Self-organization Inter-cell Synchronization Slot Synchronization

Technology Reports

Decentralized Slot Synchronization for Cellular Mobile Radio

This article studies the application of a biologically inspired algorithm that describes the synchronous flashing of huge populations of fireflies to distributed time-synchronization in cellular networks. In particular application to the WINNER system is addressed, and the proposed algorithm enables self-organized inter-base station synchronization.

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1. Introduction

In order to accelerate the development of a new air interface targeted at IMT-Advanced[*1], the European research project Wireless INitiative NEw Radio (WINNER) has been established. The WINNER consortium comprises 41 partners from industry and academia. One innovative feature of the WINNER system concept [1] is its ability for inter-cell slot synchronization in a decentralized and self-organized way. Slot synchronization consists in aligning the timing reference of all Base Stations (BSs) and User Terminals (UTs) in a wireless network, referred to as nodes, so to agree on a common start of a transmission slot. Inter-cell slot synchronization is an enabling component for coordination of cellular wireless networks, such as the mitigation of mutual interference between cells. Furthermore, Single Frequency Networks (SFN) can be established that support multicast and broadcasting services. While access to satellite navigation systems, such as the Global Positioning System (GPS), provide a universal timing reference, the reception of a GPS signal cannot always be guaranteed, e.g., in an indoor environment. As a central control entity in the form of a radio network controller is not foreseen by the WINNER system concept, a network slot synchronization protocol cannot rely on a centralized algorithm. Instead, a self-organized approach is pursued here.

One interesting example of self-organized synchronization in nature has been observed in South-East Asia alongside riverbanks. At dawn, fireflies gather on trees and synchronize their blinking. It seems as though the whole tree is flashing in perfect synchrony. Mirollo and Strogatz derived a theoretical framework for the convergence to synchrony [2], which is summarized in Chapter 3.

Application of this model to wireless networks has been previously considered, in particular for ad hoc networks[*2] where no master node is available. In [3], the characteristic pulse of Ultra Wide Band (UWB)[*3] was utilized to mimic the pulse of a firefly. In [4], long synchronization messages are considered instead. This reflects the duration of several Orthogonal Frequency Division Multiplexing (OFDM)[*4] symbols, which is more practical for implementation in wireless systems than a single pulse. A modification to the original model was presented in [4] to cope with the induced delays and to regain

*1 **IMT-Advanced**: A standard positioned as the successor to IMT-2000 at International Telecommunication Union - Radiocommunication sector (ITU-R). It calls for data rates of about 100 Mbit/s for high mobility and 1 Gbit/s for low mobility.

*2 **ad hoc network**: A network in which several mobile terminals communicate without any dedicated infrastructures such as base stations or access points.

*3 **UWB**: A wireless communication system featuring location-measurement, radar and high-speed-communication functions capable of several hundred Mbit/s to several Gbit/s at short range.

accuracy.

Based on the biologically inspired slot synchronization scheme of [4], in Chapter 4, a decentralized network synchronization protocol is presented that was successfully integrated into the WINNER system concept [1]. The algorithm enables the network to cope with any timing misalignment. It is demonstrated through simulations, that in a typical indoor scenario, the network always synchronizes within 10 periods. It is also shown that for cell sizes up to 1km, an accuracy below 1µs is achieved.

2. WINNER

The WINNER project aims at identification and assessment of key technologies for Systems Beyond (IMT-Advanced) . The project started in January 2004 and terminated after four years in December 2007. The goal of the WINNER mobile access network is a system concept that is highly flexible and efficient and can provide a wide range of services to a multitude of users in many different environments. This chapter provides an overview of the WINNER system concept and several of its key innovative components [1].

2.1 Multiple Access and Medium Access Control

The WINNER system is designed for short delays over the radio interface. A low latency is important for several reasons; it enables adaptivity with respect to fast channel variations, and fast retransmissions with Hybrid Automatic Repeat reQuest (H-ARQ)[*5], which provides reliable links even for real-time services.

The OFDM based resource allocation scheme is highly flexible and can be deployed in a wide variety of system bandwidths and propagation scenarios. Frequency-adaptive transmission adapts the modulation individually for each time-frequency resource unit, called chunk, while the same code rate is applied to all chunks of the same user.

2.2 Advanced Multi Antenna Systems

The generic multi-antenna transmit/receive scheme can be configured into various diversity, multiplexing and multi-user Multiple-Input Multiple-Output (MIMO)[*6] configurations. The spatial transmission can be adjusted individually to the needs of different packet flows to/from a mobile terminal.

