Abstract—This paper presents a synchronization-free TDoA localization method (SF-TDOA) that can be used in wireless networks of hundreds and thousands of mobile nodes. The location of mobile node is determined based on the differences of the reception times of radio packets at node (packets transmitted by anchors), knowledge of anchors’ location and anchors mode of operation. Since mobile nodes do not need to transmit any messages, the communication overhead of the method does not depend on their number. This makes the method highly scalable to large networks. Moreover, since all the nodes only measure the time of their own activities there is no need to have their clocks synchronized.

The SF-TDOA was evaluated in OMNeT++ simulator taking into account inaccuracies of clocks. Due to inherent delay in the localization procedure the algorithm performs better for slowly moving nodes. Still, for the network of 2,500 m$^2$, nodes running 10 ppm clocks, moving at 10 m/s and using no time synchronization, the algorithm achieves average localization accuracy of 10.8 meters.

I. INTRODUCTION

Indoor localization is a well established scientific problem that latterly became very popular among researchers. Recent advances in electronics and wireless communication technologies was one of the main incentive for Internet of Things (IoT) concept, that significantly changed the way people perceive interworking. Simultaneously, development of small, long-lasting and powerful smart devices became feasible and cost effective. IoT networks composed of such smart devices can be adopted in wide range of industry applications in order to improve overall performance. For instance logistic and management can gain from dedicated IoT systems that continually monitor and localize assets in areas where satellite navigation systems cannot be used (tunnels, warehouses, etc.)

Among all time-based localization methods Time Difference of Arrival (TDoA) methods are suitable for large scale IoT networks. Such methods are capable of localizing large number of nodes using small number of messages exchanged between infrastructure and mobile nodes. Typically TDoA methods require infrastructure nodes to have synchronized clocks and overall localization accuracy relies on the accuracy of clock synchronization. Clock synchronization in low-power IoT networks is itself a challenging problem that has been investigated for several years now, with number of solution proposed [1]. Still, from large IoT network perspective, the clock synchronization remains a challenging task, as it implies additional radio transmissions and consumes bandwidth that can otherwise be used for application specific communication. Difficulties in the development of efficient and accurate synchronization protocol resulted in creation of so called synchronization-free TDoA approaches (e.g. [2], [3], [4]). Despite the name, most of these methods perform on-demand synchronization of the infrastructure (anchor’s) clocks, i.e. synchronization is done during the localization procedure and only if initiated by mobile node. This paper presents another synchronization free TDoA approach, however in contrast to other approaches our method can easily scale to networks of large number of devices and is truly synchronization-free.

The remaining part of this paper is organized as follows. Next section presents related work and provides rationale for the proposed method. Section III provides detailed description of SF-TDOA and its properties, while simulations are presented in section IV. Last section concludes the paper and discusses possible future improvements and research areas.

II. RELATED WORK

Until now a number of synchronization-free TDoA localization methods have been proposed. These methods assume there is no periodic clock synchronization between network nodes but localization procedure is constructed in such a way that simultaneous clock synchronization and location estimation is possible. These methods require a mobile node to actively participate in the localization procedure as nodes need to initiate the procedure. This requirement effectively limits applicability of these methods to small networks as number of localization-related messages exchanged between the nodes increases with the number of mobile nodes in the network.

Whistle [2] is an example of synchronization-free infrastructure-based TDoA localization method. Localization procedure is initiated by mobile node that broadcasts a radio message (beacon) to nearby anchors. One of the anchor, called the base or whistling anchor, receives the message and retransmits it after predefined delay. The beacon and the retransmitted message are received by all anchors in the communication range. Anchors time-stamp reception of both messages using local clocks and send it to the backend server, for processing and position estimation. Before the TDoA values can be computed the reception timestamps (collected using
unsynchronized clocks) need to be transformed to the unified time domain (as if they were measured using synchronized clocks). Whistle does this by comparing time-stamps of the messages originated from the mobile node and the whistling anchor. Knowing the delay in whistling anchor and distances between anchors Whistle determines TDoA values which are then used for localization. In order to determine mobile node position two or three messages (depending on whether mobile node should be aware of its position) have to be used. Since the localization procedure is initiated by a mobile node, thus for large scale networks mobile nodes require a method of coordinated radio channel access – otherwise collision rate would effectively lower network performance. Whistle does not scale well to large networks as communication overhead for localization increases with the number of mobile nodes and whistling anchors (in networks that span across large areas more than one whistling anchors will be required).

