Bridging Interference Barriers in Self-organized Synchronization

Parth Amin, Vishnu Prasad Kaushik Ganesan, Olav Tirkkonen
Department of Communications and Networking, Aalto University, Finland
{parth.amin, vishnu.kaushik, olav.tirkkonen}@aalto.fi

***Abstract*—We consider self-organized synchronization in a wireless network, in a setting where there may be transmissions in the network interfering with the reception of synchronization pulses. Persistent existence of interference may prevent synchronization pulses from being heard, which potentially divides the network to multiple connected components separated by interference barriers. We investigate methods to coordinate the synchronization transmission and/or reception strategies within connected components, so that they may grow by bridging barriers. Symmetry in the self-organized connected component growth is broken by synchronization IDs, with a resolution mechanism allowing a finite ID space. Simulation results in a random network with distance-dependent path loss are presented. The coordination methods increase the probability of convergence from multiple connected components to a single connected component covering the whole network significantly.**

Keywords: Synchronization, self-organization, wireless network, interference

I. Introduction

Time synchronization is an essential problem in networking, which has commanded much attention in the research community [1]–[18]. A particularly important type of synchronicity is event or frame synchronicity [1], [2], [6]–[8], [10], [12]–[18], where network nodes coordinate their actions so that their periodic behavior patterns have the same timing. Event synchronicity is a milder form of synchronicity than strict time synchronicity—if there is time synchronicity, event synchronicity automatically follows, whereas to get time synchronicity from event synchronicity, one needs to agree of a global count of events.

For wireless networks, event synchronicity may be desirable for multiple reasons related to Medium Access Control (MAC) or Radio Resource Management. Examples discussed in the literature are duty-cycle and MAC optimization for sensor networks [4]–[9], [11], [14], interference reduction in Time-division Mutlple Access or Time Division Duplexing (TDD) systems [2], [16], or distributed sensing and other cooperative network actions [10], [13], [17]. The main motivation of this paper comes from future cellular networking, where small cell wireless networks are foreseen to complement traditional macro cellular networks. Achieving network synchronization will play an important role delivering the promise made by such future heterogeneous networks, where synchronization will be beneficial for TDD operation, efficient performance of Coordinated multi-point transmission, inter-cell interference cancellation and management techniques, relaying, positioning and mobility operations.

It is an important principal distinction, whether synchronization is performed based on an external timing reference or not. In [4], [5], [9], [11], wireless networks are synchronized by generating a spanning tree rooted at a node with an external timing reference. Self-organized synchronization, without external clocks, is addressed in [1], [2], [6]–[8], [12]–[18]. As small-cell networks are likely to be to a large extent indoors, where satellite position systems have poor coverage, we concentrate here on the self-organized synchronization problem, where no external source of timing exists, and where the network nodes synchronize based on listening to transmissions from each other.

In modern cellular systems, such as Long Term Evolution (LTE) [19], synchronization between infrastructure base stations and mobile stations is based on period transmissions of known synchronization sequences using the same radio resources that are used for data transmissions. When synchronizing a network of base stations (BSs), it is natural to use the same, or similar synchronization channels, reserving a specific channel just for network synchronization would be wasteful. As a consequence, synchronization based on listening to other nodes would suffer from interference. Both synchronous and non-synchronous BSs would disturb a non-synchronous base station (BS) trying to synchronize with another BS. From this it follows that interference often prevents the whole network from synchronizing - the network is divided into multiple connected components so that no BS in one component is able to hear any BS in another. Within a connected component, self-organizing synchronization would be possible, but between these components, there would be interference barriers preventing synchronization. Little is known in the literature regarding methods to spread self-organizing synchronization over barriers of interference caused by other uses of the radio resources used for transmitting synchronization pulses. In [10], it was suggested that nodes should transmit with higher power with a specific pattern, which would increase the Signal-to-Interference-plus-Noise Ratio (SINR) of synchronization signals when heard by nodes on the other side of interference barriers. This solution would be wasteful in the sense that Power Amplifiers, the most expensive analog components of a radio, would have to be dimensioned for synchronization purposes only.

In this paper, we explore mechanisms to coordinate the actions of nodes within synchronized connected components, in order to enable synchronization pulse transmissions to bridge interference barriers in the network in a self-organized manner. We use coordinated transmission methods considered in hierarchical tree-based synchronization [20], as well as coordinated measurement gaps at the receivers of the kind used in cellular systems [21] to reduce the interference when nodes are listening to synchronization signals from other nodes.

The contributions of this paper are fourfold. First we propose a detailed protocol for coordinating the reception within a synchronized connected component. Second, we combine coordinated reception with coordinated transmission methods of [20]. Third, we make coordinated transmission and reception self-organizing. For this, we follow a common practice in distributed algorithms [22], [23], by using identifiers (IDs) to break symmetry, which in this case is related to the direction of growth of colliding synchronized connected components of the network. We provide a conflict resolution algorithm which is capable of dealing with a finite ID space. Finally, we investigate the performance benefits of such self-organizing bridging of interference barriers.

The rest of the paper is organized as follows. Section II presents the system model and basic assumptions. Section III defines the self-organized synchronization protocol based on coordinated transmission and reception for a wireless network. Further in section IV, we define the conflict resolution protocol for finite synchronization ID spaces. Finally in section V, we present the simulation results, analysis and conclude in section VI.

II. System Model

A. Network Model

We consider a wireless network consisting of N Transmitter-Receiver nodes. These nodes may e.g. be infrastructure Base Stations of network of small cells, or cluster heads in ad hoc networks. It is crucial that the considered nodes have a primary desire to communicate with other nodes, mobile stations or clients, that are not part of our model here—this can be considered as node-internal communication. Communication between the nodes is limited, and the desire to synchronize the network comes from the increased capability to coordinate network operation to optimize node-internal communication.

The network is modeled as a fully connected weighted graph $G(V, E; \mathbf{P})$, where V is the set of the N nodes, and E are the edges. The weights $\mathbf{P}$ on the edges of the graph correspond to received signal powers when one of the nodes connected by the edge transmits, and the other receives. For simplicity we assume that all nodes have the same transmit power P_0, and that the channel between the nodes is reciprocal, so that the graph is bidirectional. The weight on the edge connecting nodes i and j is denoted by P_{ij}. For nodes that are far from each other, $P_{ij} \approx 0$. To simplify notations, we assume that $P_{ii} = 0$.

