted at the DODAG root n_0, where $n_0 \in V_T$, $V_T \subseteq V$, and $E_T \subseteq E$.

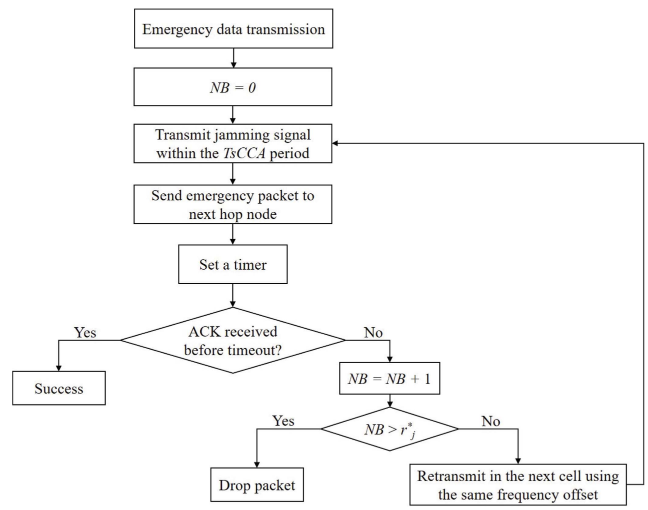


Fig. 3. Flowchart of transmitting emergency packet in REA-6TiSCH.

All nodes are synchronized to a TSCH schedule that consists of consecutive slot frames and allocates cells for nodes communications. Each cell is represented by the pair (t_O, f_O), where t_O denotes the slot offset and f_O denotes the channel offset. The cell allocation in a slot frame is decided by either a centralized or a distributed scheduling algorithm and the slot frame is repeated periodically based on the application refresh rate. Fig. 1(b) shows a possible schedule for the considered network, which is represented by a slotframe of both dedicated and shared cells. Within a time slot, data are communicated between two nodes following the slot timing shown in Fig. 2 [22]. The transmitting node forward its packet to the next-hop node after a duration of *TsTxOffset* and waits for a link-layer acknowledgment. The network supports two types of data flows. Regular data, which are represented by periodic measurements, e.g., temperature, vibration, and pressure based on the application refresh rate and transmitted through the preassigned cells in the TSCH schedule. Critical data, such as emergency alarms, which are triggered sporadically due to emergencies or anomalies and must be timely and reliably delivered to the DODAG root in order to take the proper action to preserve the system stability and avoid possible dangerous consequences. Since emergencies occur occasionally, we consider that, at most, one critical flow exists in the network and propagates toward the DODAG root along a predefined path, which is managed by RPL. With the gas monitoring scenario as an example, CO leakage is detected through the transmission of a single emergency flow toward the DODAG root [23]. Though, the proposed REA-6TiSCH scheme still achieves improved performance even by considering multiple emergency flows in the network. We assume that both traffic types are legitimate and all nodes are authenticated as trusted members upon joining the network through the constrained join protocol (CoJP) for 6TiSCH [24], [25]. Further details on the authentication process are out the scope of this article.

B. Incorporating Emergency Alarms in the TSCH Schedule

In order to provide timely delivery for a critical flow along with efficient resource utilization, we introduce a prioritized channel access scheme. A node with critical data is enabled to hijack cells assigned for regular traffic along the delivery path from the source node to the DODAG root. The node selects the nearest communication cell based on the current absolute slot number (ASN) and a random channel offset. Both values are used in a lookup table-based function to generate the transmission frequency [3]. A channel offset is an integer number that is randomly selected in the range from 0 to the number of available channels with excluding blacklisted channels. The procedures of transmitting an emergency packet are summarized in Fig. 3 and described in more detail as follows.

Before transmitting the regular traffic, the cell owner performs CCA during the *TsCCA* period, shown in Fig. 2. If the channel is idle, the node initiates its transmission, otherwise, it defers its transmission. Once the emergency alarm is generated, the source node transmits a jamming signal within the *TsCCA* period to hijack the current cell from its owner as the latter detects a busy channel within the mentioned period. Then, the node transmits the emergency packet within the Tx packet period indicated in Fig. 2. After transmitting the emergency alarm, the source node waits for the acknowledgment from the receiver, i.e., parent node. If the acknowledgment is not received within the predefined timeout, the source node will retransmit the packet in the subsequent time slot using the same channel offset, without a backoff procedure, following the same aforementioned priority access scheme. If the number of retries NB exceeds the value of retransmissions limit r_j^*, the packet is dropped. The estimated value of r_j^* is illustrated in the next section. The prioritized transmission is performed in each hop along the path to the DODAG root. The slot owner will try to transmit its deferred regular data through one of the shared slots in the current slotframe, otherwise, it will transmit the deferred data in its next assigned time slot. This is to alleviate the rigors effect on the regular data due to the transmission of the emergency flow and keep the ratio of dropped regular packets as minimum as possible.

Note that a node with emergency data is only permitted to hijack the cell before the end of the *TsTxOffset* period, that is, before the cell owner starts its regular data transmission, as the regular traffic transmission cannot be preempted in this case.

The robustness of the predefined end-to-end path of the emergency alarm should be guaranteed against parent switch situations due to either poor link quality or the parent running out of battery. In that context, RPL keeps a list of backup parents from which a candidate can be selected as the new preferred parent [5].