Asynchronous TDoA (ATDOA) [3] is another synchronization-free and infrastructure-based localization method. In ATDOA mobile node position is calculated by the network infrastructure from two messages transmitted by moving mobile node from two distinct locations \((x_a \neq x_b)\). Anchors record reception timestamps of those two messages and calculate TDoA values with respect to their local clocks. Collected timestamps are then transfered to backend server, where coordinates of \(x_a\) and \(x_b\) can be uniquely determined. Similarly to Whistle, localization of a single node is performed with two or three messages depending on whether mobile node should know it’s position or not. Unfortunately, applicability of ATDOA is limited as it can be only used to localize moving nodes. When applied to large scale networks the ATDOA method, similarly to Whistle, requires a channel access method. As in Whistle the number of radio communications used during localization increases with the number of mobile nodes in the network.

A synchronization-free TDoA method with clock drift compensation is presented in [4]. This method requires infrastructure composed of stationary anchors (with known positions) transmitting beacons periodically. Among all the anchors one is selected to be a so-called zone coordinator that is wire connected with backend server. Localization is initiated periodically by zone coordinator which broadcasts first beacon. Upon reception each of the remaining anchors transmits its own beacon – they send these beacons with predefined delays to avoid collisions in the communication channel. Both mobile node and anchors record reception timestamps for all the beacons using their local clocks. Collected timestamps are transferred to the backend server which transforms the timestamps to common time domain and estimates mobile node position. Single localization iteration in 2D requires anchors to send three messages and each mobile node to forward recorded timestamps to zone coordinator. Additional message from coordinator is required if mobile node is to be informed about the estimated location. As a result the communication overhead of this method grows both with the number of anchors and mobile nodes. Consequently this method is less applicable to large scale networks as it does not scale well.

### III. THE METHOD

#### A. Prerequisites

The proposed SF-TDOA method does not depend on any specific wireless communication technology, hence it can be applied to any wireless network consisting of nodes having following properties. The network is composed of \(N\) anchors \(A_i\) and mobile devices \(M_j\). In the proposed method of localization anchors need to be a fully-featured radio transmitters able to transmit and receive radio packets. On the other hand it is enough that mobile devices are passive and only capable of receiving the transmissions. Both anchors and mobile devices need to be able to unambiguously determine sender of each message received. Moreover, they need to be able to accurately time-stamp received radio packets and execute transmission after predefined delay. As in every time-based localization system, the resolution of time-stamping and precise initiation of delayed transmission has direct impact on the resulting accuracy of localization. Mobile nodes need also be aware of anchor localization – they can be either preloaded with this information or receive it in radio transmissions from anchors. With no loss of generality we assume the localization is performed in a 2D area. We denote anchor \(A_i\) location as \(x_i = [x_i, y_i]\) and unknown position of mobile node as \(x = [x, y]\). The distance between anchors \(A_i\) and \(A_j\) is denoted as \(d_{ij} = ||x_i - x_j||\).

#### B. SF-TDOA Localization procedure

Localization procedure is executed in turns by all network anchors according to the predefined schedule known to all the infrastructure devices (both anchors and mobile nodes). The schedule defines order in which anchors are supposed to broadcast beacons during single iteration. Schedule can be defined statically (once per deployment) or dynamically (for each iteration).

The SF-TDOA iteration is initiated by one of the anchors, say \(A_1\) (Fig. 1) which sends its beacon at \(t_{A1}\). Upon reception of the beacon each anchor \(A_j\) \((j \neq i)\) schedules its own transmission delayed by \(T_{Dji} = ((j - i) \mod n) \cdot T_d\) where \(T_d\) is a fixed delay (common to all the anchors) and \(n \leq N\) is a system wide parameter limiting maximum delay. Mobile device records timestamps of beacons received \(t_i, t_j\) and \(t_k\) respectively. Because \(t_i\) denotes time when beacon from \(A_i\) is received by mobile node, therefore:

\[
t_i = t_{A1} + \text{tof}_{A1\rightarrow M},
\]

where \(t_{A1}\) is beacon transmission time from \(A_i\) (measured by \(A_i\) and unknown to \(M\)) and \(\text{tof}_{A1\rightarrow M}\) denotes time of flight from \(A_i\) to the mobile node. Similarly:

\[
t_j = t_{A1} + \text{tof}_{A1\rightarrow A_j} + T_{Dji} + \text{tof}_{A_j\rightarrow M},\]

