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Multi-Hop Clock Synchronization Based on Robust Reference Node Selection for Ship Ad-Hoc Network

Xin Su, Bing Hui, and KyungHi Chang

Abstract: **Ship ad-hoc network (SANET) extends the coverage of the maritime communication among ships with the reduced cost. To fulfill the growing demands of real-time services, the SANET requires an efficient clock time synchronization algorithm which has not been carefully investigated under the ad-hoc maritime environment. This is mainly because the conventional algorithms only suggest to decrease the beacon collision probability that diminishes the clock drift among the units. However, the SANET is a very large-scale network in terms of geographic scope, e.g., with 100 km coverage. The key factor to affect the synchronization performance is the signal propagation delay, which has not being carefully considered in the existing algorithms. Therefore, it requires a robust multi-hop synchronization algorithm to support the communication among hundreds of the ships under the maritime environment. The proposed algorithm has to face and overcome several challenges, i.e., physical clock, e.g., coordinated universal time (UTC)/ global positioning system (GPS) unavailable due to the atrocious weather, network link stability, and large propagation delay in the SANET. In this paper, we propose a logical clock synchronization algorithm with multi-hop function for the SANET, namely multi-hop clock synchronization for SANET (MCSS). It works in an ad-hoc manner in case of no UTC/GPS being available, and the multi-hop function makes sure the link stability of the network. For the proposed MCSS, the synchronization time reference nodes (STRNs) are efficiently selected by considering the propagation delay, and the beacon collision can be decreased by the combination of adaptive timing synchronization procedure (ATSP) with the proposed STRN selection procedure. Based on the simulation results, we finalize the multi-hop frame structure of the SANET by considering the clock synchronization, where the physical layer parameters are contrived to meet the requirements of target applications.**

Index Terms: **Adaptive timing synchronization procedure (ATSP), multi-hop, ship ad-hod network (SANET), synchronization, timing synchronization function (TSF).**

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I. INTRODUCTION

MARITIME communication systems, such as the global maritime distress/safety system and the automatic identification system (AIS) [1]–[3], have focused their applications on ship security, location tracking, identification and so on. Recently, there has been a gradual demand in maritime communication for various multimedia services such as marine video surveillance and under water video sensing. Without loss of generality, satellite system can be a good candidate to realize the multimedia services. If a ship rarely finds other neighboring ships, satellite communication is an inevitable option for obtaining services. However, when ships can easily locate their neighboring ships, satellite system becomes burdensome due to its remarkably high cost. The ship ad-hoc network (SANET), a maritime counterpart of the terrestrial vehicle ad-hoc network, can provide ships with diverse multimedia services. Based on the survey of the terrestrial vehicle ad-hoc network and the maritime communication environment, we realize that simply implementing the radio transmission technology (RTT) of terrestrial vehicle ad-hoc network for the maritime communication holds many challenges and open problems. For example, the SANET often has immense communication coverage over 100 km, which requires multi-hop functionality to keep the link reliability. For the purpose of enhancing the service quality of maritime communications, RTT for SANET, based on the Recommendation ITU-R 1842-1 (very high frequency (VHF) band) [4], is designed in our previous work [5]–[8]. Reference [5] focused on the design of the SANET physical layer, where a novel frame structure was proposed based on ad-hoc self-organizing time division multiple access (ASO-TDMA) scheme as provided in [9] and [10]. Different from [9] and [10], the proposed frame structure in [5] considered the special topology of SANET, where the number of ships located near seashore is usually more than the area far from seashore. Reference [6] presented the SANET transmission resource block and evaluated the performance of channel equalization based on the measured maritime wireless channel model, and [7] and [8] tried to improve the link reliability for SANET by employing multiple antennae. In this paper, we realize there lacks the consideration of clock synchronization in [5], [9] and [10]. The difference among the clock oscillators of the network terminals accumulates for a time period causing the clock drift, also known as clock skew, is also a crucial index that can decrease the system performances dramatically [11].

In order to realize the real-time services under the maritime environment, it requires a robust multi-hop synchronization algorithm to support the communication among hundreds of the

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ships joining in the SANET. An effective clock synchronization is required to help the SANET terminals to specify the boundary of frames, sub-frames and time slots accurately during the communications. Generally, all units in a distributed system are required to agree on the same time, and this time is not essential to be exactly same with the real time. For example, it is adequate that all units agree that it is 10:00 of the logical clock even if it is really 10:02 of the physical clock [12]. In this paper, we assume a scenario, where the physical clock reference, e.g., coordinated universal time (UTC) or GPS is unavailable due to atrocious weather etc. The proposed synchronization algorithm thus is dedicated to logical clock. According to our survey, in order to improve the performance of logical clock synchronization, most of existing algorithms are proposed only to decrease the beacon collision probability [11], [13], [14]. However, the propagation delay, which is the key factor to affect the synchronization performance in the large-scale ad-hoc network in terms of geographic scope, is not considered carefully by the conventional algorithms. Consequently, we propose a logical clock synchronization algorithm with multi-hop function for the SANET, namely multi-hop clock synchronization for SANET (MCSS), which not only reduces the beacon collision probability but also takes care of the propagation delay to improve the synchronization performance. In the case of non-available UTC/GPS, the proposed MCSS works in an ad-hoc manner, and the multi-hop functionality ensures the link reliability for the large-scale SANET, e.g., over 100 km coverage. The selection of synchronization time reference nodes (STRNs) can be optimized by the criteria of "selection of the previous hop boundary ships (HBSs)" and "propagation delay reduction." Because the accumulated clock drift (ACD), is a key factor to evaluate the synchronization algorithm [11], [13], [14], in this paper, we mainly compare the proposed MCSS with conventional algorithm based on the ACD. The simulation results indicate that the proposed MCSS yields a lower ACD compared with conventional algorithms. For example, at most 1 ms ACD is yielded by MCSS (while 1.8 ms ACD is caused by [13]) when over 100 ships in the SANET with 120 km coverage.