C. Optimized Retransmission Scheme

As mentioned earlier, the limit of retransmissions in 6TiSCH networks is set to a fixed value, after which the packet is dropped. This in turn decreases the probability that an emergency packet is delivered successfully within its deadline bound. To that end, we introduce an optimization algorithm to find the retransmission limit that maximizes the probability of successfully transmitting an emergency alarm to the DODAG root within its deadline. Considering the emergency flow shown by the dashed line in Fig. 1(a), p_j denotes the probability of transmission failure in the jth hop along the emergency path. If the retransmission bound for all nodes is set to R, then the probability that the packet is delivered successfully to n_0 is given as

$$P_{\text{suc}} = \left(1 - p_1^{(R+1)}\right)\left(1 - p_2^{(R+1)}\right)\left(1 - p_3^{(R+1)}\right) \tag{1}$$

where the term $(1 - p_j^{(R+1)})$ represents the probability that a packet is successfully delivered in the jth hop having the retransmission bound of R. It is clear that increasing R would in turn improve the value of P_{suc}, however, this fixed approach does not consider neither the link quality nor the corresponding deadline of the transmitted emergency flow. In other words, it does not make sense to consume communication resources to retransmit the out-of-date packet. The aim of the optimization approach is to enable each node along the emergency path to dynamically adjust the value of retransmissions in each hop, considering the link quality and the corresponding deadline. This is to maximize the summation of the probability of successfully delivering an emergency alarm to the DODAG root within its specified deadline bound and avoid unnecessary action of dropping the failed packet before its deadline.

We represent the delivery path of an emergency alarm that consists of H hops by the set V_E, where $V_E \subseteq V$ and $|V_E| = H + 1$. If we denote D as the deadline bound for the triggered emergency alarm and R_j as the retransmission bound set for the link of the jth hop, the problem of finding the optimal value R_j^* along the delivery path can be formulated as follows:

$$\begin{aligned} \max_{R_j} \quad & \sum_{j=1}^{H}\left(1 - p_j^{(R_j+1)}\right) \\ \text{s.t.} \quad & \sum_{j=1}^{H}\left(R_j + 1\right) \leq D. \end{aligned} \tag{2}$$

The value of D in (2) represents the deadline in terms of the number of time slots, where we consider that one transmission/retransmission trial takes one-time slot duration in the TSCH schedule. Therefore, D denotes the deadline normalized to the packet transmission time. The optimization problem in (2) implies maximizing the probability of an emergency alarm being successfully transmitted while guaranteeing its deadline bound. If we let $r_j = R_j + 1$, then the maximization problem in (2) can be reduced to the following minimization one:

$$\begin{aligned} \min_{r_j} \quad & \sum_{j=1}^{H} p_j^{r_j} \\ \text{s.t.} \quad & \sum_{j=1}^{H} r_j \leq D. \end{aligned} \tag{3}$$

The term $p_j^{r_j}$ in (3) is equivalent to $e^{r_j \ln p_j}$. Since $e^{\alpha x}$ is convex $\forall \alpha \in \mathbb{R}$, the objective function in (3) is convex and can be solved using the Lagrangian duality theory [26] to obtain r_j^*. The primal problem in (3) can be replaced with a duality maximization problem by augmenting the objective function with a weighted sum of the constraints.

The Lagrangian functions $L(r_j, \lambda_j)$ are described as

$$L(r_j, \lambda_j) = \sum_{j=i}^{H} p_j^{r_j} + \sum_{j=i}^{H} \lambda_j (r_j - D) \tag{4}$$

where λ_j is the Lagrange multiplier. Then, the dual function $g(\lambda_j)$ is given as the minimum value of $L(r_j, \lambda_j)$ over r_j

$$g(\lambda_j) = \min_{r_j} \quad L(r_j, \lambda_j). \tag{5}$$

Based on the dual function $g(\lambda)$ in (5), the dual problem associated with the primal problem in (3) can be formulated as

$$\begin{aligned} \max_{\lambda_j} \quad & g(\lambda_j) \\ \text{s.t.} \quad & \lambda_j \geq 0. \end{aligned} \tag{6}$$

The optimization problem can be solved via the subgradient method using constant step size rule [27]. For $k \geq 0$, the values of r_j are updated as follows:

$$r_j^{(k+1)} = r_j^{(k)} - \alpha s^{(k)} \tag{7}$$

where $s^{(k)} = \nabla_{r_j} L(r_j^{(k)}, \lambda_j^{(k)})$. The values of the Lagrange multiplier λ_j are updated as follows:

$$\lambda_j^{(k+1)} = \lambda_j^{(k)} + \alpha u^{(k)} \tag{8}$$

where $u^{(k)} = \nabla_{\lambda_j} L(r_j^{(k)}, \lambda_j^{(k)})$.

The duality gap can be used as a nonheuristic stopping criterion for the considered subgradient method. For a given accuracy $\varepsilon_{\text{opt}} > 0$, the duality gap given the dual point $\lambda_j^{(k)}$ and the primal point $r_j^{(k)}$ is given as

$$p_j^{r_j^{(k)}} - g\left(\lambda_j^{(k)}\right) \leq \varepsilon_{\text{opt}}. \tag{9}$$

This guarantees that when the algorithm is terminated, the obtained r_j^* is ε_{opt} suboptimal.

The optimization problem is solved at each node in the delivery path of an emergency alarm as follows. The source node, i.e., the node that generates the emergency alarm, solves the problem in (3) to find r_1^* for the given values of H and D while considering the default values of $r_2, r_3, \ldots, r_H$. Each next-hop node solves the problem in (3) with the updated values of $H = H - 1$ and $D = D - T_i$, where T_i denotes the number of time slots spent to successfully transmit the emergency packet from n_i to n_{i+1}. This is to consider for the remaining time until the deadline of the emergency packet when estimating the value of r_j^*.

