Collision vs non-Collision Distributed Time Synchronization for Dense IoT Deployments

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Abstract—Massive co-located devices require new paradigms to allow proper network connectivity. Internet of things (IoT) is the paradigm that offers a solution for the inter-connectivity of devices, but in dense IoT networks time synchronization is a critical aspect. Further, the scalability is another crucial aspect. This paper focuses on synchronization for uncoordinated dense networks without any external timing reference. Two synchronization methods are proposed and compared: i) conventional synchronization that copes with the high density of nodes by frame collision-avoidance methods (e.g., CSMA/CA) to avoid the superimposition (or collision) of synchronization signals; and ii) distributed synchronization that exploits the frames’ collision to drive the network to a global synchronization.

The distributed synchronization algorithm allows the network to reach a timing synchronization status based on a common beacon with the same signature broadcasted by every device. The superimposition of beacons from all the other nodes enables the network synchronization, rather than preventing it. Numerical analysis evaluates the synchronization performance based on the convergence time and synchronization dispersion, both on collision and non-collision scenario, by investigating the scalability of the network. Results prove that in dense network the ensemble of signatures provides remarkable improvements of synchronization performance compared to conventional master-slave reference.

I. INTRODUCTION

The exponential increment of interconnected devices makes crucial a proper management of cooperative communication and coordinated medium access control which are enabled by a proper synchronization across the network. The interconnectivity of a large number (say > 100) of heterogeneous and mutually interfering devices, and their synchronization are open issues. Internet of things (IoT) [1] embeds the intercommunication of heterogeneous devices in different contexts, such as smart home, medical metering, public safety, smart grids, automobile, smart traffic, etc. Factory of Things (FoT) [2] enables the connectivity for manufacturing with critical latencies. Even if these paradigms are expected to be part of discussion on 5G systems [3], there are still some characteristics to be considered for a proper synchronization solution in a dense (saying 50 – 100 nodes) interconnected network, mainly: i) to allow scalability of the network as it could be difficult to provide a common synchronization reference to all node of the network as this would scale poorly with number of nodes; ii) to allow fast synchronization of the whole network; and iii) to mitigate power consumption that might follow from excessive synchronization signaling.

In an environment where the closeness and density of nodes makes them prone to collision of transmitted beacon signals, there has been an intense research to reduce (or avoid) the collision of beacon signals. For example, hierarchical architecture or multi-hop scenario by scheduling the node transmission implying the need of coordination among nodes [4], [5]. IoT technologies have been built based on several standards that support the connectivity such as IEEE 802.15.4e [6] with Time-Slotted Channel Hopping (TSCH) that exploits channel hopping to avoid interference operating at the same frequency band and low-power consumption. In wirelessHART [2] synchronization is based on scheduling where the time is divided into time slots and transmissions within a time slot follow some specific timing requirements.

In IEEE 802.15.4e the network synchronization is defined on MAC-layer schedule, and it can be centralized (“coordinated” node is responsible to built and maintain the network schedule) or distributed (each node decides on which links to schedule or distributed node is responsible to built and maintain the network schedule) [7]. However, the maintenance of the schedule is a drawback as the node has to wake up due to lack of scheduling and this limits the scalability of the network and their synchronization [8], [9].

Thus, instead to avoid the signals’ collision, the distributed synchronization method proposed here exploits the superimposition of transmitted signals to drive the network to a global synchronization. The distributed synchronization algorithm is based on consensus paradigm that enables the network to reach asymptotically a global convergence based on the exchange of a common beacon (i.e., the same synchronization beacon is used by all nodes in the network) or distributed (each node decides on which links to schedule with each neighbor) [7]. However, the maintenance of the schedule is a drawback as the node has to wake up due to lack of scheduling and this limits the scalability of the network and their synchronization [8], [9].

The beacon structure is based on chirp-like signature to give the start of the frame at the physical layer interface, so that locally all the devices can estimate and correct their timing offset (TO) of the frame structure based on distributed phase locked loop (D-PLL) algorithm [10]. The devices cooperate with each other to asymptotically reach a global network synchronization in only few beacon exchanges without any external coordination, or any master node acting as TO refer-
Fig. 1. Sketch of TO synchronization evolution. (a) Distributed synchronization based on colliding signals. At received node, say k-th, the TO is updated based on the relative TO error locally estimated with respect to the ensemble of received signals $\tau_k = \sum_{i \in N_k} a_{ik} \tau_i$ used as reference. At synchronization stage, all frames are TO-aligned to the start of the frame. (b) Synchronization based on collision-avoidance. The k-th received node searches for signal free-of-collision (left) to update its TO based on the relative TO error with respect to the collision-free slot (e.g., $\tau_k = \tau_1$ in (b) used as reference. If there is no signal free-of-collision (middle), there is no correction of the TO. At synchronization, the frame of each node starts at the same timing with a node-dependent shift.