This paper is organized as follows: Section II overviews the conventional clock synchronization algorithms; Section III describes the adaptability of the conventional algorithms for the multi-hop SANET clock synchronization; The beacon contention window designed for maritime communication and MCSS are given in Section IV; The numerical analysis and simulation results are illustrated and discussed in Section V and VI, respectively; Section VII finalizes the SANET frame structure, and conclusions are summarized in Section VIII.

II. CONVENTIONAL CLOCK SYNCHRONIZATION ALGORITHMS

A. Clock Synchronization in AIS

AIS works on VHF radio systems over sea that can apply the services such as ship identification, ship positioning, and email [3]. There are two dedicated frequencies used in AIS: 161.975 MHz and 162.025 MHz. 2250 time slots are repeated every 60 seconds for the units, where the packets are transmitted during each slot. According to the ship-to-ship communication condition, AIS uses self organized time division multiple access (SOTDMA) technology that can process more than 2000 reports in one minute. Typically, the AIS units can communicate with the base station (BS) at seashore to establish the ship-to-seashore information network and obtain the maritime requests via the BSs. The AIS considers the multi-hop synchronization in case of UTC indirect, that is, a unit which is unable to direct access to UTC can receive beacons from other units to indicate the UTC. However, the low synchronization rate, i.e., once per 3.3 seconds for the BS and once per 2 seconds for the mobile station, makes it impractical to support the real-time transmission for the SANET.

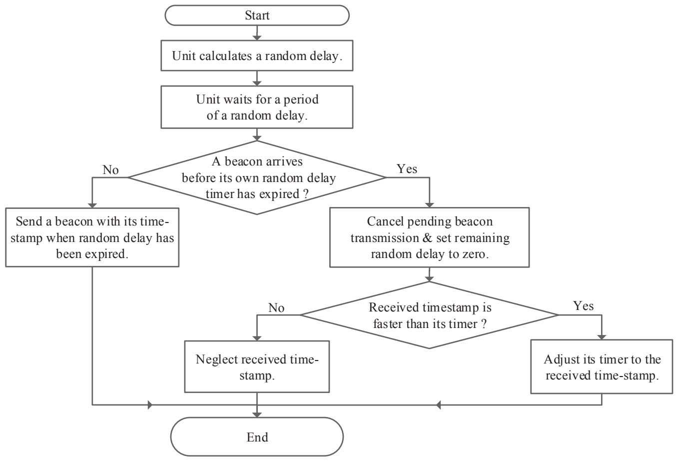

Fig. 1. Flow chart of timing synchronization function (TSF).

B. Clock Synchronization in Terrestrial Trunked Radio

Terrestrial trunked radio (TETRA) gives the performance requirements of the clock synchronization [15]. That is, the unit uses a single frequency source with accuracy which should be better than $\pm$ 0.2 ppm ($\pm$ 0.1 ppm of frequencies above 520 MHz) for clocking the time-base. Here, time-base refers the device which determines the timing state of signals transmitted by a unit. The clock drift between the start of time slot on different carriers shall be less than 125/9 μs. In case of timesharing of the same carrier by different unit, the clock drift between the time-base references of two units shall be less than 250/9 μs. However, TETRA does not clearly define the synchronization procedures among the units, and it should be consequently specified by the manufacturers.

C. Clock Synchronization in IEEE 802.11a

In IEEE 802.11a timing synchronization function (TSF) [16], the unit maintains a clock with modulus 2^{64} counting in increment of the clock tick which is fixed as 1 μs. Clock synchronization is achieved by units periodically exchanging timing information via the beacon which contains a time-stamp among other parameters. The unit needs to adapt its clock if the received time-stamp value from any beacon is faster than its own TSF timer. Fig. 1 depicts the flow chart of the TSF with the explanation by following steps, where *aCWmin* denotes the minimum size of the beacon contention window (BCW) in unit of *aBeaconTime*.

Step-1: The unit calculates a random delay uniformly distributed in the range between zero and *aCWmin*aBeaconTime*.
Step-2: And the unit waits for a period of a random delay.
Step-3: If a beacon arrives before the random delay timer has been expired, the unit cancels the pending beacon transmission and sets the remaining random delay as zero.
Step-4: Then, the unit sets its TSF timer according to the received time-stamp from the beacon if the value of the received time-stamp is faster than its own value.
Step-5: Otherwise, when the random delay timer expires with no received beacons, the unit transmits its own beacon with a time-stamp equal to the value of its TSF timer.

It is shown that the unit may fail to successfully transmit beacons due to the collision [11], [16]. Because the TSF mode lets the units only synchronize to the one which has the fastest clock, it is inefficient to give an equal contention opportunity for all units to submit the beacons in the network simultaneously. The scalability of TSF to support a network with a large number of units, as a result, may cause serious problem.

D. ATSP Clock Synchronization Algorithm

A distributed algorithm called adaptive timing synchronization procedure (ATSP) was proposed to address the scalability problem [11]. ATSP works much better than TSF for an ad-hoc network with tens of units. For ATSP, same with TSF, the unit only can set their timers forward, i.e., synchronizes to the units which have faster clock. However, the synchronization performance becomes better if the units with faster clock are given a higher priority to send their beacons. Thus by ATSP, the ith unit is assigned with an integer $I(i)$ determining how often it should participate in the beacon contention. The unit contends for beacon transmission once for every $I(i)$ beacon period. Then, the unit has a higher chance to send beacon with the smaller value of $I(i)$. Let the maximum possible value of $I(i)$ be $I_{\max}$, and let $C(i)$ be a counter at the ith unit that counts beacon periods, then the ATSP illustrated in Fig. 2 can be described as follows.

Step-1: For the ith unit, let $I(i)$ be a random number between one and $I_{\max}$, and let $C(i)$ equals to one. Then, the ith unit participates in beacon contention iff $C(i)$ modulo $I(i)$ is zero.
Step-2: When the ith unit receives a beacon with a time-stamp value faster than its own, the unit synchronizes its timer to this value.
Step-3: The unit increases $I(i)$ by one if $I(i)$ is less than $I_{\max}$, and the unit sets $C(i)$ as zero thereafter.
Step-4: If the ith unit does not receive any beacon with a time-stamp value faster than its own for $I_{\max}$ consecutive beacons, it decrements $I(i)$ by one if $I(i)$ is larger than or equal to two, and then sets $C(i)$ as zero.
Step-5: After a BCW, each unit increases the $C(i)$ value by one.