and

\[
t_k = t_{A1} + \text{tof}_{A1\rightarrow A_k} + T_{Dki} + \text{tof}_{A_k\rightarrow M},
\]
where $\text{tof}_{Ai\rightarrow Ak}$ denotes time of flight from anchor $A_i$ to $A_k$. Note that values of $\text{tof}_{Ai\rightarrow Ak}$ are known and fixed as respective positions of anchors are known and constant (in ideal scenario $\text{tof}_{Ai\rightarrow Aj} = d_{ij} \cdot c$, where $c$ denotes speed of light). The differences of (2) and (1) as well as (3) and (1) are therefore equal to:

$$t_j - t_i = \text{tof}_{Ai\rightarrow Aj} + T_{Dji} + \text{tof}_{Aj\rightarrow M} - \text{tof}_{Ai\rightarrow M}$$

$$t_k - t_i = \text{tof}_{Ai\rightarrow Ak} + T_{Dki} + \text{tof}_{Ak\rightarrow M} - \text{tof}_{Ai\rightarrow M}.$$  

(4)

The difference $\text{tof}_{Ak\rightarrow M} - \text{tof}_{Ai\rightarrow M}$ is a time difference of arrival for beacons from $A_i$ and $A_k$ at mobile node. Denoting this difference as $\text{tdoa}_{Ak\rightarrow Ai}$ we can rewrite (4) as:

$$\text{tdoa}_{Aj\rightarrow Ai} = t_j - t_i - \text{tof}_{Ai\rightarrow Aj} - T_{Dji}$$

$$\text{tdoa}_{Ak\rightarrow Ai} = t_k - t_i - \text{tof}_{Ai\rightarrow Ak} - T_{Dki}.$$  

(5)

Together with known anchor locations ($x_i, x_j$, and $x_k$), this enables estimation of mobile device location $x$ by solving:

$$\begin{cases} 
\|x - x_i\| - \|x - x_j\| = \text{tdoa}_{Aj\rightarrow Ai} \cdot c \\
\|x - x_i\| - \|x - x_k\| = \text{tdoa}_{Ak\rightarrow Ai} \cdot c
\end{cases}$$  

(6)

where $\|x - x_i\|$ denotes the distance between the two locations. The above set of equations can be solved analytically [5].

C. Sources of inaccuracies

The localization error $e$ for the proposed method is a sum of three components:

$$e = e_s(x_1, \ldots, x_n, x) + e_m(M) + e_d(A_1, \ldots, A_n, M).$$  

(7)

The first component represents the error resulting from the spatial distribution of network elements (anchors and mobile node). This component does not depend on clock drift and speed of move but only on anchors’ and mobile node’s locations [6]. Value of $e_s(\cdot)$ can be controlled through appropriate deployment of network infrastructure, both number and locations of anchors. Although this error may have significant impact on localization accuracy, its minimization is beyond the scope of this paper and will not be addressed.

Second component ($e_m(M)$) captures error resulting from the movement of the mobile device. Because anchors send their beacons in turns therefore the moving mobile node changes location during the localization procedure and receives each beacon at different position. As a result, estimated TDoA values are inaccurate and imply localization error. Since node’s speed is much slower than the speed of light, thus this error has small impact on the localization accuracy, and can be controlled by appropriate choice of $T_d$ parameter.

The last component ($e_d(A_1, \ldots, A_n, M)$) represents error resulting from the inaccuracies of time measurements in network nodes involved in localization, i.e. incorrect time stamping of received packets and inaccuracies in the delay of delayed transmission. Reception time-stamping can be inaccurate due to imperfections of radio receivers and radio propagation phenomena. Receivers may for example spend variable amount of time detecting incoming packets or fail to estimate the exact beginning of the packet at the radio interface. Reception time-stamp can be also affected with Non-Line-of-Sight (NLOS) propagation, signal reflections, and clock drifts. NLOS propagation and reflections cause delays in signal propagation and delay the arrival of the signal (as it travels longer distance compared to what is expected from the location of communicating devices). Consequently, it might happen that $\text{tof}_{Ai\rightarrow Aj} \neq d_{ij} \cdot c$. Since anchors have fixed positions thus the network may measure tofs during setup phase (e.g. using symmetric double side two way ranging (SDS-TWR) procedure [7]) and update it periodically (to adjust to possible changes in propagation conditions). Although sound this approach is not applicable to mobile nodes as their location is unknown. To mitigate this issue mobile nodes should implement dedicated algorithms to detect NLOS propagation and reject NLOS signals received (c.f. [8], [9]).

Clock drifts are another source of inaccuracy in time-stamping of events. Because drift fluctuates with time, therefore it may lead to discrepancies between the measured difference of two timestamps and real value of that difference. If the actual value of the drift changes between time-stamping reception of successive packets, then the difference $t_i - t_j$ is not equal to the real time that has elapsed between events when packets (from anchors $A_i$ and $A_j$) reached the receiver. Clock drifts also cause the inaccuracies in delayed transmission — when anchor schedules delayed transmission to $T_{Dji}$, clock drift cause the transmission to start at different moment than planned, contributing to overall localization error.

