On the Pitfalls of Desynchronization in Multi-hop Topologies

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Abstract: Biologically inspired self-organization methods can help to manage the access control to the shared communication medium of wireless ad-hoc networks. One lightweight method is the primitive of desynchronization, which has already been implemented as MAC protocol for single-hop topologies successfully. Here, each periodically transmitting node is able to establish a collision-free TDMA schedule autonomously. However, multi-hop topologies are more realistic, but also more difficult to handle. For instance, the hidden terminal problem is inherent in such topologies and complicates an implementation of this primitive as MAC protocol for multi-hop topologies: Each node requires knowledge about its two-hop neighborhood to establish a collision-free TDMA schedule. Moreover, the problem of stale information is inherent in the primitive of desynchronization and even could destabilize the whole system.
In this paper we describe our experience when extending a single-hop MAC protocol based on the primitive of desynchronization for its usage within multi-hop topologies. During development, we identified some pitfalls of desynchronization in multi-hop topologies, like stale information. As a result, we present our solution of a self-organized MAC protocol based on the primitive of desynchronization for multi-hop topologies.

1 INTRODUCTION

Wireless ad hoc networks, and wireless sensor networks in particular, are characterized by their ability to communicate wirelessly. All participating nodes interact via a single shared medium. Access control for this shared communication medium is a desirable but also considerable task. The degree of difficulty of such a task, amongst other things, depends on several network parameters, like the network size (i.e., the number of nodes), connectivity (i.e., the degree of the nodes), or density (i.e., the ratio of number of extant links to number of potential links). However, access control is commonly intended to reduce the probability of occurrence of collisions. For this reason, several protocols for medium access control (MAC) already exist, mostly classified into contention-based *carrier sense multiple access* (CSMA) and schedule-based *time division multiple access* (TDMA). Within this paper, we will focus on self-organized TDMA protocols, which divide the shared communication channel into several time slots providing exclusive access for the actually assigned node. Such an assignment requires coordination among the nodes. This coordination can be achieved, for instance, by explicit synchronization of these time slots using a global clock, which must then be provided by a dedicated base node. Otherwise, the nodes must already have a priori knowledge about the schedule of adequate time slots. However, the centralized approach of synchronization always involves a single point of failure, whereas a fixed schedule (which is based on a priori knowledge) is much too rigid and might be unable to handle topology dynamics satisfactorily.

Instead, the biologically inspired primitive of *desynchronization* as TDMA protocol for single-hop topologies is proposed in (Degesys et al., 2007). One main goal of such a self-organized MAC protocol using desynchronization is the avoidance of collisions, even in the absence of both, a central scheduler as well as the a priori coordination of the nodes. To achieve this, each node calculates its next time of transmission autonomously. This computation is based solely on locally available data, which makes the protocol scalable, robust, and adaptive for single-hop topologies. Therefore, this MAC protocol is well suited for ad hoc networks showing dynamics, variations, and mobility.

The timeliness of the used data for an autonomous decision making process is of utmost importance. Since, however, self-adjustments by the nodes are always made without any other node's knowledge, nodes could rely on potentially stale information. This obsolete information might result in packet

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collisions or fluctuations of transmission time (cf. Sect. 4.2). Finally, even the whole system could destabilize. Indeed, this problem is inherent in the primitive of desynchronization and is intensified at multi-hop topologies due to a prolonged information propagation. The expansion from single-hop to multi-hop topologies further complicates the development of a self-organized MAC protocol due to the so called *hidden terminal problem*. This problem is inherent in multi-hop topologies, and requires each node to gain knowledge about its two-hop neighborhood for a collision-free but self-organized communication.

The remainder of this paper is structured as follows: Section 2 formalizes the primitive of desynchronization as well as the emerging self-organized MAC protocol for single-hop topologies, which builds the basis for the MAC protocol analyzed herein. In Section 3, we discuss problems and solutions arising when extending this MAC protocol from single-hop to multi-hop topologies, e.g., the hidden terminal problem. The pitfall of stale information, which is inherent in the primitive of desynchronization, is analyzed for single-hop as well as for multi-hop topologies in Section 4. Section 5 presents our lightweight approach to cope with stale information in multi-hop topologies: The impact of our new approach is discussed and a side effect is exemplified which helps to solve emerging collisions in particular multi-hop scenarios. Next, we give a short survey of recent work dealing with MAC protocols based on the primitive of desynchronization in Section 6. Finally, Section 7 concludes the paper with a short outlook to future work.

2 DESYNCHRONIZATION

This section describes the primitive of desynchronization and introduces an implementation as MAC protocol for single-hop topologies. This formalization will be the core for the following sections.

2.1 The Primitive of Desynchronization

Based on the first mathematical model of pulse-coupled oscillators (Mirollo and Strogatz, 1990), the biologically inspired primitive of *desynchronization* (Degesys et al., 2007) implies that each node "oscillates" at the same frequency $f = 1/T$. Applied to the domain of wireless sensor networks, each node tries to transmit a so called *firing packet* after every period T. Such periodical data transmissions are common, for instance, in biomedical sensor networks due to periodic sensor sampling (Støa and Balasingham, 2011).

Desynchronization is the "logical opposite" (Degesys et al., 2007) of synchronization, i.e., each node tries not to perform its (periodic) transmission at the same time, but instead at a maximum temporal distance to all related nodes. For single-hop topologies, in which each node reaches each other node in a single hop, desynchronization results in the temporally equidistant transmission of firing packets: If such a network consists of a set N of nodes, the time span between successively transmitting nodes equals $T/|N|$.

2.2 Desynchronization as MAC Protocol

The self-organized MAC protocol DESYNC (Degesys et al., 2007) for single-hop topologies uses this primitive of desynchronization. Each participating node can determine its next time of transmission within such a (fully connected) network autonomously. Therefore, each node possesses a unique identifier[1] i, and – as already mentioned before – each node periodically transmits its firing packet.

