DecTDMA: A Decentralized-TDMA with Link Quality Estimation for WSNs

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Abstract. In wireless sensor networks (WSNs), different motes may transmit packets concurrently, i.e., having overlapping transmission periods. As a result of this contention, there are no packet reception guarantees and significant bandwidth can be lost. This contention can have a strong impact on the performance together with other kinds of interference sources, e.g., ambient noise. As a result, WSN's connectivity tends to have a very dynamic nature.
In this paper, we devise DecTDMA (Decentralized-TDMA), a fully decentralized medium access controller (MAC) that significantly reduces contention. It is based on a self-stabilizing algorithm for time division multiple access (TDMA). This self-stabilizing TDMA algorithm uses no external assistance or external references, such as wireless access points (WAPs) and globally-synchronized clocks. We present the design and implementation of DecTDMA and report encouraging results: our Cooja simulations and Indriya testbed experiments show stable connectivity and high medium utilization in both single and multi-hop networks. Since DecTDMA has favorable characteristics with respect to connection stability, we show that common link quality estimation (LQE) techniques further improve the operation of DecTDMA in the dynamic environment of low-power wireless networks.

1 Introduction

Wireless sensor networks (WSNs) are self-organizing systems where computing devices, so called motes (or nodes), set up – by themselves – a networking infrastructure without relying on external assistance. In this paper, we focus on medium access control (MAC) in WSNs. We present DecTDMA (Decentralized-TDMA) — a fully-decentralized MAC protocol for WSNs. Our decentralized solution does not assume access to external references, such as wireless access points (WAPs), and individual nodes in DecTDMA do not have special tasks, such as acting as elected coordinators. In this work, we aim to mitigate one of the key sources of internal interference: concurrent transmissions by neighboring motes, which cause radio interferences. The event of concurrent transmissions refers to the occurrence of multiple transmissions, such that the periods of these transmissions overlap. Concurrent transmissions have a great impact on the throughput in WSNs. For example, they can reduce the packet reception ratio (PRR) [1]. DecTDMA uses a self-stabilizing algorithm [2] for time division multiple access (TDMA) that significantly reduces the occurrence of concurrent transmissions. In addition, we show that DecTDMA deals well with other causes of WSN dynamics, such as mote or link failure and wireless links of intermediate quality, i.e., links with a PRR between 10% and 90%. DecTDMA uses a link quality estimation (LQE) technique for estimating the PRR of both broadcasts and their respective acknowledgements. We use this elegant (lightweight) and software-based technique for masking short term link failures, i.e., sporadic (receiver-side) packet omissions. It allows DecTDMA to sift out both disconnected links and (many) intermediate quality links. We present a TinyOS implemention of DecTDMA and evaluate it via Cooja simulations and experiments in the Indriya testbed [3]. During these experiments, we observe rather stable PRR values. Moreover, during our experiments, DecTDMA achieves PRR values that approach the analytical bounds.

Challenges. In wireless communications, a single message may reach many receivers (due to the broadcast nature of radio transmissions). The success of message arrival depends on the distance between the transmitter and potential receivers as well as complex signal propagation patterns: wireless signals propagate unequally in different directions due to antenna characteristics, over many paths, and are subjected to interference. In WSNs, different (possibly neighboring) transmitters may send concurrently. In such cases, there are no guarantees for any receiver to get the packet and significant bandwidth can be lost. Thus, one of the key challenges in simplifying the use of WSNs is to limit the occurrence of such local contention factors. The studied question is whether one can device a MAC protocol that avoids contention, i.e., significantly reduces the occurrence of concurrent transmissions. We present DecTDMA and report encouraging results about the feasibility of TDMA protocols that require no external references, such as WAPs and global clocks.

Evaluation criteria. Medium access control with high throughput is essential for many WSN protocols, especially for routing protocols [4]. Using statistical characterization, methods for link quality estimation (LQE) provide insights for routing protocols on which links they should forward packets. By avoiding low and intermediate quality links, the MAC layer can limit its packet loss, reduce the number of re-transmissions, and provide better connectivity. This also impacts the higher layers, e.g., it reduces the need for selecting new routes at the network layer and reduce the end-to-end latency of the transport layer.

PRR is a common evaluation criterion in (wireless) communication networks [4]. For WSNs, PRR is often an elegant criterion that is easy to implement and according to which routing protocols can estimate link quality. In this work, we are interested both in the PRR values themselves and their stability over time. The motivation for the latter criterion is by the fact that stable PRR values are easier to work with (from the point of view of the higher layers).

The literature refers to PRR both as an evaluation criterion and as a basic mechanism for evaluating link quality. It is well-known that there are more advanced LQE mechanisms that provide more stable estimation than the average PRR mechanism [4]. We follow the common practice that often use average PRR mechanisms for simplicity and choose an LQE mechanism that considers the PRR values of both messages and their acknowledgements.

Design criteria. In this paper, we focus on MAC protocols for low-power wireless networks that autonomously set up their networking infrastructure. WSNs are subject to faults that occur due to temporal hardware or software malfunctions or the dynamic nature of low-power wireless communications.

Fault-tolerant systems that are self-stabilizing [5] can recover after the occurrence of transient faults. These faults can cause an arbitrary corruption of the system state (as long as the code of the program is still intact). Transient faults can also represent temporary violations of the assumptions according to which the communication links and the entire dynamic networks behaves during normal operation. In order to provide DecTDMA with properties of self-organization and self-recovery, we base the implementation of DecTDMA on an existing self-stabilizing TDMA algorithm [2]. This algorithm helps DecTDMA to significantly reduce the occurrence of concurrent transmissions. We note that the design of the TDMA algorithm in [2] focuses on packet loss due to concurrent transmissions and models all other kinds of packet loss as transient faults (after which a brief recovery period is needed). DecTDMA extends this, by utilizing an LQE technique for masking sporadic packet loss. Thus, DecTDMA considers fewer occurrences of sporadic packet loss as transient faults than the TDMA algorithm by Petig et al [2]. As a result, DecTDMA avoids unnecessary recovery periods. This increases the performance and the stability of the packet reception ratio (PRR) values.