The aim is to synchronize this frame-timing in the network in a self-organized manner. In particular this means that *there is no root node in the system,* with a global timing reference. We follow the literature in self-organized synchronization [6]–[8], [12]–[15], [18] in that nodes strive for synchronization by periodically transmitting synchronization pulses, corresponding to their current frame timing. The synchronization pulses have a predetermined structure, known to all nodes.

B. Interference Barriers and Connected Components

We depart from the literature dealing with both self-organizing synchronization [1], [6], [8], [16] and spanning-tree synchronization [4], [5], [9], [11] in assuming that the nodes use the same channel that they use for transmitting synchronization signals for transmitting payload data, and that the load of such transmissions is high. In the motivating small cell network scenario, the payload transmissions are predominantly node internal transmissions intended to the mobile stations in the cell served by the network node. Inter-node signaling may also be part of the payload.

This assumption changes the synchronization problem. We concentrate on the worst case, when the nodes have full load. Then the nodes transmit all the time, and the synchronization pulses are just a number of symbols with a predetermined structure in the continuous transmission stream of the nodes. In this case, if nothing particular is done, the Signal-to-Interference-and-Noise Ratio (SINR) of a synchronization pulse transmitted by j and received by i becomes

$$\gamma_{ij} = \frac{P_{ij}}{\sum_{k \neq j} P_{ik} + N_0} \tag{1}$$

where N_0 is the thermal noise power density. That is, transmissions from all other nodes except i and j interfere with the reception. In [13], a similar assumption on the channel structure was considered, with synchronization pulses multiplexed with data transmissions. However, there, network connectivity was still based on Signal-to-Noise Ratio, not on SINR.

Furthermore, we assume that there is a threshold H_{synch} characterizing the success of reception of a synchronization pulse. When $\gamma_{ij} > H_{\text{synch}}$, we assume that i hears the synchronization pulse transmitted by j, and synchronization is possible. The synchronization threshold summarizes all receiver properties affecting synchronization pulse reception into one number: the receiver sensitivity, diversity combining methods etc.

These characteristics of our model have two consequences.

- The success of synchronization does not depend on the connectivity of the graph $G(V, E; \mathbf{P})$, but on the connectivity of $G(V, E; \mathbf{\Gamma})$, where $\mathbf{\Gamma}$ is the edge weight matrix of SINRs. This is by default a bidirectional graph.
- Due to the thresholding, $G(V, E; \mathbf{\Gamma})$ may not be connected. There may be multiple connected components $\mathcal{C}_i$ such that if $i \neq j$, no node in $\mathcal{C}_i$ hears any node in $\mathcal{C}_j$ and vice versa. With state of art synchronization algorithms, each of these connected components could synchronize within itself, but the whole network could not synchronize.

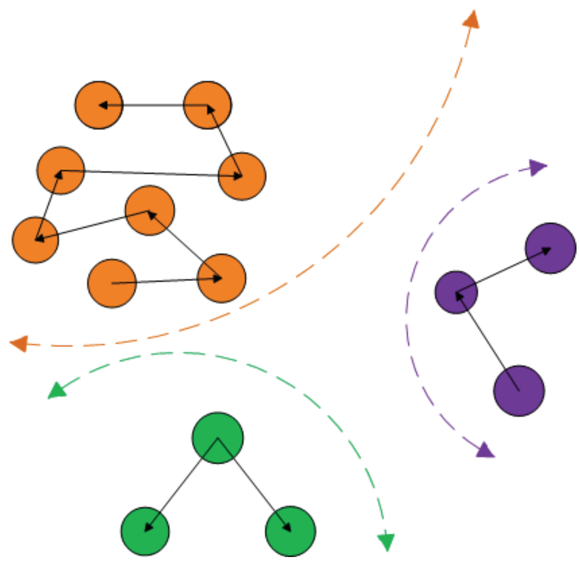

Fig. 1. Network divided into three connected components which are separated by SINR-barriers.

Figure 1 depicts a network divided into three connected components which are not able to synchronize with each other with methods discussed in the literature. As synchronization pulse transmissions in one connected component overlap with payload transmissions in neighboring connected components, interference barriers arise between the connected components.

It may be argued that network synchronization is not needed in a network that is not connected. However, in the motivating scenario where the nodes are small-cell Base Stations (BSs) in a network offering coverage over the entire network area, synchronization may be beneficial even if the BSs are not able to directly hear each other. The channels determining the benefits of synchronization are the channels between BSs and the served mobile stations, not the channels between the BSs themselves, which are used for synchronization of the network. Network synchronization may be desirable to optimize performance for example to avoid Time-Division Duplexing -induced interference problems [24] or to enable network Multiple-Input-Multiple-Output transmissions [25].

C. Node Operation

We assume that the operation of the nodes follow a regular pattern with a fixed duration. The nodes listen to pulses transmitted by their neighbors, and adjust their timing accordingly. For simplicity we assume that the nodes update their timing state asynchronously and periodically, so that no two nodes update their state simultaneously. Also, problems related to clock drift and propagation delays within a connected component is out of the scope of the paper. We are motivated by networks of small cells, where the synchronization target, given e.g. by the length of a Cyclic Prefix applied for transmissions, is much longer than the propagation delay between neighboring nodes in the network. Methods of e.g. [26] may be used to solve the problems arising from propagation delays and clock drift.

Concretely, we model the synchronization state of node i as an oscillator, following the convention of pulse-coupled oscillator synchronization. To cope with the specific problem addressed here, we refine the model to have two periods.

