Reliable Channel Allocation for Mission Oriented Low-power Wireless Networks

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***Abstract*—Multichannel communication is an important means to improve the reliability of low power wireless networks (LPWNs). For mission oriented LPWNs, data transmissions are often required to be delivered before a given deadline, thus making deadline-driven channel allocation an essential task. The existing works on multichannel allocation often fail to establish channel schedules to meet the deadline requirement as they often assume transmissions can be successful within one transmission slot. Besides, the impact of allocation orders for different paths and channels are also overlooked. In this paper, we propose a Retransmission enabled Deadline-driven Channel Allocation scheme for mission oriented LPWNs (ReDCA). Compared to the existing works, 1) we propose a novel prioritization scheme for the channel allocation for different paths and channels, which jointly considers link quality, deadline urgency and network topology; 2) we consider enabling retransmissions within the same transmission cycle and assign additional channel/slot pairs to lossy links for possible retransmissions. We conduct both simulation and testbed experiments. The results show that ReDCA can significantly improve the packet delivery ratio before deadline without incurring extra energy consumption compared to the existing works.**

I. INTRODUCTION

Low power wireless networks (LPWNs) are a fundamental infrastructure for the Internet of Things (IoT)systems [1]. The LPWNs are deployed for certain interests such as air/water quality monitoring, disaster alarming, etc [2], [3], [4]. The sensor data is transmitted to a central sink node for data analysis and processing. Many LPWNs are mission oriented such as smart home [5], [6] and building monitoring [7], where the sensor data is required to be delivered to the sink node before a given deadline in order to keep a real-time monitoring of the target patients and areas [8].

Reliability is one of the key issues in LPWNs, especially for mission oriented networks with strict deadlines [9]. Due to the lossy nature of low-power wireless communications and the interference between different links, it is non-trivial to guarantee the data to be delivered to the sink before deadline. Multichannel communication is an effective approach to improve the communication reliability for low power devices. Chen *et al.* [10] proposed a centralized multi-channel MAC protocol based on TDMA to improve the overall packet reception rate. Le *et al.* [11] proposed a distributed multichannel protocol, in which channel switching overhead of the hardware is also minimized. Some successive works further take the deadline constraint into account. Saifulah *et al.* [13] designed a channel scheduling algorithm with deadline in Wireless HART networks. In these works, the deadline is met by assigning enough slots for routing paths. For example, if the deadline is four slots, a three-hop path will be assigned three slots before the fourth time slot.

There are two limitations for the existing works. First, the importance and impact of the assignment orders for different paths are overlooked, which may lead to resource waste of wireless channels or even channel starvation (explained with an illustrative example in Section II). Second, the existing works often assume that the packet transmission can be successful in one slot, which is not true in real-world networks. Some works increase the slot length to allow retransmissions to guarantee successful packet deliveries within one slot. However, the lengthened slot will cause much delay for links with good quality. At the same time, many slots are unused by the existing works (in order to reduce energy consumption), which is potential to be used for retransmissions.

To address the above limitations and improve the reliability before deadline, we investigate the problem of multichannel assignment for deadline driven and unreliable LPWNs. We propose a "two-round" channel allocation scheme where the first round assigns the slots in appropriate priority according to the link quality and the deadline requirement, and the second round re-assigns unused slots for future retransmissions. In the first round, we propose a mechanism that jointly considers link quality, deadline urgency and network topology to prioritize the most appropriate links and paths. In the second round, we consider the retransmission probability and assign the unassigned slots (in the first round) to the most appropriate links to accommodate more retransmissions within one cycle. A retransmission scheme is also devised to effectively exploit these slots. It is worth noting that the retransmission slots will be used for only lossy links and no extra overhead will be incurred for those good links without packet losses. We implement ReDCA and conduct both simulation and testbed experiments. The evaluation results show that compared to the existing works, ReDCA greatly improves the packet delivery ratio before deadline (PDR-BD) and does not incur extra energy overhead.

The main contributions of this paper are summarized as follows.