This paper compares the synchronization for dense wireless network (Fig. 1): frame collision-avoidance (based on conventional synchronization) and frame-collision (based on distributed synchronization). In order to establish a fair setting where both synchronization approaches can be compared, we choose a scenario where each node autonomously and independently decide if to transmit or receive under half-duplex constraint. The optimum duplexing strategy is evaluated here for uncoordinated arbitrarily dense network. Contribution is the analytical derivation of the optimum duplexing strategy that maximizes the synchronization convergence of the network. The duplex strategy is addressed in [11] for distributed synchronization algorithm. Here, it is extended to the conventional non-collision based synchronization by proving that in this case the convergence and residual TO error is very sensitive to the choice of the optimum duplexing and the network density. Numerical analysis confirms that in dense networks, the collision of beacon-signals provides an excellent reference for distributed synchronization that implicitly averages over the active nodes the individual impairments (e.g., clock drift), and the performance is almost independent on the number of nodes. This offers a unique feature to scalability for inter-connected heterogeneous devices as it is in the case of IoT networks.

The paper is organized as follows. Section II defines the system model. The synchronization algorithm based on collision-avoidance and the distributed synchronization algorithm based on consensus paradigm are introduced [11]. Finally, Section IV demonstrates numerical results followed by concluding remarks in Section V.

II. SYSTEM MODEL

Let us consider a dense wireless network of $K$ uncoordinated nodes (devices) fully connected (i.e., all nodes are allocated in a small geographic area such that each signal transmitted can be received by almost all the other nodes, so propagation delay is negligible and connectivity graph is simple, just for simplicity) without any external synchronization reference. Time is discretized into frames and nodes are aware of the nominal frame period $T_F$ (this assumption is not strictly necessary [12]). In network system, the node timings are nominally the same and oscillators of each node are affected by independent frequency fluctuations that make the frame-time $\tau_k[n]$, evaluated at $n$-th frame for $t \in [nT_F + \tau_k[n], (n + 1)T_F + \tau_k[n]]$, and carrier angular frequency $\Omega_k(t) = \Omega_o + \omega_k(t)$ change over time ($\Omega_o$ is the nominal RF frequency). Here it is not considered the analysis for carrier frequency synchronization to reach $\Omega_k(t) = \Omega_o(t)$ that would follow a similar theoretical infrastructure. Similarly, the distributed synchronization method can be designed for join time and carrier frequency synchronization as in [13]. The network is synchronized by periodically exchanging a synchronization signature embedded into a beacon structure. Each node is equipped with oscillators that run autonomously by their local drifting, thus timing offset (TO) is locally adapted based on programmable frequency dividers of local oscillators.

The synchronization signature is denoted as $x(t)$, and the modulated payload of the i-th node within the $n$-th frame is denoted as $x_{Di}(t)$. All frames can be considered as mutually misaligned one another and delayed by the (absolute) time $\tau_i[n]$. Within the $n$-th frame period, each node randomly can be on transmitting and receiving mode. The transmitting nodes broadcast their synchronization information, whilst at receiving nodes, they receive the superimposition of signals.
to extract the synchronization information and locally correct their TO.

The signal received by the \( k \)-th node over the \( n \)-th frame interval \( T_F \) is the superposition of synchronization signatures \( x(t) \) by all the neighboring nodes \( \mathcal{N}_k \):

\[
y_k(t|n) = \sum_{i \in \mathcal{N}_k} h_{ki}(t) * x(t - \tau_i[n]) \exp(j\Omega_i(t)t) + w_k(t|n),
\]

here referred to the absolute time-reference, for simplicity. \( h_{ki}(t) \) is the channel response for the link \( i \rightarrow k \) that accounts for multi-paths and small propagation delays. Term

\[
w_k(t|n) = \sum_{i \in \mathcal{N}_k} h_{ki}(t) * x_{Di}(t - \tau_i[n]|n) \exp(j\Omega_i(t)t)
\]

is the superposition of all payloads as these are not of interest for synchronization process, noise can be included as well. This term is modeled here as white Gaussian as being realistic enough based on the assumptions so far. The TO error for each of the nodes \( \{\tau_i\}_{i \in \mathcal{N}_k} \) belonging to the neighborhood \( \mathcal{N}_k \) is evaluated by the \( k \)-th receiver with respect to the local reference as

\[
\Delta \tau_{ki}[n] = \tau_i[n] - \tau_k[n].
\]