Assuming that there is a global time t, the state of node i is characterized by two phase variables. The frame phase variable takes the value

$$\phi_i(t) = \phi_i^{(0)} + 2\pi\omega t \mod 2\pi \ . \tag{2}$$

Here ω is the phase advancement rate, or clock frequency, and $\phi_i^{(0)}$ is a node-specific phase variable that characterizes the frame timing of the node. The phase variable makes one round in the frame length $T = 1/\omega$. This model cleanly separates the problem of clock/frequency synchronization where the ω are aligned over nodes, from event/frame synchronization, where the node specific constant phases $\phi_i^{(0)}$ are aligned. Here, as discussed above, we concentrate on event synchronization, and assume that all nodes have the same clock frequency ω and frame length T. Full time synchronization would mean agreeing about a global system frame number in addition to $\phi_i^{(0)}$.

In addition to the frame phase, each node has a discrete time node update variable which rotates with a slower pace,

$$\theta_i(t) = \theta_i^{(0)} + \left\lfloor \frac{\phi_i^{(0)}}{2\pi} + \omega t \right\rfloor \mod N_U. \tag{3}$$

Here $N_U \in \mathbb{Z}$ is an update period length, $\lfloor \circ \rfloor$ is the largest integer not larger than $\circ$, and $\theta_i^{(0)} \in \mathbb{Z}$ is a node specific super-frame phase shift. This variable is essentially a system frame number counter modulo N_U. It takes values in $\{0, 1, \dots N_U - 1\}$, and its period is a super-frame of duration $N_U T$.

The synchronization protocol is governed by the update variable θ_i. Always when $\theta_i(t) = 0$, the node performs an synchronization update. Also, for at least one value of θ_i, there is a measurement gap for node i, so that the node does not transmit anything but only tries to receive synchronization signals from other nodes. If TDD is used in node internal (cellular) communication, during a measurement gap there is no transmission in the cell. To avoid collisions where the measurement gap of two neighboring nodes are persistently at the same time, preventing the nodes to synchronize to each other, the measurement gap may be considered to be at a pseudo-random value $\theta_i(t) < N_u - 1$, changing in each super-frame.

When half-duplexing properties of nodes are not considered, N_U is not an issue, and may be taken to be one. Similarly, when contention based multiple access is used, it may be assumed that when a node is not allowed to transmit, it may receive. In that case $N_U = 1$ together with time stamping of packets and a so-called reachback principle is sufficient to deal with the half-duplexing problem [8]. In the case of interest here, receiving synchronization signals requires omitting payload transmissions for the duration of the measurement gap. This is obviously not a desirable feature. Synchronization accuracy has to be traded off against loss from measurement gaps, and accordingly N_U should be large. Note that the principal reason for transmitting synchronization signals by a node is to keep node internal (cellular) communication synchronized, thus it is not wasteful to transmit synchronization signals in each frame, even if a neighboring node is able to receive this signal only once every N_U frames.

In normal frames, transmission is governed by the phase variable ϕ_i. In the interval $0 < \phi_i(t) \leq 2\pi T_S/T$, the node transmits a synchronization sequence of a predetermined structure on a predetermined part of the spectrum occupied by the system. The duration of this synchronization signal is T_S. When $\phi_i(t) > 2\pi T_S/T$, the node transmits payload data. It is assumed that scheduled transmissions are transmitted exactly at the scheduled time. There is no contention based multiple access or carrier sensing in the system—all transmissions collide directly in the physical medium. Thus the receiving time at node j of a synchronization sequence from node i tells the receiver exactly the value of $\phi_i^{(0)} - \phi_j^{(0)}$, up to propagation delays. Due to the periodicity of ϕ, the absolute timing difference between two nodes is then given by

$$\Delta_{ij}^{(0)} = \min\left(|\phi_i^{(0)} - \phi_j^{(0)}|, 2\pi - |\phi_i^{(0)} - \phi_j^{(0)}|\right) \ . \quad (4)$$

We assume that the synchronization sequence of node i carries an ID I_i, which takes values in a finite ID-space. The role of these IDs is to distinguish the nodes from each other. Thus, in a cellular system, the transmissions from different BSs need to be distinguishable by the mobile stations, and this is usually realized by using different synchronization pulses.

The target is to frame-synchronize the nodes with an accuracy Δ, so that the node-specific phase difference $\Delta_{ij}^{(0)} \leq \Delta$. A simple synchronization update principle is assumed here, where the node analyzes the received signals during the measurement gap, for all possible identifiable node IDs I_j. That is, node i is able to receive all transmissions of synchronization sequences within the measurement gap, which have SINR $\gamma_{ij} > H_{\text{synch}}$. It records the $\phi_i^{(0)} - \phi_j^{(0)}$ values for these transmissions, together with the SINR, if it is needed. When $\theta_i(t) = 0$, the node updates its phase shift $\phi_i^{(0)}$ according to the protocol in use by extending or shortening the frame. This update rule is inspired by the Reachback principle of [8].

If synchronization within a connected component only is considered, any synchronization protocol from the literature [7], [8], [13], [15], [18] may be used to calculate the update value of the phase variable, as long as the update itself is delayed until $\theta_i(t) = 0$. Here, due to the characteristics of the protocols used to bridge interference barriers discussed below, and due to the assumptions of no propagation delays and no clock drifts, the details of the protocol keeping synchronization within a connected component need not be considered. The self-organizing interference-barrier-bridging synchronization protocol will be discussed in Section IV.

Finally, to enable network synchronization despite interference barriers, we assume that once two nodes are synchronized, they can establish a signaling channel as part of their payload transmission, to exchange information and coordinate their actions.

To add concreteness to the parameters discussed here, we quote some values that would apply if the system were based on the LTE radio interface [19]. The frame duration (as defined here) would be 5 ms, and the synchronization target given by the Cyclic Prefix would be $\Delta = 4.7\mu$s. Thus propagation delays from distance differences < 1.5km would be within the synchronization target. The LTE system has 504 different synchronization pulses that a BS may transmit, and the synchronization pulses occupy a few percent of the time-frequency resources of a cell. The synchronization signals in LTE are structured to two parts, there is a primary synchronization signal, with three alternatives, from which the timing of a transmission is sought. In a second part, there are 168 alternatives expanding the ID space, which may be sought for with known timing.