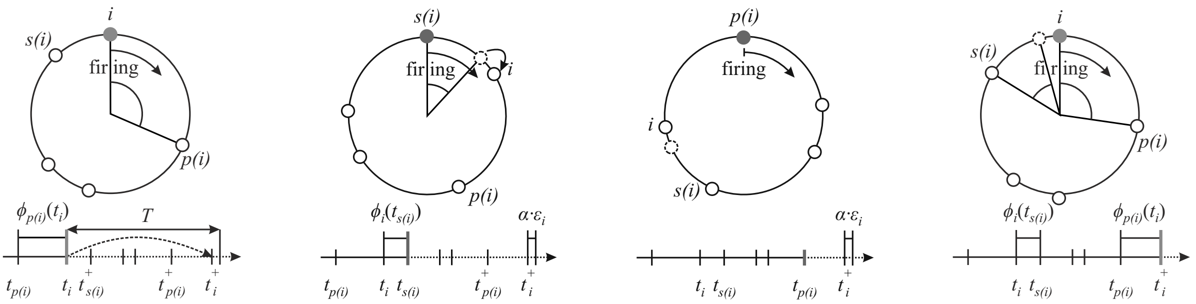
To simplify the following analysis, we make some (idealized) assumptions. First of all, the radio communication range equals the interference range. Next, all links are reliable and symmetrical. Moreover, each node supports half-duplex mode, i.e., it can either transmit or receive a packet at the same time. Finally, each node has a finite buffer for (incoming) packets.

Let t_i be the current time of firing of node $i \in N$, and let t_i^+ be its next time of firing. When node i finishes its period, it broadcasts its firing packet, resets its phase, and updates t_i^+. The phase shift $\phi_i(t) \in [0, T)$ of a node i denotes the elapsed time since its current firing t_i and the given point in time t, normalized to the period T as

$$\phi_i(t) = (t - t_i) \bmod T. \quad (1)$$

Let $N_1(i)$ be the set of *one-hop neighbors* and let $d_i = |N_1(i)|$ be the *degree* of node i. Please note, for (fully connected) single-hop topologies holds $N_1(i) = N \setminus \{i\}$ and $d_i = |N| - 1$ for every node $i \in N$. Every time, node i receives a firing packet of its one-hop neighbor $j \in N_1(i)$ at time t_j, node i is able to calculate the phase shift $\phi_i(t_j)$ towards this one-hop neighbor j according to (1). For example, $\phi_i(t_j) = 0.5 \cdot T$ means that node i has finished half of its current period when node j transmitted its firing packet at time t_j.

[1] For the sake of simplicity, we do not further distinguish between the identifier itself and the node's ordinal in N. Moreover, without loss of generality let $1 \leq i \leq |N|$.



(a) At time t_i, node i is firing. It calculates the phase shift $\phi_{p(i)}(t_i)$ and schedules its next firing at t_i^+, according to (3).

(b) At time $t_{s(i)}$, successor $s(i)$ of node i is firing. Node i calculates the phase shift $\phi_i\left(t_{s(i)}\right)$.

(c) At time $t_{p(i)}$, predecessor $p(i)$ of node i is firing. Node i has to record this time $t_{p(i)}$.

(d) Now, t_i^+ is reached and becomes t_i. The next steps correspond to Figure 1(a).

Figure 1: Snapshots of the desynchronization process from node i's point of view. Nodes move clockwise on the circle at frequency $f = 1/T$ with period T.

Two neighbors of node i are of special interest for the DESYNC algorithm: The successive phase neighbor $s(i) \in N$ (*successor*) and the previous phase neighbor $p(i) \in N$ (*predecessor*). The successor broadcasts its firing packet just after, whereas the predecessor broadcasts its firing packet just before node i (cf. Figure 1(b) and Figure 1(c), respectively).

The primitive of desynchronization forces each node to transmit its firing packet at a maximum temporal distance towards both phase neighbors, i.e., each node attempts to achieve the midpoint of its phase neighbors. Therefore, each node just has to observe the firing packets of its phase neighbors $s(i)$ and $p(i)$ to calculate the corresponding phase shifts $\phi_i\left(t_{s(i)}\right)$ and $\phi_{p(i)}(t_i)$. Using both phase shifts, node i is able to compute its *adjustment factor* ε_i as

$$\varepsilon_i = \frac{\phi_i\left(t_{s(i)}\right) - \phi_{p(i)}(t_i)}{2}. \quad (2)$$

Finally, each node is able to set its next (absolute) time of firing t_i^+ as

$$\begin{aligned} t_i^+ &= t_i + T + \alpha \cdot \varepsilon_i \\ &= t_i + (1-\alpha) \cdot T + \alpha \cdot (\varepsilon_i + T). \end{aligned} \quad (3)$$

The *jump size parameter* $\alpha \in [0,1]$ regulates how fast node i moves toward the assumed midpoint between its phase neighbors $p(i)$ and $s(i)$. The endpoints of this interval will not be considered within this paper, since $\alpha = 0$ means no movement at all, whereas $\alpha = 1$ forces the nodes always to jump onto the current midpoint of its phase neighbors without any damping. One achieves good results using $\alpha = 0.95$ as damping factor (Degesys et al., 2007). The last expression of (3) shows its similarity to the exponentially weighted moving average, which smooths out short-term fluctuations but highlights long-term trends.

If each node i respects the same (temporal) distance to its phase neighbors (i.e., $\varepsilon_i = 0$), the stable state of *desynchrony* is reached. Once, the system is in stable state, the transmission times do not change anymore – apart from clock drifts and topology changes.