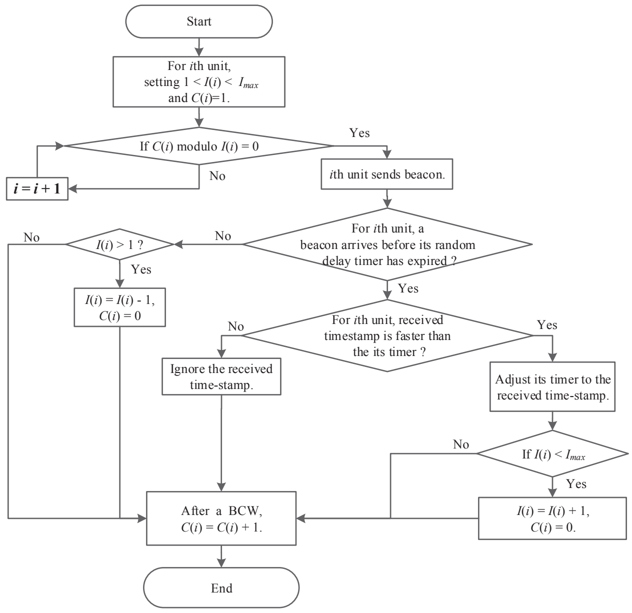

Fig. 2. Flow chart of adaptive timing synchronization procedure (ATSP).

E. Flooding Time Synchronization Protocol

Flooding time synchronization protocol (FTSP) defines two types of time-stamps [13]. The global time-stamp stores the clock value of the network root unit while the local time-stamp has the clock information of the synchronization reference unit. At the root selection step, if a unit does not receive the beacon from other root unit, it declares itself as the root. Thus, there may be multiple roots in the moment. Then, these roots are compared with each other via the *RootID*, and the one which has the smallest *RootID* will perform as the network root. Others give up the status of the root thereafter. For the root re-election, only the root of the previous round and well synchronized units participate the competition, and the units which have comparative large clock drift are not involved the root re-election process. Once the root unit is fixed, it broadcasts the beacon to its neighbors. The units, which can directly connected with the root, synchronize to the root. For other units which cannot directly connect with the root, they are synchronized to the root via the flooding protocol.

F. Mobi-Sync Protocol

Mobi-Sync protocol assumes that each unit is able to estimate its own inaccuracy bound at any given time, and each beacon exchanged between units carries the current time and the inaccuracy bound of the sender [14]. Mobi-Sync is an on-demand algorithm which performs the synchronization as one of following three requirements is fulfilled. A node detecting a beacon adjusts its time-stamp if the inaccuracy bound carried by the beacon is smaller than its own inaccuracy bound. A node initiates synchronization requests on-demand only when its inaccuracy bound approaches the specified maximum inaccuracy bound. When the synchronization requests cannot be satisfied by the reference node, the requests are then delegated to the

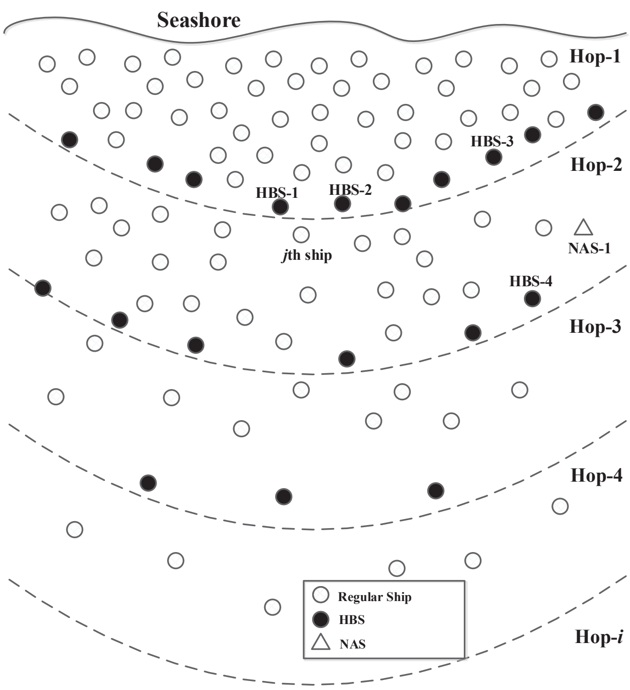

Fig. 3. Multi-hop SANET deployment model.

its neighbor nodes. These three demands forms a synchronization scheme that can efficiently operate in the network where the connectivity among nodes may be very short-lived.

III. ADAPTABILITY OF CONVENTIONAL ALGORITHMS FOR MULTI-HOP SANET

A. Multi-hop SANET Model

In this paper, we consider a SANET at coastline area. Therefore, we assume a sufficient number of ships are deployed in the network as illustrated in Fig. 3. Fig. 3 illustrates the multi-hop SANET deployment model, where the number of ships located near seashore is usually more than the area far from seashore. The circles represent the regular ships, the black dots denote the hop boundary ships (HBSs), and the triangle is the new access ship (NAS) which performs as a new coming ship and intends to join the SANET. Additionally, we assume that each hop covers about 30 km [5].

B. Adaptability of Synchronization Algorithms for SANET

In this part, we discuss the adaptability of synchronization algorithms for SANET. Note that, the synchronization procedures in AIS and TETRA are not compatible for SANET because the former is not designed to support real-time transmission and the latter lacks of specification details as we discussed in Section II.

Due to the oscillator offset of the local timer, the clock drift, also referred as clock skew, compared with the reference time is yielded at each ship. The clock drift is accumulated for following two reasons: The first reason is that the unit may not timely synchronized due to the beacon collisions, and the second is mainly caused by the propagation delay between the network units. In this paper, the adaptability of synchronization algorithms for SANET is analyzed mainly based on the accumulated clock drift (ACD), because it is the key factor to evaluate the synchronization performance as in the literature [17], [18], [19], [20], [21]. Note that, the units processing delay is assumed as perfect that is not included in the analysis.

