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Development of Self-Synchronized Drones' Network Using Cluster-Based Swarm Intelligence Approach

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ABSTRACT Timing synchronization has a vital role in swarm drones' network (SDN) or a swarm of unmanned aerial vehicle (UAV) network. Current timing synchronization methods focus on enhancing single-hop skews which remarkably improve timing synchronization precision at this level. The improper clock of the drone system can cause interference, affect spectrum precision and interrupt the operation of the transceiver. In the drones' network, master drones' (MD) neighbor drone's timing synchronization approaches like Reference Broadcast System (RBS) realize a good performance. However, the requirement of one super drone with a large number of broadcasts for RBS makes it unrealistic to use in some situations like SDN network situation. Appropriate study and adjustments are needed to have real timing synchronization by eliminating the clocks drift and enhancing the timing synchronization precision. Therefore, a new self-timing synchronization approach is proposed in this paper where several MD drones can autonomously generate swarm clusters. The cluster head (CH) instigates a timing synchronization procedure starting with intra-Swarm cluster timing synchronization. The intermediate drones (ID) are elected between two swarm clusters to synchronize all drones in line with the inter-swarm cluster timing synchronization approach. The proposed approach is distributed and flexible to achieve high timing synchronization precision. The paper proposes a novel self-timing synchronization approach for in large scale semi-flat SND network architecture. Self-timing synchronization is swarm cluster-based and applicable for a huge number of master drones in SDN. One is the intra-Swarm cluster where the timing synchronization procedure starts with the CH to synchronize all CM. Secondly, in the inter-swarm cluster timing synchronization, two clusters are synchronized via intermediate drone (ID). However, the simulations demonstrated that in many cases all CHs are synchronized by the synchronized CHs from intra-swarm cluster timing synchronizations; this increased the system throughput and synchronization delay to about 75% compared to what we planned to achieve. Moreover, the simulation results also proved that the achieved synchronization precision can be used for position estimation and prediction with high accuracy.

INDEX TERMS Drones' network, timing synchronization, unmanned aerial vehicle (UAV), cluster, swarm.

I. INTRODUCTION

In recent few years, and inspiring and markable progress in the use of swarm drones' network (SDN) or swarm of the unmanned aerial vehicle (UAV) network for quite widespread domains of deployments and applications, for civilian, commercial and military. Many successful deployments and applications of UAVs and drones are now offered by many vendors and alliances that include, crop surveys, traffic control, oversight of natural resources i.e., oil/gas

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exploration, surveillance, aerial photography, remote sensing, reconnaissance, search and rescue, 3D-mapping, on-demand emergency applications, etc. Given the extraordinary rapidity of these industries and developments, there is a crucial need for inventing and providing, dependable, efficient, and reliable communication channels not only among UAVs /drones and their control point, entities, consumers but also between the UAV themselves. UAVs networking overlays the way towards substantial opportunities but it is also a problematic and challenging task. This will open quite widespread research areas where issues like modeling, automatic control, applications, and physical layer design, and wireless communications are rich with many problematic issues and revolutionized the use of UAVs and drones.

In addition to these research areas, the more challenging situation of using MD drones with low-level timing synchronization is considered a vital topic without the need for a specially equipped reference drone in the network. Drone timing synchronization guarantees that the data and control traffic exchange is done properly without error, collision, or interference. One of the major advantages of SDN synchronization the high precision for location and positioning which are quite important in many applications. Clustering has been extensively used in literature as a hierarchical technique that helps in coordinating the relationship between the various nodes especially in multi-hop and ad-hoc types of network. The clustering procedure in SDN starts instantaneously as well as randomly in the whole network.

The absence of timing synchronization may produce a suboptimal choice of Cluster-Head (CH), especially for probabilistic approaches. However, the clustering procedure can be generated by CHs with faster clock timing [1]–[5]. This happens when such drones start broadcasting beacon packets to their neighbors' cluster members (CM) for exchanging information to initiate the clustering procedure. Beacon frame comprises identity, timing, and clock synchronization information. Nodes received beacon frames trigger the clustering procedure at their neighbors until disseminated the entire network. All the drones in the network do not start the clustering procedure simultaneously. Network initialization is done via beacon broadcasting where the neighbor drones periodically transmit the beacon packets to their neighbors. This type of beacon procedure is carried out independently by individual drones [7].

In general, mobile users are synchronized to the swarm drones' control center (SDCC) by transmitting signals. In such a network, the signals of the legacy mobile cellular mobile users arrive at a master drone' (MD) asynchronously, which produce interference problems such as inter-carrier-interference in orthogonal frequency domain multiple access (OFDMA) systems [8]–[12]. However, swarm drones' network (SDN) normally cannot use this method because an MD cannot always receive the signal from swarm drones' control center (SDCC) due to the poor legacy mobile cellular-signal coverage or because sometimes the MD is installed in a rural area where there is no legacy mobile cellular coverage at all.

For the neighboring drones' timing synchronization into the clusters, the Reference Broadcast Timing synchronization (RBS) introduced in [13] is the key idea to synchronize the time. With the RBS technique, a super drone transmits beacon packets periodically to other neighboring drones. However, the receiver drone uses the beacon packet's arrival times to compare the timing of the clock. The protocol involves the concept of a time-critical path defined as the packet path contributing to non-deterministic errors in a protocol [14]–[18].

For transmitter-receiver protocols, the allotted time for transmitting a packet from a transmitter to a receiver is the outcome of the four factors: transmit time, access time, propagation time, and receive the time, which can vary non-deterministically. For small wireless, the propagation time is supposed null in the RBS network because the overall error is not affected by the propagation time difference. Thus, the biggest non-deterministic latency is stamped out from the critical path for synchronizing receivers with one another by using the broadcast channel. consequently, more accurate timing synchronization is achieved in comparison with the algorithms that measure the round-trip delay [19].

This paper presents a detailed analytical evaluation along with the derivation of a mathematical model, MAC layer sync frame structure, and timeline of the proposed scheme which fulfills the purposes through simulation verification of the precise timing synchronization for the whole network. The proposed approach is analyzed through MATLAB simulation and the achieved results are evaluated for the clock offset, drift and skew enhancement, and best timing synchronization precision.