To minimize the error resulting from clock drift the time differences in (5) (i.e. $t_i - t_j$ and $T_{Dji}$) should be kept as small as possible. This can be achieved if both $n$ and $T_d$ parameters are small. However, when selecting $n$ and $T_d$ one needs to take into account the number of anchors in the network and total capacity of the communication channel.
Small $n$ in large and dense network may increase beacon collisions, while small $T_d$ increases channel utilization leaving not much bandwidth for other communication. The problem of beacon collisions is a subject for separate research on collision avoidance and medium access control mechanisms and it is therefore beyond the scope of this paper. Selection of those two parameters needs to trade-off resulting accuracy of localization with network performance and communication bandwidth available.

IV. SIMULATION

A. Overview

Simulation model for the proposed SF-TDOA method was developed with OMNET++, a discrete event component-based simulator [10], enhanced with INET framework. Data obtained from simulation was then analyzed in Matlab. The model developed aims to simulate typical localization use case in constrained and controlled environment. For the network modeled we assume all nodes are located in an open area with no obstacles that could affect radio propagation. For the sake of method simulation, communication channel was significantly simplified, hence number of radio waves propagation phenomena are not considered. In particular the model does not take into account path-loss, reflections and noise. The considered radio wave propagation properties are communication radio range and collisions in the communication channel. In simulations radio waves propagate with the speed of light in vacuum.

For the purpose of simulation two types of wireless nodes were implemented (anchors and mobile nodes). Both node types aim to satisfy prerequisites discussed in Section III-A. Anchors are static nodes, while mobile nodes are capable of moving with desired speed and direction. All nodes communicate using dedicated network interface (NIC), that does not resemble any particular wireless technology and implements simplified Media Access Control (MAC) layer. Modeled NIC is capable of gathering precise timestamps of the beginning of radio frame reception. This is justified as there is number of off-the-shelf radio transceivers having similar functionality (e.g. DW1000 from DecaWeave [11]).

Simulation is highly configurable and extensible. Both number and positions of nodes can be freely adjusted. Particular components, such as path-loss model can be replaced with more realistic equivalents. Simulation model’s source code and Matlab scripts are available on https://git.e-science.pl/tjankowski/ipin2017.

B. Simulation parameters

In order to assess SF-TDOA localization approach we have run simulation of 2D localization scenarios. The network was deployed over a square area having side length equal to 500 meters with no obstacles. The network was composed of three ($N = n = 3$) anchors ($A_1$, $A_2$ and $A_3$) deployed at locations $[150,50]$, $[650,150]$ and $[400,550]$ respectively. In stationary simulations the mobile node was located on a square grid with the top-left corner in $[177,102]$ and left-bottom in $[573,496]$ (Fig. 2a). In simulations where mobile node was moving across the area its initial position was set to $[100,Y]$ with $Y = \{100,120,140,\ldots,500\}$. The node was then moving along the X axis all the way to the position $[500,Y]$. To reflect operation of real-life network we have set simulation parameter $T_d$ equal to 35 ms. The choice of $T_d$ value corresponds to timings we have used in the past, during localization experiments with Decawave’s transceiver.

To simulate inaccuracies of time-stamping the simulated operation of nodes was controlled by inaccurate clocks. We have used the clock model proposed in [12] to take into account short term instability and investigate how it affects the localization error. Based on the information provided in [12] we have used two settings of the clock model:

- ideal clock (no drift) – to prove that the proposed approach for localization works, and assess error corresponding to $e_s$ and $e_m$ components,
- standard low-cost clock, i.e. clock with 10 ppm drift and drift variance equal to $10^{-8}$ – to investigate accuracy of localization for nodes running low cost clocks without synchronization.

For each set of parameters, used during evaluation, the duration of simulation was set to different values. Simulations with stationary nodes were run for 30 seconds (of simulated time) and preformed 29 rounds of localizations. When simulating moving mobile node the goal was to localize node traveling the distance of 400 meters at the speed of 10 m/s. Therefore in this scenario we have simulated 40 seconds of operation.

C. Results of evaluation

The SF-TDOA localization algorithm was evaluated in various scenarios using different clock models as well as stationary and moving mobile node.