Our design criteria of self-organization and self-recovery simplify the use of WSNs. It reduces the effect of local and low-level complications, such as contention management, that many systems leave to be handled by the higher layers. Consequently, we provide an important level of abstraction that allows the higher layers to focus on their tasks, such as routing table construction, packet forwarding, and end-to-end communications.

We do not claim that the studied implementation is self-stabilizing. Note that the implementation of a self-stabilizing system requires every system element to be self-stabilizing [6], rather than just a subset of the needed algorithms. This includes the use of compliers that preserve any invariant that is related to the corretness proof [7], as well as the use of self-stabilazing CPUs [8], self-stabilazing operating systems [9] to name a few.

Our Contribution. In this paper, we present DecTDMA — a decentralized TDMA that does not assume access to external references, such as wireless access points (WAPs) or a global clock. For DecTDMA, we (a) extend and (b) implement an existing self-stabilizing algorithm [2] and (c) evaluate our implementation both via WSN simulations and a real-world testbed. By that, we provide stable connectivity with high values of packet reception ratio (PRR). We also offer a masking technique as a way to further improve the channel stability by considering sporadic packet losses as normal faults rather than transient ones. The studied technique estimates the stability of every TDMA time slot and lets

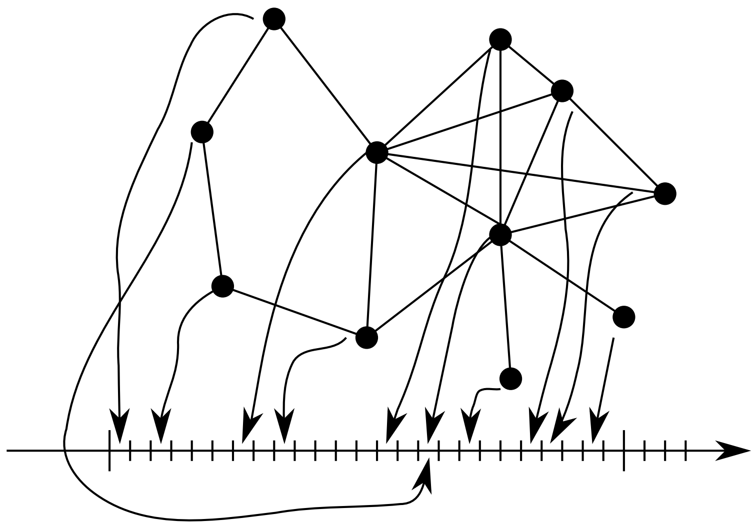

Fig. 1: Time slot assignment in multi-hop network graphs. Neighbours with a distance of at least 3 can share the same time slot without collision.

DecTDMA to keep only time slots that are above a predefined threshold. We evaluate our TinyOS implementation via Cooja simulations on both single and multiple hop networks as well as on Indriya Testbed at NUS (with 97 motes). The results validate that DecTDMA (and its LQE technique for masking sporadic packet loss) provides stable connectivity with high PRR values. For the studied cases of network simulations, DecTDMA achieves PRR values that are rather stable and approach the analytical bounds.

We believe that these findings demonstrate the feasibility of decentralized reference-free TDMAs that provide stable communication among the WSN motes without the need for an external coordinator nor access to a global time reference. The design and implementation of DecTDMA exposes the advantage of following the self-stabilization design criteria. DecTDMA is a multifaceted TDMA protocol that can deal with a number of failures. This fault model includes concurrent transmissions and sporadic packet loss, as well as different violations of the algorithm assumptions, which we model as transient faults.

Document Structure. As background knowledge (Section 2), we present the self-stabilazing TDMA algorithm by Petig et al. [2], which DecTDMA extends. We complete the description of DecTDMA by discussing the details of our LQE technique (Section 3). We present our evaluation of DecTDMA by studying the results of our experiments (Section 4). Finally, we discuss the related work (Section 5) and our concluding remarks (Section 6).

2 Background: Time Slot Alignment and Allocation

DecTDMA uses a TDMA algorithm by Petig et al. [2] for aligning the frame and letting each mote access a time slot that is unique within its 2-hop neighbourhood (Figure 1). For the sake of self-containment of this paper, we describe the algorithm and how it works under the assumptions of Petig et al. [2]. In real-world WSNs, there are different sources for interferences that cause packet loss. The TDMA algorithm of Petig et al. [2] focuses on packet losses that are due to concurrent transmissions and models all other kinds of packet losses as transient faults (after which brief recovery periods are needed). Therefore, DecTDMA extends it and uses an LQE technique for masking sporadic packet loss (Section 3). We show that DecTDMA can perform well in real-world WSNs, which do not need to follow the assumptions made by Petig et al. (Section 4).

In the TDMA algorithm by Petig et al. [2], motes send both data and control packets. Also, the motes can play an active or a passive role according to their (local) status. When the mote p_i's status is active, it sends data packets during a time slot that is designated for p_i's data packets, which we call p_i's transmission time slot, s_i. When p_i's status is passive, it listens to the active motes, and it does not send any data packets. The motes send, regardless of their status, control packets which include the frame information (FI). The field FI includes data about the recently received data packets from direct neighbours. That information refers both to the sender identity and the packet sending time. The TDMA algorithm by Petig et al. aggregates the frame information it receives during the past frame. The algorithm relies on FI to acknowledge transmissions, resolve hidden terminal phenomena and avoid concurrent transmissions. The mote active-passive status changes according to the filed FI.