1) We propose a novel multichannel assignment scheme

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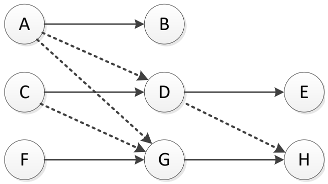

Fig. 1. Example for assignment priority.

for mission oriented LPWNs. By jointly considering link quality and the deadline requirement, the most appropriate transmission paths are prioritized in the multichannel scheduling. Both centralized and distributed algorithms are devised.

2) We propose a re-assignment scheme to efficiently use the spare slots for improving the packet delivery ratio before deadline, with which the retransmissions can be done within one scheduling cycle.
3) We implement and evaluate ReDCA with both simulation experiments and TelosB testbed. The evaluation results show that ReDCA significantly improves the transmission performance compared to the existing works in terms of PDR-BD.

The rest of this paper is organized as follows. Section II presents the motivation of our work with illustrative examples. Section III presents the design details of ReDCA. Section IV evaluates ReDCA with simulation experiments. Section V presents the related works. Section VI concludes this work.

II. MOTIVATION

In this section, we use an example to illustrate our work on the impact of path assignment priority. Despite the limited number of channels and possible interference for LPWNs, we argue that the path assignment order also has large impact on the channel assignment. We use Figure 1 and Figure 2 to illustrate the impact of the assigning order for the paths.

As shown in the figure, there are three paths in which three source nodes A, C and F have one packet to be sent to nodes B, E and H, respectively. The directed dotted lines represent interfering links. The deadline for the paths and the number of available channels is both 2.

Figure 2 demonstrates the assignment process with different assignment orders. We will compare the delay of the assigned schedules with different assigning orders. In Figure 2 (a) and Figure 2 (b), the links “F-G“ and “G-H“ are first assigned in the two available time slots, then “C-D“ and “D-E“ are assigned in channel 0 to avoid interference. Link “A-B“ is eventually put in time slot 2 and channel 1 without interference. Differently in Figure 2 (c) and Figure 2 (d), after assigning links “F-G“ and “G-H“, “A-B“ is assigned in time slot 1 and channel 0. In this case, the last remaining link “C-D“ will conflict with both links in the two channels in time slot 1 and cannot be assigned to any slot. Apparently in this case, the channel resources are wasted.

We can infer from the above example that the priority for assignment can dramatically affect the efficiency of channel assignment, limiting the utilization of wireless channels. Intuitively, we need to first resolve the most conflicted links and slots in order to avoid the channel starvation problem.

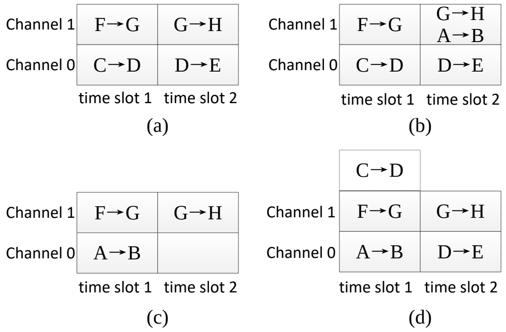

Fig. 2. Assignment with different priorities.

Besides, the existing works often assume a packet can be always delivered in one slot, which is apparently not true for real-world LPWNs. One alternative is to increase the length of each slot to accommodate retransmissions to increase the PDR within one slot. However, as the slot length for all slots are required to be the same in order to synchronize the channel switching, the lengthened slots will lead to much extra delay for good links with few packet losses. Some works also consider retransmissions, which are arranged in the next transmission round, which leads to at least one full-cycled delay.

We identify an optimization opportunity as follows. With the existing works, on one hand, potential retransmissions cannot be scheduled in advance as they are unpredictable; on the other hand, there are some slots left unused after the channel scheduling. Our key idea is to exploit those unused spare slots for possible retransmissions in a probable manner. The detailed design will be presented in Section III.

III. MAIN DESIGN OF REDCA

In this section, we present the main design of ReDCA.