III. Bridging Interference Barriers

Within a connected component, any method known in the art may be used to synchronize the nodes. However, except for a particular case of firefly synchronization, which will be discussed below, no method known in the art will be able to bridge the gaps between connected components in the scenario discussed. To bridge the gaps, the interference connections $\mathbf{\Gamma}$ between nodes, as experienced during measurement gaps, have to be changed. There are two alternative methods to do this. Either the numerator in Equation (1) is increased, or the denominator is decreased. Increasing the numerator would mean that the transmit power of the synchronization pulses is increased as compared to the normal payload transmissions [10]. This would mean that the power amplifiers of the nodes would be over dimensioned with respect to their normal payload operation, and would thus be an expensive solution. The alternative, to reduce the denominator $\sum_{k\neq j} P_{ij} + N_0$ requires coordination of the nodes in a synchronized connected component.

In this paper, we study methods to coordinate the synchronization pulse transmission and reception strategies within synchronized connected components of the network, to enable the self-organized growth of the connected components across interference barriers to preferably the whole network.

The logical prerequisite enabling this is membership awareness—nodes in a synchronized component need to know about the component they belong to, in order to coordinate with the other synchronized nodes, and make the synchronized component grow. Once a a number of nodes knows that they belong to a specific synchronized component, they may either coordinate their transmissions, their reception, or both. We assume that such coordination among the nodes is instantaneous.

A. Membership Awareness and Symmetry Breaking

It is well known that symmetry needs to be broken in self-organizing graph algorithms, to determine the direction of propagation of order [22]. In the problem at hand, we may have multiple growing synchronized components colliding, and symmetry between these needs to be broken. In the firefly algorithm [1], symmetry is broken by ignoring the synchronization pulses of neighbors with a timing slightly after the own timing. Alternatively, randomization may be used to break the symmetry, which was done e.g. in [16]. In the problem at hand, firefly-type and randomization solutions are generally not applicable, as the network is bi-directional. In addition, in growth problems, it is beneficial to have a momentum, so that a particular growing component is likely to overcome all other growing components. In both firefly-type and randomized symmetry breaking, growth would be intermittent.

We solve the problem of symmetry breaking with the classical method of using IDs, proposed in [22]. We assume that each synchronized connected component $\mathcal{C}_c$ carries a synchronization ID S_c, shared by all the nodes in that component. This ID can be realized in three ways

S-1) It may be broadcast on a channel which has a structure that depends on the synchronization signal I_i used by the node.

S-2) The synchronization ID S_c may be a subset of pulse IDs I_i, so that a pulse ID indirectly indicates the synchronization ID.

S-3) The pulse ID I_i may equal S_c, so that all nodes in a synchronized component transmit exactly the same pulse.

In the first two cases, there may be interference between the synchronization transmissions from nodes in the same connected component. In the third alternative, the synchronization signals cannot be used for distinguishing between the nodes anymore. Thus this would not be an alternative in a cellular system, where the prime objective of a synchronization signal is to identify the different BSs in the system for the mobile stations. Also, if the second alternative is used in a cellular system, the number N_{ID} of distinct synchronization IDs S_c has to be restricted, not to reduce the number of remaining IDs that may be used to identify BSs too much.

Using a broadcast ID for a synchronized connected component automatically provides membership awareness. If a node hears synchronization pulses with similar timing as its own, but different ID, it knows that these pulses comes from a component it has not coordinated its actions with.

The basic method of growth for synchronized components is that if a node i currently using synchronization ID S_i hears a synchronization pulse with ID $S_j < S_i$, it adopts both the timing of node j and the synchronization ID S_j. A connected component grows like a synchronization tree of the type discussed in [4], [5], [9], [11]. However, here there are no predetermined roots, and there may be multiple simultaneously growing trees. We shall not keep track of the possible tree structure in this paper, we are only interested in which connected component each node considers itself to belong to.

B. Coordinated transmission

In the context of improving spanning-tree synchronization to a root node, coordinating the transmissions of synchronized nodes was discussed in [20]. Here, we consider two of the three methods discussed in [20] for self-organizing synchronization with multiple connected components.

1) Fully orthogonal transmission: In fully orthogonal transmission, all nodes in a synchronized connected component coordinate their synchronization pulse transmissions by transmitting on orthogonal channels and thereby remove interference when nodes outside the connected component receive synchronization signals. This could be realized by Time-Division Multiplexing (TDM) of the synchronization pulses transmitted by the different nodes in a connected component. By inter-node signaling, the nodes align their super-frame phase shifts $\theta_i^{(0)}$, and share the transmissions so that at each node transmits its synchronization sequence only for specific values of $\theta_i(t)$, and otherwise transmits nothing in the resources reserved in the frame for synchronization transmissions.

When a node i, not belonging to the connected component $\mathcal{C}_j$, is receiving a synchronization signal from node $j \in \mathcal{C}_j$, the received SINR is

$$\gamma_{ij} = \frac{P_{ij}}{\sum_l P_{il} - \sum_{m \in \mathcal{C}_j} P_{im} + N_0}. \quad (5)$$

There is no interference from nodes belonging to the same component as the transmitting node *j*.

2) Macro diversity transmission: Macro diversity based transmission is a mechanism to increase the power of the synchronization pulses, in which all synchronized nodes simultaneously transmit similar synchronization pulses on the same channel. This would naturally happen if alternative S-3 is used for the synchronization ID of a connected component, and nodes synchronize to transmit simultaneously. The signals transmitted combine in the air, and on average they combine in the power domain:

$$\gamma_{ij} = \frac{\sum_{m \in \mathcal{C}_j} P_{im}}{\sum_l P_{il} - \sum_{m \in \mathcal{C}_j} P_{im} + N_0}, \quad (6)$$

C. Coordinated reception

The nodes within a synchronized connected component may coordinate so that they arrange simultaneous measurement gaps. By inter-node signaling, the nodes align their super-frame phase shifts $\theta_i^{(0)}$, and agree about a common measurement gap for a specific value of $\theta_i(t)$. Such coordination within a connected component increases the likelihood of allowing synchronization pulses from neighboring connected components to bridge barriers. The SINR at node i belonging to connected component $\mathcal{C}_i$, when receiving a transmission from node $j \in \mathcal{C}_j$, becomes

$$\gamma_{ij} = \frac{P_{ij}}{\sum_{k \neq j} P_{ik} - \sum_{l \in \mathcal{C}_i} P_{il} + N_0}, \quad (7)$$

Due to coordinated reception within the connected component, interference from the own connected component has been removed. In order to hear neighboring connected components with all possible timings with a high probability, the measurement gap has to rotate through all frame positions in the super-frame of length $N_U T$ in a pseudo-random manner. The arrangements of GSM measurement gaps [21] point to possible solutions for this problem.