(1) **The passive mote $\mathbf{p_i}$ takes the following steps in order to become active.** It selects a random time slot, s_i, that no active mote within two hops uses according to p_i's FI. Mote p_i tests the use of time slot s_i by sending a control packet and waiting for acknowledgement from neighbouring motes. These acknowledgements are included in their data and control packets. Whenever that test works, mote p_i changes its status to active and uses s_i as its transmission time slot for data packets.

(2) **The active mote $\mathbf{p_i}$ can become passive due to the following.** An active mote p_i changes its status to passive after its FI field reports about another mote, p_j, that transmits during its time slot s_i, where p_j is at most two hops away from p_i. Recall that during the occurrence of hidden terminal phenomenon, mote p_i has a neighbour, p_j, and a distance two neighbour, p_ℓ, such that p_i and p_ℓ use time slots with overlapping periods. In this case, there is no grantee that p_i receives p_j's frame information (and acknowledgements) to p_i's packets. In order to deal with this issue, the TDMA algorithm by Petig et al. also considers the absence of p_j's acknowledgement as an implicit report on a possible occurrence of the hidden terminal phenomenon. Note that, unlike the TDMA algorithm by Petig et al., DecTDMA uses an LQE technique for mitigating the effect of sporadic packet loss, say, due to ambient

noise. Namely, DecTDMA lets p_i change its status from active to passive only according to LQE indication (Section 3).

Petig et al. [2] uses a random back-off mechanism for dealing with contention scenarios in which "too many" passive motes are testing random time slots concurrently, see case (1) above. This mechanism counts down (from a randomly selected backoff value) every time the node observes a time slot that for which it receives no message. The TDMA algorithm by Petig et al. also adopts a technique for clock synchronization according to which it aligns the TDMA time slots. Petig et al. [2] show that their self-stabilizing TDMA algorithm can provide, after a convergence period, guarantees that each active mote can transmit successfully once in every TDMA frame. The proof of self-stabilization by Petig et al. assumes that packet loss occurs only due to concurrent transmissions. However, in real-world WSNs the above assumption does not hold. This work proposes DecTDMA, which does not follow this assumption. Instead, it uses an LQE technique for avoiding a change in p_i status from active to passive due to the occurrence of sporadic packet losses (and does allow this change whenever p_i's time slot, s_i, losses packets repeatedly, see Section 3).

3 TDMA Protocol with Link Quality Estimation

In real-world WSNs, packet losses occur due to many reasons, such as external interference or concurrent transmissions, i.e., when neighboring nodes transmit during overlapping periods. DecTDMA addresses the challenge of sporadic packet losses via a Link Quality Estimation (LQE) procedure. Here, mote p_i does not stop sending a data packet in its transmission time slot s_i due to a sporadic packet loss. We use a software-based LQE technique that estimates p_i's LQE by accumulating the acknowledgments that p_i receives over a time window and comparing them to the number of transmitted packets. We use this lightweight LQE technique for deciding whether p_i shall keep its transmission time slot, s_i, or try to randomly select a new one after a random back-off period (Section 2).

Our LQE technique considers a time window of w TDMA frames. We use arrays of integers, $ack_i[]$ and $rx_i[]$ (each of w entries), which in the beginning of every time window, we initialize each entry with the zero value. During each time window, when p_i receives a data packet during time slot s_j, it increments $rx_i[j]$. Moreover, if that packet includes an acknowledgement for the packet p_i sent previously, it also increments $ack_i[j]$. At the end of each time window, p_i tests whether there is a time slot s_j for which $rx_i[j] \geq \mathcal{T}_{rx}$ (the reception threshold) and $ack_i[j] \leq \mathcal{T}_{ack}$ (the acknowledgement threshold). In case p_i finds such s_j, it stops using its transmission time slot, s_i. This process repeats in every time window during which p_i's status is active.

Note that we assume that the communication links have symmetrical packet loss behavior. We justify the packet reception and acknowledgement thresholds of $\mathcal{T}_{rx}$, and respectively, $\mathcal{T}_{ack}$ by considering a pair of neighbouring motes, p_i and p_j. Suppose that the successful transmission probability from p_i to p_j (and visa verse) is p. In a given time window of w frames, the expected number of p_i's packets that p_j receives is wp and the expected amount of acknowledgements is wp^2. During our experiments, we have selected a window of $w = 20$ TDMA frames, the reception threshold $\mathcal{T}_{rx} = 0.8w = 16$ by taking $p = 0.8$ and considering a value that includes all reliable links, which are defined as the ones that have 90% PRR [4]. We decided to consider $\mathcal{T}_{ack} = 0.4w = 8$ as the acknowledgement threshold since it presented a more stable behavior than $p^2 = 0.64$ during our experiments (Section 4).

4 Evaluation

We evaluate DecTDMA with respect to channel stability and throughput via the Cooja simulator and the Indriya Testbed at NUS with 97 motes. We implemented DecTDMA on top of TinyOS version 2.1.1. For the Cooja simulations, we select both single and multiple hop topologies whereas in the testbed experiments the focus is on the multiple hop case. Our results show a high throughput as well as acceptable channel stability performances of DecTDMA under real-world conditions. We also show that DecTDMA further improves the TDMA algorithm by Petig et al. [2] via the proposed mechanism for channel quality estimation.