A. Network model

We focus on the deadline driven data collection where sensing data are relayed by other nodes in LPWNs through a given spanning tree routing topology. The root is the sink node capable of analyzing or processing the collected data. We assume time synchronized slotted underlying MAC protocol (e.g., TDMA). Time is synchronized and slotted with standardized length which allows a node to send a maximum-size data frame and receive the related acknowledgment. All the nodes are equipped with a single transceiver, a sensor can only be scheduled on one channel and one given time slot, and the network operates in repeated duty cycles.

B. Overview

ReDCA consists of two assignment rounds. In the first round, the most appropriate paths are prioritized to minimize the chance for collisions. The metric used for prioritization considers link quality, path length and topological collisions. The scheme is detailed in Section III-D. After the first round assignment, all links are assigned at least one channel/slot pair. At the same time, some slots are left unassigned. Then the second round continues by assigning these unused slots to links that are likely to experience packet losses. The detailed re-assignment scheme is described in Section III-E. During the channel allocation process, link quality is estimated using the in-packet corruptions [14] and the 4b link estimation [15] is used to measure the link quality for each channel/slot pair. The notations used throughout this paper are summarized in Table I.

TABLE I
NOTATIONS

Symbols	Notations
l_i	The length of path starting from node s_i
c_i	The number of collideing paths of path starting from node s_i
A_i	The set of available slots/channels for retransmitting link i
$b^l_{t,c}$	Whether link l is assigned to time slot t and channel c
$p^l_{t,c}$	The link quality of link l on time slot t and channel c
P_i	Path i
pr_i	Quality improvement for link i
pr_g	Quality improvement for link set g
q_b	Link quality before retransmission
q_n	Link quality after retransmission
T	The number of given time slots
ci	The number of available channels
Re	Retransmission set

C. Wireless link measurement

Our allocation scheme relies on the link quality for each channel/slot pair. However, one challenge is to obtain the link quality profile for each channel/slot pair as only one channel quality can be measured at a time. Similar with [16], we use the 32KHz timer to measure the in-packet byte-level RSSI values. From the in-packet RSSI values, we can obtain the statistical relationship between byte error probability with different RSSI distances. We can also infer that the error rate increases when RSSI distance becomes larger. With the byte error rate, we can further calculate the link quality as follows:

$$q = prod_{i=1}^{n}(1 - b_i) \tag{1}$$

where q denotes the link quality and b_i denotes the byte error rate of the ith byte. Each node periodically exchanges beacons with neighboring nodes in different channels and estimate the link quality corresponding to certain slots and channels.

D. Path based channel assignment

1) Path prioritizing: Given the available channels, ReDCA assigns time slots and channels for links among a path in the network iteratively until all paths are assigned. We propose a novel path prioritization metric, where the path length, interference and the number of generated packets are considered.

At first, since the deadline is assumed identical for all the nodes, paths with more links have less available time slots and are more urgent to be assigned because the available slots and channels decrease as the assignment processes. Besides, we quantify the interference situation using the number of conflicting links. Links that are conflict with the assigned paths are excluded to transmit data on those slots and channels. The paths with worse interference situation and higher probability to conflict with other links should be to be served earlier.

As a result, our prioritization metric based on two factors is designed as follows:

$$m_i = \alpha l_i + (1 - \alpha)c_i \tag{2}$$

where l_i represents the length of paths and c_i represents the number of colliding links. Using this metric, the longer paths with more packets to transmit and more collisions are first allocated.

2) Link quality aware channel allocation: Next we assign time slots and channels for links in a path. Since our allocation aims to maximize PDR-BD, with the constraint of link scheduling order and interference, we consider the allocation as a nonlinear programming problem as follows:

$$\begin{aligned}
&\max \prod_{b^l_{t,c=1}} p^l_{t,c}, (l \in P_i, t \in T, c \in C),\\
&s.t. \forall l \in P_i, t_l < t_{l+1}\\
&\forall l \in P_i, 0 < t_l < d\\
&\forall l \in P_i, \forall m \in As, b^l_{t,c} \neq 1, if\ hear(recv(m), l)\\
&\forall l \in P_i, \forall m \in As, b^l_t \neq 1, if\ adjacent(m, l)
\end{aligned} \tag{3}$$

Due to the varying quality of links, the packets generated by source nodes cannot always reach the destination node, in ReDCA, we apply the retransmitting scheme to improve the reliability of transmission.