Ideal clock. The ideal clock was used to validate the localization approach proposed for stationary mobile node and node moving at speed of 10 m/s. In stationary scenario (Fig. 3) the algorithm correctly estimates node positions, confirming correctness of the proposed localization method – localization error is below 0.3 mm. In this scenario the error results from time-stamping precision used in simulation (i.e. 1 ps) and spatial distribution of anchors. Figure shows that for the simulated network area the $e_s(\cdot)$ component of the error is...
small. When mobile node moves at 10 m/s then the average localization error is below 1 m. This is in accordance to what was expected as during the localization procedure time (i.e. $T = T_d * n = 105$ ms) mobile node travels the distance of $d = 10$ m/s $* 105$ ms $\approx 1$ m. As expected the spatial distribution of error is a consequence of anchors positions and relative location of the mobile node – error increases outside the triangle defined by the anchor.

**Standard low-cost clock.** The low-cost clock model was also used to evaluate localization for stationary and moving nodes. For stationary scenario and low-cost clock model (10 ppm drift) the localization error increases but has the same spatial distribution as for ideal clock (Fig. 4). For the whole evaluation area the largest error slightly exceeds 25 meters while the average and median errors are both below 11 meters. Moreover, inside the triangle area defined by anchor locations, the error is always below 15 meters and drops to as low as 2.3 meters for some of the locations.

For moving nodes running imperfect clock the error depends both on the clock drift, speed of move and relative position in the area. As presented in Fig. 5 the error pattern does not exhibit the spatial distribution seen on previous plots and has slightly smaller values compared to stationary scenario. This is because the error is mainly determined by the drift-dependent error component [13]. This evaluation confirms that drift-dependent error is the most significant component of the resulting localization error.

To evaluate further how drift affects the localization accuracy of moving nodes, we have simulated nodes running different clocks. Simulation results (filled boxes in Fig. 6) confirm that short period stability of the clock frequency has substantial impact on overall localization accuracy – localization error grows with clock drift. The errors are not small (in absolute values) but it is worth to notice that for a speed of 10 m/s and 10 ppm clocks the error is always below 20 meters. Although the error is not small it is achieved with no clock synchronization between anchors and mobile nodes. If 1 ppm clocks are available, or clock synchronization is used (to effectively lower the drift), then the error drops to the values below 12 meters.

We have also compared the SF-TDOA algorithm to Whistle [2] in order to see how they perform in the same simulation environment and clock parameters. As presented in Fig. 6 increasing clock drift affects errors of both methods in the same manner although error of the proposed method grows
For moving nodes the error of localization increases with speed of the move. Consequently the proposed algorithm is better suited for networks with stationary and slowly moving mobile nodes. Nevertheless, for typical, low-cost clocks and speeds of up to 10 m/s (which are typical for vast range of IoT applications), the influence of the move-dependent error can be neglected. For nodes moving at higher speeds $e_m(M)$ error component will further increase localization error and thus may significantly impair localization precision.

Another practical advantage of the SF-TDOA approach is the homogeneity of all anchors. Since there is no anchor playing special role (as is the case with zone coordinator in [4]) there is no single point of failure. Consequently SF-TDOA is more robust and inherently resilient to anchor failures.

Indoor localization challenges remain in the center of our research interest. As part of future work we plan to enhance simulator software with more features including advanced transceiver models, realistic propagation and environment models, additional localization techniques. Our research work will be focused on localization techniques as we spot number of scientific challenges in this area. One of them is error behavior in localization systems and error propagation in localization algorithms.

V. CONCLUSION AND FUTURE WORK

The SF-TDOA method proposed in this paper is true synchronization-free TDoA localization algorithm that achieves acceptable localization error using low-cost clocks. Our method does not require mobile nodes to transmit any messages and enables mobile nodes to estimate their position based only on the reception times of the radio packets sent by infrastructure nodes. To make the SF-TDOA localization possible anchors transmit packets in a predefined order and delay. Because mobile node estimates its own position and performs no radio transmissions therefore the communication overhead of the localization procedure depends just on the number of infrastructure devices and does not depend on the number of mobile nodes in the network. Consequently the algorithm scales well and is suitable for networks with large number of mobile nodes. This differentiates the algorithm from typical TDoA approaches where either synchronization is required or overhead increases with the number of mobile nodes in the network.

SF-TDOA achieves relatively small localization error. In the test network of 2,500 m² and three anchors, the error is always below 25 m for nodes running standard, low-cost 10 ppm clocks. Comparison with Whistle [2] confirms that the algorithm performs well (median error for 10 m/s and 10 ppm is larger by at most 57%) while being more suitable for large networks.

Fig. 6. Comparison of the proposed method (filled boxes) and Whistle (empty boxes) for node moving at 10 m/s running imperfect clocks

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