Let $\Delta_i(t)$ denote the ACD at the ith ship, then we have

$$\Delta_i(t) = \Delta_i^{\text{collision}}(t) + \Delta_i^{\text{delay}}(t) \tag{1}$$

where $\Delta_i^{\text{collision}}(t)$ is the ACD caused by the beacon collisions and $\Delta_i^{\text{delay}}(t)$ is the ACD generated via the propagation delay between the network units. Consider that there are N ships in local area, and each of them sends the beacon randomly during a BCW. In this case, the collisions may occur if the multiple beacons are submitted at the same time. Assuming there are S beacons which can be allocated during one BCW, the average network access probability of a ship is λ, and L ships attempt to send beacon at the same instance. The expected number of a beacon $k_L^{S,N}$ occupied by L ships is given as:

$$k_L^{S,N} = S\binom{\lambda N}{L}\left(\frac{1}{S}\right)^L\left(1-\frac{1}{S}\right)^{\lambda N - L}. \tag{2}$$

With the occupancy number of L = 1, the beacon is successfully allocated without collision. Thus we have

$$K = \lambda N\left(1-\frac{1}{S}\right)^{\lambda N - L} \tag{3}$$

where K is the number of beacons successfully allocated during one BCW.

The ACD of the ith unit then is updated as

$$\Delta_i(t) = A_i\frac{S}{K} + \Delta_i^{\text{delay}}(t) \tag{4}$$

where A_i is the oscillator offset for ith unit.

According to our findings in references, we know that most of the conventional algorithms try to optimize the network access probability λ of a unit in order to increase K. Thus, the $\Delta(t)$ can be decreased due to the decrement of $\Delta_i^{\text{collision}}(t)$. For example, the ATSP uses the parameter $I_{\max}$ to control λ [11], the FTSP only let the root of the previous round and well synchronized units participate the root re-election to manage λ [13], and the Mobi-Sync implements several bounds to affect λ [14]. However, the SANET is a large-scale network in terms of geographic scope, and the key factor to affect the synchronization performance is the propagation delay among the ships, which has not being carefully considered in the existing algorithms. Therefore, it requires a robust multi-hop synchronization algorithm to support communication among the hundreds of ships under the maritime communication environment, and the proposed algorithm should decrease both $\Delta_i^{\text{collision}}(t)$ and $\Delta_i^{\text{delay}}(t)$ simultaneously.

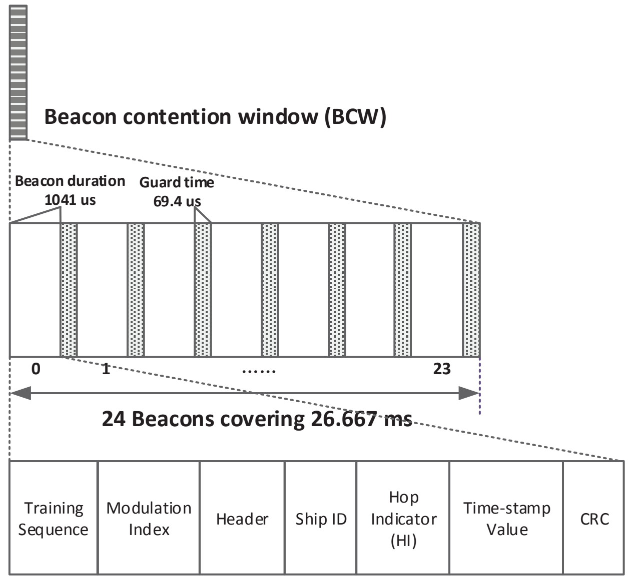

Fig. 4. Proposed beacon contention window for SANET.

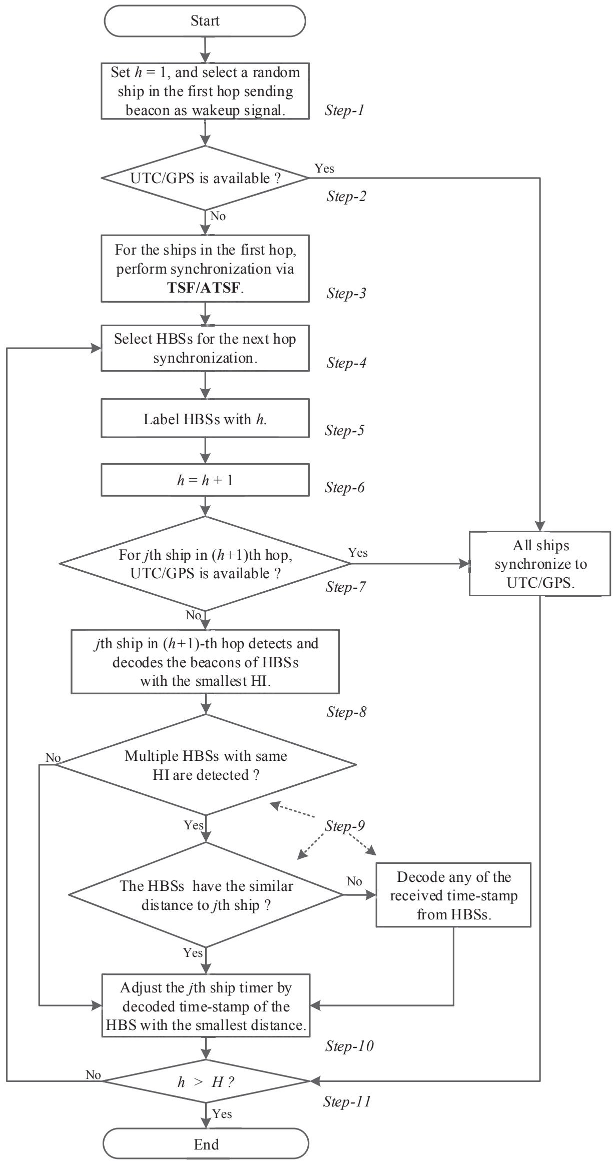

Fig. 5. Proposed multi-hop clock synchronization procedure, MCSS.