E. Channel allocation for retransmission scheme

To further improve the PDR-BD of transmission, we use spare time slots after the first round and channels for retransmission. Our retransmission scheme works in two steps. First, for a time slot and channel, links that require retransmissions are determined. In the second step, links in the retransmission link set are divided into several conflict-free sorted subsets, the best subset is then chosen for retransmission assignment.

For a time channel/slot pair, if a link meets the sequence and conflicting requirements, it will be added to the retransmission link set of this slot/channel.

The sorting process is based on two factors: the quality profit and retransmission chances.

For an available link in a retransmission set, we can get the quality profit of retransmission as follows.

$$pr_i = 1 - (1 - q_b)(1 - q_n) - q_b \tag{4}$$

where q_{before} and q_{now} represent the succeeding probability without and with this retransmission. The quality profit represents the improvement of link quality with the existence of retransmission. Since some links can be assigned retransmission concurrently on the same channel/slot pair, for links in a subset, their quality profit can be expressed as:

$$pr_g = \sum_{n=1}^{G} pr_i \tag{5}$$

Furthermore, the number of available retransmission slots/channels differ from each other due to collisions and link dependency among the paths, which are considered as the retransmission chances. Links with less retransmission chances have higher priorities to be retransmitted. Above these two aspects, we propose a specific metric to prioritize the links waiting to be retransmitted as follows.

$$mr_g = \alpha pr_g + (1-\alpha) \mid \bigcup_{g=1}^{G} A_i \mid \tag{6}$$

With this retransmission metric, the subsets with better quality profit and less retransmission chances are assigned earlier, the detailed algorithm of the retransmission scheme is demonstrated as followed in Algorithm 1.

ALGORITHM 1: Retransmission for time slot$t$ and channel ch

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Input: The set of links assigned on time slot $t$, $D(t)$;
The set of all links in the network, $L = \{link_i\}$;
Output: The retransmission links $re\_assigned(t/ch)$ ;
for each $l \in L$ do
    if $l.time<t$ & $next(l).time>t$ & $conflict(l, D(t)) ==$
      $false$ then
        $Re.append(link)$
    end
end
Divide($Re$)
Get($mr_g \in Re$)
Sort($Re$)
$re\_assigned(t/ch) = arc\max(Re)$
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F. Distributed ReDCA

The operation of ReDCA requires global information of the whole network, for example, computing the priority of a path utilizes the collision situation which is hard to get for nodes within one hop. So the centralized scheme may not be appropriate in practice. In order to deal with the difficulties of collecting global information, we extend the ReDCA into a distributed one, which requires the information from only one-hop neighbors.

Specifically, a source node plans to transmit its packet on the best channel and computes its priority we proposed above. After communicating with neighbors, this node decides whether to transmit it or suppress the transmission. If its priority is the largest compared to all its neighbors, it transmits the packet immediately. If there is a neighbor node with higher priority, it will expect to transmit on the second-best channel, and compare with other neighbors using the new channel. If this node cannot transmit on all of its channels, it need to wait for the next transmission. Besides, if transmission failure happens, the node will update its own priority with consideration of the retransmission cost.

Fig. 3. Testbed for performance evaluation.

IV. PERFORMANCE EVALUATION AND ANALYSIS

In this paper, we evaluate the performance of ReDCA by both simulations with the TOSSIM [17] simulator and real environment experiments with TinyOS/TelosB testbed. The following metrics are used for illustrate the performance.

1) Packet delivery ratio before deadline. PDR-BD represents the reliability of the transmission. PDR-BD can be obtained by gathering the link quality among the transmission path.
2) Channel resource utilization. The utilization is calculated as the proportion of slots/channels that are actually assigned in the channel allocation scheme. It reflects the influence of retransmission assignment.
3) The number of retransmissions. The number of retransmissions are required when packet losses happen for different assignments.