2.3 Relaying Concept

Owing to the envisaged high data rate requirements for Fourth-Generation mobile communication systems, current cellular network topologies may fail to deliver universal coverage at affordable cost for network infrastructure and maintenance. The bandwidth requirements, and the resulting needs to resort to high carrier frequencies, will lead to significantly reduced cell sizes. As a consequence, multi-hop network topologies that constitute relay-enhanced cells are an integral part of the WINNER system concept. These cells utilize advanced decode-and-forward relay nodes, so to reduce the deployment cost, extend the range of transmission, cover shadowed areas, and redistribute the offered capacity between centers of cells and cell borders.

2.4 Dynamic Spectrum Use

Given the number of wireless systems already deployed today and the increased use of these, identification of exclusive spectrum for new radio systems is becoming increasingly difficult. Flexible spectrum use and spectrum sharing can therefore be seen as key enabling technologies for future radio networks.

The trend towards multi-hop network topologies, spectrum sharing scenarios where various mobile operators operate in license exempt spectrum, call for distributed control functions. Maintaining a synchronized network in such an environment is a challenging task, which is the subject for the remainder of this article.

3. Firefly Synchronization

A firefly is modeled as an oscillator that flashes periodically and interacts with other nodes through pulses. These systems of pulse-coupled oscillators are known to show interesting phenomena ranging from perfect synchrony to pat-

*4 **OFDM**:A digital modulation system developed to improve resistance to multi-path interference. It converts a signal with a high data rate to multiple low-speed narrow-band signals and transmits those signals in parallel along the frequency axis. OFDM enables signal transmission with high spectrum efficiency.

*5 **H-ARQ**: Technology combining Automatic Repeat reQuests (ARQ) and error correction codes to increase error correction capacity during repeats and reduce the number of repeats.

*6 **MIMO**: A technology for increasing data transmission speeds through the use of multiple antennas.

tern formation [5].

This chapter describes, using **Figure 1**, how time synchronization is achieved between pulse-coupled oscillators, i.e., all oscillators pulse simultaneously.

3.1 Mathematical Model

As a simple mathematical representation, a pulse-coupled oscillator is described by its phase function $\phi_i(t)$. This function increases linearly over time until it reaches a threshold value. When the phase reaches the threshold, the oscillator is said to fire, meaning that it will transmit a pulse and reset its phase (A in Fig.1). If not coupled to any other oscillator, it naturally oscillates and fires with a period T.

The phase function can be seen as an internal counter that dictates when a pulse should be emitted. The goal of the synchronization algorithm is to align internal counters, so that all nodes agree on a common firing instant. To synchronize, nodes adjust their phase function. In the following sections, we assume that all nodes have the same period T, i.e., clock jitter and drift are considered negligible.

3.2 Synchronization of Coupled Oscillators

When coupled to others, an oscillator i is receptive to the pulses of its neighbors. When receiving a pulse at instant τ_j, a node instantly increments its phase by an amount $\Delta(\phi_i(\tau_j)) > 0$ that depends only on its current value:

$$\phi_i(\tau_j) \rightarrow \phi_i(\tau_j) + \Delta(\phi_i(\tau_j)) \quad (1)$$

when receiving a pulse (B in Fig 1).

The received pulse causes the oscillator to fire early (C in Fig 1). By appropriate selection of $\Delta(\phi_i(\tau_j))$, a system of identical oscillators forming a fully meshed network is able to synchronize their firing instants within a few periods [2].

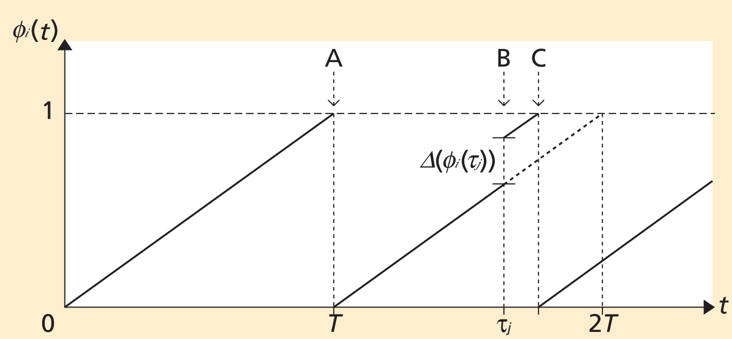

Figure 1 Phase function of a pulse-coupled oscillator

An example of the synchronization of pulse-coupled oscillators is shown in **Figure 2**. In this figure, all nodes start with a random phase initially; all phases evolve linearly until one phase reaches the threshold. At this instant and each time a phase reaches the threshold, all nodes increment their phases. Over time, order emerges from a seemingly chaotic situation where nodes fire randomly, and after six periods in Fig.2, all nodes fire in synchrony.