IV. PROPOSED BEACON CONTENTION WINDOW AND MULTI-HOP CLOCK SYNCHRONIZATION PROCEDURE FOR SANET

A. Proposed Beacon Contention Window for SANET

Beacon and BCW design is crucial for the SANET, where the pivotal indexes should adapt to the maritime communication environment. Fig. 4 depicts the proposed BCW which has the same length with the data slot in [5]. According to Fig. 4, a BCW holds 24 beacons where each of them is composed by 16 symbols. A beacon should restore the information including the ship identity, hop indicator (HI) which reflects the hop index of the ship currently located in, and the time-stamp value increased in unit of μs representing the clock value of a ship. Note that 69.4 μs duration assigned for a symbol is allocated as a guard time between neighbor beacons.

B. Proposed Multi-hop Clock Synchronization Procedure for SANET

The clock synchronization is necessary to adjust the local clock of each ship to the reference time that specifies the index of the frames and slots, i.e., whether the system reaches the timing of which specific frame and slot. Typically, when the UTC/GPS is not stable due to the atrocious weather, the clock synchronization has to work in an ad-hoc manner. The conclusions in [22] show that the TSF and ATSP have high adaptability for the single-hop SANET because they can perform well with tens of ships. In this paper, we propose a multi-hop clock synchronization for SANET, namely MCSS, based on TSF or ATSP. The ATSP-based MCSS may outperform the TSF-based MCSS because the former can further reduce the beacon collisions to decrease the clock drift. Note that a perfect synchronization in the physical layer is assumed throughout this paper. Fig. 5 is the flow chart of the proposed MCSS with the details of the procedure explanation as follows.

Step-1: Initialize the HI(h) as one, and randomly select a ship located in the first hop to send beacon as a wake up signal.

Step-2: If UTC/GPS is available, all ships located in the first hop synchronize to UTC/GPS.

Step-3: Otherwise, the ships located in the first hop can perform TSF or ATSP that synchronize to the ship with the fastest clock. Note that ATSP outperforms TSF by reducing the collision probability of the beacon submissions [11].

Step-4: By assuming all ships are communicating with an equal transmission power, the HBSs selection are based on the transmission power decay profile and the path-loss. The HBSs denoted by the black dots in Fig. 3 usually receive the lowest power from the previous hop HBSs or which sends the wake up signal in the first hop.

Step-5: Then, the selected HBSs are labeled with h to specify the hop index. And this information should be updated in the beacons of HBSs for the synchronization of the next hop.

Step-6: Update h by $(h + 1)$ representing the synchronization procedure for the next hop.

Step-7: If UTC/GPS is available in the next hop, all ships located in the $(h + 1)$th hop area synchronize to UTC/GPS.

Step-8: Otherwise, HBSs submit beacons and suppose at least one HBS with HI = h can be detected by the ships in the next hop, then the next hop ships, i.e., with HI = $(h + 1)$, synchronize to the HBSs from the previous hop. This criterion guarantees that the ships synchronize to the HBSs which close to the network root ship to avoid increasing the propagation delay. The network root ship is the one which has the fastest oscillator located in hop-1 area.

Step-9: If multiple HBSs in the previous hop are detected by the $(h + 1)$)th area hop ships, then these ships synchronize to the HBS with the smallest communication distance. For example, if the *j*th ship can detect the beacons from HBS-1 and HBS-2 as illustrated in Fig. 3, the *j*th ship synchronizes to HBS-1 because it has a shorter transmission distance compared to the case of HBS-2. The selection of HBS-1 is also based on the comparison of transmission power decay profile and the path-loss. If the detected HBSs have similar transmission distance with the *j*th ship, then the ship can select any of them for synchronization. The finally selected HBS is known as the STRN for the *j*th ships.

Step-10: Adjust the *j*th ship timer by the decoded timestamp of the STRN.

Step-11: Repeat *Step-4* to *Step-10* until *h* > *H*, where *H* represents the maximum number of hops.

For the proposed two criteria, the first criterion 'selection of the previous hop boundary ships' is realized in *Step-8*, and the second criterion 'propagation delay reduction' by *Step-9*. Both of them can avoid to increase the propagation delay. The first criterion makes sure that the ships except those located in hop-1 area synchronize to a group of HBSs closed to the network root ship, that is, the one which has the fastest oscillator located in hop-1 area. Take an instance in Fig. 3, the ship in hop-2 area may detect the beacons from HBS-3 and HBS-4 simultaneously, where the HBS-3 is directly synchronized to the network root ship and the HBS-4 is indirectly synchronized via its STRN. Therefore, compared with the HBS-4, the HBS-3 has a higher priority to be selected as a STRN for the second hop area ships. Meanwhile, the second criterion ensures the ship synchronizing to a HBS with the smallest distance, which is also beneficial in reducing the clock drift caused by propagation delay. In addition, the ATSP-based MCSS may outperform TSF-based MCSS because the former can further decrease $\Delta(t)$ via reducing $\Delta_i^{\text{collision}}(t)$.

For synchronization of a NAS denoted by the triangle in Fig. 3, the criteria of 'selection of the previous hop boundary ships' and 'propagation delay reduction' are also applied. Taking an instance in Fig. 3, the NAS-1 synchronizes to HBS-3 rather than HBS-4 according to the first criterion. If there is a HBS located in hop-1 area that has shorter distance than HBS-3 to NAS-1, the NAS-1 then select this HBS as its STRN based on the second criterion.