The TO synchronization is achieved when \( |\tau_i[n] - \tau_k[n]| \leq \sigma_{TO} \), for any pair \((i,k)\) with an upper TO limit \( \sigma_{TO} \) that depends on the value tolerated by the data-communication protocols. The relative error value with respect to the reference of the TO of the \( k \)-th node is

\[
\Delta \tau_k[n] = \hat{\tau}_k[n] - \tau_k[n],
\]

where \( \hat{\tau}_k[n] \) is the TO reference. Distributed synchronization is a consensus-based process where every node is using as TO reference the average timing \( \hat{\tau}_k[n] = \sum_{i \in \mathcal{N}_k} a_{ik}[n] \tau_i[n] \) \( (a_{ik}[n] \) is a weighted coefficient) of the neighboring nodes that is estimated from superimposed synchronization signatures \( y_k(t|n) \) (see Fig. 1a). Whilst, in conventional synchronization nodes use as TO reference the timing information from one not-colliding signal detected, say \( \hat{\tau}_n[n] = \tau_n \), of one neighbor node (Fig. 1b). The TOs are periodically measured and corrected every \( T_F \) by comparing the local values with respect to the reference \( \hat{\tau}_k[n] \) by the exchange of the synchronization signatures \( x(t) \) among all nodes to minimize the TO mismatch one another.

### III. Colliding vs Not-Colliding Frames in Synchronization Approach

Synchronization at PHY-level is to align the frame structure and the corresponding time-slots to enable MAC-level functionalities. The timing synchronization of the network is achieved when all the \( K \) frames are temporally aligned and the relative TOs are (close enough to) zero. In uncoordinated networks, nodes randomly choose to transmit or receive the synchronization beacon \( x(t) \) to iterate the broadcast and correction of TO several times. When the node is transmitting, it broadcasts its synchronization state, while the receiving nodes update their TO locally based on the information extracted from the received signal. Thus, the \( k \)-th receiving node updates its TO at \( n \)-th synchronization step based on the relative error \( \Delta \tau_k[n] \), accordingly to the updating

\[
\tau_k[n + 1] = \tau_k[n] + \varepsilon \Delta \tau_k[n] + v_k[n] = (1 - \varepsilon) \tau_k[n] + \varepsilon \hat{\tau}_k[n] + v_k[n],
\]

where \( \varepsilon \in (0,1) \) is a design parameter, and \( v_k[n] \) is a stochastic perturbation due to oscillator’s instability. Network reaches the TO synchronization when \( \tau_1[n] = \tau_2[n] = ... = \tau_K[n] = \tau_\infty \) for a certain \( n \), and it is achieved asymptotically (\( n \rightarrow \infty \)) for a connected network.

In dense networks (say \( K \geq 100 \) nodes), the collision of signals is highly likely, even more when there is no scheduler or coordinator agent. Under this scenario, focus here is to compare two synchronization approaches based on: collision-avoidance and collision of signals. The former is a conventional synchronization based on master-slave reference, where the TO reference \( \hat{\tau}_k[n] \) is extracted from the detection of received signal free of any collision. The latter is based on distributed synchronization where the reference \( \hat{\tau}_k[n] \) is estimated from the superimposition of the received signals. Synchronization methods are thus conceptually one the opposite of the other, and the analysis here is for collision vs non-collision synchronization.

#### A. Non-Collision based Synchronization

The synchronization algorithm is based on master-slave reference. Each receiver locally corrects its TO based on the relative TO error \( \Delta \tau_k[n] \) with respect to the TO of the signal free-of-collision detected from its neighborhood \( \mathcal{N}_k \), when available (Fig. 1b). The received signal \( y_k(t|n) \) is a filter matched to the local copy of the synchronization signature \( x(t) \) and it is conventionally used to search for a signal free-of-collisions. If it is detected a signal free-of-collisions from
a transmitting node, say $i$-th, the receiver corrects its TO with respect to the reference $\hat{\tau}_k[n] = \tau_i[n]$, otherwise the local oscillator is in free-running mode making the TO drift-apart.