The proposed method is quite different from the previous swarm drone's timing synchronization techniques invented by IEEE 1588, Reference Broadcast System (RBS), and even synchronized single-hop methods by forming swarm clusters among random MD drones' number and implementing hybrid (one way and two ways) messaging system for both inter-swarm cluster and intra-swarm cluster timing synchronization approaches. The approach includes apprising and synchronizing the timing of the clock through transmitting a beacon packet for the entire SDN. The proposed self-timing synchronization approach is cluster-based and can be applied for a large number of swarm drones' or master drones (MD) in SDN. Two approaches have been proposed for neighbor drone timing synchronization. The approaches are identified by clustering, intra-swarm cluster, and inter-swarm cluster. The proposed approach is distributed and flexible to achieve high timing synchronization precision. The main advantage of this method is that it does not require any special device, node, or equipment as a reference timing node in the network. The simulation shows that our approach improves the timing synchronization precision notably through reducing the packet overheads for many scenarios of up to 200 drones or unmanned aerial vehicles (UAV).

The remainder of the paper is organized as follows: in section II, the related works with a summary of contributions and open issues were presented. In section III, the proposed synchronization strategy is described and discussed. Section IV presents a self-organizing timing synchronization model for warm drones' network synchronization. Section V is devoted to the analysis and the discussion of the results. Finally, a conclusion and some recommendations were given in section VI.

II. RELATED WORKS

From customers' opinions, the poor performance of the mobile networks and the low indoor coverage led to many at-home usage problems. These problems are mainly caused by the wall attenuation of the radio signal. One of the major challenges of cellular service providers is improving indoor signal strength. The radio waves are strongly attenuated when they face the walls. Indeed, the RF signal is seriously impaired by fading effects caused by building materials. For instance, the GPS is attenuated 4dB to 4dB for cellular when penetrating a wall [20]–[22].

Generally, the indoor Received Signal Strength (RSS) is significantly undermined. This attenuation is more serious at higher frequency bands which are increasingly employed with higher bit rate operations. The swarm master drones' (MDs) known as Swarm drones' network (SDN) Access Points have emerged as radio base stations (BS) enabling users of certain cellular service (UMTS, CDMA2000, etc.) and WiMAX to make all indoor calls over their internet broadband connection, thus eliminating reduced RSS problem inside buildings [23].

Timing synchronization and interference are considered problematic issues for the practical deployment of SDN [24]. For TDD, timing synchronization between neighbor MDs drones should be preserved to avoid inter-symbol interference. Particularly, various interference mitigation schemes such as swarm master drones' (MDs) cooperation, soft frequency reuse, etc., need precise timing synchronization. Various situations have been proposed in [25] to compare different scenarios in terms of interference. It was found that the interference in two-tier networks can be mitigated within an adaptive open-access scenario. It is worth noting that the advantage of the mitigated interference adopted in the paper is not weakened only by the loss of resources, but reduced over-the-air (OTA) and backhaul capacities as well [26].

The interference avoidance using a physical layer and sectoral antennas for a time-hopped Code Division Multiple Access (CDMA) is analyzed in [27]. In the work [28], it was proposed that each swarm drones' network (SDN) accesses a random subset of sub-channels within the available swarm drones' network spectrum to avoid persistent collision within neighboring OFDMA swarm drones' networks. Some requirements and parameters for swarm drones' network self-organization have been specified in [29]. Nevertheless, the self-organizing strategy assessment remains a challenging issue and a deep investigation of additional requirements and parameters remains interesting.

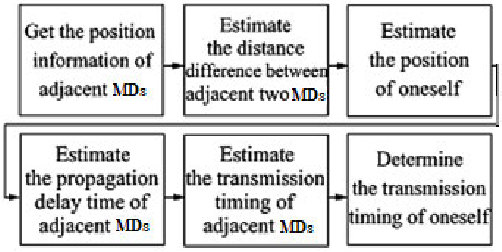


FIGURE 1. Timing evaluation algorithm at each swarm master drones' (MDs).

A new method for estimating the position of swarm master drones' (MD) for frame timing synchronization is introduced in [30]. The timing evaluation algorithm determines the timing of an MD and a series of procedure flows at a swarm drone [31]–[35]. The procedure flows at an MD between positioning and decision of transmission timing is shown in Figure 1. In this algorithm, it is ensured that swarm master drones' (MD) perform at the first time and repeats the algorithm until determining transmission timing cyclically. However, there is an evaluation error of the range difference which may create timing synchronization of transmission timing [36].

A reference broadcast timing synchronization (RBS) is used [37]. It was stated that a reference broadcast does not contain an explicit timestamp. Moreover, it requires at least one super drone which can broadcast the reference beacons and impedes its use in Master drones' (MDs) [38]. In other words, it is centralized; which might be inappropriate for a self-organized timing synchronization approach for swarm drones' network (SDN).

RBS protocol uses the least-squares linear regression algorithm to minimize the error and compute the clock skew between the two drones [39]. Even though the RBS protocol is accurate, the exchanged number of timing packets between drones is huge. Also, a large number of unnecessary clock packets create network overhead deteriorating the overall performance which should be considerably reduced.

To have a possible swarm drones' timing synchronization solution a Mobile station assisted (MS) receiver-receiver timing synchronization strategy is illustrated and discussed in [40]. To validate more inclusive accessibility, two-timing synchronization approaches are proposed for various situations. These approaches adopted and assisted the Reference Broadcast Timing synchronization (RBS) methodology to enhance the clock's timing offset, drift, and skew by using the swarm drones' control center (SDCC).

In recent years, many clustering algorithms have been invented and contributed to the wireless vehicular network which stresses some explicit parameters such as vehicle speed, mobility direction [41], [42] position, energy, and the random distribution technique that the vehicles are following.

TABLE 1. Summarize the related works main contributions and open areas.

Method	Contributions	Open areas for research
Network Time Protocol (NTP) and Simple Network Time Protocol (SNTP) [24-25].	• Offer the accuracy, reliability, and security for an efficient and reliable network in a less complex client implementation • For high transmission delays (slow links, rush-hours, etc.) the received time is more accurate. • Low cost (clients and NTP Servers) • Low network load • No extra network elements are required (e.g., edge clocks)	• NTP and SNTP shows poor performance in the CH environment in terms of milliseconds • Can be affected by packet network jitter • Slow initial convergence • The large initial error of 500ppb
IEEE 1588 Precision time protocol (PTP) [26-28]	• Can synchronize with an independent clock. • In IP based cellular network, it is applicable for synchronizing symmetric communication links. • fast re-synchronization is possible when system changes occur • synchronization of clocks is done with various precision, resolution, and stability • Offers low-cost implementation in multicast messaging networks such as Ethernet	• Misalignment of the time of the master clock and the slave clock. • Not applicable for synchronizing asymmetric communication links. • Requires hardware assistance as well as upgrading the network devices • work only for a few subnets (locally)
Enhanced time synchronization algorithm [29].	• Optimize the Offset (bias error) for the asymmetric IP-based communication links.	• Inefficient for asymmetric backhaul link.
Frame timing synchronization [30-33].	• Needs to correct the effect of propagation delay time.	• An estimation error of the distance may create a misalignment of transmission timing.
Receiver-Receiver synchronization scheme [35]	• Clock Offsets and Skews are minimized.	• For a large number of CH node, this scheme will make network overhead by generating the message flooding
Multihop synchronization scheme [37]	• overcomes the path loss effect that improves the network synchronization performance compared to the conventional single-hop based scheme	• nodes suffer for accurate timing with faster convergence and more accurate CDR estimation
MS-assisted Receiver-Receiver synchronization scheme [40]	• Followed reference broadcast synchronization and clock offsets and skews minimized.	• this scheme will make network overhead by generating the message flooding for a large number of CH node