This synchronization property is very appealing. Nodes do not need to distinguish between transmitters, and simply adjust their internal clock by a phase increment when receiving a pulse, and transmit a pulse when firing. After some time, synchronization emerges from an initially unsynchronized situation, and pulses are transmitted synchronously. Thus decentralized synchronization is achieved without relying on any central control entity.

3.3 Refractory Period

When delays are considered, such as propagation delays, a system of pulse-coupled oscillators becomes unstable, and the system is unable to synchronize [6]. To regain stability, a refractory period of duration $T_{refr} < T$, is introduced after transmitting a pulse. In this state, no phase increment is possible [3]. A node's receiver is switched on, but the phase function stays equal to 0 even if a synchronization message is received.

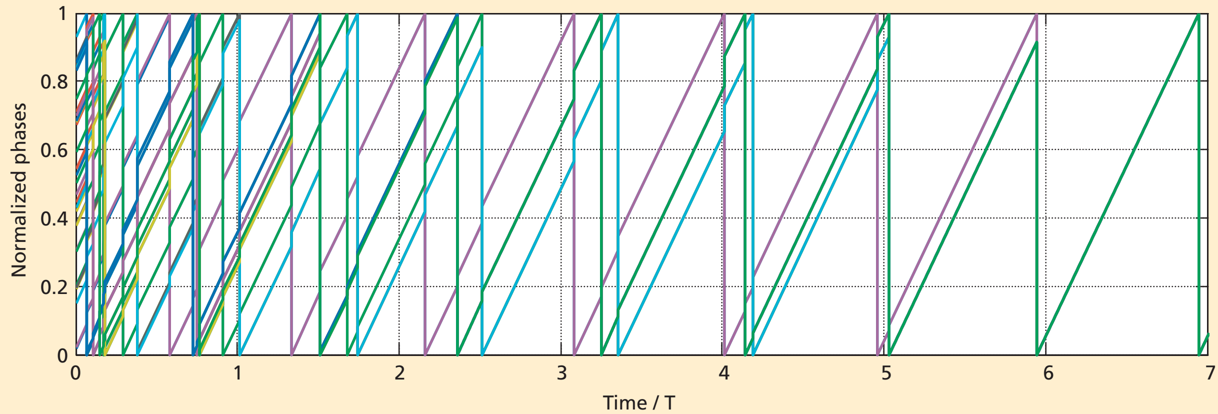

Figure 2 Synchronization example of pulse-coupled oscillators

4. Slot Synchronization in WINNER

This chapter presents an adaptation of firefly synchronization to the WINNER super-frame structure. Instead of solitary pulses, two synchronization words are introduced: one utilized by BSs and the other by UTs.

4.1 Principle

Initially when a UT accesses the network, it needs to synchronize with its BS by following its timing reference, so that it does not disturb ongoing transmissions. The step is shown on top of **Figure 3**. BSs periodically broadcast a DownLink Synchronization word, denoted DL Sync, which is used by UTs to synchronize. This Master-Slave type of synchronization is common for intra-cell synchronization, and is deployed in current cellular networks.