Every WSN has a number of inherent uncertainties. In this dynamic environment, it is challenging for any node to maintain a stable rate of packet reception. This channel stability criterion is one of the important metrics, which we evaluate. Another important criterion is the throughput of DecTDMA, which considers the number of successful packet receptions. Note that for the simulation results, we normalize these numbers of successful packet receptions and compare them to an analytical maximum (which we tailor for each studied topology).

The TDMA frame setup. We use the notation below when presenting our results. DecTDMA considers the case in which every node uses at most one time slot per TDMA frame for data packets. Despite this assumption, DecTDMA is obviously extendable by simply allowing each mote to use more than one time slot. We use τ to denote the number of time slots per TDMA frame and ξ to refer to the length of each time slot in seconds. Node that each mote can transmit at most $((1\ \mathtt{s}/\xi)/\tau)$ packets per second. In our frame setup, $\varphi = ((1\ \mathtt{s}/\xi)/\tau) = 2$ is an upper bound on the number of frame per seconds that each node uses (after convergence) for data packets in every second.

Single hop WSNs: simulation results. Single hop WSNs represent the case in which every mote can communicate directly with any other mote. The complete graph topology of these networks is absent from multi-hop dynamics that are due to, for example, fading signal strength. Moreover, this setup has a clear analytical upper bound of the throughput, i.e., in a network of n transmitters at most $n - 1$ packets are received per transmission. In this basic setup, we are able to demonstrate that DecTDMA's throughput approaches the analytical upper bound. Note that even though this setup is simpler than all the others that we study, the presented performances are not straightforward, because our fully-decentralized implementation has no access to external assistance, such as access points, or external references, such as a global clock. Yet, we show that DecTDMA's performances are close to the analytical bounds.

We model a single-hop graph using the complete graph K_n. During the Cooja simulation, we use p as the transmission success probability when a packet is sent from a node to a neighboring one. We use these settings for evaluating how close can DecTDMA approach the analytical bounds, which depend on p. We normalize the number of received data packet per second using $\#pkts/T/(n-1)/(\varphi/n)$, where $\#pkts/T$ refers to the average number of received packets per second over a time period T and φ is the amount of data packets per node that we expect per second. Note that, $(n-1)/(\varphi/n)$ defines the expected number of received packets in K_n (if there is no packet loss). Therefore, $\#pkts/T/(n-1)/(\varphi/n)$ should approach p, when the packet reception probability is p.

The plot in Figure 2 presents the (normalized) number of received packets for different numbers of nodes when considering K_n, where $n \in \{5, 6, \ldots, 40\}$. The chart shows that DecTDMA behaves well when the transmission (and reception) success probability is $p = 1$. Note that this is the case in which we are running DecTDMA as an implementation of Petig et al., because the settings are similar to the ones that Petig et al. considered in [2]. Since Petig et al. do not consider the case of $p < 1$, DecTDMA version with LQE indeed out performs the one without. Thus, for the case of single hop networks, DecTDMA with LQE performs well for the case of $p < 1$ and for the case of $p = 1$, there is no need to use LQE as a masking technique (and the theoretical assumption that $p = 1$).

Multiple hop WSNs: simulation results. The phenomenon of hidden terminal consider the case in which mote p_1 can communicate directly with both p_0 and p_2 but p_0 and p_2 cannot communicate directly (Figure 3). In this case, node p_0 is hidden from p_2 and thus the only way that it can identify that its transmissions occur concurrently with p_2 is via p_1 assistance. We consider a multiple hop setup, in which the hidden terminal phenomenon exists and yet we are able to compare between DecTDMA's throughput and an analytical upper bound that we tailor. Interestingly, these simulations show a behavior that is similar to the above single hop networks, which use the complete graph K_n.

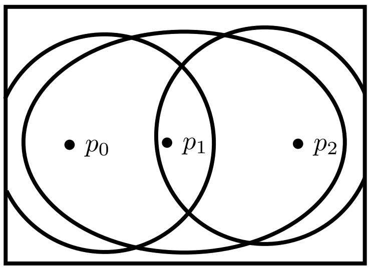

Fig. 3: The hidden terminal.

We also consider settings for the a 2-hop graph $G_2(n) := (V, E)(n)$ with n vertices. The set of vertices is partitioned in four sets S_0, S_1, S_2 and S_3, such that each set forms a clique in G_2 (Figure 4). We define a cardinally constraint that requires these cliques to be of similar size: $|S_{i+1}| + 1 \geq |S_i| \geq |S_{i+1}|$ for $i \in \{0, 1, 2\}$ and $|S_3| + 1 \geq |S_0|$. In addition to the edges within every vertex to any other vertex in its clique, we define an edge between every vertex and any