V. ANALYSIS ON THE MAXIMUM CLOCK DRIFT

Table 1 illustrates the details of parameters we used for the ACD analysis. For FTSP, the estimated ACD for the ship i, of which is the farthest one from the network root ship, can be given as (5), where $E\{.\}$ represents the expectation. The $Term$–1 is the ACD due to the beacon collisions, the $Term$–2 gives the ACD caused by the delay in the first hop, and the $Term$–3represents the ACD in the rest of hops. The suggestions in [13] and [14] only try to decrease the clock drift by minimizing the beacon collision probability. The proposed MCSS in this paper ensures the synchronization flow from the first hop to the last hop by the first criterion, and selects the STRN with the smallest distance to decrease propagation delay by the second criterion. Thus, the estimated ACD for the ship i by MCSS can be given as (6). In (6), the $Term$–1 is the ACD due to the beacon collisions, the $Term$–2 gives the ACD caused by the delay from the first hop to the $(H-1)$th hop, and the $Term$–3 represents the ACD at the last hop. Note that, the proposed MCSS can either be based on TSF or ATSP, and the ATSP-based MCSS not only can reduce the transmission delay but also can minimize the beacon collision probability to decrease the ACD. In Fig. 6, the numerical results of the ACD generated by FTSP and MCSS are depicted, where the ACD value for both synchronization schemes is shown that increases linearly with extending of network coverage. According to Fig. 6, the slope of the ACD plots obtained by FTSP is larger than the case of proposed MCSS. This is because the proposed MCSS can optimize the propagation delay to keep a small ACD efficiently via the two criteria considered in the proposed multi-hop clock synchronization procedure. On the other hand, the ACD value is found that is increased with more number of ships being deployed for both synchronization schemes. This is due to the increment of beacon collision probability, where the case of 150 ships being deployed yields the largest ACD by both synchronization schemes. Consequently, the proposed ATSP-based MCSS is aimed to further decrease the ACD by reducing the collision rate, and the advantages of the ATSP-based MCSS will be demonstrated and discussed in the following section.

VI. SIMULATION PERFORMANCE OF THE PROPOSED MCSS

This part verifies our proposed multi-hop clock synchronization algorithm via simulations. The simulations follow the frame structure in [5], and we replace all the data slots in a frame by the BCWs introduced in Fig. 4. According to the literatures, the SANET performance are verified usually with tens or hundreds ships at coastline area [2], [3], [9], [10]. In this paper, we intend to evaluate the scalability of the proposed algorithm with a similar number of ships as examined in the literatures. Therefore, three cases of ship distribution, i.e., 50 ships of Case-1, 100

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$$\Delta_i^{FTSP}(t) = \underbrace{\left(A_i \frac{S}{K}\right)}_{Term-1} + \underbrace{\left(\frac{E\{d(t)\}}{c} + P\right)}_{Term-2} + \underbrace{\left(\frac{L - E\{d(t)}{E\{T(t)\}}\right)\left(\frac{E\{T(t)\}}{c} + P\right)}_{Term-3} \tag{5}$$

$$\Delta_i^{MCSS}(t) = \underbrace{\left(A_i \frac{S}{K}\right)}_{Term-1} + \underbrace{(H-1)\left(\frac{D}{c} + P\right)}_{Term-2} + \underbrace{\left(\frac{E\{z(t)\}}{c} + P\right)}_{Term-3} \tag{6}$$

Table 1. Parameter notations.

Notation	Parameter	Value
N	Number of total ships	50, 100, 150
L	Network coverage	90–300 km
H	Number of hops in the SANET	3–10
$T(t)$	Distance between neighbor ships	100–500 m
S	Number of beacons in one BCW	24
λ	Network access probability	1
P	Unit processing delay	10 μs
$d(t)$	Distance between the root ship and a ship which can receive the signal from it	1–30 km
$z(t)$	Distance between the ship i at the last hop and its STRN	1–30 km
D	One hop length	30 km
c	Light speed	$3 * 10^8$ m/s
A	Oscillator offset	$\pm$ 0.01%
$I_{\max}$	Maximum beacon submission interval in ATSP-based MCSS	5

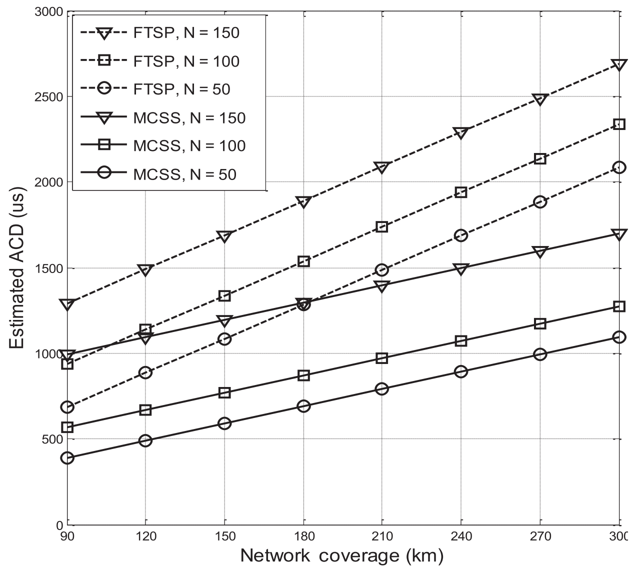

Fig. 6. Network coverage vs. estimated ACD.

ships of Case-2, and 150 ships of Case-3, are used in the simulations, where the link outage due to the absent of ships in a particular hop is not considered in this paper. These three cases are:

Case-1: 20 ships in hop-1; 15 in hop-2; 10 in hop-3; and 5 in hop-4,
Case-2: 40 ships in hop-1; 30 in hop-2; 20 in hop-3; and 10 in hop-4,
Case-3: 60 ships in hop-1; 45 in hop-2; 30 in hop-3; and 15 in hop-4.

Generally, the ship-to-ship communications are carried out under the coastline area and open sea area. In the coastline area, the maritime signal propagation might be reflected by terrestrial obstacles. While in the open sea area, the maritime signal propagation often follows the flat fading channels with line-of-sight signal component [23]. This paper considers the open sea area, and under such an environment, the 1% target error rate of beacon detection due to the SANET fading channel is employed at each terminal. This is because in our previous work, such as [7] and [8], we have improved the link reliability of SANET to meet 1% target error rate. And other parameters are same as in Table 1. Note that, $I_{\max}$ is set as 5 in our simulations for the scenario with tens of deployed ships in the first hop of SANET. At the network initialization period, the ships exchange beacons to set up the network. Due to the contention, the cost of beacons is dramatically increased as the number of ships increased. Table 2 demonstrates the average network setup time (in the unit of beacon) for the three cases, where for example in *Case-1*, 353 beacons are spent to setup the network when 50 ships complete to synchronize with each other.

Table 2. Summary of simulation results for three cases.