IV. Convergence Analysis of the Proposed Optimized Retransmission Scheme

In this section, we analyze the convergence properties of the proposed optimization problem to give a proof that the considered optimization solution converges to the optimal retransmission value within a finite number of steps under the constant step size rule.

We assume that we have a bounded norm of the subgradients, i.e., for all k, there exist B such that $\|s^{(k)}\|_2 \leq B$. This assumption is valid since the objective function satisfies the Lipschitz condition [28]. We also assume that a number C is known that satisfies $C \geq \|r_j^{(1)} - r_j^*\|_2$. Here, C denotes an upper bound on the distance between the initial point and the optimal one. For the subgradient method, the key quantity is the Euclidean distance to the optimal value, not the function value. Since we have r_j^* as an arbitrary optimal point that minimizes the objective function, then we have

$$\begin{aligned} \left\| r_j^{(k+1)} - r_j^* \right\|_2^2 &= \left\| r_j^{(k)} - \alpha s^{(k)} - r_j^* \right\|_2^2 \\ &= \left\| r_j^{(k)} - r_j^* \right\|_2^2 - 2\alpha s^{(k)} \left(r_j^{(k)} - r_j^* \right) \\ &\quad + \alpha^2 \left\| s^{(k)} \right\|_2^2 \\ &\leq \left\| r_j^{(k)} - r_j^* \right\|_2^2 - 2\alpha \left(f\left(r_j^{(k)} \right) - f^* \right) \\ &\quad + \alpha^2 \left\| s^{(k)} \right\|_2^2 \end{aligned} \tag{10}$$

where f represents our objective function and $f^* = f(r_j^*)$. The last inequality follows from the definition of subgradient:

$$f\left(r_j^*\right) \geq f\left(r_j^{(k)}\right) + s^{(k)} \left(r_j^* - r_j^{(k)}\right). \tag{11}$$

By applying (11) recursively, we get

$$\begin{aligned} \left\| r_j^{(k+1)} - r_j^* \right\|_2^2 \leq \left\| r_j^{(1)} - r_j^* \right\|_2^2 - 2 \sum_{i=1}^{k} \alpha_k \left(f\left(r_j^{(i)} \right) - f^* \right) \\ + \sum_{i=1}^{k} \alpha_i^2 \left\| s^{(i)} \right\|_2^2. \end{aligned} \tag{12}$$

Since we have $\|r_j^{(k+1)} - r_j^*\|_2^2 \geq 0$ and $\|r_j^{(1)} - r_j^*\|_2 \leq R$, so we have

$$2 \sum_{i=1}^{k} \alpha_k \left(f\left(r_j^{(i)} \right) - f^* \right) \leq C^2 + \sum_{i=1}^{k} \alpha_i^2 \left\| s^{(i)} \right\|_2^2 \tag{13}$$

and we also have the following inequality:

$$\begin{aligned} \sum_{i=1}^{k} \alpha_i \left(f\left(r_j^{(i)} \right) - f^* \right) &\geq \left(\sum_{i=1}^{k} \alpha_i^2 \right) \min_{i=1,2,\ldots,k} \left(f\left(r_j^{(i)} \right) - f^* \right) \\ &= \left(\sum_{i=1}^{k} \alpha_i^2 \right) \left(f_{\text{best}}^{(k)} - f^* \right) \end{aligned} \tag{14}$$

where $f_{\text{best}}^{(k)}$ is the best objective value found within k iterations so far, i.e., $f_{\text{best}}^{(k)} = \min\{f_{\text{best}}^{(k-1)}, f(r_j^{(k)})\}$. By combining (13) with (14), we get

$$f_{\text{best}}^{(k)} - f^* \leq \frac{C^2 + \sum_{i=1}^{k} \alpha_i^2 \left\| s^{(i)} \right\|_2^2}{2 \sum_{i=1}^{k} \alpha_i}. \tag{15}$$

With $\|s^{(k)}\|_2 \leq B$, (15) is given as

$$f_{\text{best}}^{(k)} - f^* \leq \frac{C^2 + B^2 \sum_{i=1}^{k} \alpha_i^2}{2 \sum_{i=1}^{k} \alpha_i}. \tag{16}$$

For constant step size rule, i.e., $\alpha_k = \alpha$, (16) can be rewritten as

$$f_{\text{best}}^{(k)} - f^* \leq \frac{C^2 + k B^2 \alpha^2}{2 k \alpha}. \tag{17}$$

For the right-hand side in (17), we have

$$\lim_{k\to\infty} \frac{C^2 + kB^2\alpha^2}{2k\alpha} = \frac{B^2\alpha}{2}. \quad (18)$$

Based on (17) and (18), we obtain

$$\lim_{k\to\infty} f_{\text{best}}^{(k)} \le f^* + \frac{B^2\alpha}{2}. \quad (19)$$

Thus, $f_{\text{best}}^{(k)}$ converges within $B^2\alpha/2$ of the optimal solution. This implies that, for instance, $f(r_j^{(k)}) - f^* \le B^2\alpha$ within a finite number of steps.

The right-hand side of (17) [upper bound of $f_{\text{best}}^{(k)} - f^*$] can be minimized by taking $\alpha = C/(B\sqrt{k})$, which yields the sub-optimality bound $f_{\text{best}}^{(k)} - f^* \le CB/\sqrt{k}$. Therefore, the number of steps to achieve the considered accuracy of ε_{opt} is at least $(CB/\varepsilon_{\text{opt}})^2$, which yields a convergence rate of $O(1/\varepsilon_{\text{opt}}^2)$.