These algorithms are useful and great in the cases of two dimensions, however, since SDN is a three diminutions network scenario some more aspects need to be considered per in mind the high computational overhead in the three dimensions, while the drones usually have very limited and scarcity resources. The highest-degree of freedom algorithm is denoted as a connectivity-based procedure, which is principally based on the number of degrees of freedom values free to vary in the ultimate vehicle clustering statistic design and calculation [43], [44].

The work in [45] described position estimation of swarm master drones' (MD) with help of frame timing synchronization which is applied by MD receiving the transmitted signals from adjacent MSs which through estimating its position, can calculate the propagation delay of transmitted signals and correcting the corrupt packets. The proposed algorithm is modeled and designed based on position information of neighbor MDs, using different time of signals arrival (TDOA), selecting two MDs from neighbor MDs and that creating a hyperbola through using position information and range differences [46]. Table 1 summarizes the related works, the main contributions, and the open issues.

III. THE PROPOSED SYNCHRONIZATION STRATEGY

The structure framework in Figure 2 is integrates timing synchronization procedure with drone clustering to construct **Semi-flat** synchronized SDN networks. In addition to synchronizing the MD network, the proposed approach enhanced the control packets overhead, which is crucial for increasing the network performance and throughput. This is work aims to concentrate on the distributed approach since it is more realistic for three diminutions large-scale master drones'(MD) distribution situations.

In the legacy system swarm drone's timing synchronization suffers from network overhead, bandwidth consumption, misalignment packet, offset. In this circumstance, the network does not perform inaccurate timing synchronization. To overcome these issues, researchers have put forward their efforts for developing algorithms and approaches. In this paper, a timing synchronization strategy is proposed to minimize the network overhead and clock offset as well as bandwidth consumption. Figure 3 illustrates the proposed timing synchronization strategy for master drones' (MD) drones. At first, the MD drone initializes the timing synchronization procedure. Then MD drone checks out whether the timing synchronization clock information is received from the swarm drones' control center (SDCC) or not [47].

If the drone receives a synchronized clock from the swarm drones' control center (SDCC), then the master drones' (MD) will be synchronized along with their IP address and cell identity. Otherwise, it will go for drone assistance checking. The MD drones will synchronize if only they get the drone assistance. However, if the MD drones do not get drone assistance, then the drones will check for broadband connectivity

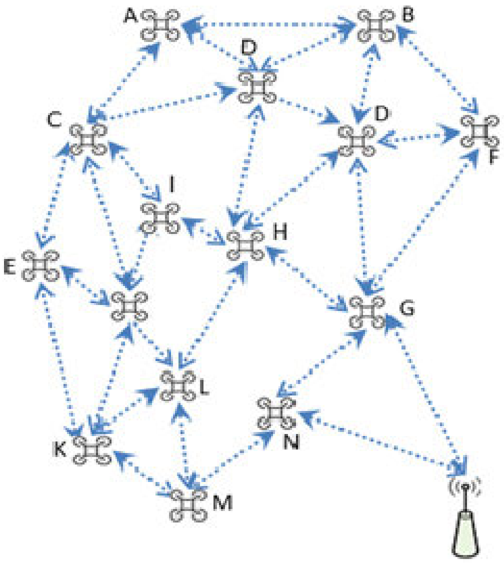


FIGURE 2. Semi-flat synchronized SDN networks neighborhood critical architecture.

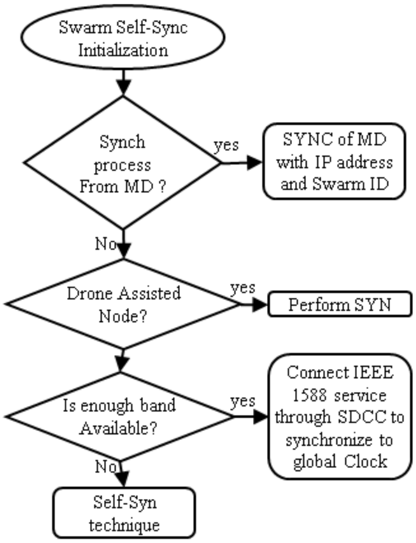


FIGURE 3. The proposed self timing synchronization strategy for swarm drones' network (SDN).

to get the most recent clock timing synchronization. Therefore, the IEEE1588 server clock will synchronize the MD drone [48]. However, in some circumstances, if the bandwidth is limited for updating the timing of the clock, then the timing synchronization procedure will be problematic which results in increasing clock offsets and delay time. To overcome these problems, MD drones can use the proposed Self-timing synchronization approach.

IV. SELF-ORGANIZING TIMING SYNCHRONIZATION MODEL FOR WARM DRONES NETWORK TIMING SYNCHRONIZATION

The proposed approach is composed of three parts involving Clustering, Intra-Cluster timing synchronization, and Inter-Cluster timing synchronization. The clustering part is based on time and range. In the Inter-Swarm cluster timing synchronization, a two-way time exchange technique is employed to determine the timing synchronization between neighbor drones and cluster heads by establishing a hierarchical topology or flat structure. In the Intra-Swarm cluster timing synchronization, MD drone transmits beacon broadcast packet to another MD drone and compares their clock time to conclude the timing synchronization between cluster heads and swarm cluster members. Finally, the linear least square method is applied to achieve a high level of precision [49].

A. SDN SYNCHRONIZATION MODEL

The proposed approach targets the self-timing synchronization approach only between Master Drone in an environment where master drones' (MDs) are located in an unplanned and uncoordinated way. As in Figure 4, Master Drone can be located near to each other while some Master Drone can be grouped autonomously. Within each swarm cluster, the synchronized clock timing will be delivered between members of a cluster. Firstly, after forming a cluster, a cluster head will be selected by the neighbor drones by comparing their local times and distances. Inside the cluster, a cluster head will broadcast clock information as a beacon to all CLUSTER MEMBERS (CM). Also, Figure 4 illustrates the algorithm of the self-timing synchronization approach as well. At the beginning of the clustering procedure among a large number of MD drones, cluster heads (CHs) will be elected.