The synchronization update (5) depends on whether a signal free-of-collision is detected, and thus to maximize the probability of synchronization update (or maximize the convergence rate), the optimization problem can be addressed in terms of the probability of a device to be on transmission mode such that the probability of collision is minimized, or equivalently the probability that only one collision-free signal in every frame is maximized.

The probability of synchronization update (or one signal free-of-collision) is given by

$$\Pr\{\text{update}|p_{Tx}, K\} = \Pr\{1 \text{ collision-free signal out of } |N_k| - 1 \text{ colliding} \} \times \Pr\{1 \text{ collision-free signal}|\ell \text{ Tx nodes} \},$$

and the optimum probability that a node transmits is given to the optimization problem

$$p_{Tx, Opt} = \arg \max_{p_{Tx}} \Pr\{\text{update}|p_{Tx}, K\},$$

where the probability of synchronization update is conditioned for a given density of nodes $K$. The optimum probability $p_{Tx}$ can be derived analytically from model (6) (omitted here for sake of compactness). Figure 2 shows this optimum probability that a node transmits $p_{Tx, Opt}$ (dash line) for different network connectivity or density given by varying $K$. Increasing $K$, the synchronization algorithm can optimize the synchronization efficiency by assigning an optimum probability of transmission that in turn it can be approximated to $p_{Tx, Opt} \approx 1/K$.

### B. Collision-based Distributed Synchronization

The distributed synchronization algorithm [13] is based on distributed phase locked loop (D-PLL) that is an iterative control system for synchronization that corrects the local TO $\tau_k[n]$ on each node, say $k$-th, based on the TO error $\Delta \tau_k[n]$ with respect to the TO of the ensemble $N_k$ (Fig. 1-a). The synchronization by D-PLL can be framed as consensus algorithm where transmitting nodes broadcast their synchronization status as TO $\tau_i[n]$ embedded into modulated signatures $x(t)$, and the nodes receiving these misaligned and superimposed signatures correct their TO accordingly. The TO reference $\hat{\tau}_k[n] = \sum_{i \in N_k} a_k[i] \tau_i[n]$ is estimated from $y_k(t/n)$ superimposing the ensemble of received signatures that embed $\{\tau_i[n]\}_{i \in N_k}$.

The estimation of the average TO $\hat{\tau}_k[n]$ from the ensemble of nodes reduces to the estimation of time of delay of superimposed multiple copies of the same signature $x(t)$ affected by different TOs. In distributed synchronization, the problem reduces to the estimation of TO centroids from the superposition of several $x(t)$ in (1). The estimation of the relative TO error from collisions is based on the timing metric from the filter matched to the synchronization signature $x(t)$

$$r(\tau) = \int y_k(t)x^*(t-\tau)dt = \sum_{i \in N_k} h_{ki}(t)g(t-\tau_{k,i})\exp(j\Omega_{ki}) + \tilde{w}_k(t),$$

where $\tilde{w}_k(t) = w_k(t) * x(t)$. This is the superposition of $|N_k|$ auto-correlations $g(t) = x(t) * x^*(t)$ with amplitudes $b_{ki}$ and delays $\tau_{k,i} = \tau_k - \tau_k$. [13]
In distributed synchronization it is necessary to estimate the average deviation of TO of \(N_k\) (not the individual values), and thus the barycentric delay value

\[
\Delta T_k = \frac{\int |r(t)|^2 dt}{\int |\tau(t)|^2 dt} \approx \frac{\sum_{i \in N_k} |h_{k,i}|^2}{\sum_{i \in N_k} |h_{k,i}|^2}
\]

(10)

\[= (\bar{\tau}_k - \tau_k)\]

is a preferred estimator of the average delay weighted by the amplitudes \(|h_{k,i}|^2\). Proof of the optimality of estimator (10) can be shown (not here).

For an optimum duplex strategy in distributed synchronization, the probability that a node is on transmission mode can be optimized to maximize the convergence rate, or equivalent by minimizing the convergence time. The decreasing rate can be shown (not here). Proof of the optimality of estimator (10) can be based on Zadoff-Chu (ZC) sequences due to their good correlation properties [13]

\[x[m] = \exp \left( j \frac{\pi}{N} u (m - N_c)^2 \right)\]

(12)

with \(N\)-samples length and cyclic prefix and suffix \(N_c\)-samples length both, for a total support \(N_u = N + 2N_c\), where \(u\) is the root index that is relative prime to \(N\) (here \(N\) is even and \(u = 1\)). At set-up \((n = 0)\) network is asynchronous: TO is normalized by signature length \(N\) and it is uniformly distributed over the frame \(\tau_k[0] \sim U(-25N, 25N)\), and the loop gain filter is \(\varepsilon = 0.5\). The mean-square deviation (MSD) \(\sigma_{TO}^2[n] = \sum_{k,i 
eq k} (\tau_k[n] - \tau_i[n])^2 / (K - 1)\) is used as metric for convergence dispersion of TO synchronization.