3 DESYNCHRONIZATION IN MULTI-HOP TOPOLOGIES

In Section 2, we presented the basic idea of a MAC protocol for periodically transmitting nodes within a single-hop topology. However, using this MAC protocol for multi-hop topologies is rather difficult. To be consistent with the primitive of desynchronization and to permit a collision-free communication in multi-hop topologies, each node i additionally requires knowledge about its set of *two-hop neighbors* $N_2(i)$ (Degesys and Nagpal, 2008). Please note that $\{i\}$, $N_1(i)$, and $N_2(i)$ are pairwise disjoint for every node $i \in N$. Therefore, this section outlines the main problems and solutions, when extending the MAC protocol based on the primitive of desynchronization from single-hop to multi-hop topologies.

3.1 Hidden Terminal Problem

The so called *hidden terminal problem* (Tobagi and Kleinrock, 1975) is inherent in multi-hop topologies. Suppose, a network consisting of three nodes a, b, and c. Nodes a and c can directly communicate with node b, but both nodes a and c are unaware of each other. If at about the same time node a as well as node c transmit a packet to node b, both radio packets collide and node b receives just corrupt data – if any. Both nodes a and c are hidden from each other, hence they cannot overcome this packet collision using *carrier sense* (CS) right before their transmissions.

One technique to solve the hidden terminal problem for contention-based CSMA protocols (Karn, 1990; IEEE, 2007) is the RTS/CTS handshake: If node a wants to transmit data to node b, node a initially sends a *request–to–send* (RTS) to node b. If node b received the RTS from node a correctly, node b in return has to respond with a *clear–to–send* (CTS). If node a correctly received this CTS, the RTS/CTS handshake was successful and node a may start to transmit data towards node b. However, our primitive of desynchronization follows a self-organizing manner which results in a schedule-based TDMA protocol. Therefore, the RTS/CTS handshake protocol is quite incompatible with it.

3.2 The Local Max Degree

As already mentioned, each node requires additional knowledge about its two-hop neighborhood to solve the hidden terminal problem in multi-hop topologies. A compact and efficiently obtainable information might be the *local max degree* $D_i = \max\{d_j \mid j \in N_1(i) \cup \{i\}\}$ of a node i. Further, let $D_N = \max\{D_i \mid i \in N\}$ be the *global max degree*. With it, there exists a desynchronization algorithm, which divides the period T into $2 \cdot (D_i + 1)$ slots and converges in $\mathcal{O}(D_N \log |N|)$ periods with high probability (Motskin et al., 2009). However, approximately half of the provided slots will remain unassigned. Furthermore, the propagation (i.e., flooding) of the global max degree D_N causes high communication costs.

In single-hop and acyclic multi-hop topologies, the provably minimal number of required time slots per period for a collision-free communication within the interference range of node i is $D_i + 1$. The M-DESYNC algorithm (Kang and Wong, 2009) is also based on the local max degree D_i. However, the M-DESYNC algorithm tries to maximize the slot utilization, i.e., to get along with the minimal number of required slots $D_i + 1$. Therefore, each node i has to exchange information about its degree d_i with all its one-hop neighbors first. After this maybe lengthy[2] exchange stage, each node i obtained knowledge about its local max degree D_i. Next, while there are still conflicts, each node i selects one of the $D_i + 1$ prioritized time slots. However, the M-DESYNC algorithm is not very flexible, since each topology change demands for both the lengthy exchange stage as well as for the competitive selection stage. Furthermore, the M-DESYNC algorithm is not applicable for cyclic multi-hop topologies (Kang and Wong, 2009; Mühlberger, 2010).

[2] There is just a contention-based back-off algorithm for this exchange phase suggested (Kang and Wong, 2009).

3.3 The Phase Shift Propagation

The propagation of (relative) phase shifts is another simple solution to obtain knowledge about the two-hop neighborhood (Degesys and Nagpal, 2008). Regarding the primitive of desynchronization, this approach was first implemented as EXTENDED-DESYNC algorithm (Mühlberger and Kolla, 2009): If each node propagates within its firing packet the complete set of its one-hop neighbors together with their (relative) phase shifts, each receiving node in turn is able to assemble its two-hop neighborhood autonomously. That means, each node i broadcasts (the identifiers of) all its (currently known) one-hop neighbors $j \in N_1(i)$ together with their relative[3] phase shifts $\phi_i(t_j)$.

In comparison to the M-DESYNC algorithm, no preliminary exchange phase is required. Instead, each newly joining node just has to listen for a couple of periods to make itself familiar with its neighborhood before transmitting its first firing packet. Therefore, the EXTENDED-DESYNC algorithm is robust and reacts quickly on topology changes. However, each node broadcasts its whole one-hop neighborhood, which takes bandwidth and energy for algorithmic purposes. Furthermore, the packet overhead increases linearly with the size of the one-hop neighborhood, i.e., a node with high degree has to transmit more data in its firing packets and thus consumes more bandwidth and more energy than a node with low degree. This dependency will also specify a lower bound for the applied period T (Mühlberger, 2009).

3.4 Further Observations

Since the phase shift propagation is universally applicable and more flexible than the local max degree approach, we will use the EXTENDED-DESYNC algorithm as basis for our further analysis on multi-hop topologies. However, regarding the primitive of desynchronization for multi-hop topologies the following difficulties can be observed:

- All nodes share the same communication medium, but a node i may just have local and limited knowledge about the multi-hop network (cf. Section 3.1).
- Therefore, the nodes in multi-hop topologies need not to have equal degree anymore, but the degree of a node i is at most $d_i \leq |N| - 1$ (cf. Section 2.2).
- Hence, the time span between successively transmitting nodes in multi-hop topologies might not equal $T / |N|$ anymore (cf. Section 2.1).

[3] From the point of view of the current sender i.