Once the CH election is finalized, then clusters would be formed by the elected CHs. As an iteration of the procedure, the intra-swarm cluster Timing synchronization approach will be communicated for all CMs. This procedure is followed by the proceeding of the Intermediate drone selection approach. The ultimate procedure which is Inter-swarm cluster timing synchronization will be performed within the clusters after selecting the CH, CM, and intermediate drones (ID) [26]. According to this algorithm, a self-organizing synchronized Approach will be applied. The proposed model for the clock timing synchronization is given below which consists of five steps:

In the proposed approach, the most recent synchronized clock and range are used to select the Cluster Heads (CHs). The swarm cluster structure is highly influenced by the CH choice. The proposed approach uses fuzzy relevance time and range to select the CH. This makes it different from existing mechanisms such as LEACH, CBRP, and Secured Clustering Algorithm (SCA). The available mechanisms select the CH using only one parameter namely, Identification (id), trust value, and mobility. However, the proposed approach uses Identification (id), fuzzy relevance time, range, and multi-hop as a Sync packet to select the CH [50].

B. TIMING SYNCHRONIZATION STRUCTURE

The clock time and range between drones are used here to determine the CH. In this procedure, a drone is not transmitting frames only, but also fuzzy value to neighboring drones. A swarm cluster is composed of a CH, an IMC, and Swarm

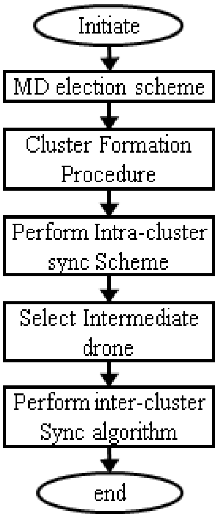
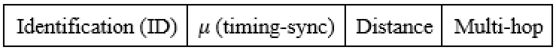


FIGURE 4. Self-timing synchronization approach for swarm drones' network (SDN).

cluster Members (CMs). For the proposed approach, the timing synchronization frame structure contains an Identification (id), μ(Sync), range, and multi-hop, as displayed in Figure 5.



Identification (ID)	μ (timing-sync)	Distance	Multi-hop

FIGURE 5. Timing synchronization frame structure.

The timing synchronization parameters are discussed below:

1) IDENTIFICATION (ID)

Identification (id), each drone should have id number the id will be exchanged during the CH selection.

2) FUZZY RELEVANCE TIME (μ)

Fuzzy relevance time (FRT) is a fuzzy value $\mu(0 \leq \mu \leq 1)$ performed by the available range, location, and time of the drones in the neighbor. In our scheme, the time-sync (μ) is randomly specified. To simplify the computation, μ is presumed as a group of fuzzy time values of (0, 0.1, to 1) in a microsecond. drone fuzzy relevance time (FRT) represents the drone's local time calculated by neighbor drones in the SDN. The proposed approach selects the CH based on FRT and range among drones. The approach performs efficient swarm clustering by selecting the CH and by using the presented parameters. For n drones of $N = \mu(\mathrm{X}_1, \mathrm{X}_2, \ldots .\mathrm{X}_\mathrm{n})$, $\mu(\mathrm{X}_\mathrm{i})$ is given by the following equation:

$$\mu(\mathrm{X}_\mathrm{i}) = (\mu(\mathrm{X}_1), \mu(\mathrm{X}_2), \ldots \mu(\mathrm{X}_\mathrm{n})) \tag{1}$$

where i is (0, 0.1, to 1), X_i is a drone member of the cluster, and $\mu(\mathrm{X}_\mathrm{i})$ is a coefficient for membership. drone X_i FRT is expressed as $\mathrm{FRT}(\mathrm{X}_\mathrm{i})$, which can be represented as:

$$\mathrm{FRT}(\mathrm{X}_\mathrm{i}) = \mu(\mathrm{X}_\mathrm{i}) \tag{2}$$

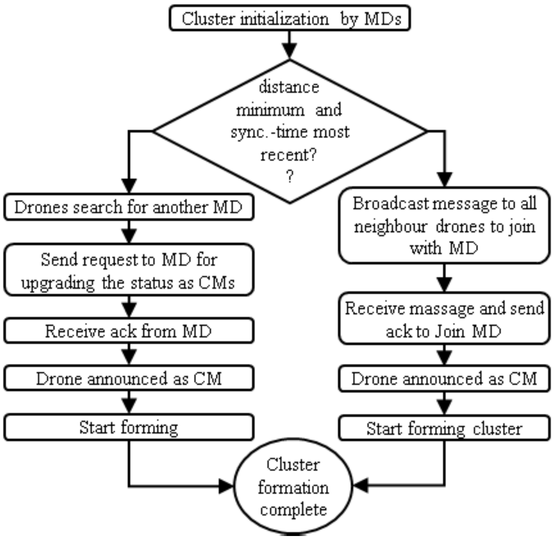


FIGURE 6. Swarm cluster formation called swarm_cluster_formation.

3) RANGE (D)

In a large number of swarm drones' networks (SDN), the range is a crucial parameter in the selection of the CH and for cluster creation. Because the MD range is 20 meters to 30 meters, the range between the CH_i and member drones j, $\mathrm{d}(\mathrm{x}_\mathrm{i}, \mathrm{x}_\mathrm{j})$ is assumed to be 30 meters to select the CH for the swarm clustering procedure [51].

4) MULTI-HOP

The management and the generation of the 1-hop cluster and 2-hop cluster as per the FRT is monitored by the Multi-hop. For large-scale networks, Cluster heads (CHs) create clusters for multi-hop. Thus, the cluster size is adjusted by multi-hop according to the network size [52].

C. SWARM CLUSTER INTER-CLUSTER SYNCHRONIZATION

The algorithm of swarm cluster formation will be initiated according to the flowchart in Figure 6. It will start with the initialization of swarm cluster formation by Cluster heads (CHs) which will request all Cluster members (CMs) by transmitting Beacon packet for swarm cluster formation. Then Cluster members (CMs) will calculate the nearest range and the SYNC time to form the clusters.