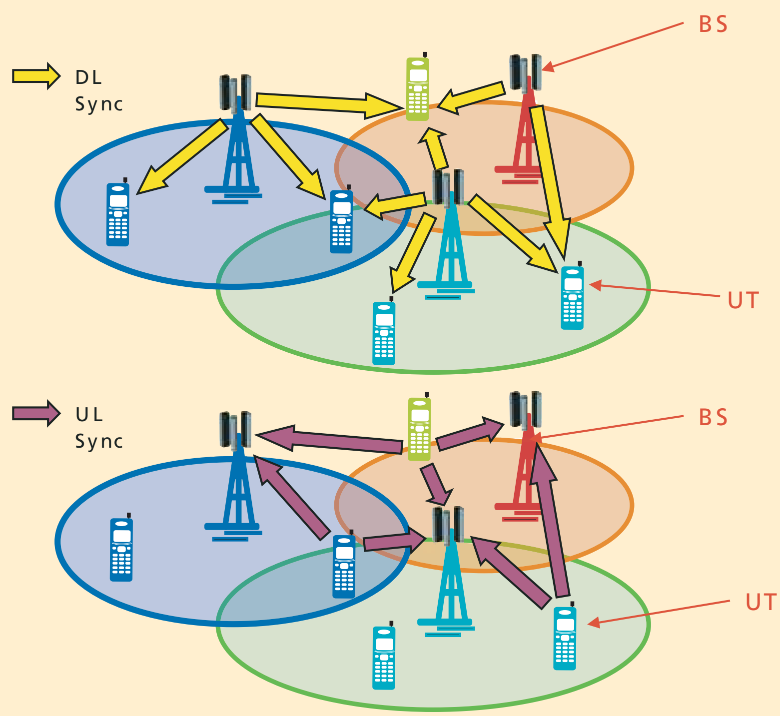

Figure 3 Self-organized synchronization principle

Based on their updated timing UTs can decide whether to transmit an UpLink Synchronization word (UL Sync), which is used by BSs to update their own timing. Not all terminals need to transmit this synchronization word, rather terminals close to the cell edge participate in the inter-cell synchronization procedure, as they are more likely to be heard by multiple BSs. As an example, on the bottom of Fig. 3, only three out of the five represented UTs transmit an UL Sync, because the other two can communicate only with their closest BS.

4.2 Synchronization Rules

The scheme described in Chapter 3 presents the advantage that synchronization emerges from any random initial situation, and does not have prerequisites regarding the distribution of initial firing instants. Thus self-organized synchronization is able to cope with changes in the network topology, which is especially interesting in mobile systems, where wireless communications do not guarantee that all nodes in the network are connected at all times.

The super-frame structure in WINNER is shown on top of **Figure 4**. It consists of a preamble and a main part used for data downlink and uplink transmissions. The preamble is divided into successive mini-slots: the Random Access Channel (RAC), a common UL Sync word, a Guard Interval (GI), a common DL Sync word, and the Broadcast CHannel (BCH).

Given the super-frame structure, Fig. 4 presents the two state machines defined for BSs and UTs, when nodes are perfectly aligned. Based on the firefly synchronization rules presented in Chapter 3, slot synchronization requires all nodes to maintain a phase function that is adjusted. To force the formation of two groups, one formed by BSs and the other by UTs, the phase function of BSs is adjusted when detecting a transmission from UTs, and vice versa. Hence two distinct synchronization sequences, UL Sync and DL Sync, are used.

From the two state machines in Fig. 4, interactions occur between the two groups (BSs and UTs) when a node transmits, and nodes from the other group detect this transmission. Detection of the distinct synchronization words is done by the physical layer link synchronization unit. This allows for robust detection and avoids too much additional processing at the receiver.

Based on the super-frame structure, the listening times for UTs and BSs are respectively equal to:

$$\begin{aligned} T_{\mathrm{UL,Rx}} &= (T_{\mathrm{preamble}} + T_{\mathrm{SF}}) - (T_{\mathrm{UL,Sync}} + T_{\mathrm{refr,UL}}) \\ T_{\mathrm{DL,Rx}} &= (T_{\mathrm{preamble}} + T_{\mathrm{SF}}) - (T_{\mathrm{DL,Sync}} + T_{\mathrm{refr,DL}}) \end{aligned} \quad (2)$$

Thus all UTs maintain a phase function, which increments linearly over time during "Listen":

$$\frac{d\phi_i(t)}{dt} = \frac{1}{T_{\mathrm{UL,Rx}}} \quad (3)$$

Similarly all BSs maintain a phase function which grows linearly over time during their listening period.

Key to separating nodes into two predefined groups is done in two parts.