D. Coordinated transmission and reception

Coordination reception removes interference from nodes of the connected component receiving the synchronization pulse, whereas coordination transmission removes interference from nodes of the connected component transmitting the synchronization pulse. By combining these, both types of interference may be mitigated.

1) Fully Orthogonal transmission with Coordinated reception: This results in receiving the synchronization channel with interference from both connected components removed. The resulting SINR is

$$\gamma_{ij} = \frac{P_{ij}}{\sum_l P_{il} - \sum_{n\in\mathcal{C}_i} P_{in} - \sum_{m\in\mathcal{C}_j} P_{im} + N_0}. \quad (8)$$

2) Macro diversity transmission with Coordinated reception: This is expected to give the best results compared to previous algorithms. The resulting SINR is

$$\gamma_{ij} = \frac{\sum_{m\in\mathcal{C}_j} P_{im}}{\sum_l P_{il} - \sum_{l\in\mathcal{C}_i} P_{il} - \sum_{m\in\mathcal{C}_j} P_{im} + N_0}. \quad (9)$$

In all coordinated transmission and/or reception methods, except for macro diversity transmission, nodes coordinate their actions in the time domain, and it is possible that measurement gaps collide, or a node has muted its synchronization signal transmission due to orthogonalization while a neighbor happens to have a measurement gap. This would lead to epidemic synchronization of the kind discussed in [18]. Here we assume that N_U is large enough to render the probability of such collisions insignificant, so that the epidemic nature arising from pseudo-randomization does not need to be taken into account in the modeling. Epidemic synchronization would become a significant factor in this scenario if randomly variable load for the payload transmissions would be considered.

IV. Node Update Protocol

In this section, we describe a protocol that enables self-organizing growth of synchronized connected components over interference barriers. The self-organization aspect is in enabling growth of connected components, with the direction of growth solved by the nodes themselves, without relying on an external authority such as the presence of a root node to determine the direction of growth.

A. Initialization & Normal Operation

A node, when switched on, listens to the neighboring nodes and synchronizes to the one having the lowest value of *S*. If the node does not successfully receive any synchronization signal, it adopts a random value S from the allowed ID-space.

In normal operation, a node i acts as described in Section II-C. In addition to collecting information about received synchronization signals, it collects information about the corresponding Synchronization IDs S_k, adding them to the set $\mathcal{S}_i = \{S_k\}$. When $\theta_i(t) = 0$, the node performs a synchronization update. It selects the timing $\phi_j^{(0)}$ of the connected component with smallest Synchronization ID $\min \mathcal{S}_i$, if this ID is smaller than its current Synchronization ID S_i. After updating, the node empties the set $\mathcal{S}_i$, and restarts the periodic procedure.

B. Finite ID-space and Synchronization ID conflict resolution

In a realistic scenario, we have a finite ID-space, with at most N_{ID} Synchronization IDs. Accordingly, we may have Synchronization ID conflicts, where there are multiple connected components with the same synchronization ID S. If two connected components have the same ID and the same timing, they are synchronized, and there is no problem for the network. If they have different timing, however, the development towards network synchrony may be halted. For this, we need a conflict resolution protocol.

First, a conflict is identified if a node i successfully receives a synchronization pulse transmission from j with the same ID S_i as itself, but with different timing, $\Delta_{ij}^{(0)} > \Delta$, where Δ is the synchronicity accuracy target, and the time difference of two nodes is given in Equation (4). A natural way to resolve the conflict is that node i starts a new connected component by adopting Synchronization ID $S_i - 1$, thus forcing the two conflicting components to follow itself.

A conflict is also identified if a node k successfully receives synchronization pulses from two nodes i and j indicating the same Synchronization ID S_i, but with different timing, $\Delta_{ij}^{(0)} > \Delta$. No conflict resolution is needed, if the synchronization ID S_k of the receiving node k is less than S_i. In this case, normal operation according to the basic rule of growing a connected component is sufficient to resolve the conflict. If $S_k > S_i$, the conflict can be resolved so that k joins the one of the conflicting components which it receives with the weaker SINR, say $\mathcal{C}_j$. After coordinating with $\mathcal{C}_j$, in the next iteration it is likely that node k still successfully receives the signal from i. If it still has different timing, node k follows the conflict resolution algorithm of the first case discussed in the previous paragraph.

Finally, due to the ID-space being finite, there is a possibility that the node identifying a conflict has the smallest ID $S = 1$, which is also the ID of the conflicting connected component. In this case, conflicts may be resolved by allowing the node identifying a conflict to temporarily use the ID $S = 0$. Strict rules are needed to prevent this leading to expansion of the ID-space. For this, we introduce an internal state variable, taking the values `Normal`, `Resolve0` and `Restrict0`, and a timer r.

When a node has $S = 1$ and it receives a non-synchronized transmission with $S = 1$, or if it receives a transmission with $S = 0$, it adopts $S = 0$, moves to `Resolve0` state and sets a timer $r = 0$. It increments r by one for each update (iteration). When $r = r_{\mathrm{resol,max}}$, the node adopts a random ID from the ID-space (not $S = 0$), moves to `Restrict0` state and sets a timer $r = 0$. It behaves otherwise as in `Normal` state, except that it ignores synchronization signals with $S = 0$. It increments r by one for each iteration. When $r = r_{\text{restr,max}}$, the node moves to `Normal` state.

This algorithm allows the the connected component with $S = 0$ grow so that it ideally covers at least both the conflicting connected components, before it changes its ID to a non-zero one.