Step 1: When the range is minimum and synchronization -the time is most recent, then the Cluster heads (CHs) will broadcast packets to all neighboring drones in the radius to join with CH. Meanwhile, the neighboring drones receive massage and transmit an acknowledgment to the particular CHs accordingly [53]. After getting the acknowledgment the drones will announce their status as Cluster members (CMs). In consequence, the formation of clusters will be initialized right after the announcement.

Step 2: When the range continues to grow and synchronization time is not the most updated, then the drones search for another CH to form swarm clusters. After, an upgrading of the status as Cluster Members (CMs) is transmitted by drones to CH. Eventually, all CMs will try joining with CHs to form clusters.

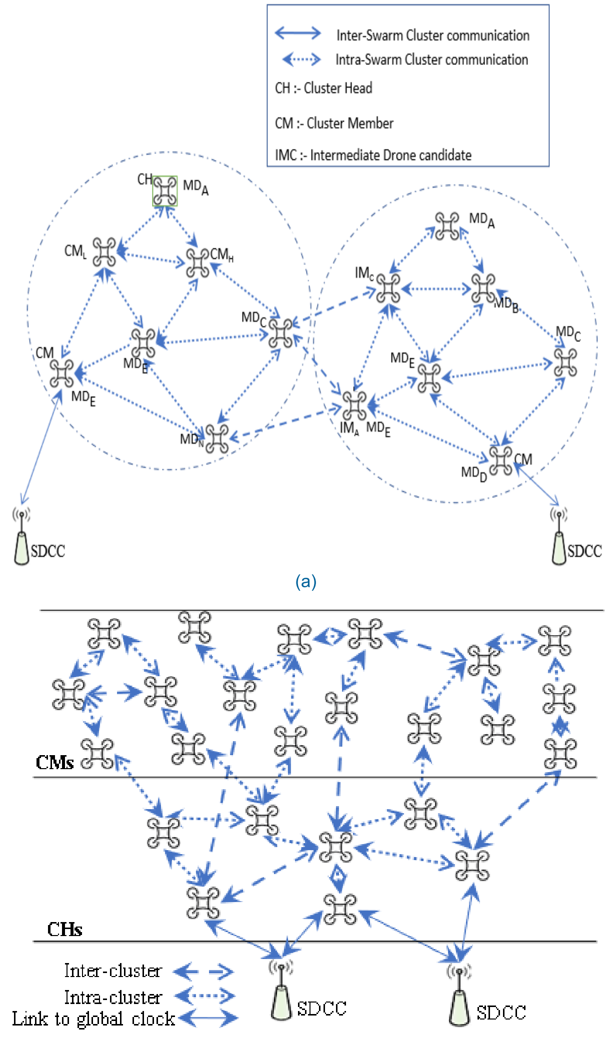
For the drones' network, clustering is a crucial issue to make the network distributive. Through implementing the aforementioned clustering techniques, the timing synchronization procedure will be accelerated as well as the overall performance and throughput of the network will be upgraded. The ultimate goal of clustering for a large number of drone networks is to segregate the network to minimize the offsets between the drones in the entire network [54]. The utilization of the clustering procedure is likely to reduce the quantity of packet flooding which results in reducing the overhead as well. In Figure 7, a situation of the swarm clustered Network Model is depicted.

The proposed approach aims to appoint Master drones' (MDs) in the network environment under imperfect channel state information (CSI) where MDs are selected in an uncoordinated and unplanned manner. Given a group of MD drones in an SDN network, the objective of SDN cluster establishment is to choose many cluster heads (CHs) so as the SDN nodes are coordinated in a hierarchical structure with a minimum area of overlapping which will help in reducing the average synchronization processes for all swarm cluster communication ranges.

A swarm drone network (SDN) is expected to be largely implemented and deployed, per in mind that all MD drones are non-stationary once they are deployed, which means that the process needs to be repeated periodically and the topology would be rapidly changing. Each MD drone can get the estimations of neighbor drones' positions employing any positioning techniques i.e., angle-of-arrival (AoA), time-of-arrival (ToA) or swarm drones' control center (SDCC) [55], or simply can exchange their GPS parameters.

In the swarm cluster-based timing synchronization carry out timing synchronization between swarm clusters, Cluster members (CMs), and CHs. Consequently, the main process is to allow selected CH from randomly deployed MD drones to form a swarm cluster. First, the CH initiates the timing synchronization procedure by broadcasting Sync messages to all cluster members (CMs). CMs calculate timing synchronization from receipt time information, then announced that they are synchronized with the CH drone. The CH selection procedure is depicted in Algorithm 1 using pseudo code. After CH is elected, the next phase is the swarm cluster formation..

In the proposed approach, once the swarm clustering is constructed, the intra-swarm cluster clock timing synchronization approach will be applied to every swarm cluster member to synchronize the timing of the clock. This will lead to establishing a better-synchronized network. Moreover, inter-swarm cluster timing synchronization will be realized using the swarm clusters after selecting the CH, CM, and IMC.



(a)

(b)

FIGURE 7. MD network swarm cluster formation SDN (a) physical (b) virtual SDN.

Timing synchronization in the intra-swarm cluster approach, the cluster heads (CHs) initiate the timing synchronization procedure by broadcast Sync. message (which is included in the beacon frame) to all cluster members (CMs). CMs receive timing synchronization messages and synchronized their clock with the CH drone by comparing time differences. Figure 8 shows and illustrates the timeline of intra-swarm cluster timing synchronization.

According to Figure 7, the swarm network has three levels of communication,

- Swarm drones' control centers (SDCC) level
- Cluster head (CH) or master drones' level
- Cluster members (CM) level
- The synchronization is performed at these three levels where SDCCs assume the role of a ground station facility with a global clock. SDCC connects to one or more cluster heads drones which provides them with the synchronization signal. the cluster heads drones are creating a network among them to transfer data and control signals; which synchronization info is disseminated for their cluster members as shown in Figure 6. Some of