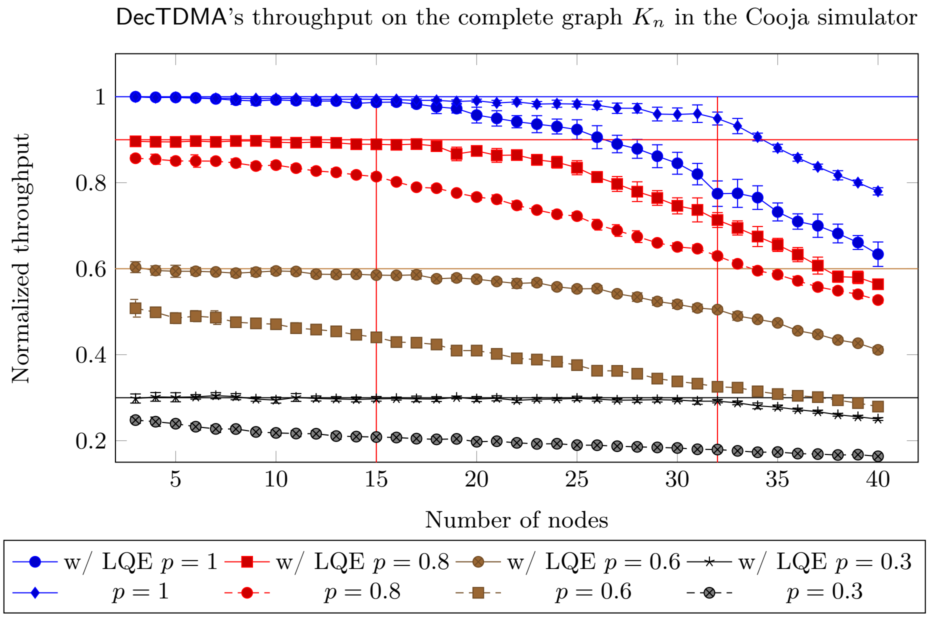

Fig. 2: DecTDMA without and with LQE on the complete graph K_n. The probability of a successful transmission is p. The throughput is normalized by $\#pkts/T/(n-1)/2/n$. The (colourful) horizontal lines represent the analytical bounds on the throughput. The (red) vertical lines stand for the bounds for guaranteed convergence, which is 15, and the frame size, which is 32.

other vertex that is in a neighboring clique. We say that clique S_i is neighboring to clique $S_{i+1 \bmod 4}$ and $S_{i-1 \bmod 4}$. Note that for the case of $n \bmod 4 = 0$, G_2 is regular, i.e., all vertexes have the same degree. During the Cooja simulation, we use p and $q = 0.4p$ as the transmission success probabilities when a packet is sent from a node to a neighboring one that shares, and respectively, does not share the same clique. In this rather simple settings for multiple hop networks, we can still evaluate how DecTDMA is close to analytical bounds that depend on p and $q = 0.4p$. Note that we study DecTDMA behavior on multiple hop graph using testbed experiments.

We normalize the throughput (Figure 5) by the expected throughput for the case there is no packet loss. The difference to the 1-hop case on the K_n is that from one clique, S_i, the opposite corner clique, $S_{i+2 \bmod 4}$, cannot be reached, thus the number of nodes we expect to received a packet is reduced by a quarter. This leads to $\#pkts/T/(\frac{3}{4}n-1)/(\varphi/n)$. In Figure 6, we use a different probability for successful reception for the neighboring cliques. Since they contain half of the nodes and packets are received with probability $q = 0.4$ in case $p = 1$, we get the bound $(0.5nq + 0.25n - 1)/(\varphi/n)$. Note that the rate q is linear in p. Thus, q scales down for smaller values of p. This leads to the fact that for a

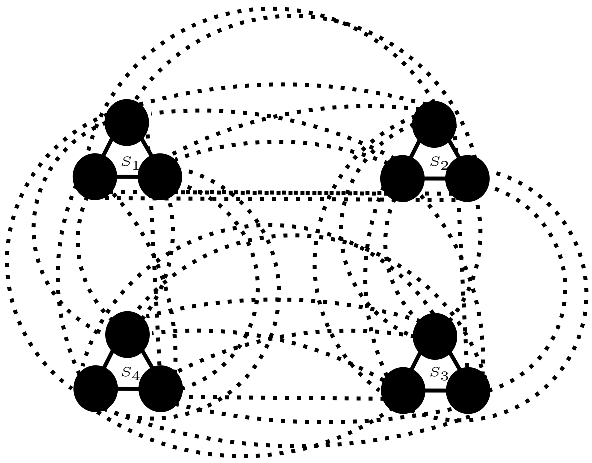

Fig. 4: The $G_2(12)$ graph. The solid lines represent communication link that their transmission success probability is p, whereas the dotted lines refers to linked with probability $q = p$ and $q = 0.4p$ as in figures 5, and respectively, 6.

given transmission success rate of p (within the clique), we also expect p to be the normalized throughput.

The plots in figures 5 and 6 present the simulation results for the $G_2(n)$ topology and $n \in \{5, 6, \ldots, 40\}$ when considering the cases in which the successful transmission probability of links that connects nodes that are at different cliques is $q = 0.4p$ and within a clique p (cf. Figure 4). We note the similarly of the results that appear in figures 2 and 5 even though the latter set of experiments refer to a two hop communication graph, rather than one hop, as in the former set. Moreover, when running DecTDMA with LQE, we observe an acceptable degree of stability in the number of packets received for every transmission. Of course, the values in Figure 6 are significantly less than the ones in Figure 5 (due to higher packet loss rate between neighboring cliques).

Multiple hop WSNs: testbed experiments. We complete our evaluation of DecTDMA by running experiments in the Indriya Testbed at NUS [3]. This is a controllable environment and yet it is representative to real-world WSNs with respect to the actual interference that the deployed motes encounter, e.g., dynamic link behavior, say, with respect to PRR values [4]. Our experiments consider running DecTDMA over 97 motes that form a multipile hop network (Figure 8). Such real-world networks are known to have different and dynamic transmission success rates. We compare between the cases in which DecTDMA includes and does not include our LQE technique. The plot in Figure 8 shows the long term impact of ambient noise on DecTDMA with and without LQE. Whereas the former is able to improve over time by learning about the presence