- Coupling at BSs: if at instant τ_j, a BS node i is in "Listen" state, where its phase function linearly increments over time, and a UT node j, which can communicate with i, started transmitting $T_{\mathrm{UL,Synch}}+T_{\mathrm{DL,dec}}$ before, then the receiving BS node i increments its current phase:

$$\phi_i(\tau_j) \rightarrow \phi_i(\tau_j) + \Delta_{\mathrm{BS}}(\phi_i(\tau_j)) \quad (4)$$

- Coupling at UTs: in a symmetric way, when a UT receives a synchro-

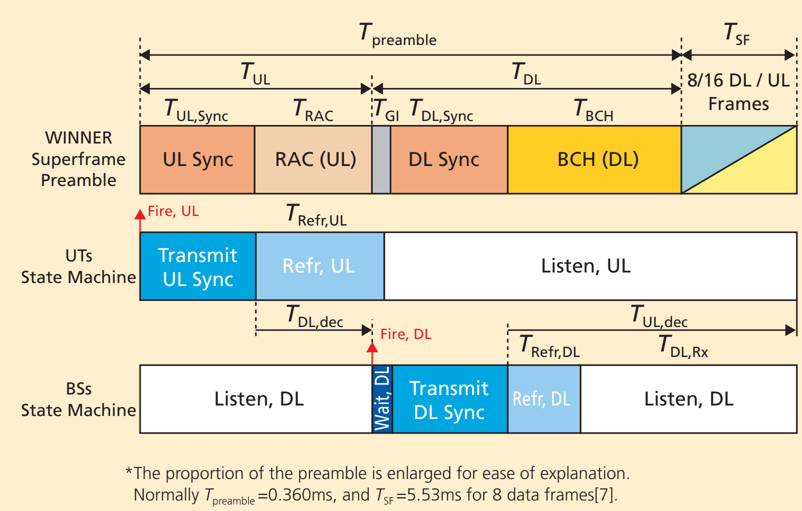

Figure 4 State machines of network synchronization units for coarse misalignments

nization message DL Sync, it appropriately adjusts its phase function in "Listen" state:

$$\phi_j(\tau_i) \rightarrow \phi_j(\tau_i) + \Delta_{UT}(\phi_j(\tau_i)) \qquad (5)$$

Thanks to this strategy, the formation of two groups is controlled: starting from a random initial state, where all nodes fire randomly, after following the simple coupling rules, UTs and BSs separate over time into two groups, all BSs firing T_{UL} after UTs and all UTs firing T_{DL} after BSs. This state corresponds to a synchronized state.

4.3 Time to Synchrony

To validate the proposed scheme, Monte-Carlo based simulations[*7] are conducted. With those simulations, the convergence of the algorithm is evaluated, and more precisely, the time taken by a given network to perform slot synchronization is evaluated.

An indoor office with two corridors and ten offices on each side is considered. Four antenna arrays are placed within the corridors. The local area network topology considered for simulations for 15 UTs participating to the slot synchronization scheme is shown in **Figure 5**. The selected UTs, shown as circles, can communicate directly with all BSs, which are marked as squares. UTs that do not participate to the network synchronization procedure do not transmit the UL Sync, and adjust their slot oscillator based on received DL Sync. The simulation results in **Figure 6** look at the time needed for the entire network to synchronize. The time to synchrony T_{sync} is normalized to the duration a super-frame T_{SF}, and is evaluated for 5,000 sets of initial conditions, i.e., all participants initially start with a uniformly distributed random clock value. The coupling value at UTs α_{UT} varies, and $\Delta_{UT}(\phi_j(\tau_i))$ in equation (5) is proportional to α_{UT}. Fig. 6 shows the Cumulative distribution function (Cdf) of the normalized time to synchrony for 15 participating UTs.

From Fig.5, the performance of the synchronization scheme can be controlled by the coupling factor α_{UT}. For a high coupling value, α_{UT}=1.3, synchronization is always reached within 10 periods, and 90% of initial conditions