- Furthermore, for multi-hop topologies, the phase neighbors of node i might be two-hop neighbors as well, i.e., $p(i), s(i) \in N_1(i) \cup N_2(i)$.
- Finally, between two nodes $i, j \in N$ in single-hop topologies holds the correlation $i = p(j) \Leftrightarrow j = s(i)$. For multi-hop topologies, this successor–predecessor correlation needs not to hold anymore.

4 PITFALL: STALE INFORMATION

The primitive of desynchronization aims for a self-organized but collision-free arrangement of time slots. Hence, the nodes are able to rely on just locally available information, which can be both self-provided and self-acquired. Consequently, received data from adjacent nodes sometimes is "stale", i.e., the information obtained from received firing packets might be obsolete at the time of its application, and thus unreliable or even invalid. This problem already exists in single-hop topologies. But it is intensified in multi-hop topologies and will be described in detail throughout this section.

4.1 Single-hop Topologies

Using the primitive of desynchronization, the problem of stale information is inherent in single-hop (as well as multi-hop) topologies (Degesys et al., 2007): While node i calculates its next time of firing t_i^+ according to (3), its two phase neighbors might already have adjusted their individual next time of firing autonomously. Therefore, the formerly measured phase shifts $\phi_i\left(t_{s(i)}\right)$ and $\phi_{p(i)}\left(t_i\right)$ might already be stale, especially if node i adjusts its next time of firing immediately after transmitting its own firing packet at time t_i (cf. Figure 1). That means, node i estimates its next time of firing t_i^+ on the basis of potentially unreliable information, here the time of firing of its phase neighbors.

In fact, the use of more recent data for the phase shift $\phi_i\left(t_{s(i)}\right)$ in (3) will omit at least one unreliable information (Patel et al., 2007). For this purpose, node i just has to calculate its next time of firing t_i^+ not immediately after the transmission of its firing packet, but immediately after the reception of the first subsequent firing packet of its successor $s(i)$. As a result, node i uses more recent data, but the equation (3) to compute the next time of firing t_i^+ remains the same. Just the time when the next time of firing is calculated was delayed from t_i to $t_{s(i)}$.

4.2 Multi-Hop Topologies

For multi-hop topologies, this problem of obsolete firing information is intensified due to the hidden terminal problem (cf. Section 3.1). Therefore, each node i additionally must take care of its two-hop neighbors. That means, each node i has to arrange itself according to the firings of both its one-hop and two-hop neighbors $N_1(i) \cup N_2(i)$ (cf. Section 3.4). However, node i gains information about a two-hop neighbor $k \in N_2(i) \cap N_1(j)$ just in cooperation with the corresponding one-hop neighbor $j \in N_1(i)$. This data flow from node j to node i is additionally delayed by at least the phase shift $\phi_k\left(t_j\right)$ between the nodes j and k.

To exemplify the impact of stale information in multi-hop topologies, we simulated a small but manageable scenario by using a self-developed simulator on an Intel Core i5 CPU with 2.60 GHz and 8.00 GB main memory under the Windows 7 Professional 64 Bit operating system.

First, we assume idealized conditions, i.e., all communication links are symmetrical and reliable, not any node will fail, and there is no clock drift. Next, the jump size parameter is set to $\alpha = 0.95$ (Degesys et al., 2007). The simulated "dumbbell" topology M_7 is easy to understand: It consists of the set $N = \{1, \ldots, 7\}$ of nodes as shown in Figure 2. This topology contains two cyclic (and complete) sub-graphs $C_3 = \{1,2,3\}$ and $C_3' = \{4,5,6\}$. Let the nodes of both disjoint single-hop topologies C_3 and C_3' start first. Therefore, both sub-graphs will desynchronize independently, since they are unaware of each other. Just when node 7 joins the network, it successively gathers knowledge of both topologies[4] C_3 and C_3'. Node 7 connects C_3 and C_3' with its first firing packet containing its one-hop neighborhood (i.e., nodes 1 and 4), and thus completes the topology M_7. Figure 3(a) shows the first 100 periods after the start up of node 7 at period 45 from its point of view. Due to the stale information in this multi-hop topology, the one-hop and two-hop neighbors of node 7 (i.e, all nodes of C_3 and C_3') rather diverge than converge, as intended by the primitive of desynchronization. In fact, approximately 20 periods after the start up of node 7, the time of transmission of each node fluctuates with a constant but individual amplitude. Moreover, the phase neighbors of node 7 are its two-hop neighbors node 6 and node 2 (cf. Section 3.4).

[4]See Section 5.4 for the extremely rare case that the time of firing of node 1 and node 4 are synchronized, i.e., $t_1 = t_4$.

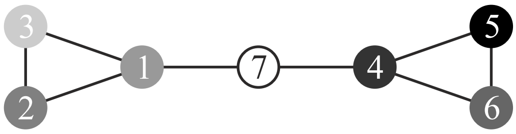


Figure 2: The ”dumbbell” topology M_7 consists of the set $N = \{1, \ldots, 7\}$ of nodes.

5 MULTI-HOP SOLUTION FOR DEALING WITH STALE INFORMATION

In Section 4, we analyzed the problem of stale information. As already mentioned, this problem is inherent in the primitive of desynchronization. For single-hop topologies it is sufficient for a node i to calculate its next time of transmission t_i^+ after receiving the firing packet of its successor $s(i)$ (cf. Section 4.1). Therefore, we will focus on multi-hop topologies in this section. However, we cannot avoid stale information at all, but with our new approach we want to take control of its evolution and reduce its impact in multi-hop topologies.