Algorithm 1 The CH Selection Algorithm

```
Start
Inputs: MD MAC address, Internal timing clock,
    cluster_no (i.e. cluster_no = 0, in case individual MD).
Define # CH_selection( ).
Set this drone as CH_candidate.
send to all drones to join as CMs and to update their
    neighbouring_Table.
If all drones are joint the other_CH.
    Compare $S_T$ (synchronization time) and d (range) of all
    drones with CH_candidate.
If one of the drone's $S_T > S_T$ of CH_candidate and new
    drone's d< the other_CH.
        joint other_CH.
    Output: send the new other_CH info to all neighbors.
    Call Swarm_clusterFormation() algorithm
Else
    If CH_candidate > one_hop & < ($S_T$ & $d$) to the old
    CH.
    Joint the CH_candidate.
Else
    If CH_candidate is announced as the CH by any new
    drone.
        State CH_candidate as IMC.
Else
    $S_T$ and $d$ of all drones to be compared with
    CH_candidate.
If $S_T$ = infinity for CH_candidate and all other drones.
    Delay (1$\mu$sec).
Else
  If $S_nT$ smaller for any drone.
      joint this drone as other_CH.
      Output: Sent this info to all neighbors' drones.
      Call Swarm_cluster_Formation().
Else
    Ignore any other calls for joint.
    Output: Send to any new drones' info of the other_CH.
Repeat
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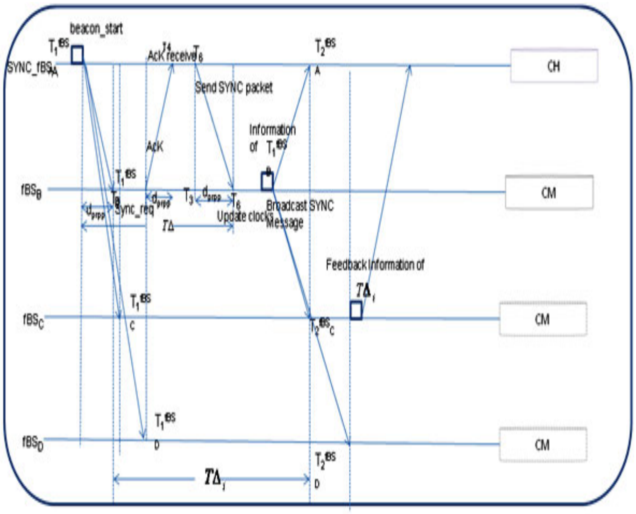


FIGURE 8. Timeline for intra-swarm cluster timing synchronization approach.

TABLE 2. Simulation and analytical specifications for swarm clustering.

Term	Quantity
Network volume	200 X 200
Drones number	50, 150, 250
Transmission range	300 m
The radius of the cluster	300 - 490 m
Delay Difference SD (σ)	10µs, 30µs, 50µs
range (R)	0 to 300m
time intervals (T)	1 sec
Timing and synchronization factor (M)	30

the cluster members are also members in two or more clusters (inter and intra_cluster) where they compare the offsite, skew, and time deviation standard deviations and report frequently for any large deviations to their cluster head (CHs) where according to algorithm 1 are frequently repeating the synchronization process.

- The above-mentioned method does not resolve the disturbance in CH functionality only, but it goes beyond that in case of malicious CH with security bugs issues. However, the security issues are out of the paper scope. More details about these issues can be found in [46]–[57].

V. RESULT ANALYSIS FOR SWARM DRONES' CLUSTER

The ultimate goal of the self-organizing swarm clustering procedure is to form the cluster dynamically by all the MD drones to obtain better timing synchronization where clock time and transmission range (range) are taken into consideration. An analytical evaluation is carried out for the proposed self-organizing approach where MATLAB software has been used for the accurate representation of clustering approach performance and throughput.

A. SIMULATION AND NETWORK SETUP

The parameters selected for simulation are taken on a random basis which is specified in Table 2. The parameters are namely local clock for drones, network size, number of drones, transmission area.

In the swarm clustering approach, the generation of an optimal number of clusters is very important to reduce the packet overhead improving the network performance and throughput. Thus, the following four situations are considered to evaluate the performance and throughput of the modified clusters.

i In the beginning, drones are created randomly in a 200 × 200 sized network

ii The numerical analysis is performed with the varying number of cluster heads assuming the numbers of drones as 50, 150, and 250 respectively.

iii In the analytical evaluation procedure, Cluster Head Election is one of the main techniques that are carried out based on the most recent clock time, network size, number of drones, and transmission range. The network size is assumed to be 300, and 400 m respectively. The selection of several cluster heads and the number of formed clusters will vary by the variable network size.