	Case-1	Case-2	Case-3
Network Setup Time (beacon)	353	575	1232
Maximum ACD for FTSP (μs)	1063	1354	1832
Maximum ACD for TSF-based MCSS (μs)	507	885	1312
Maximum ACD for ATSP-based MCSS (μs)	347	554	931
BCR for FTSP	0.186	0.395	0.622
BCR for TSF-based MCSS	0.137	0.309	0.493
BCR for ATSP-based MCSS	0.126	0.291	0.486

The ships located at the last hop are crucial for network clock synchronization because they usually have a larger clock drift compared with others. Thus, we trace the clock drift of one random ship at the hop-4 in our simulation, and the tracing period covers 1000 BCWs. Fig. 7 shows the ACD performances of the traced ship under network deployment of the Case-1, where Fig. 7(a), Fig. 7(b), and Fig. 7(c) are obtained by the synchronization schemes of FTSP, TSF-based MCSS, and ATSP-based MCSS, respectively. Due to collisions, the traced ship cannot be successfully synchronized by these three schemes during every BCW, and thus the clock drift is accumulated. According to Fig. 7(a), we observe that most of the ACD values generated by FTSP are lower than 600 μs. In contrast, most of the ACD values generated by the proposed TSF-based MCSS in Fig. 7(b) can maintain within 400 μs, and by the proposed ATSP-based MCSS in Fig. 7(c) can keep below 200 μs efficiently. This is mainly because the TSF/ATSP-based MCSS compared with the FTSP can decrease clock drift by considering propagation delay via our suggested two criteria. In addition by comparing Figs. 7(b) and 7(c), it confirms that the ATSP-based MCSS can further reduce beacon collisions that minimizes clock drift compared with the TSF-based MCSS. According to the simulation results, we can also observe that the maximum ACD value is 1063 μs in Fig. 7(a) for FTSP, 507 μs in Fig. 7(b) for TSF-based MCSS, and 347 μs in Fig. 7(c) for ATSP-based MCSS. The proposed ATSP-based MCSS thus is recommended for SANET applications to maintain the minimum ACD.

Table 2 describes the maximum ACD for FTSP, TSF-based MCSS, and ATSP-based MCSS under the *Case-2* and *Case-3*. The maximum ACD for each case is dramatically increased with more ships being deployed. According to Table 2, we can see that the maximum ACD performance enhancement of ATSP-based MCSS compared with FTSP is 67.4% in *Case-1*. Meanwhile, 59.1% and 49.2% enhancement in *Case-2* and *Case-3*, respectively, and it demonstrates that the efficiency of the proposed MCSS can be improved with less number of ships. However, the simulation results still validate that the proposed MCSS has higher adaptability for the SANET with a large number of ships.

$$BCR = \frac{Total\ Nr.\ of\ collided\ beacons}{Total\ Nr.\ of\ beacons} \tag{7}$$

We also simulate the beacon collision ratio (BCR) as defined in (7) for FTSP, TSF-based MCSS, and ATSP-based MCSS with three cases of ship distribution. The BCR is an important index affecting the network overhead, where a lower collision ratio accompanies a lower rate of beacon re-transmissions that decreases the network overhead. As listed in Table 2, we can observe that the BCR enhancement of TSF-based MCSS compared with FTSP are 26.3%, 21.8%, and 20.7% under the *Case-1*, *Case-2*, and *Case-3*, respectively. This is mainly due to the TSF-based MCSS allows part of terminals, e.g., HBSs, to submit beacons to decrease the collision probability by considering propagation delay. Moreover, the BCR enhancement of ATSP-based MCSS compared with FTSP are 32.8%, 26.3%, and 21.9% under the *Case-1*, *Case-2*, and *Case-3*, respectively. It demonstrates that the proposed ATSP-based MCSS is an efficient anti-collision scheme which reduces the frequency of beacon submissions from the terminals with slow clock timers to decrease the collision probability. Note that in this paper, we employ the exponential backoff procedure after beacon collision. That is, the ship terminals will choose a random waiting time for beacon resubmission after collision within a BCW. However, our proposed algorithm can reduce the beacon collision probability by applying ATSP at the first hop and only allowing hop boundary ships to submit beacons at other hops. The advanced backoff procedure to further enhance the performance as well as optimize the adaptive BCW regarding the variance of network range will be considered in our future works.