5.1 Refractory Threshold

In multi-hop topologies, the effect of stale information is intensified due to the delayed propagation of information about two-hop neighbors (cf. Section 4.2). To some extent, our approach follows the *law of similars*, because we suggest to intentionally delay the adjustment of a node's next time of firing. Therefore, we introduce an additional *refractory threshold* $\rho \in [0,1]$ along with a continuous random variable $X_i \in [0,1]$ following the continuous uniform distribution $\mathcal{U}(0,1)$. According to the random variable X_i, the adjustment factor ε_i will be considered, and node i will set its next time of firing t_i^+ as

$$t_i^+ = \begin{cases} t_i + T + \alpha \cdot \varepsilon_i & \rho < X_i \quad (4a) \\ t_i + T & \text{otherwise} \quad (4b) \end{cases}$$

Obviously, choosing $\rho = 0$ lets the nodes always adjust their time of firing, which results in the same behavior as described in Section 4.2. In contrast, choosing $\rho = 1$ is useless, since a node will not use its adjustment factor according to (2) for its next time of firing anymore.

In some sense, the refractory threshold ρ contradicts the primitive of desynchronization, because it ”skips” the adjustment of the next time of firing using (2). However, it allows a node to keep its phase (and thus its time of firing) with a probability of ρ. Nevertheless, this behavior helps the system to converge: Let node i be phase neighbor of another node $j \in N_1(i) \cup N_2(i)$. According to Section 3.4, node j in turn needs not to be phase neighbor of node i. If node i skips the adjustment of its phase using (4b), node j's estimation of its next time of firing remains valid regarding the phase shift towards node i. The information about node i remains reliable.

5.2 Algorithmic View

To explain the algorithmic view of our refractory threshold, we present pseudo-code of our approach to omit stale information in multi-hop topologies in Listing 1. Of course, this pseudo-code is based on the phase shift propagation (cf. Section 3.3).

```
1  // upon firing:
2  if (firingTimerExpired()) {
3    setFirstPacketReceived(true);
4    transmitFiringPacket();
5    t_i = now();
6    t_i^+ = t_i + T;
7    φ_p(i)(t_i) = (t_i − t_p(i)) % T;
8    setFiringTimer(t_i^+);
9  }
10 // upon receiving firing packet:
11 if (isFirstPacketReceived()) {
12   setFirstPacketReceived(false);
13   t_s(i) = now();
14   t_p(i) = now();
15   φ_i(t_s(i)) = (t_s(i) − t_i) % T;
16   ε_i = 0;
17   if (ρ < Random.nextDouble()) {
18     ε_i = (φ_i(t_s(i)) − φ_p(i)(t_i))/2;
19   }
20   t_i^+ = t_i + T + α·ε_i;
21   setFiringTimer(t_i^+);
22  } else {
23   t_p(i) = now(); }
24 }
```

Listing 1: Pseudo-code with integrated refractory threshold ρ.

If the firing timer of node i is expired (cf. Listing 1, line 2), node i transmits its firing packet (cf. l. 4) at time t_i (cf. l. 5). Due to the fact that the link between transmitter and receiver could be unreliable (e.g., the former transmitter might have left the network or ran out of energy, or a collision occurred at the receiver due to a newly joining node) node i cannot predict if there (once again) will be a successor transmitting a firing packet. Therefore, by reasons of precaution, node i has to schedule (cf. l. 8) its next time of firing as

$t_i^+ = t_i + T$ (cf. l. 6). Node i uses this scheduled time of firing if it does not receive any other firing packets. Otherwise, node i is receiving another firing packet (cf. ll. 10–24) before its firing timer expires again.

If node i receives the first subsequent firing packet (cf. l. 11) of its successor $s(i)$ at $t_{s(i)}$ (cf. l. 13), it calculates the current phase shift towards its successor (cf. l. 15). Since successor and predecessor of node i could be the very same neighbor node, node i also sets $t_{p(i)}$ here (cf. l. 14). If the refractory threshold is less than a continuous random value (cf. l. 17), node i calculates its adjustment factor ε_i (cf. l. 18). Anyway, node i updates the (already scheduled) next time of firing t_i^+ (cf. l. 20) and sets its firing timer (cf. l. 21). Otherwise, if the currently received firing packet is not the first subsequent firing packet, it could originate from node i's predecessor $p(i)$. Therefore, node i has to set $t_{p(i)}$ precautionary (cf. l. 23).

5.3 Simulation Results

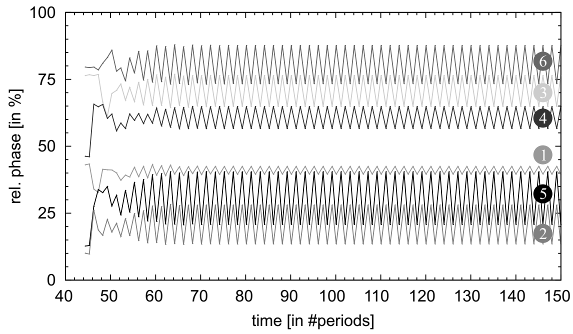
We will exemplify the impact of our new threshold on the simple scenario from Section 4.2, where the two disjoint single-hop topologies C_3 and C_3' are combined by node 7 (cf. Figure 2). Again, we use the self-developed simulator on the same computer as well as the idealized conditions as mentioned in Section 4.2. As suggested in literature (Degesys et al., 2007), we set $\alpha = 0.95$ again.

However, this time, each node calculates its next time of firing according to (4) using $\rho = 0.25$. That means, on average each node keeps its phase at every fourth period. In contrast to the scenario described in Section 4.2, which results in fluctuating time of transmission of each node (cf. Figure 3(a)), the refractory threshold now helps the network to converge after about 25 periods since the start up of node 7 (cf. Figure 3(b)). Moreover, the phase neighbors of node 7 again are its two-hop neighbors node 6 and node 2 (cf. Section 4.2).