V. Performance Evaluation

In this section, we evaluate the performance of our proposed scheme through a set of Monte Carlo simulations in MATLAB based on the parameters shown in Table I. We compare our proposed scheme against Orchestra [12]. Orchestra is a simple and light scheduling scheme that does not require any central entity or negotiation between neighbor nodes. We compare REA-6TiSCH with two modes: 1) Orchestra sender-based slots (Orchestra-SB) and 2) Orchestra receiver-based slots (Orchestra-RB) [12]. All nodes, except the DODAG root, generate regular data packets periodically based on a certain refresh interval. We consider aperiodic critical flow representing the event of emergency alarm that is generated according to a Poisson process with parameter λ. We repeat each simulation run 100 times, with each run lasting for a duration of 1000 consecutive slotframes and the following simulation results are averaged over 100 times. The slotframe duration is based on the refresh interval of the periodic regular data. In each slotframe, a set of shared slots is distributed to enable retransmission of failed packets (and deferred packets in our proposed scheme). It has been reported in [29] that in the process automation scenario, both periodic traffic and aperiodic traffic, e.g., emergency data, have typically a payload size in the order of 10–100 B. For the sake of simplicity, we consider a fixed packet length of 100 B for both traffic types. Though, our proposed scheme can still achieve improved performance even with the maximum useful payload size. Throughout the simulations, we consider log-normal shadowing distribution for the channel model with the specified standard deviation selected according to the measurements reported in [30].

First, we evaluate the delay performance of REA-6TiSCH with respect to emergency alarm transmissions and compare it with those of Orchestra-SB and Orchestra-RB. Fig. 4 shows the end-to-end (E2E) delay of REA-6TiSCH, Orchestra-SB, and Orchestra-RB against different refresh intervals of the regular data in the five-hops network. The E2E delay is calculated as the time elapsed between the generation of the emergency alarm and the instant it is received by the DODAG root. From Fig. 4, we can clearly note the capability of REA-6TiSCH in delivering emergency alarms with much lower E2E delay compared to Orchestra-SB and Orchestra-RB under different refresh rates. For instance, REA-6TiSCH achieves a reduction in the E2E delay of emergency alarms by 75% and 82% compared to Orchestra-SB and Orchestra-RB, respectively. This is primarily due to the feature of cell hijacking that enables emergency alarms to immediately take over the scheduled cells for regular data along the E2E delivery path to the DODAG root. In Orchestra schemes, there is no mechanism to prioritize the transmission of an emergency alarm, instead the triggered emergency alarm has to wait for its scheduled cell (shared cell in Orchestra-RB) in the TSCH schedule which significantly increases its E2E delay and leads to deadline miss, especially if we increase the slotframe length, i.e., increase the refresh interval.

In order to provide further insights into the effectiveness of REA-6TiSCH in terms of real-time performance, Figs. 5 and 6 provide a comparison of the on-time packet

TABLE I
Simulation Parameters

Parameter	Value
Propagation model	Shadowing (Log-normal)
Standard deviation	14 dB
Data rate	250 kB/s
Packet length	100 B
Timeslot length	10 ms
Default retransmissions	3
No. of nodes	50
No. of channels	4
Buffer size	10
λ	1/50 s

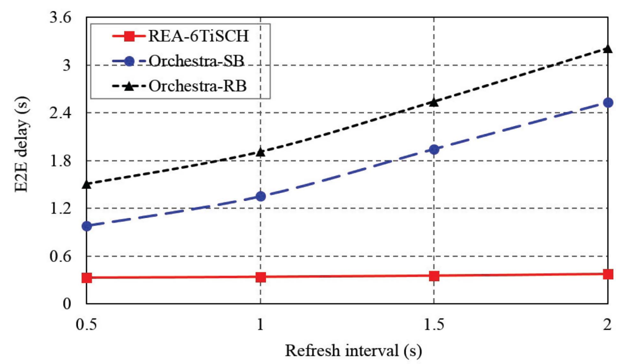


Fig. 4. E2E delay comparison.

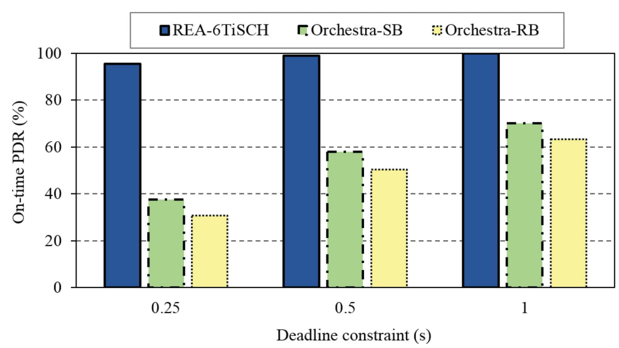


Fig. 5. On-time PDR under different deadline constraints in five-hops network with 1-s refresh interval.

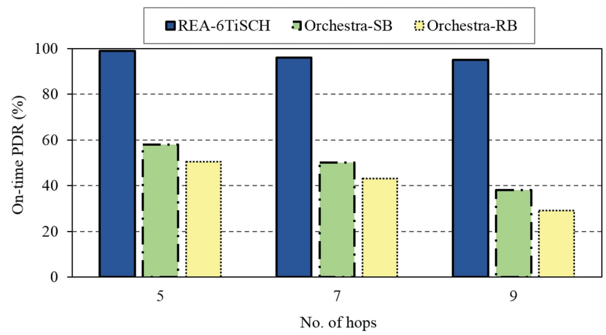


Fig. 6. On-time PDR under different number of hops with 500-ms deadline constraint and 1-s refresh interval.