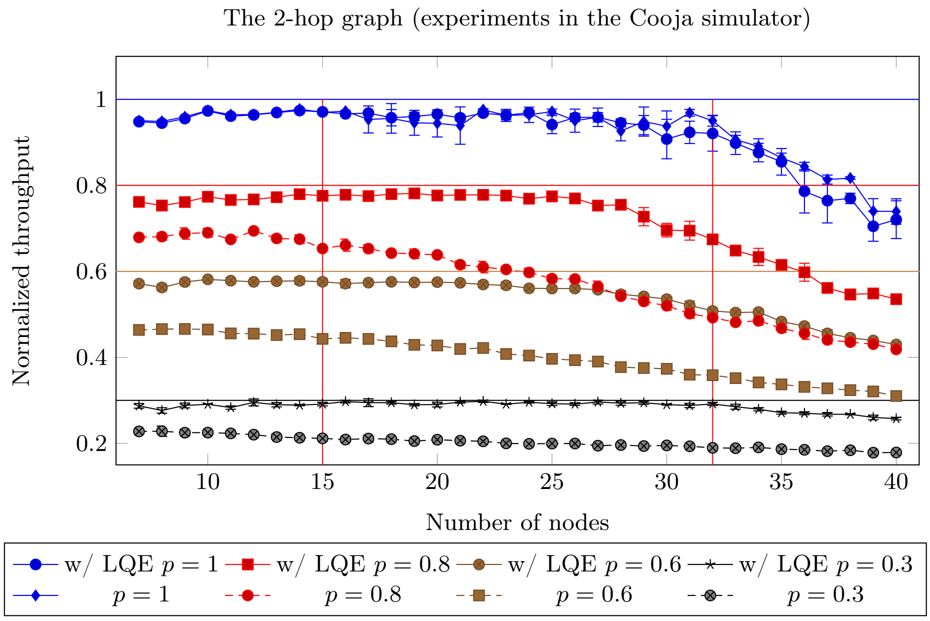

Fig. 5: DecTDMA with and without LQE on the 2-hop graph $G_2(n)$ and uniform probability, p, of successful transmissions, where $n \in \{6, 7, \ldots, 40\}$ and $p \in \{0.3, 0.5, 0.8, 1.0\}$ is the probability for successful transmission between any pair of motes that can communicate directly. The horizontal (colourful) lines represent the analytical bounds and the (red) vertical lines the bounds for convergence (15) and the frame size (32). The throughput is normalized by $\#pkts/T/(0.75n - 1)/2/n$.

of links with low PRR values, the latter can spiral down due the fact the Petig et al. [2] do not consider sporadic packet omission.

Since this work considers experiments that run both on the Cooja simulator and the Indriya testbed, we also wanted to run in Cooja experiments on a multiple hop graph that resembles the one that the Indriya testbed uses (Figure 7). Broadly speaking, the two plots in figures 7 and 8 resembles. We note that there is no clear recipe for Cooja to consider in detail the dynamics of real-world WSNs, such as the Indriya testbed. Hence, differences between these plots are inevitable. Also, there is no straightforward way to compare our results on the Indriya testbed to an analytical bound, as we did in figures 2, 5 and 6.

Evaluation summary. DecTDMA with LQE presents high and stable throughput values in Cooja simulations (in single and multiple hop networks) that approach our analytical bounds. The Indriya testbed experiments show stability of the throughput values that resembles to the ones in the Cooja simulations.

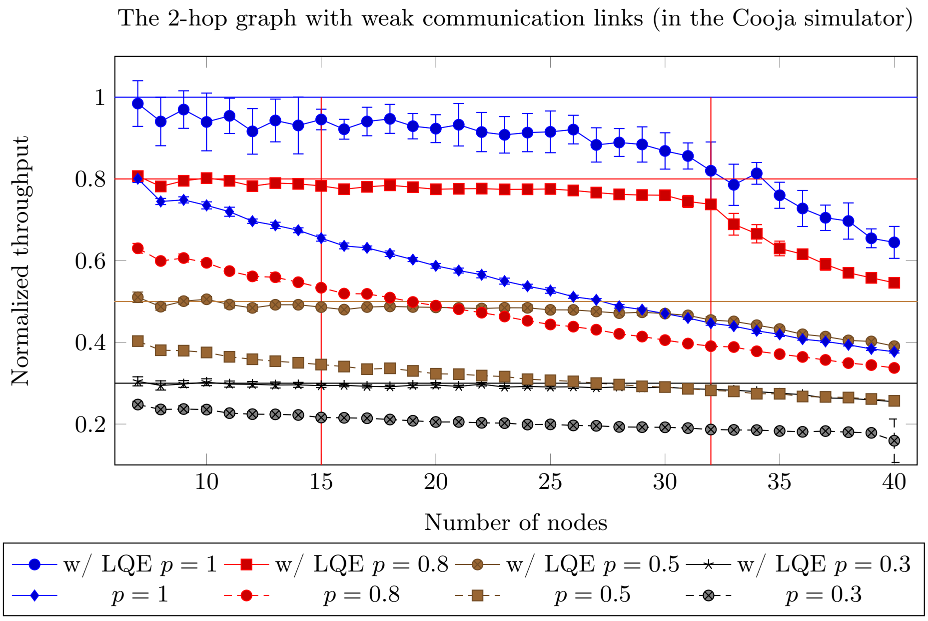

Fig. 6: DecTDMA with and without LQE on the 2-hop graph $G_2(n)$, where $n \in \{6, 7, \ldots, 40\}$. The probability of successful transmissions between any two motes that belong to the same clique is $p \in \{0.3, 0.5, 0.8, 1.0\}$. The ones that belong to neighboring cliques have the probability of $q = 0.4p$. The horizontal (colourful) lines represent the analytical bounds, which depends on p, and the (red) vertical lines the bounds for convergence (15) and the frame size (32). The throughput is normalized by $\#pkts/T/(0.75n - 1)/2/n$, as in Figure 5.