iv The number of CH can vary with the number of random MD drones.

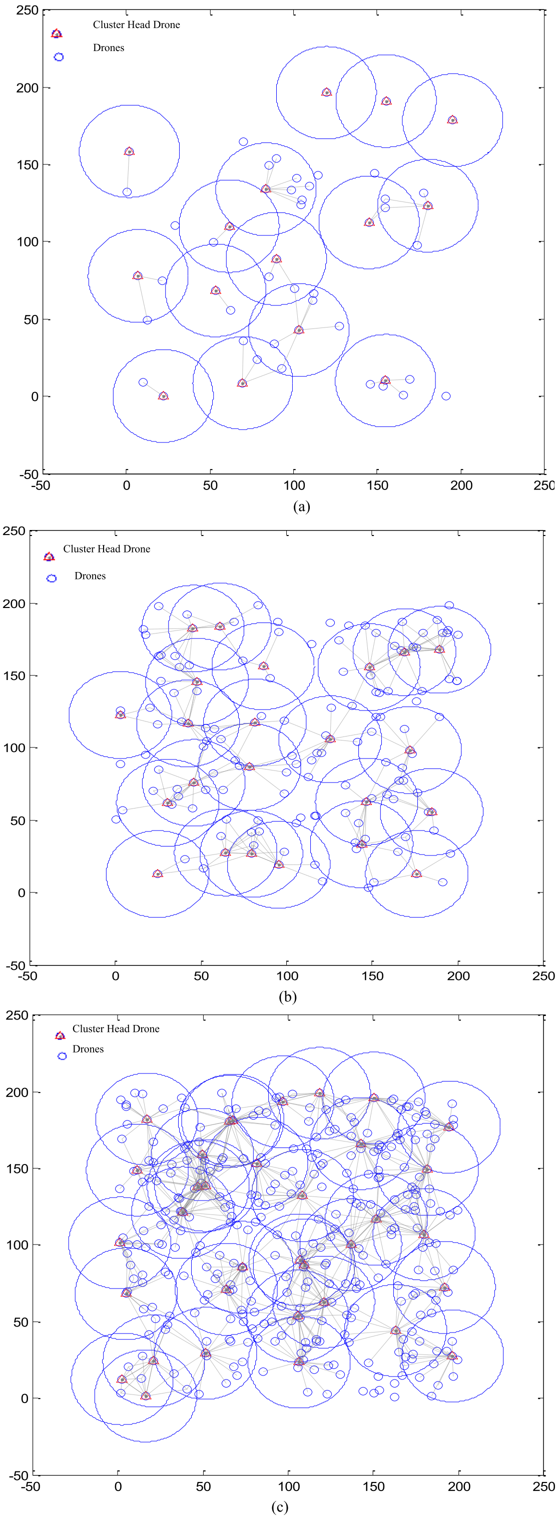
MATLAB software illustrates and demonstrates the results for cluster Head section and cluster formation in the case of 50, 150, and 250 drones. As shown in Figure 9. Figure 9 shows MATLAB simulation illustration for CH selection and swarm cluster creation for a different number of drones i.e., 50, 150, and 350 with 200 × 200 network area size, where the drone's distribution was distributed using normally distributed i.e., with mean μ and SD σ; the simulation shows that 15 cluster heads (CHs) have been selected for 50 drones. For 350 normally distributed drones, the selected cluster heads (CHs) were increased to 37. assuming the random clock time and minimum range.

After selecting the CHs, the simulation starts to disseminate information to all members of the cluster (CMs) and then forms the swarm cluster. Some drones may not join any cluster because the clock time and range are not fulfilled any of the cluster's requirements. These drones can be synchronized as individual nodes by any of the conventional synchronization techniques. If individual drones (a.k.a. drones outside the swarm) are large means standard deviation of the normal distribution is large, which means need to run additional algorithms to narrow down the standard deviation.

B. AVERAGE CLOCK OFFSET ANALYSIS

To achieve the average of timing offset as well as the best timing synchronization precision, timing synchronization procedures are considered to be performed 25 times using different time difference in standard deviation ($\sigma = 10\mu$s, 15 μs, 20 μs, and 30 μs) as shown in Figures 10 and 11. We can see that when several drones are 10 and σ is 10μs, then after 20 timing synchronization procedures, the average clock offset achieves 1μs. However, the clock offset is fully eliminated after 25 procedures which ensure high timing synchronization precision.

Moreover, the precision decreases for a large value of σ [65]. For instance, Figure 10 demonstrates that when the value of σ is 30 and the timing synchronization procedure is achieved 10 times, then the mean offset value raises to 10 μs, approximately. This result is unexpectedly lesser precision of timing synchronization. Meanwhile, with the repetition of the timing synchronization procedure up to 25 times, the average offset is significantly reduced to 7 μs which guarantees precise timing synchronization. In a nutshell, we can say that the proposed Intra-swarm cluster synchronized approach can minimize the clock offsets and achieve a better timing synchronization precision as summarized in Table 3. Also, the proposed approach's performance and throughput are even much better with a large number of MD drones in the swarm cluster of drones' networks.



(a)

(b)

(c)

FIGURE 9. Cluster head selection and swarm cluster formation for (a) 50 (b) 150 (C) 350 Drones.

The performance and throughput of the proposed self-timing synchronization approach are compared and benchmarked with the standard receiver- receiver timing

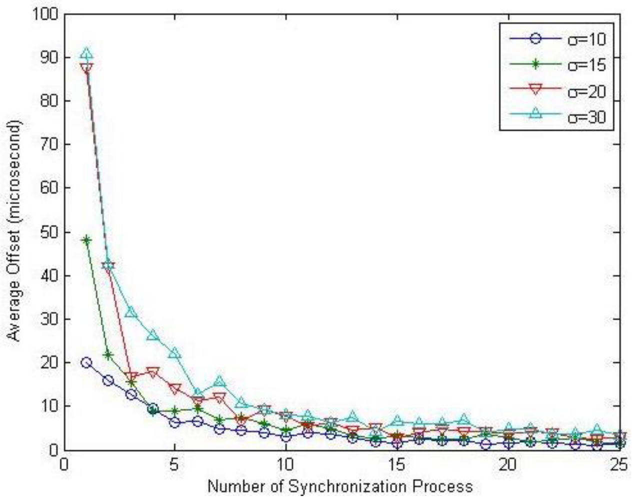


FIGURE 10. Average timing offset for 50 drones based on different time delay that differs in SD.

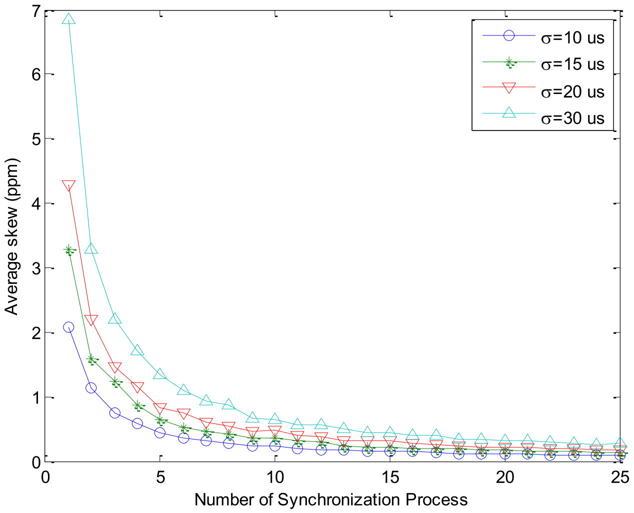
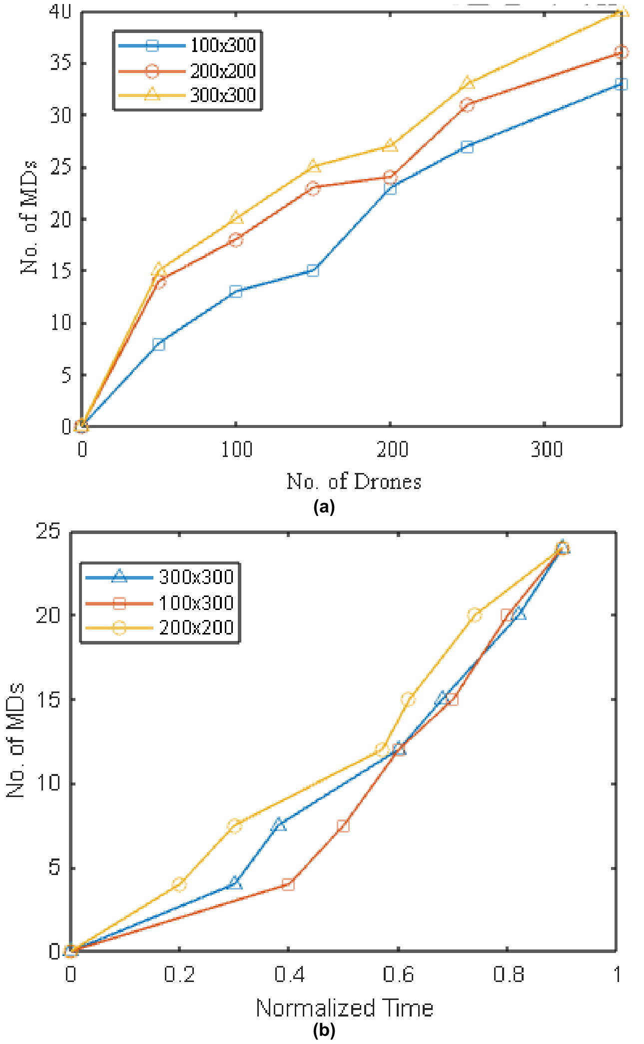


FIGURE 11. Average clock skew on different receive time delay difference SD.

TABLE 3. Clock offsets and timing synchronization precision.

Number of Drones	Synchronization process M and the value of time deviation σ			
	M=10		M=25	
	σ= 10 µs	σ= 30 µs	σ= 10 µs	σ= 30 µs
10	2.519µs	7.853 µs	1.082 µs	5.459 µs
50	4.054 µs	10.49 µs	1.455 µs	4.457 µs