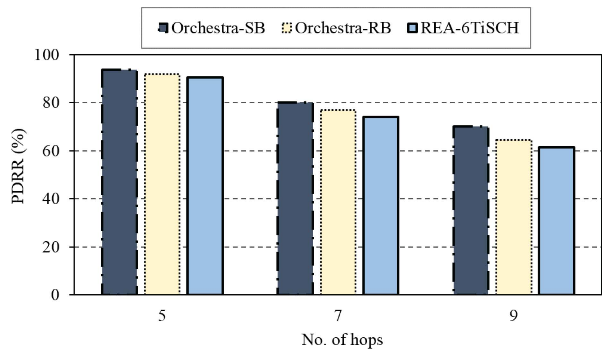


Fig. 7. PDRR versus the number of hops with 1-s refresh interval.

delivery ratio of the emergency alarms (on-time PDR) against different deadline constraints and the number of hops, respectively. The on-time PDR is calculated by dividing emergency packets that are successfully delivered within their corresponding deadline bound by the total generated emergency packets. As depicted in Fig. 5, REA-6TiSCH manages to deliver 95% of emergency packets within 250-ms deadline constraint, while almost all packets are delivered to DODAG root on-time when we increase the deadline limit to 500 ms and 1 s. On the other hand, Orchestra schemes manage to deliver less than 75% of emergency alarms within a deadline limit of 1 s while this percentage falls below 40% for a deadline of 250 ms. Considering a 500-ms deadline constraint, the improved real-time performance of REA-6TiSCH is further confirmed through Fig. 6. Although the on-time PDR decreases for the three communication schemes as the number of hops increases, REA-6TiSCH still outperforms Orchestra-SB and Orchestra-RB by 150% and 227%, respectively, with nine hops. Besides the hijacking mechanism that enables timely delivery of emergency alarms, the optimized retransmission feature offered in REA-6TiSCH improves the transmission reliability of such traffic by considering both the link quality and the deadline bound, which in turn leads to improved on-time PDR. Such a function is not offered by Orchestra schemes and instead, a fixed retransmission value is set, causing with high probability that an emergency packet is dropped, even if there is still a chance for more retries before reaching the deadline bound.

The improved real-time performance of REA-6TiSCH in handling emergency data is achieved at the expense of deferring regular packets for a number of time slots. Therefore,

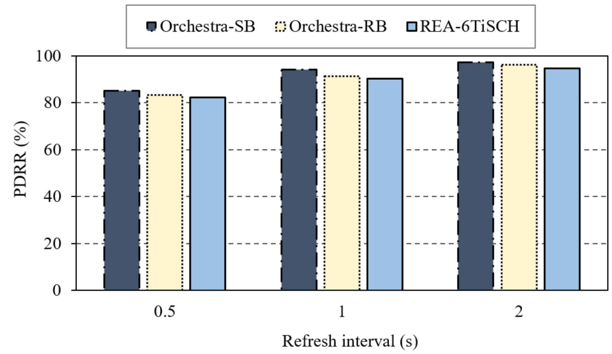
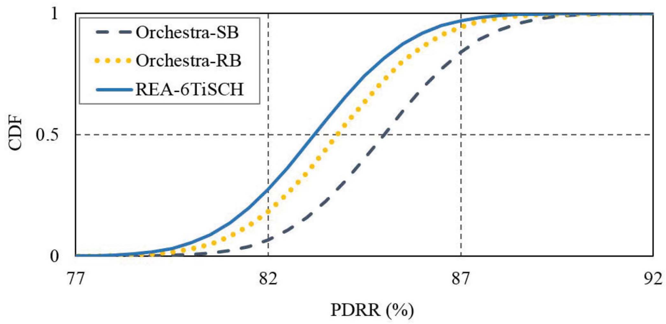


Fig. 8. PDRR versus the refresh interval with five hops.

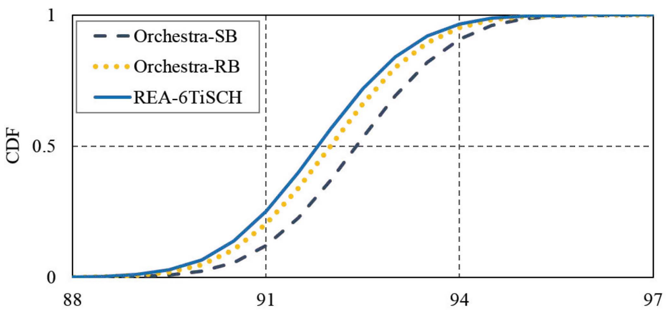
we investigate such effect by comparing the packet delivery ratio of the regular traffic (PDRR) for the three communication schemes in Figs. 7 and 8 under different values of the number of hops and the refresh interval, respectively. In Fig. 7, while performing mostly similar to Orchestra-RB, REA-6TiSCH introduces a 11% decrease in the PDRR with respect to Orchestra-SB under the nine-hops network while this ratio reduces to only 3% when the number of hops is reduced to 5. This could be considered as an insignificant cost with respect to the gained real-time performance achieved by REA-6TiSCH in delivering emergency alarms in industrial scenarios. A similar trend is also shown in Fig. 8, where Orchestra-SB achieves the best PDRR among the three communications schemes for different refresh intervals. On average, REA-6TiSCH imposes a reduction of 3% compared to Orchestra-SB while still performing similar PDRR performance with respect to Orchestra-RB.