5 Related Work

ALOHAnet and its many variances [10] are MAC protocols that schedule the medium access randomly. Time division multiple access (TDMA) follows a scheduled approach that divides the radio time into TDMA frames and then further divides these frames into time slots. We note that at high and stable PRR values, TDMA protocols offer inherently a greater degree of predictability than the ones that access the medium randomly. The TDMA task that we consider in this work includes both the alignment of frames and time slots as well as the allocation of these time slots to the motes, rather than just the latter part of the task, as many existing TDMA protocols do.

Existing approaches for MAC-layer contention management consider priorities (for maintaining high bandwidth utilization while meeting the deadlines, such as [11]) or modifying the signal strength or carrier sense threshold [12]. We view both approaches as possible extensions to DecTDMA, which considers a single priority and does not adjust the radio settings dynamically. DecTDMA uses fixed size TDMA frames and it allocates TDMA time slots until saturation,

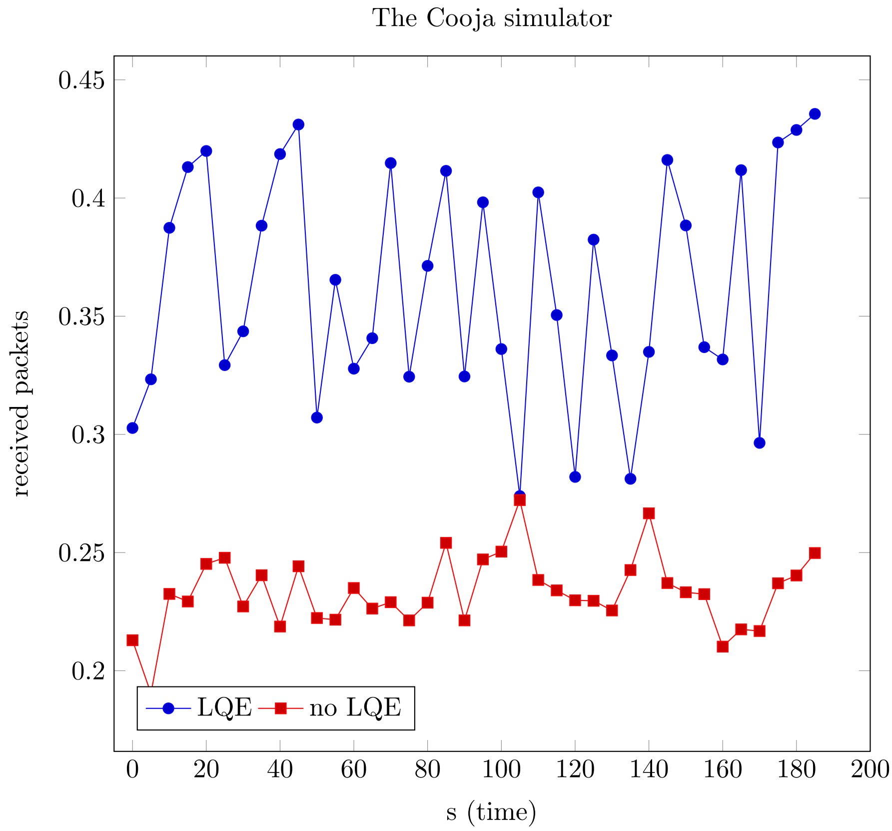

Fig. 7: Comparison between TDMA with and without link quality estimation on the Cooja simulator. This plot shows the number of received packets accumulated in intervals of 100 s in Cooja. The overall time of the experiment is 200 s on the 2-hop graph $G_2(40)$.

i.e., no more time slots are left to allocate. Note that a number of techniques can prevent starvation in saturated situations, such as limiting the number of TDMA frames that the application can use consecutively without deferring further communication. Once, we apply such techniques, the (common) back-off mechanism of DecTDMA will prevent starvation.

The literature considers receiver-side collision detection [12, 13], which requires hardware support for signal processing as well as receivers to notify senders about the success or failure of transmissions. In this paper, we assume hardware that does not support collision detection (on the sending side or on the receiving side). In DecTDMA, however, the payload does include a short summary of the frame information (FI) [2]. We prefer not to assume access to external references and provide a fully-decentralized implementation since unbounded signal failure can occur, e.g., in underground tunnels. STDMA [14] is an example of a protocol