The resulting complete node update algorithm for node i is summarized as Algorithm 1. In addition to the internal state variable and the timers, each node keeps track of the Synchronization ID S that it is broadcasting, as well as the phase variables $\phi_i(t)$ and $\theta_i(t)$. A synchronization pulse transmission starts always when $\phi_i(t)$ jumps from 2π to 0, and an update happens when $\theta_i(t) = 0$, i.e. every N_uth time when $\phi_i(t) = 2\pi$. At the start, a node has a random Synchronization ID in the range $(1, N_{ID})$.

Algorithm 1 Distributed Connected Component Growth

if `Resolve0` and $r = r_{\text{resol,max}}$ **then**
do state=`Restrict0`
do $S_i = \text{rand}(1, N_{ID})$
do r = 0
elseif `Restrict0` and $r = r_{\text{restr,max}}$ **then**
do state=`Normal`
endif
if `Normal` or `Restrict0` state **then**
$\mathcal{I}$ = { all S_k received since last update }
if `Restrict0` **then** $\mathcal{I} = \text{Complement}(\mathcal{I}, \{0\})$ **endif**
$S_{\text{cand}} = \min\ \mathcal{I}$
$\mathcal{K} = \{k \mid S_k = S_{\text{cand}}\}$
if $S_{\text{cand}} < S_i$ **then**
$S_i = S_{\text{cand}}$
$j = \arg\min_{k \in \mathcal{K}}(\gamma_k)$
$\phi_i^{(0)} = \phi_j^{(0)}$
elseif $S_{\text{cand}} = S_i$ **then**
$\mathcal{T} = \{\Delta_{ik}^{(0)} \mid k \in \mathcal{K}\}$
if $\max \mathcal{T} > \Delta$ **then**
$S = S - 1$
endif
endif
if $S = 0$ **then**
state = `Resolve0`
r=0
endif
if `Resolve0` or `Restrict0` state **then**
do r=r+1
endif

V. Simulation Results

We compare the performance of the algorithms explained in Section III with uncoordinated synchronization where a node synchronizes with its neighbor node having lower S_c, but no coordination is performed to improve the reception of the synchronization signal. Performance of various synchronization algorithms at specific synchronization thresholds is analyzed in terms of mean number of connected components, convergence time, mean number of conflicts and sensitivity to maximum synchronization ID space N_{ID}.

TABLE I
System Level Simulation Assumptions

Number of nodes N	100
Node location	random
Area size	1 square unit
Synch Thresholds	$-13, \ldots, 4$ dB
Load on shared & control channels	full
ID space N_{ID}	2, 4, 8, 16, 32
$r_{\text{resol,max}}$	1
$r_{\text{restr,max}}$	10
Number of instances	100
Number of iterations per instance	100

A. Simulation Assumptions

We drop N nodes in a unit square, and the nodes randomly select their synchronization ID S from the finite ID space with size N_{ID}. We assume that each node continuously transmits payload data and synchronization pulses, which causes interference to neighboring nodes. For simplicity we model received signal powers P as

$$P = \frac{1}{d^4} \tag{10}$$

where d is the distance between nodes. We do not consider thermal noise - the reception of synchronization signals is interference limited. We assume that all transmitters have the same transmit power, so that we do not need a numeric value for it.

We assume that all node updates are performed asynchronously and periodically, and that propagation delays are negligible. One iteration is the time $N_U T$ that it takes for all nodes to update once. The designs of measurement gaps and muting patterns is assumed perfect in the sense that when a node updates at $\theta_i(t) = 0$, it has successfully received a synchronization signal from all nodes that the state of the coordination protocols during the past $N_U - 1$ frames enables, without considering possible measurement gap/muting collisions. Nodes within a connected component, maintain their synchronization without drift. Interference from all nodes in the network has been accurately modeled, when a node is trying to synchronize with a specific transmitting node. No contention is assumed on the channel - all transmissions collide directly, and detection performance is modeled by the synchronization threshold H_{synch}. The system level assumptions are depicted in Table I.

B. Simulation Results and Analysis

Figures 2, 3 and 4 depict the performance of various algorithms proposed in Section III for finite ID space with $N_{\text{ID}} = 32$. Uncoordinated synchronization is taken as an reference case for comparing various algorithms.

In Figure 2, the number of connected components is depicted as a function of the synchronization threshold. Macro diversity transmissions with Coordinated reception performs best, yielding the smallest number of connected components

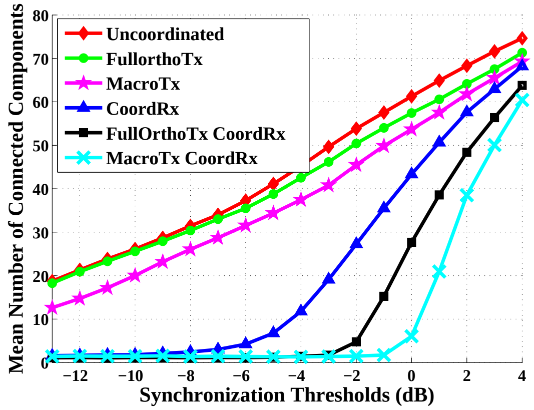

Fig. 2. Mean number of Connected Components

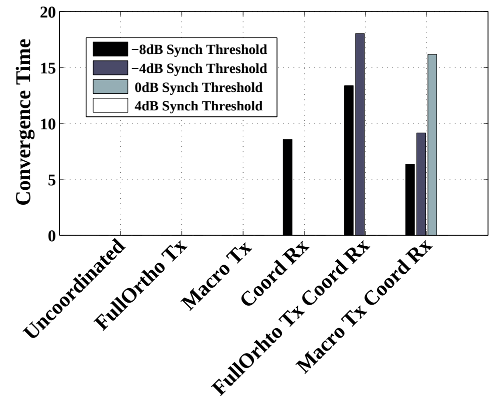

Fig. 3. Convergence Time

at any synchronization threshold. Complete synchronization in a network is achieved when there is one connected component covering the entire network. For larger synchronization thresholds, indicating worse reception of synchronization signals, the number of connected components increases for all coordination algorithms.