The effect on the regular traffic is further illustrated by plotting the cumulative distribution function (CDF) of the PDRR under refresh intervals 500 ms and 1 s in Fig. 9(a) and (b), respectively. With 500 ms, REA-6TiSCH achieves a PDRR of 80% in more than 50% of the times while Orchestra-SB outperforms this ratio by 2%. When we increase the refresh interval to 1 s, the PDRR performance is improved for the three communication schemes, and the degradation in PDRR of REA-6TiSCH becomes less significant compared to that in Orchestra-SB, e.g., Orchestra-SB achieves a 0.5% better PDRR performance than that of REA-6TiSCH. The degradation in the PDRR of REA-6TiSCH is insignificant because we allow the blocked slot owner to transmit its deferred regular packets in one of the shared slots distributed in the TSCH schedule as mentioned in Section III.

It is worth mentioning that the deferral of the regular data occurs only in the event of an emergency situation, which is normally rare. Moreover, the regular traffic is typically characterized by relaxed requirements regarding the delay and reliability [31], and delaying such traffic for a number of time slots or even dropping the packet after a certain time-to-live will not cause serious situations. Hence, regular data can be sacrificed in favor of the emergency data, which has very tight delay limits and violating these limits could lead to dangerous situations. Therefore, REA-6TiSCH can be considered as a viable solution for industrial applications, where it is acceptable to sacrifice a portion of the regular traffic in favor



(a)



(b)

Fig. 9. CDF comparison of PDRR with five hops. (a) Refresh interval = 500 ms. (b) Refresh interval = 1 s.

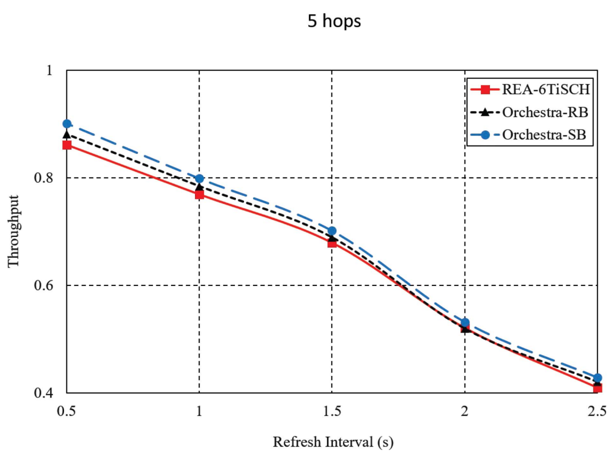


Fig. 10. Throughput comparisons with five hops.

of guaranteeing reliable and timely delivery of time-critical traffic.

Another interesting point is to show how the throughput is affected as a result of the proposed priority-based channel access. Fig. 10 shows the throughput comparisons between REA-6TiSCH, Orchestra-SB, and Orchestra-RB under different refresh intervals.

The throughput is defined as the fraction of time slots used to successfully transmit packets. From Fig. 10, we note that REA-6TiSCH slightly reduces the throughput of Orchestra-SB and Orchestra-RB. This is mainly due to the deferral of the regular packet transmission in the event of an emergency. REA-6TiSCH reduces the throughput by at most 2% compared to Orchestra schemes. On the other hand, the proposed optimized retransmission method in REA-6TiSCH hinders the retransmission of out-of-date packets, hence avoid wasting the channel to transmit useless data. However, in Orchestra schemes, where a fixed retransmission limit is utilized, a node may still retransmit a packet even if its deadline is already missed. In that sense, it is considered a successful transmission with respect to the throughput definition. If we consider the channel utilization as the fraction of time the channel carries useful information, then the transmission of out-of-date packets is useless from the channel utilization perspective. In that respect, the proposed REA-6TiSCH scheme improves channel utilization while having an insignificant reduction in the network throughput.

VI. On the Implementation in 6TiSCH Networks

To complement our simulation-based analysis, we discuss the practical applicability of the proposed method and provide guidelines for the implementation in 6TiSCH networks. As the first aspect, we analyze the challenges of collecting suitable link-quality metrics for estimating the networkwise link-failure probabilities and suggest two methods for collecting such metrics. Later, we examine the runtime feasibility of the proposed optimization by practically testing its execution time on a strongly resource-constrained IoT platform.

A. *Modeling Link-Specific Reliability*

A key point for the feasibility of the proposed optimization algorithm is the knowledge of the packet error rate (PER) over the radio links of interest, which reflects on the probabilities of transmission failure p_j in the objective function in (3).

1) Baseline Assumptions: The estimation of link-specific PER at runtime is generally a complex task since the PER depends both on the properties of the radio channel (which can be time varying in industrial settings [32]) and on the transmission scheme used by the studied radio system. The most relevant factors influencing PER are the multipath fading and attenuation (MFA) and the interference from eventual external radio networks [33]. In this section, we show how to use the results of [34] to derive an expression for the link-specific transmission failure probability, understand its properties, and the impact in the solution of the optimization problem in (3). The analysis takes into account the characteristics of the IEEE 802.15.4 PHY and the effect of signal-to-noise ratio (SNR) concerning the statistical properties of the industrial radio channel over medium-long time horizons [32]. We note that under the assumptions that the effect of external interference and intersymbolic interference is negligible, p_j has a closed-form expression and can be easily calculated at run time. Under these assumptions, the probability of failure after r-retransmission attempts is both convex and monotonically decreasing. Then, the minimization problem in (3) is convex.