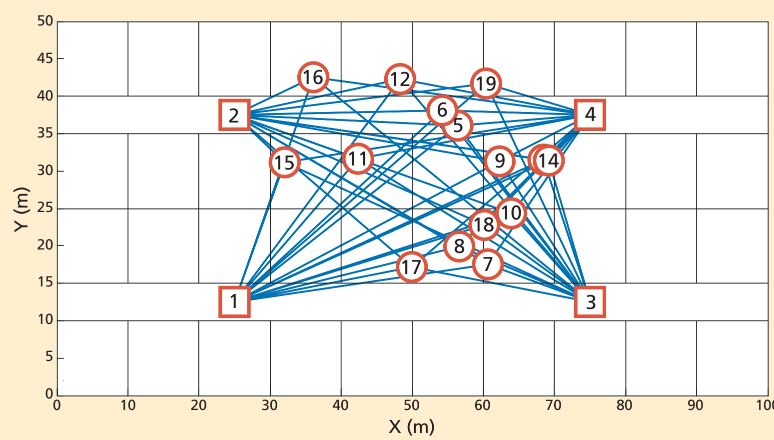

Figure 5 Considered local area network topology for 15 UTs

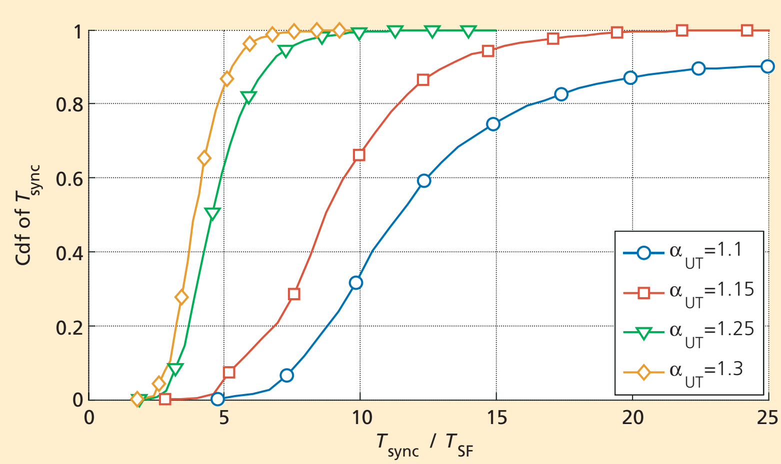

Figure 6 Local area simulation results for 15 UTs

*7 **Monte-Carlo based simulations**: Method used for simulating complex systems, and relying on repeated computation and random or pseudo-random numbers.

lead to synchrony within 5 periods, which is relatively quick given the facts that nodes start from a random timing and that direct communication between BSs is not possible.

4.4 Achieved Accuracy

The wide area scenario defined in WINNER considers a typical outdoor cellular deployment with hexagonal cells such as shown in **Figure 7**. In this case, given the large propagation delays, the main concern for the network synchronization scheme is the achieved accuracy. More precisely, the misalignment in time between neighboring BSs cannot be larger than the GI duration of an OFDM symbol, which is equal to 3.2 μs in the wide area scenario.

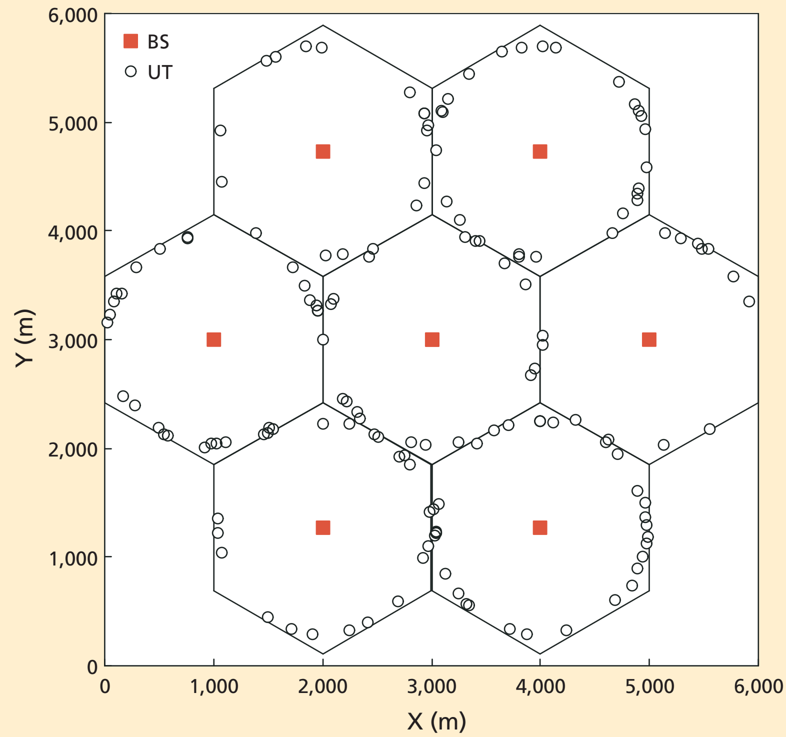

Figure 7 Example of wide area network topology for 7 BSs and 150 participating UTs