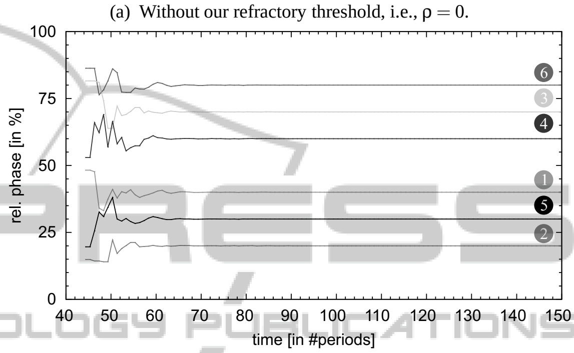
Notably, a larger refractory threshold slows down the convergence rate: In comparison to the scenario described above, we just raised the refractory threshold to $\rho = 0.9$. The simulation result is shown in Figure 3(c): The refractory threshold is clearly set too high, but still the network is approximately desynchronized after about 50 periods since the start up of node 7. In comparison to the previous simulation results, the phase neighbors of node 7 have changed to its two-hop neighbors node 2 and 5.

On the other hand, if the refractory threshold is set too low, the system rather diverges than converges. For instance, if we set $\rho = 0.1$ at the same scenario from above, the time of transmission of each node again fluctuates, but with a smaller amplitude (cf. Figure 3(d)).

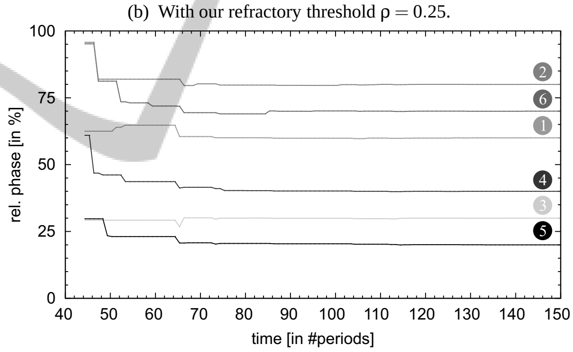
The simulation results so far exemplify the capa-



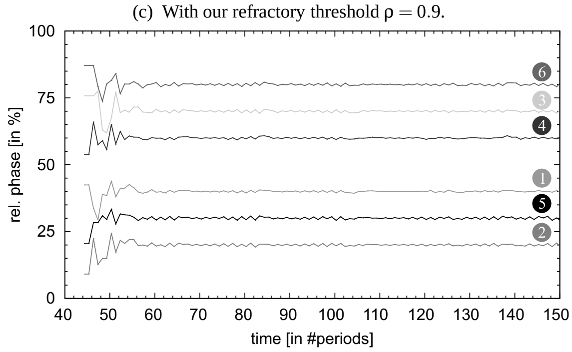
(a) Without our refractory threshold, i.e., $\rho = 0$.



(b) With our refractory threshold $\rho = 0.25$.



(c) With our refractory threshold $\rho = 0.9$.



(d) With our refractory threshold $\rho = 0.1$.

Figure 3: Simulation of M_7 (about 110 periods since the start up of node 7 at period 45), $\alpha = 0.95$, point of view: node 7.

bility of our refractory threshold. Indeed, to have a substantial impact, the refractory threshold must exceed a certain value according to the particular topology and start up scenario. However, the refractory threshold ρ must be set carefully in combination with the jump size parameter α (cf. Section 7).

5.4 Side Effect

Our refractory threshold obviously introduces a probabilistic component. This component can also help to solve emerging collisions in multi-hop topologies. Therefore, to exemplify the impact of our refractory threshold on emerging collisions, we slightly modify the simple scenario from Section 4.2, where the two disjoint single-hop topologies C_3 and C_3' are combined by node 7 (cf. Figure 2). Again, we use the self-developed simulator on the same computer as well as the idealized conditions as mentioned in Section 4.2. This time, we synchronize the start up sequence of the subgraphs C_3 and C_3', i.e., nodes 1 and 4 start up at the same time, nodes 2 and 5 start up at the same time, and node 3 and 6 start up at the same time.

First, we set $\alpha = 0.95$ and $\rho = 0$, i.e., we make no use of our refractory threshold (cf. Section 5.1). As expected, the disjoint single-hop topologies C_3 and C_3' will desynchronize independently. However, due to the idealized conditions and the lack of any probabilistic component, nodes 1 and 4 have chosen the very same time of firing. That means, when node 7 starts up and tries to join the network, all firing packets of node 1 and 4 collide at node 7 due to the hidden terminal problem. Therefore, node 7 receives just corrupt data, and thus is not able to gain any knowledge about the topologies C_3 and C_3'. In contrast, both nodes 1 and 4 receive the empty firing packets of node 7, but thus remain unaware of each other (cf. Section 3.1).

The start up sequence of the subgraphs C_3 and C_3' remains synchronized as described above. But now, we increase the refractory threshold $\rho = 0.25$, and thus activate our probabilistic component. Therefore, the disjoint single-hop topologies C_3 and C_3' will still desynchronize independently. However, even though both nodes 1 and 4 had the same start up time, their time of firing drift apart with high probability. That means, when node 7 joins the network, it now receives the firing packets of both nodes 1 and 4. With its first firing packet containing both one-hop neighbors (i.e., nodes 1 and 4), node 7 connects C_3 and C_3', and thus completes the "dumbbell" topology M_7 again. Figure 4 shows about the first 110 periods from the point of view of node 1 since its start up at period 1.

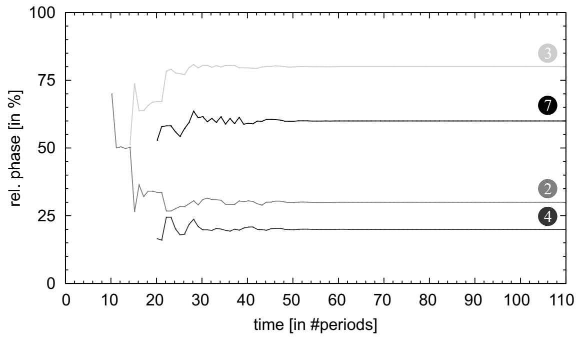


Figure 4: Simulation of M_7 (about 110 periods since the start up of node 1 at period 1), $\alpha = 0.95$, $\rho = 0.25$, point of view: node 1.