2) PHY-Model for the Error Rate: The PHY of IEEE 802.15.4 standard implements a direct-sequence spread-spectrum (DSSS) techniques that sequentially maps four data bits to one among 16-pseudonoise sequences, which are

32-chips long. Couples of sequential chips are then modulated using the O-QPSK technique. As this communication scheme has well-studied performance (see [34] and references therein), it is possible to write the probability of erroneous demodulation of a chip as $P_c = 1/2 \cdot \mathrm{erfc}(\sqrt{\gamma})$, with γ SNR of the received signal. The related symbol error P_s is

$$P_s = \sum_{i=1}^{32} \binom{32}{i} P_{ce}(i) P_c^i (i - P_c)^{32-i} \tag{20}$$

where $P_{ce}(i)$ (available in lookup table form [34]) is the probability of symbol error when i-out-of-32 erroneous chips are received. Since IEEE 802.15.4 does not mandate any form error correction at PHY, an error on symbol decision leads inevitably to a corrupted or missed packet, depending on the position of the error [35]. Then, the probability of failed transmission of an l-bit packet at the jth hop of an emergency path follows as:

$$p_j = 1 - \left(1 - P_s(\gamma_j)\right)^{2l} \tag{21}$$

with γ_j SNR of the received packet. Then, we take into account the results of [32], which show that on a long time scale, the mean of the received signal strength indicator (RSSI) of a static industrial radio link can display sudden and significant variations. This behavior suggests modeling the long-term distribution of RSSI as a multimodal mixture of distributions. Also, the switching period between distributions is reported to be in the order of magnitude of hundreds or thousands of seconds depending on the environment and the specific link [36]. Taking into account this behavior, we assume that closely spaced (within a 6TiSCH superframe) attempts to retransmit a packet on the same link are subject to the same fading distribution. Then, we can approximate the SNR of the jth hop with its expected value $\bar{\gamma}_j$ and write the probability of failing r-successive transmission of the l-bit long packet as

$$p_j^{(r)} = \left(1 - \left(1 - P_s(\bar{\gamma}_j)\right)^{2l}\right)^r \tag{22}$$

which is, as expected, both monotonically decreasing and convex with respect to the number of retransmissions $r \in \mathbb{N}$.

In the next sections, we analyze two key aspects concerning the runtime applicability of the proposed method in 6TiSCH networks operating with COTS devices. They are: 1) the runtime estimation of the PER for the links of the emergency path and 2) the complexity of local solution of the optimization problem concerning memory and processing time. We leave instead to future works the analysis on how to efficiently construct and maintain emergency paths in TSCH- and RPL-based networks.

B. Estimating the Link-Failure Probability

We describe two main approaches to estimate the link-specific PER at runtime: 1) a direct method based on existing 6TiSCH reliability metrics and 2) an indirect method based on the estimated SNR for the emergency links only.

1) Using 6TiSCH Metrics: The first method consists of estimating PER by using only the link statistics that are autonomously collected according to the RPL protocol adopted by 6TiSCH. The RPL protocol defines link-specific metrics, such as link quality-level reliability (LQL) and an expected transmission count (ETX) [37]. The ETX for a radio link j is typically calculated as $\mathrm{ETX}^{(j)} = 1/\mathrm{PRR}^{(j)}$, with $\mathrm{PRR}^{(j)}$ the estimated packet reception rate [38]. The LQL is instead a generic indicator representing the link reliability on a discrete scale from 0 to 7 while the runtime method for LQL calculation is left to the specific implementation [39]. We note that since its definition, the ETX can be used as a direct estimation of the probabilities p_j, which are required for solving the optimization problem of interest. Despite being straightforward, this approach presents a drawback. As analyzed in [38], the ETX metrics are constructed and updated on a packet-transmission basis. Consequently, the ETX of a link which is part of an emergency route only (hence, sporadically used) might be outdated and misrepresent the link state, which is generally time varying [32]. Therefore, we recommend using the ETX metric only when: 1) the transmission of regular packets over the emergency links of interest is sufficiently frequent and 2) the ETX is updated using a proper hysteresis-based filtering technique, e.g., exponential smoothing, as recommended in [38].

2) Autonomous SNR Estimation: We discuss instead an alternative approach for estimating PER, which exploits the model in Section VI-A and avoids the shortcomings of outdated ETX information. The method is based on the idea that even if a specific link is not scheduled to be used for periodic traffic, the receiver can estimate p_j by overhearing a generic packet from the designated transmitter, computing SNR[1] and then applying the model in (22). Following this approach, an SNR metric of the next-hop node in the programmed emergency route can be constructed and maintained. It is worth noting that while this procedure suggests the demodulation of the packets, a demodulation-free estimation of SNR [hence of p_j, due to (22)] is also possible by using energy-sensing approaches, as shown in [40].

A focal point with this respect is the definition of a rationale for setting the nodes' wake-up frequency for updating p_j metrics. As the proposed approach is, in practice, an estimator of the expected value of the SNR ($\bar{\gamma}_j$), we rely on the results of [32] and [36], which describe the RSSI distribution of fixed links in industrial settings as nonstationary over medium and long time scales. In particular, the mean of the SNR distribution can change abruptly between consecutive time segments, which are in the range of 100–1000 s in the examined industrial environments. Since a runtime characterization of the link-dynamics above seems unrealistic for the network in analysis, the conservative practice would be to update the estimates of the SNR mean with a period that is at most half of the length of one segment [36], e.g., on a minute basis. Ultimately, as adequately up-to-date SNR statistics are available, p_j can be computed at runtime in a lightweight manner by using the IEEE 802.15.4 PHY-based model in (22).