100	324 µs	10.37 µs	1.283 µs	941 µs
200	028 µs	10.31 µs	1.339 µs	4.058 µs

synchronization strategy. The frequency precision of the proposed approach is observed to be almost the same as the receiver-receiver approach employing the ordinary linear regression model [36], [37]. This is because; a constant difference like propagation error does not have any effect on the frequency precision, which can be treated as the speed of a clock. In the receiver-receiver approach, the two-way framing paradigm was utilized while our proposed scheme utilizes a hybrid one-way and two-way framing.



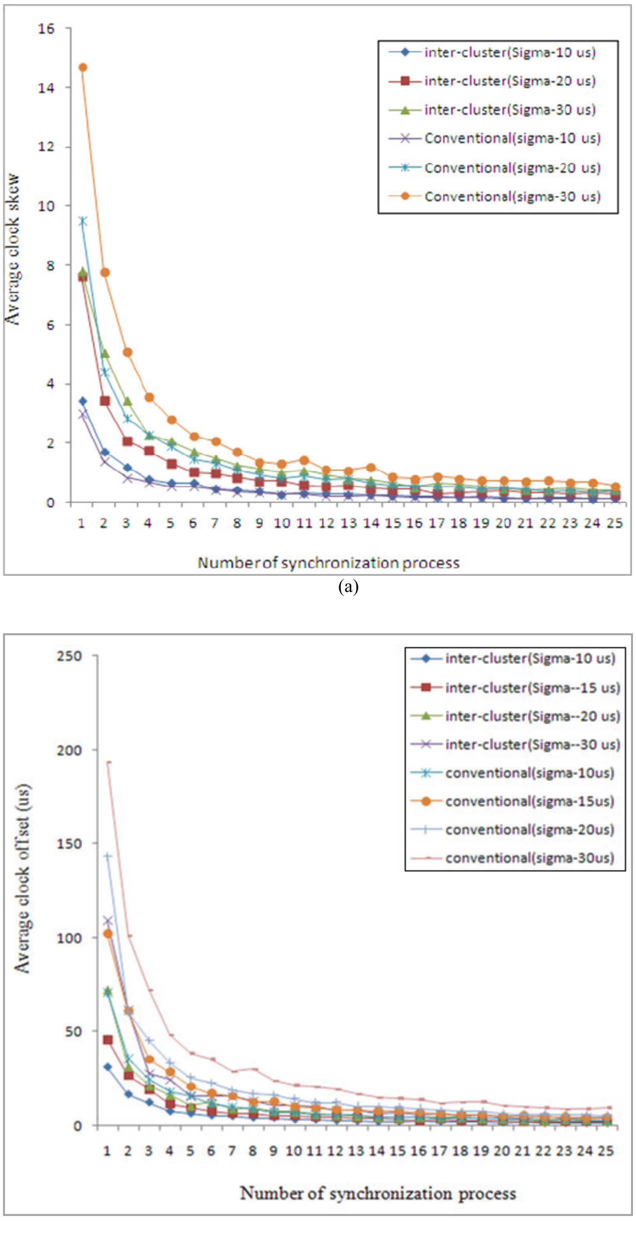
(a)

(b)

FIGURE 12. The comparison under different number of drones in the SDN (a) number of drones vs the number of CH drones (b) normalized time delay.

Therefore, the local receiver-to-receiver scheme experience low timing precision rate as well as high control messages overhead when the number of drones increases. Nevertheless, the intra and inter-cluster timing scheme synchronization scheme are focuses on message exchange reduction and synchronization precision is dramatically enhanced when the number of drones' is increasing with acceptable accumulated delay. Figures 10 and 11 show the Average timing offset and clock skew for 50 drones, where the simulation achieved less than 1 ms for 20 synchronization processes with standard deviations bands from $\sigma = 10$ to 30 μs.

Figure 12 shows that the number of CH keeps increasing with the growing number of nodes. The network clock offsets and timing synchronization precision increase when raising the number of drones in the SDN as shown in table II. Figure 12 (a) indicates three Network sizes in the simulation. i.e., 100 × 300, 200 × 200, and 300 × 300. Figure 12 (b) demonstrates that the normalized time delay increases whit the number of cluster head drones.



(a)

(b)

FIGURE 13. Comparison of the inter-cluster and conventional scheme for the average (a) clock skews (b) Clock offsets.

C. BENCHMARKING

Figure 13 illustrates a benchmarking and comparison of average timing offset and skew between conventional synchronization given in [15] and the proposed inter-cluster, where the Figure shows a significant improvement of at least 25% for standard deviation $\sigma = 10$ for the range of synchronization processes up to 25 processes. Generally, different communication and network standards have various frequency precision and timing precision requirements. For example, in real-time (RT) applications, the requirement of timing precision for OFDMA is 1.5 μs [37], wherein simulation has been achieved directly through 15 timing and synchronization messages in the proposed approach. The precision of clock drift and skew requirement of OFDMA has also been validated in the simulation with 25 messages for timing and synchronization.

VI. CONCLUSION

Clock skew, drift, and offset have been considered as performance metrics in many literature reviews and industry studies for drones/UAVs swarm network, where have been proved that it results in a vital disruption for the UAVs operation and data exchange. The proposed approach aims to perform self-synchronizing for the MD in the semi-flat swarm drones' network (SDN) architecture. The result shows that clock offset, drift, and skew errors are notably significantly reduced to abated value for a different standard deviation (SD). This performance and throughput are better than the other existing timing synchronization approaches on the same scenario and platform. In the simulation, it is verified that the self-timing synchronization approach offers acceptable precision for drone swarm and certifies that the overhead is minimalized up to 75% of the overall traffic without our synchronization approach.

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