The accuracy is defined as follows. Let $\tau_{\mathrm{UT},i}$ and $\tau_{\mathrm{BS},j}$ respectively denote the firing instant of ith UT and jth BS, which are marked as Fire, UL and Fire, DL in Fig.4 at the end of listening periods in each state machine. From Fig.4, it is clear that when nodes are synchronized, there is a constant misalignment between UTs and BSs, which is equal to the durations of the RAC and the UL Sync. Thus, the accuracy between the ith UT and the jth BS is defined as:

$$\mathrm{accuracy}=\left|\tau_{\mathrm{UT},i}-\left(\tau_{\mathrm{BS},j}-\left(T_{\mathrm{UL,Sync}}+T_{\mathrm{RAC}}\right)\right)\right| \quad (6)$$

Given this definition, if nodes are perfectly aligned in time, the accuracy is equal to zero. However, given the propagation delay between two nodes, it is rarely the case.

A common procedure for compensating the propagation delay is for terminals to advance their transmission by this delay. Thus the firing instant of UTs $\tau_{\mathrm{UT},i}$ is advanced by the propagation delay with its own BS $\theta_{\mathrm{UT},i,\mathrm{BS}(i)}$, so that uplink transmissions are effectively performed according to the new timing reference instant:

$$\tau_{\mathrm{UT},i}\rightarrow\tau_{\mathrm{UT},i}-\theta_{\mathrm{UT},i,\mathrm{BS}(i)} \quad (7)$$

The accuracy of the self-organized network synchronization scheme is verified considering seven loaded cells with 150 cell edge UTs distributed in the network and participating to the synchronization procedure by broadcasting the UL Sync word. Participating UTs are chosen if their distance from their own BS is superior to $d_{\mathrm{selection}}$. An example of a wide area network topology for seven BSs and 150 participating UTs is shown in Fig.7 for a cell radius of 1000 meters and a selection range of $d_{\mathrm{selection}}$=950m. **Figure 8** shows the synchronization accuracy with compensation of propagation delays, by advancing the timing references of UTs as a function of the propagation delay

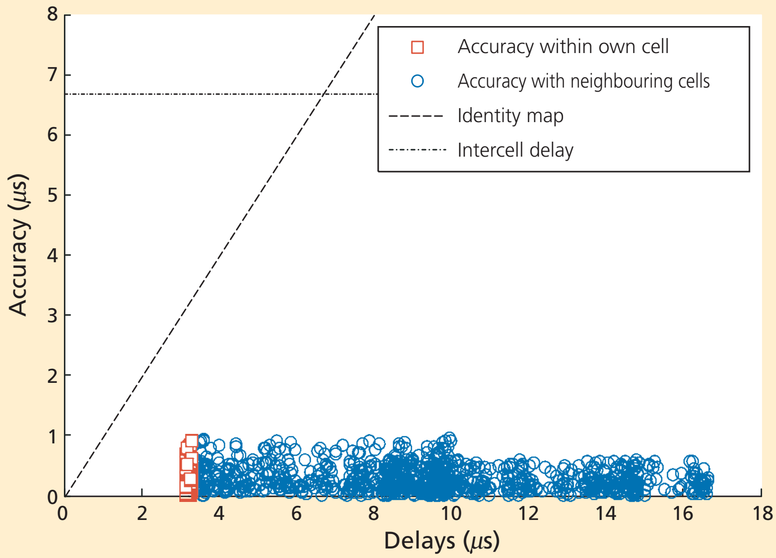

Figure 8 Network synchronization accuracy with compensation of propagation delays

between UTs and BSs.

By this timing advance, nodes are synchronized with a maximum misalignment of 1μs, which is lower than the inter-BS propagation delay, which equal to 6.66μs (inter-BS spacing of 2km). Furthermore, the achieved accuracy fulfils the requirement of being smaller than the OFDM guard interval.

5. Conclusion

This article described the applicability of a self-organized slot synchronization algorithm inspired by firefly synchronization to WINNER. A modification of the original algorithm was introduced to regain high accuracy and to correctly split BSs to form one group and UTs to form another.

Thanks to these rules, a system of nodes starting from a totally unsynchronized condition is always able to reach an agreement on a common time reference.

As the size of the network grows, i.e., more hops are added, the time to synchrony increases. To this end, concerns regarding scalability of the algorithm can be tackled by imposing a global reference onto firefly synchronization [8]. This extension, along with more extensive results of the presented slot synchronization scheme, as well as an extension to synchronization with relays can be found in [9].

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