We first evaluate the performance of ReDCA with the TOSSIM simulator. The network contains 50 nodes, with one node be the sink node and other 49 nodes source nodes. Data from source nodes traverse to the sink node through a specific path, which is generated with least hop count. Then, we evaluate the performance of the distributed ReDCA with the testbed, which contains 20 TelosB motes, with node ID from 1 to 20. The node with $ID = 20$ acts as the sink node, other nodes generate 100 packets and transmit them to the node 20 through a shortest-path tree. There are three channels for data transmission, channel 11, 18 and 26.

A. Simulation results of TOSSIM simulation

Figure 4 shows the PDR-BD among ReDCA and Wave [18]. The different PDR among different paths is due to the different path lengths and packet loss rates. It can be seen that the PDR-BD of ReDCA without retransmission is larger than that of Wave. The reason is that ReDCA intends to select slots/channels with better link qualities before the deadline, while the quality of slots/channels in Wave is often worse, at the same time, leaving the spare slots and channels. In this case, ReDCA with retransmission scheme performs better than that without retransmission. It can be inferred that with an appropriate retransmission scheme, the reliability of data

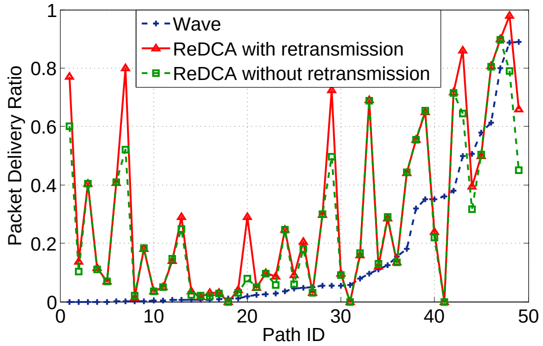

Fig. 4. Comparison of packet delivery ratio before deadline.

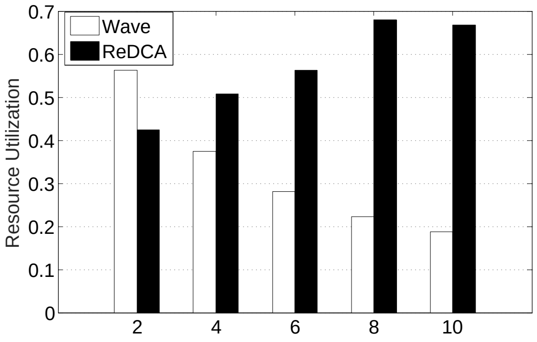

Fig. 5. Comparison of resource utilization.

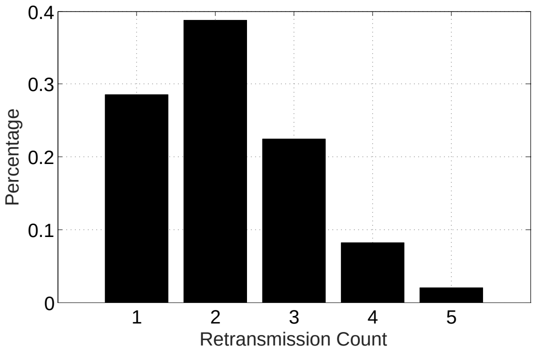

Fig. 6. The number of transmissions.

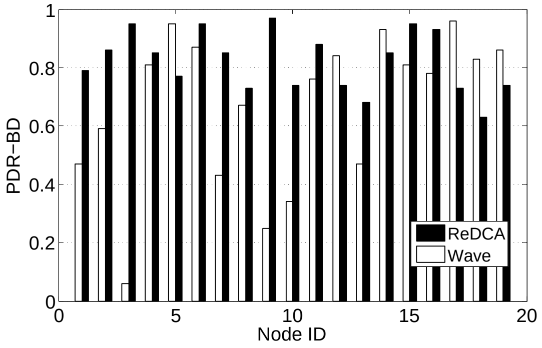

Fig. 7. Packet delivery ratio before deadline.

collection can be significantly improved. Note that there are a few paths that Wave performs better than ReDCA, this is because ReDCA assigns a few links on worse slots/channels for the purpose of realizing overall PDR-BD improvement reflecting in path priority and retransmission assignment.