As seen in the Figure 2, coordinated reception removes more interference than coordinated transmission. The reason for this is that the interference sources removed by coordinated reception are on the average closer than the interference sources that removed by coordinated transmission. The latter are on the other side of the interference barrier, while the former are on the same side as the receiver. Moreover, macro diversity may in the best case double the synchronization signal power heard by a third node. Therefore, macro diversity transmission and coordinated reception have complementary strengths in network synchronization.

In Figure 3, the average number of iterations for different algorithms with different thresholds to converge to a single connected component are depicted. Macro diversity transmissions with Coordinated reception performs best in terms of convergence time for any given threshold. Again, performance of coordinated reception techniques were better than coordinated transmission techniques. At synchronization threshold $H_{\text{synch}} = 4$ dB, none of the methods are able to converge the network completely, even with 100 iterations. Moreover, at $H_{\text{synch}} = 0$ dB, neither coordinated transmission nor coordinated reception is able to reach convergence individually, but convergence is achieved on combining coordinated transmission with coordinated reception.

In Figure 4, the mean number of nodes in conflict resolution state are reported. Coordinated reception algorithms were able to hear more nodes, thereby detecting a higher mean number of conflicts and also resolving them. As a result, coordinated reception methods converged better. These results validate the performance of the conflict resolution protocol described in Section IV-B.

As Macro diversity transmission with Coordinated reception

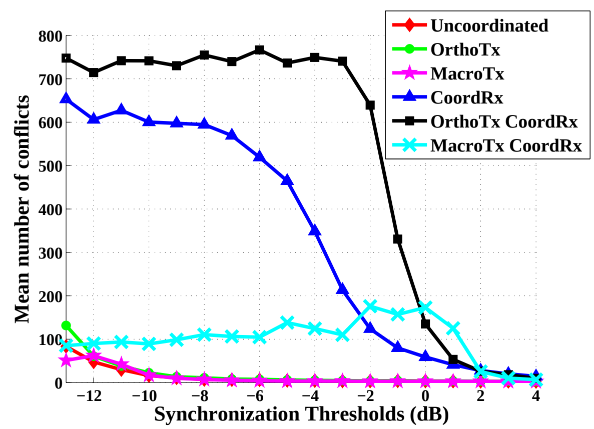

Fig. 4. Mean number of conflicts

is performing better than other synchronization algorithms, we analyze the network convergence of this algorithm with different sizes of the ID space, $N_{\text{ID}} = 2, 4, 8, 16$ and 32. For LTE, a particularly interesting option is $N_{\text{ID}} = 2$. As discussed at the end of Section II-C, there are three alternative primary synchronization signals, and selecting these as the Synchronization ID space would enable macro diversity transmission. Keeping one of the signals as the fallback $S_c = 0$ signal, needed for conflict resolution, leaves $N_{ID} = 2$ for normal use. This would lead the 168 alternate secondary synchronization signals to be used as IDs I_i of individual nodes.

Figure 5 depicts the network convergence for Macro diversity transmissions with Coordinated reception for $H_{\text{synch}} = -4$ dB. As seen in the figure, network converges faster with least connected components as we increase the value of ID space N_{ID}. This is based on the fact that lesser conflicts are to be resolved at higher value of N_{ID}.

Optimum values of $r_{\text{resol,max}}$ and $r_{\text{restr,max}}$ are not explored throughly. However, as depicted in Figure 6, $r_{\text{resol,max}} = 1$ and $r_{\text{restr,max}} = 10$ gives best result, in terms of network convergence, for all possible combinations of $r_{\text{resol,max}}$ and $r_{\text{restr,max}}$ equal to one and ten. Figure was plotted for Macro diversity

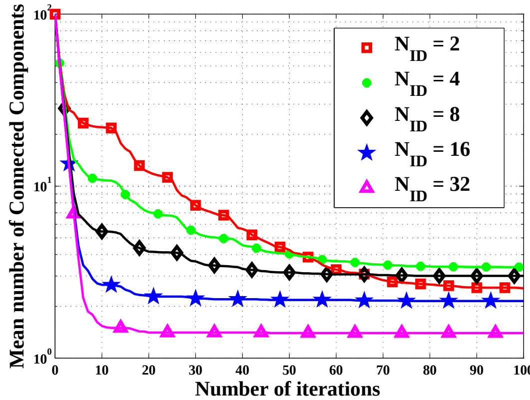

Fig. 5. Network Convergence for Macro diversity transmissions with Coordinated reception with finite ID space

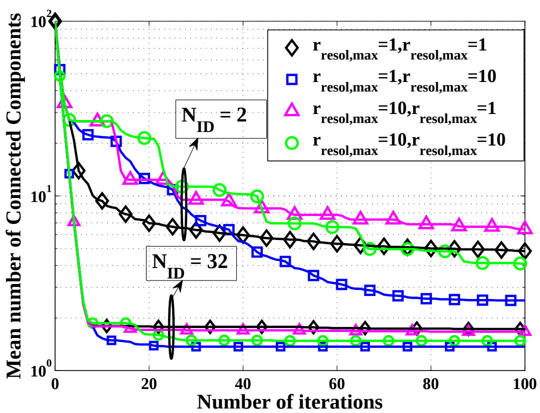

Fig. 6. Network Convergence for combinations of $r_{\mathrm{resol,max}}$ and $r_{\mathrm{restr,max}}$

transmissions with Coordinated reception for $H_{\mathrm{synch}} = -4$ dB. Higher value of $r_{\mathrm{restr,max}}$ compared to $r_{\mathrm{resol,max}}$, successfully removes the ping-pong effect by restricting the node from adopting $S = 0$ again in short interval.

VI. Conclusion

We have considered self-organized synchronization in a wireless network, where there are payload transmissions interfering with the reception of synchronization pulses. Interference barriers dividing the network to multiple connected components make achieving complete network synchronization challenging in such a loaded wireless network. We investigate methods to improve the reception of synchronization pulses across connected components. To achieve this, we coordinate transmission and/or reception of synchronization pulses within a connected component. We provide a self-organizing algorithm enabling growth of connected components, where the direction of growth of a component is governed by a ID carried by a component. A conflict resolution algorithm is proposed to cope with conflicts arising when a finite ID space is used. The emergent property of this self-organizing algorithm is network-connectivity on the level of synchronization signals, in a situation where the network a priori consists of multiple connected components.