TO synchronization toward convergence is illustrated in Fig. 3 for \(K = 500\) nodes fully connected (all-to-all connectivity) and each one is affected by an independent clock-drift. Fig. 3a compares both synchronization approaches on a no-optimum duplexing scenario by increasing the probability of node transmission \(p_T = 0.01\), for both methods. Notice that when the probability of collision increases, the detection of a signal free-of-collision is low, and hence the network does not reaches the minimum dispersion of TO error that allows the proper communication. The optimum duplexing is shown in Fig. 3b, where \(p_{T_x,Opt} = 0.002\) for no-collision and \(p_{T_x,Opt} = 0.03\) collision scenario. The distributed synchronization algorithm...
provides stable performance by reaching a convergence status in few iterations and reduces the synchronization dispersion error for large $n$ on both not-optimum and optimum duplexing. However, the fact that the optimum $p_{TX}$ is low in conventional synchronization, it is an advantage on reduction of power consumption.

Figure 4 shows the MSD $\sigma_{TO}$ vs synchronization iteration $n$ for both collision and non-collision -based synchronization approach for a network of $K = 1000$ nodes fully connected (all-to-all). The convergence time $T_{CONV}$ and steady-state MSD $\sigma_\infty$ are the metrics used to evaluate and compare the performance of both synchronization algorithms. The optimum probability of transmission is used for both methods to compare for the best $T_{CONV}$, that for collision-based is $p_{TX,Opt} = 0.02$ and non-collision is $p_{TX,Opt} \approx 1/K$. Results in Fig. 4 illustrates that the distributed synchronization algorithm improves the convergence time $T_{CONV}$ by 32% and the MSD $\sigma_\infty$ by 61% in comparison to collision-avoidance scenario.

Based on the example in Fig. 4 the synchronization algorithms are evaluated and compared on the basis of $T_{CONV}$ and $\sigma_\infty$. Fig. 5 illustrates the convergence time $T_{CONV}$ vs MSD $\sigma_\infty$ for different network density $K = 100, 500, 1000$ with its corresponding optimum probability of node transmission $p_{TX,Opt} = 0.07, 0.03, 0.02$ (collision-based) and $p_{TX,Opt} \approx 1/K$ (non-collision based) by varying the perturbation noise of the local oscillator $\sigma_0 = 0.01 : 0.1$. Experimental results in Fig. 5 prove that the distributed synchronization is uniformly better in terms of $T_{CONV}$ and $\sigma_\infty$ independently of $K$ in comparison with collision-avoidance approach. $T_{CONV}$ is reduced by 30%, and the $\sigma_\infty$ is reduced by 60% for any increasing perturbation noise (due to oscillator’s instability). On the other hand, the performance of the non-collision based synchronization is degraded significantly for any sub-optimum probability of transmission $p_{TX} = 0.03 : 0.05$ thus limiting the scalability of the network.

V. CONCLUSION

The novel distributed (collision-based) synchronization algorithm is compared with conventional (non-collision) synchronization under an uncoordinated dense network scenario without any reference agent where all nodes in the network are assigned the same synchronization signature. The conventional synchronization algorithm is based on detection of signal free-of-collision to enable the update synchronization, whilst distributed synchronization exploits the collision of signals to extract the synchronization information to enable the TO update. The impact of the network scalability is investigated for both synchronization approaches by comparing the convergence time and synchronization dispersion error. Numerical results prove that superposition of signals provides remarkable improvements in synchronization compared to conventional non-collision based synchronization, even on network settings that degrades the performance of the synchronization. This feature makes the proposed method more robust for synchronization in dense IoT networks. The synchronization setting fits the requirements involved on heterogeneous networks, allowing scalability, minimizing the signaling overhead by using the same signature in beacon to take benefit of collision, and considerably reducing the complexity of the synchronization algorithm at price of a change of signal processing paradigm at PHY-layer. However, the duplexing strategy in distributed synchronization implies that more nodes will be on transmission mode, it translates in a drawback of augmented power consumption.

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