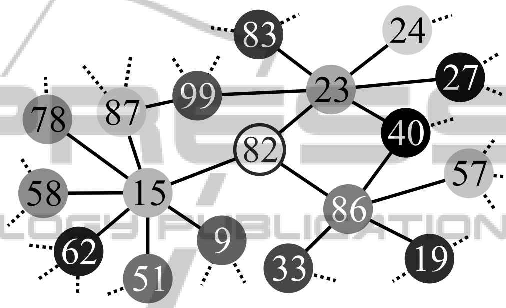


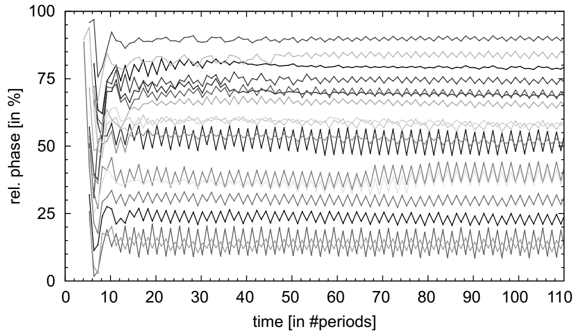
Figure 5: One-hop and two-hop neighborhood of node 82 of topology R_{100}, consisting of the set $N = \{1, \ldots, 100\}$ of nodes.

5.5 Scalability Test

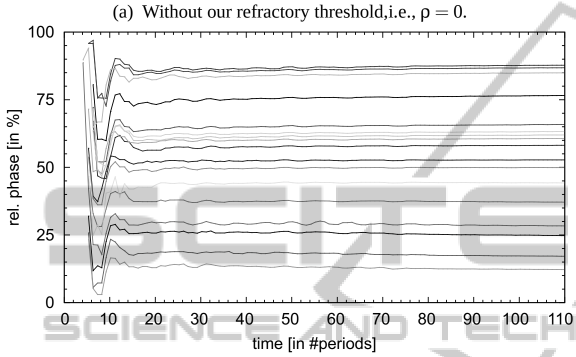
To demonstrate the scalability of our new approach, we simulated a more complex scenario by our self-developed simulator under the idealized assumptions from Section 4.2. This time, the topology R_{100} consists of the set $N = \{1, \ldots, 100\}$ of nodes. Symmetrical links between nodes are set randomly. Each node starts up randomly within the first period. Since our analysis will focus on node 82, Figure 5 just shows the one-hop and two-hop neighbors of node 82 within the observed topology R_{100}.

First, we set $\alpha = 0.95$ and $\rho = 0$, i.e., we make no use of our refractory threshold (cf. Section 5.1). As already observed in Section 4.2, the time of transmission of each node fluctuates, i.e., the one-hop and two-hop neighbors of node 82 rather diverge than converge (cf. Figure 6(a)).

If we just increase the refractory threshold $\rho = 0.25$, the system converges after about period 75 (cf. Figure 6(b)). If each node keeps its phase at every fourth period on average, the network is well desynchronized, although the network consists of 100 nodes. Therefore, our approach not only scales well with the network size, but it is also suitable for large networks.



(a) Without our refractory threshold,i.e., $\rho = 0$.



(b) With our refractory threshold $\rho = 0.25$.

Figure 6: Simulation of R_{100} (about 110 periods since the start up of node 82 at period 1), $\alpha = 0.95$, point of view: node 82.

6 RELATED WORK

In the previous sections, we have already referred to work regarding the primitive of desynchronization. Therefore, this section describes further work dealing with the primitive of desynchronization as MAC protocol, or with the refractory treatment of information.

6.1 Refractory Period

In Section 5, we have introduced our refractory threshold ρ to handle obsolete and potentially unreliable data from neighbor nodes. Therefore, a node probabilistically skips the adjustment of its next time of transmission to provide more reliable data. Similar to our approach is the so called *refractory period* (Degesys et al., 2008), which helps to synchronize (not to desynchronize, as we do) strongly pulse-coupled oscillators: If an oscillator receives the firing of a neighbor within the refractory period, the receiving oscillator does not process this incoming firing. That means, the phase shift between sender and receiver is too short to be considered, and thus, the receiver temporarily does not adjust its next time of firing. Moreover, the phase shift between two oscillators specifies in this approach, whether an oscillator skips the adjustment of its next time of firing or not. In contrast, our refractory threshold is probabilistic and independent from the phase shift between two nodes.

6.2 Artificial Force Field

Another approach to desynchronize a single-hop network is the DWARF algorithm (Choochaisri et al., 2012), which mainly reduces the impact of erroneous information from phase neighbors. Thus, the next time of firing of a node *i* does not only depend on the firings of its phase neighbors. Instead, the next time of firing is specified by an artificial force field which is defined by all other nodes. Each force is weighted by the phase shift of the corresponding neighbor node towards the adjusting node *i*. This approach is very efficient for single-hop topologies. It also results in the equal time span $T / |N|$ between successively transmitting nodes. However, to the best of our knowledge, an extension for multi-hop topologies is currently missing.

6.3 Orthodontics-inspired Approach

The orthodontics-inspired algorithm (Taechalertpaisarn et al., 2011) makes use of the fact that the time span between successively transmitting nodes within a single-hop topology equals $T / |N|$. Therefore, knowing $|N|$, each node can decide autonomously, if it is already desynchronized, i.e., adequately arranged, or if it still has to adjust its next time of firing. Each already desynchronized node simply keeps its phase. With it, the impact of obsolete information is reduced. However, due to the observations in Section 3.4, this approach is not applicable for multi-hop topologies.