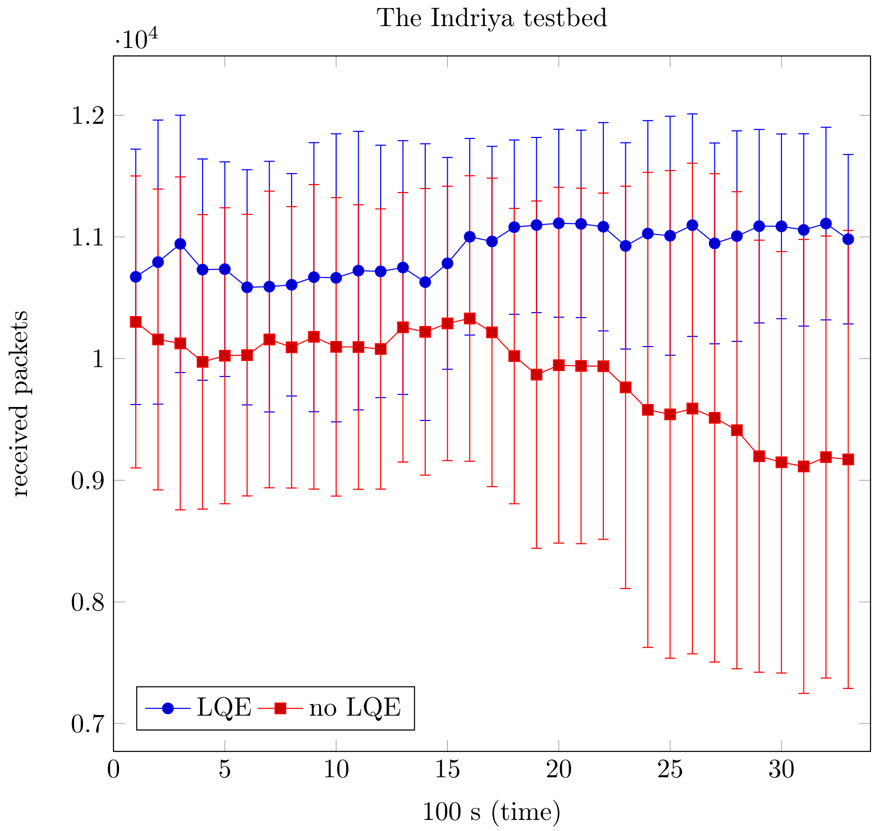

Fig. 8: Comparison between TDMA with and without link quality estimation on the INDRIYA testbed [3]. This plot shows the number of received packets accumulated in intervals of 100 s as an average over 10 run each. The total run time for each run is 3600 s. The error bars represent in both graphs the standard deviation.

that assumes the availability of an external reference (GNSS [15]). It allocates bandwidth according to the position of motes.

The (self-stabilization) literature on TDMA algorithms often does not answer the causality dilemma of "which came first, synchronization or communication." On one hand, existing clock synchronization algorithms often assume the existence of MAC algorithms that offer bounded communication delay. However, on the other hand, existing MAC algorithms that provide bounded communication delay, often assume access to synchronized clocks. For example, some TDMA protocols [16] assume the availability of a clock synchronization algorithm that can reach the needed clock synchrony bound before starting the allocation of time slots. Where there is no external reference or assistance, the implementation of TDMA protocol requires time slot alignment *during* the time slot allocation process. DecTDMA needs to address these tasks at the same time (without external reference). Busch et al. [17] and Petig et al. [2] propose TDMA algorithms that address the above challenge without assuming access to external references. Busch et al. [17] address this by assuming that the number of time slots in each frame is at least $2(\Delta + 1)$, where Δ is an upper bound on the number of nodes with whom any node can communicate with using at most one intermediate node for relaying packets. Petig et al. [2] provides a solution that requires a frame size to could be $O(\sqrt{\Delta})$ times smaller. Moreover, they show that you cannot do much better than that. Schneider and Wattenhofer [18] present a local algorithm for vertex coloring that could be the basis a for self-organizing TDMA protocol. We chose to base DecTDMA on a TDMA algorithm [2] that considers self-stabilization explicitly. Other proposals for self-stabilizing MAC algorithms exist [19–21] as well as other algorithm cited by [2]. We choose the one that can deal with networks dynamics, assume no access to external reference, has a more attractive overhead (with respect to the frame information) and follows conventional TDMA practice, such as fix packet size.

We are not the first to consider the provision of improved link quality. One of the most notable examples is a line of research work that has started by Kuhn, Lynch and Newport [22], which presented the abstract MAC model. They propose a number of high-level communication primitives that use an (abstract) unreliable MAC layer, and yet provide guarantees with respect to the packet delivery to the application layer at the receiver-side, say, after a bounded number of retransmissions. We follow a complementary approach to the one of Kuhn, Lynch and Newport [22], because we are interested in possible guarantees with respect to the packet reception at the receiver-side without considering the possibility to retransmit a lost packet.

6 Discussion

Designing and implementing a MAC protocol for WSNs is a non-trivial task. The challenges include a various source of interferences as well as the need to recover rapidly from the occurrence of failures that these interferences cause. Using DecTDMA, we were able to exemplify how to have the self-stabilization design criteria in mind while designing a MAC protocol that works well in a real-world WSN testbed, such as Indriya [3].

This design process started with the self-stabilizing TDMA algorithm by Petig et al. [2]. That algorithm modelled, for example, the communication graph and the manner in which the motes exchange messages. The focus of Petig et al. is on dealing with one of the most destructive interferences in WSNs, which is packet loss due to concurrent transmissions. Petig et al. consider a fault model that includes concurrent transmissions whereas sporadic packet losses, say, due to ambient noise, are considered as transient faults. This focus on concurrent transmissions allows, via a rigorous analysis, an exact design of their self-stabilizing TDMA algorithm. Our experiments validate that indeed, in the absence of transient faults, e.g., sporadic packet loss, the self-stabilizing TDMA algorithm Petig et al. addresses the challenge of avoiding concurrent transmissions (figures 2 and 5).

We present DecTDMA, which is a TDMA protocol that extends the fault model of Petig et al. and thus sporadic packet loss are no longer considered as transient faults. This paper shows that via an elegant LQE technique that masks the effect of sporadic packet loss, the PRR levels of DecTDMA are higher significantly than the ones of Petig el al. [2]. Moreover, we observe the stability of these PRR values also in a real-world testbeds, such as Indriya [3] (Figure 8).

This work shows how to deal with failures and interferences in non-trivial real-world challenges, such as the design of fully-decentralized reference-free TDMA protocol. Our design process enhanced iteratively the fault model during the design of Petig el al. [2] and then in this work, we used an elegant masking technique to further enhance the fault model. DecTDMA is a successful example of the above design and development process that have the self-stabilization design criteria in mind. As future work, we offer the reader to study real-world problems and use the presented design and development process.

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