Figure 5 compares the resource utilization of ReDCA and Wave. The utilization is calculated as the proportion of the utilized slots/channels over the total number of slots/channels. Note that a larger resource utilization does not mean more energy consumption, since the assigned slots/channels include slots for retransmission, and the retransmission slot/channel would be active only if the transmissions failed. The figure depicts that when there are two available channels, the utilization of ReDCA is lower than Wave, which is because that with limited channels, ReDCA choosing high quality slots and channels results in more conflict than Wave, leading to some links cannot be assigned. While as the available channels increase, the resource utilization of ReDCA is higher than Wave. This is because extra retransmissions are allowed in ReDCA while in Wave a full-cycled delay will be incurred when there are packet losses.

The retransmission statistics is demonstrated in Figure 6. The cases without a retransmission scheme are not considered in this figure. Among all the bars, 29% links retransmit their packets once, and about 39% links use two retransmissions. There are about 22% links having three retransmissions, and retransmissions happen for four times on 8% links. At last,there are 2% links using five retransmissions. We can get that most links are lossy and retransmissions are necessarily required, and for these cases with retransmissions, the PDR-BD is greatly improved.

B. *Testbed results*

Figure 7 shows the PDR-BD among distributed ReDCA and Wave [18]. It is obvious that the packet delivery ratio before deadline of ReDCA is much larger than that of Wave in most source nodes, which are all above 0.6. And the average PDR-BD of all the source nodes in ReDCA is improved around 22% compared to that in Wave. The reason is that the proposed ReDCA considers the varying link quality and tends to choose higher quality for transmission links. Furthermore, ReDCA takes the advantage of retransmit the failing links, which lead to a much larger PDR-BD compared with Wave that ignores the chance of good link quality and retransmission. Note that for some nodes, the PDR-BD of Wave could be larger than ReDCA, this is because that the two algorithms adopt different nodes assigning orders, to guarantee the transmission of nodes with higher priority, ReDCA might sacrifice a few nodes that are not urgent to be transmitted or with fewer collisions, which can be acceptable compared to the increasing of global performance.

V. RELATED WORKS

Channel allocation in multichannel LPWNs has been extensively studied in recent years. In many application scenarios such as health emergency alarm [19], real time monitoring

[20] and fire rescue robots [21], strict deadline for the data transmission is often required to keep the real-time monitoring for target people and areas.

Works on guaranteeing the transmission deadline mainly include [12], [13], [22], [23]. The basic idea of these works is to allocate enough slots for a routing path before its deadline. Most of the existing works are based on an assumption: a transmission can be successful in one slot or the slot is long enough for several retransmissions to ensure the packet can be delivered within one slot. Kumar *et al.* [12] aim at minimizing the total energy consumption while meeting deadline constraints. They tend to choose equidistant paths for different sources, which is proved to be optimal in terms of energy consumption. Dao *et al.* [22] try to ensure the packets to be delivered before deadline with a specific probability. Apparently, the assumption is often not true in real world networks and packet losses will have significant impact on the overall packet delivery delay: 1) If the slot length is suitable for one transmission, packet loss will lead to that the transmissions are deferred to the next duty cycle [23], which will incur a full-cycled delay. 2) If the slot is long to allow retransmissions within one slot, there will be considerable delay incurred for the links without packet losses as the slot lengths are the same for all links.

Compared to these works, ReDCA does not assume loss-free channels for scheduling the slots. Instead, ReDCA considers the packet losses during the two-round channel allocation. For those paths that may not meet the deadline, the spare slots which are not used in the first-round assignment will be assigned to these links to meet the deadline requirement.

VI. CONCLUSIONS

In this article, we propose a novel channel assignment scheme for mission oriented LPWNs, which considers the lossy nature of wireless links and maximizes the packet delivery ratio before deadline. A path priority scheme is proposed to improve the channel utilization, which jointly considers path length, packets/deadline demands and topological collisions. Moreover, we develop a retransmission scheme to take efficient use of the unassigned idle slots/channels, which significantly improves the reliability. Extensive simulation experiments are conducted implying that ReDCA outperforms the state-of-art works.

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