7 CONCLUSIONS AND OUTLOOK

In this paper we described the biologically inspired primitive of desynchronization as MAC protocol for wireless sensor networks. The resulting self-organized protocol for single-hop as well as for multi-hop topologies has to manage the problem of stale information as well as the hidden terminal problem. Due to these problems, the periodical transmission times of the nodes may fluctuate in a multi-hop topology. Therefore, we installed the refractory threshold ρ. According to this threshold, and contrary to the primitive of desynchronization, each node is now able to probabilistically skip the adjustment of its next time of firing. Based on some sample scenarios, we demonstrated the impact of our approach for a small but manageable multi-hop topology as well as for a complex network with 100 nodes and randomly selected links. As a result, our approach managed to damp the mentioned fluctuation: The time of transmission of each node did converge faster than without and thus the whole system did desynchronize quite fast.

Our future work will be mainly dedicated to the refractory threshold: First, we want to discover an optimal combination of the probabilistic refractory threshold ρ and the jump size parameter α. Next, we want to analyze the convergence behavior of several scenarios if our threshold depends on certain topology related factors, e.g., the degree of the corresponding node. Moreover, we have already implemented our algorithm for wireless sensor nodes, however an analysis under real-world conditions of this implementation is still missing. In particular, these real-world conditions include asymmetrical and unreliable links, as well as clock drifts, and erroneous nodes.

REFERENCES

Choochaisri, S., Apicharttrisorn, K., Korprasertthaworn, K., Taechalertpaisarn, P., and Intanagonwiwat, C. (2012). Desynchronization with an Artificial Force Field for Wireless Networks. *SIGCOMM Comput. Commun. Rev.*, 42(2):7–15.

Degesys, J., Basu, P., and Redi, J. (2008). Synchronization of Strongly Pulse-Coupled Oscillators with Refractory Periods and Random Medium Access. In *Proceedings of the 2008 ACM symposium on Applied computing*, SAC '08, pages 1976–1980, New York, NY, USA. ACM.

Degesys, J. and Nagpal, R. (2008). Towards Desynchronization of Multi-hop Topologies. In *Proceedings of the 2008 Second IEEE International Conference on Self-Adaptive and Self-Organizing Systems*, SASO '08, pages 129–138, Washington, DC, USA. IEEE Computer Society.

Degesys, J., Rose, I., Patel, A., and Nagpal, R. (2007). DESYNC: Self-Organizing Desynchronization and TDMA on Wireless Sensor Networks. In *Proceedings of the 6th international conference on Information processing in sensor networks*, IPSN '07, pages 11–20, New York, NY, USA. ACM.

IEEE (2007). *IEEE Standard for Information technology - Telecommunications and information exchange between systems - Local and metropolitan area networks - Specific requirements, Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications* (IEEE Std 802.11-2007). IEEE Computer Society, New York, NY 10016-5997, USA.

Kang, H. and Wong, J. L. (2009). A Localized Multi-Hop Desynchronization Algorithm for Wireless Sensor Networks. In *INFOCOM 2009, IEEE*, pages 2906–2910, Rio de Janeiro, Brazil. IEEE.

Karn, P. (1990). MACA - A New Channel Access Method for Packet Radio. In *Computer Networking Conference*, pages 134–140, London, ON, Canada.

Mirollo, R. E. and Strogatz, S. H. (1990). Synchronization of Pulse-Coupled Biological Oscillators. *SIAM Journal on Applied Mathematics*, 50(6):1645–1662.

Motskin, A., Roughgarden, T., Skraba, P., and Guibas, L. J. (2009). Lightweight Coloring and Desynchronization for Networks. In *INFOCOM 2009, IEEE*, pages 2383–2391, Rio de Janeiro, Brazil. IEEE.

Mühlberger, C. (2009). Energetic and Temporal Analysis of a Desynchronized TDMA Protocol for WSNs. In Institut für Telematik, editor, *8. GI/ITG KuVS Fachgespräch Drahtlose Sensornetze*, pages 59–62, Hamburg, Germany. Technische Universität Hamburg-Harburg, Institute of Telematics.

Mühlberger, C. (2010). Desynchronization in Multi-Hop Topologies: A Challenge. In Kolla, R., editor, *9. GI/ITG KuVS Fachgespräch Drahtlose Sensornetze*, pages 21–24, Würzburg, Germany. Universität Würzburg, Institut für Informatik.

Mühlberger, C. and Kolla, R. (2009). Extended Desynchronization for Multi-Hop Topologies. Technical Report 460, Institut für Informatik, Universität Würzburg.

Patel, A., Degesys, J., and Nagpal, R. (2007). Desynchronization: The Theory of Self-Organizing Algorithms for Round-Robin Scheduling. In *Proceedings of the First International Conference on Self-Adaptive and Self-Organizing Systems*, SASO '07, pages 87–96, Washington, DC, USA. IEEE Computer Society.

Støa, S. and Balasingham, I. (2011). Periodic-MAC: Improving MAC Protocols for Biomedical Sensor Networks Through Implicit Synchronization. In Laskovski, A. N., editor, *Biomedical Engineering Trends in Electronics, Communications and Software*, chapter 26, pages 507 – 522. InTech, Rijeka, Croatia.

Taechalertpaisarn, P., Choochaisri, S., and Intanagonwiwat, C. (2011). An Orthodontics-Inspired Desynchronization Algorithm for Wireless Sensor Networks. In *Communication Technology (ICCT), 2011 IEEE 13th International Conference on*, pages 631–636, Jinan, China.

Tobagi, F. A. and Kleinrock, L. (1975). Packet Switching in Radio Channels: Part II–The Hidden Terminal Problem in Carrier Sense Multiple-Access and the Busy-Tone Solution. *Communications, IEEE Transactions on*, 23(12):1417–1433.