[1]We rely on the assumption that the SNR of over-the-air packets can be estimated by COTS WSN nodes basing on recorded RSSI data and the noise-floor level measured during calibration, as reported in [41].

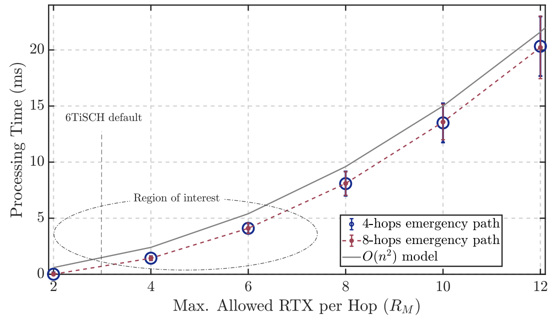


Fig. 11. Processing time required for solving the optimization problem, as measured with TelosB WSN devices.

C. Optimizing at Runtime

In this section, we discuss and analyze the feasibility of running the proposed optimization algorithm at runtime with typical resource-constrained WSN devices. We indeed recognize that an extended processing time would jeopardize the proposed strategy, as the optimization process needs to be solved at each hop of the emergency path. To investigate such a challenge, we have implemented a solver of the optimization problem on a Crossbow TelosB WSN mote [42] running Contiki OS and monitored its performance in terms of memory consumption and execution time. We have deliberately chosen a WSN platform with modest computational capabilities to obtain a reasonably conservative performance estimation. Furthermore, to examine a worst case performance scenario for the processing delay, the solver performs an exhaustive search over the cost function of the primal optimization problem in (3), concerning the retransmission variable r_j. To randomize the outcomes of different runs, we take care of regenerating the probabilities of transmission failures p_j as uniform random variables in $[0, 1]$ and the default retransmission parameters $r_1, r_2, \dots, r_H \in \mathbb{N}$ as discrete uniform random variables in $[1, R_M]$, with R_M maximum allowed number of retransmissions per hop. We show in Fig. 11 the mean and the standard deviation of the measured processing time, calculated over 1000 runs per data point. As expected, the delay scales up with the maximum allowed retransmission per hops R_M. Additionally, the measured delay is in the order of few ms for R_M in the range of interest for this work, which gives useful insights into the suitability of the proposed method for real applications. We explain the dependency on R_M, considering that the constraint on the maximum number of retransmissions directly affects the domain of the cost function in (3) and thus increases the number of data points to examine quadratically. We also note that higher values of H, the number of hops in the emergency path, do not affect the processing time significantly, at least for the size of the 6TiSCH networks of interest for this work (i.e., $H < 10$). We explain this by noting that the parameter H only affects the terms $1, 2, \dots, H$, which constitute the additive part of the cost function in (3) and need to be calculated only once at the beginning of the algorithm. Also, the experimental delay T_D appears to scale up in a quadratic manner with R_M, which is also expected. We consider a simple model for the processing delay as $T_D = (n_A T_\mu) R_M^2$, with T_μ clock period in ms of the employed TI-MSP430 microcontroller (i.e., 0.12×10^{-3} ms) and n_A average number of elementary operations per evaluation cycle of the objective function, which is derived experimentally. The comparison between the model and the experimental curves is shown in Fig. 11. Finally, the average memory overhead needed for the execution of the algorithm with the selected hardware/OS is ∼2.3 kB, which is around 4% of the total memory (RAM + ROM) available with the TelosB nodes [42]. It must also be considered that more recent low-cost WSN hardware, such as [43], outperforms the analyzed platform, ensuring five to ten times more memory and faster microcontrollers. Therefore, the results presented in this section give solid guarantees on the suitability of the proposed optimization algorithm for a broad range of WSN platforms.

VII. Conclusion

In this article, we have introduced REA-6TiSCH, a reliable real-time communication scheme for handling emergency alarms in 6TiSCH networks. In REA-6TiSCH, the aperiodic emergency traffic is enabled to hijack scheduled slots for the regular traffic in a nonconflicting manner. In order to further improve the communication reliability, an optimization approach has been introduced with the aim to improve the probability that the emergency flow is delivered successfully within its deadline bound. We have thoroughly discussed the runtime applicability of the proposed method in 6TiSCH networks and implemented the underlying optimization process in low-cost WSN nodes. Limited processing delay and memory consumption render the proposed method appealing for implementation in networks with resource-constrained devices. Performance evaluations have revealed the robustness of REA-6TiSCH in delivering emergency alarms in 6TiSCH networks compared to Orchestra scheduling schemes. Hence, REA-6TiSCH can be a viable solution for a variety of time-critical scenarios within IIoT applications.

As part of future work, the work in this article can be further investigated considering the following aspects. The proposed prioritized channel access in REA-6TiSCH can be extended to support mixed-criticality scenarios, which is the case in various IIoT applications. The industrial radio channel is complex and dynamic, conducting measurements to evaluate the performance of the proposed scheme in real scenarios can be also investigated. In addition, the effect of retransmission on communication determinism and predictability needs to be addressed.

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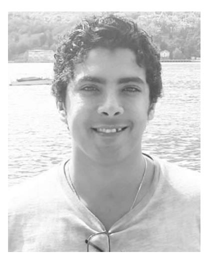

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