Self-organizing interference barrier bridging algorithms with coordinated transmission and reception are compared by Monte Carlo simulations in terms of the resulting mean number of connected components, convergence time, mean number of conflicts and sensitivity to the number of synchronization IDs. We observed that coordinated reception bridges interference barriers better than coordinated transmission, because coordinating reception within a connected component removes interference from closer sources. The simulations show that the discussed self-organizing algorithm is able to significantly improve network connectivity in an interference limited situation. Combining macro diversity transmissions with coordinated reception provides the best performance.

References

[1] R. E. Mirollo and S. H. Strogatz, "Synchronization of pulsecoupled biological oscillators," *SIAM J. Appl. Math.*, vol. 50, no. 6, pp. 1645–1662, Dec. 1990.

[2] Y. Akaiwa, H. Andoh, and T. Kohama, "Autonomous decentralized inter-base station synchronization in TDMA microcellular systems," in *Proc. IEEE VTC*, May 1991.

[3] D. L. Mills, "Internet time synchronization: The network time protocol," *IEEE Trans. Comm.*, vol. 39, no. 10, pp. 1482–1493, Oct. 1991.

[4] S. Ganeriwal, R. Kumar, and M. B. Srivastava, "Timing-sync protocol for sensor networks," in *Proc. ACM SenSys'03*, 2003, pp. 138–149.

[5] J. van Greunen and J. Rabaey, "Lightweight time synchronization for sensor networks," in *Proc. Wireless Sensor Networks and Applications*, 2003, pp. 11–19.

[6] D. Lucarelli and I. Wang, "Decentralized synchronization protocols with nearest neighbor communication," in *Proc. ACM SenSys*, 2004.

[7] Y.-W. Hong and A. Scaglione, "A scalable synchronization protocol for large scale sensor networks and its applications," *IEEE J. Sel. Areas Comm.*, vol. 23, no. 5, pp. 1085–1099, May 2005.

[8] G. Werner-Allen, G. Tewari, A. Patel, M. Welsh, and R. Nagpal, "Firefly-inspired sensor network synchronicity with realistic radio effects," in *Proc. SensSys*, Nov. 2005, pp. 142–153.

[9] L. Dai, P. Basu, and J. Redi, "An energy efficient and accurate slot synchronization scheme for wireless sensor networks," in *Proc. 3rd Internat. Conf. Broadband Communications, Networks and Systems*, Oct. 2006, pp. 1–8.

[10] X.-L. Luo and G. Giannakis, "Raise your voice at a proper pace to synchronize in multiple ad hoc piconets," *IEEE Trans. Sign. Proc.*, vol. 55, no. 1, pp. 267–278, Jan. 2007.

[11] L.-M. He, "Time synchronization based on spanning tree for wireless sensor networks," in *Proc. 4th Internat. Conf. Wireless Communications, Networking and Mobile Computing*, Oct. 2008, pp. 1–4.

[12] R. Olfati-Saber, J. Fax, and R. Murray, "Consensus and cooperation in networked multi-agent systems," *Proc. IEEE*, vol. 95, no. 1, pp. 215–233, Jan. 2007.

[13] A. Tyrrell, G. Auer, and C. Bettstetter, "Emergent slot synchronization in wireless networks," *IEEE T. Mobile Computing*, vol. 9, no. 5, pp. 719–732, May 2010.

[14] S. Barbarossa and G. Scutari, "Bio-inspired sensor network design: Distributed decision through self-synchronization," *IEEE Signal Processing Magazine*, vol. 24, no. 3, pp. 26–35, May 2007.

[15] O. Babaoglu, T. Binci, M. Jelasity, and A. Montresor, "Firefly-inspred heartbeat synchronization in overlay networks," in *Proc. 1st IEEE Int. Conf. on Self-Adaptive and Self-Organizing Systems*, 2007, pp. 77–86.

[16] J. Yu and O. Tirkkonen, "Self-organized synchronization in wireless network," in *Proc. 2nd IEEE Int. Conf. on Self-Adaptive and Self-Organizing Systems*, Oct. 2008, pp. 329–338.

[17] J. Nieminen, R. Jäntti, and L. Qian, "Time synchronization of cognitive radio networks," in *Proc. IEEE GLOBECOM*, Dec. 2009, pp. 1–6.

[18] I. Scholtes, J. Botev, M. Esch, and P. Sturm, "Epidemic self-synchronization in complex networks of Kuramoto oscillators," *Advances in Complex Systems*, vol. 13, no. 1, pp. 33–58, 2010.

[19] 3GPP, "Evolved universal terrestrial radio access; physical channels and modulation (Release 11)," Tech. Rep. TS 36.211 v8.6.0, 2012.

[20] P. Amin and O. Tirkkonen, "Network listening based synchronization techniques for femtocell systems," in *IEEE 22nd International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC)*, Sept. 2011, pp. 1 –5.

[21] 3GPP, "Requirements for support of radio resource management (release 11)," Tech. Rep. TS 25.133 v11.0.0, 2012.

[22] N. Linial, "Locality in distributed graph algorithms," *SIAM J. Computing*, vol. 21, no. 1, pp. 193–201, 1992.

[23] S. Basagni, "Distributed clustering for ad hoc networks," in *Proc. Internat. Symp. Parallel Architectures, Algorithms and Networks*, 1999, pp. 310–315.

[24] W. S. Jeon and D. G. Jeong, "Comparison of time slot allocation strategies for cdma/tdd systems," *IEEE J. Sel. Areas Comm.*, vol. 18, no. 7, July 2000.

[25] M. K. Karakayali, G. J. Foschini, and R. A. Valenzuela, "Network coordination for spectrally efficient communications in cellular systems," *IEEE Wireless Commun.*, pp. 56–61, Aug. 2006.

[26] N. Gresset and J. Letessier, "A random broadcast consensus synchronization algorithm for large scale wireless mesh networks," in *Wireless Communications and Networking Conference (WCNC), 2012 IEEE*, Apr. 2012, pp. 1573–1577.