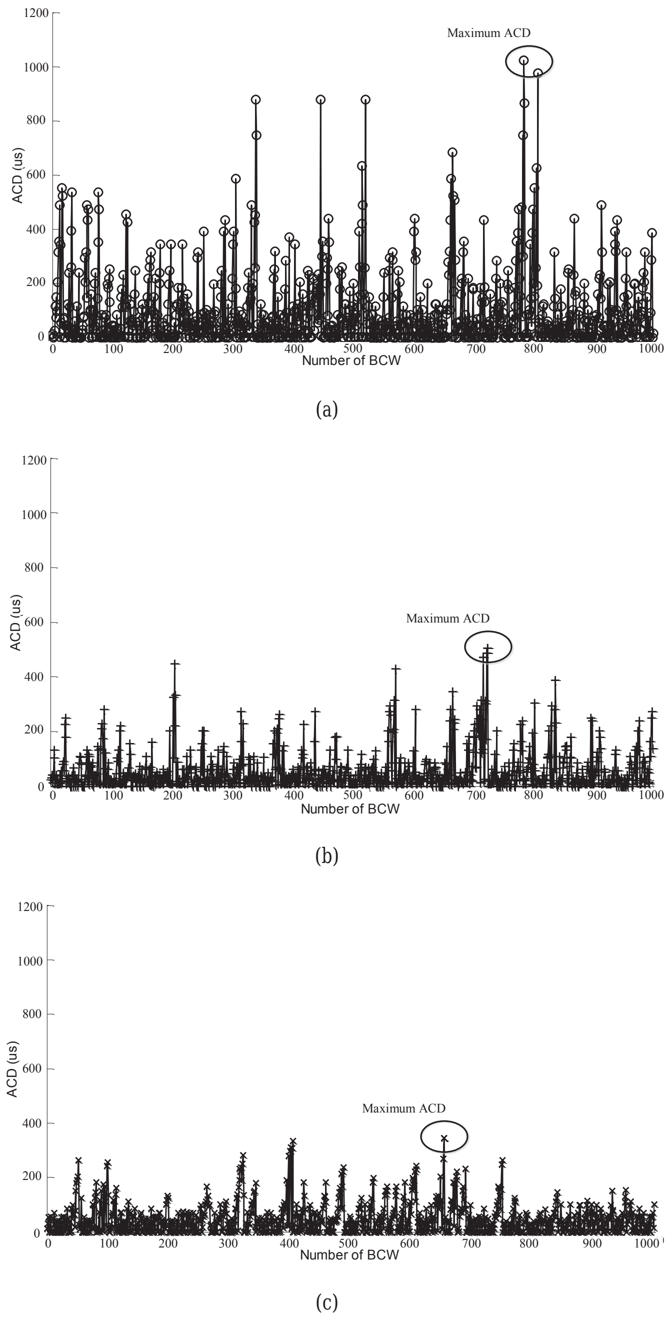

Fig. 7. ACD simulation results for the Case-1 : (a) by FTSP, (b) by TSF-based MCSS, and (c) by ATSP-based MCSS.

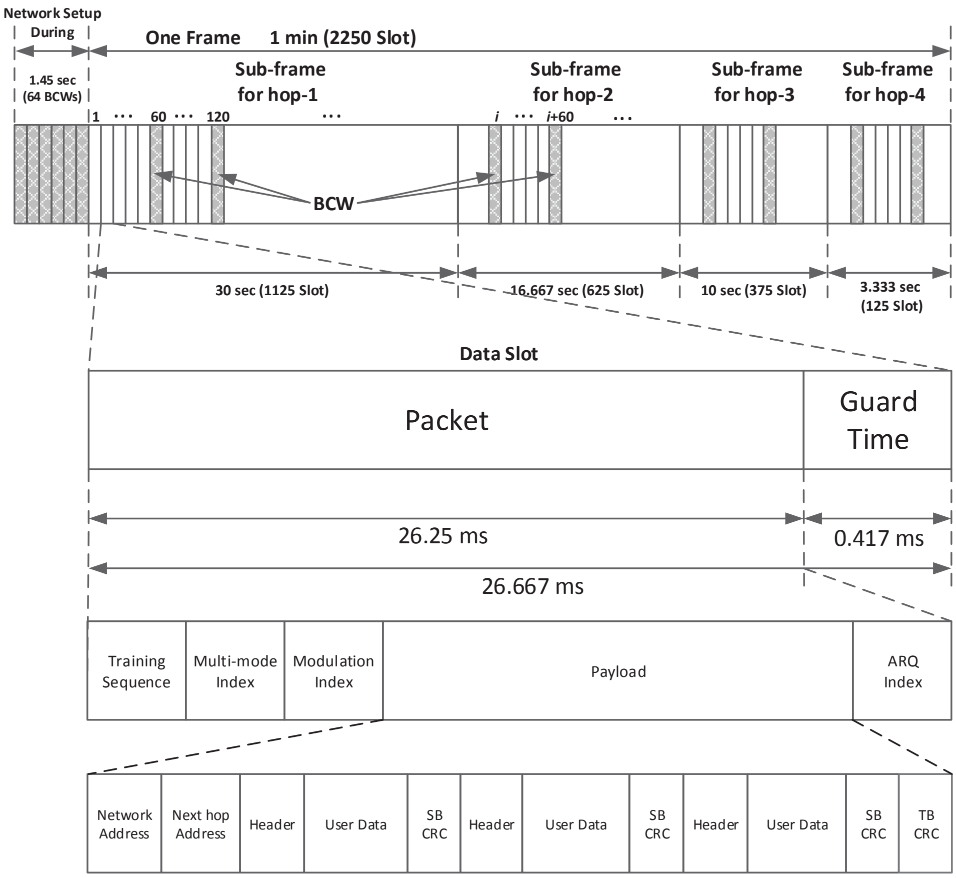

Fig. 8. SANET frame structure with beacon contention window being incorporated.

VII. SANET FRAME STRUCTURE

In this study, we notice that there lacks the consideration on the clock synchronization for the frame structure designed in [5], [9] and [10], where modifications are required based on the research findings in this paper. Fig. 8 demonstrates the finalized SANET frame structure by incorporating the BCWs. According to Fig. 8, the network setup duration is assigned by 64 BCWs. And there are total 1536 beacons allocated in this period which is enough to support the network setup for *Case-3*, where 1232 beacons are required. The frame length is set as one minute consisting of 2250 equal length data slots. There are four sub-frames allocated in a frame, and the first one serves the ships located in the first hop, so as for the rest of three sub-frames. The length of sub-frames are different due to the various ship density in each hop. The first sub-frame has 1125 data slots occupying half of the total number of slots in a frame; the second sub-frame contains 625 slots with the length of 16.667 seconds; the third sub-frame has 375 data slots with the length of 10 seconds, and the fourth sub-frame is assigned with 125 data slots. For the purpose to avoid the inter-slot interference, a guard time assigned for each slot is required. The length of guard time has been calculated to guarantee minimum 30 km propagation delay at a single hop, and hence it is set as 0.417 ms. According to [24], the QoS requirements for multimedia services are specified, where less than 100 ms clock drift is preferred for audio and video applications. Consequently, we fix the BCW interval by 60 data slots in order to avoid the ACD exceeding 60 ms. This is determined by the simulation result of the ATSP-based MCSS under *Case-3*, where the maximum clock drift is about 1 ms (i.e., 931 μs) that yields about 60 ms of ACD over 60 data slots.

VIII. CONCLUSIONS

In this paper, we investigate the clock synchronization in the large-scale SANET in terms of geographic scope. Through the survey of several existing synchronization algorithms, we realize that they are not suitable for the SANET because there lacks the consideration on propagation delay. Therefore, we propose a multi-hop clock synchronization algorithm, i.e., MCSS, to efficiently maintain a small clock drift for the ship-to-ship communications, where two criteria of ‘selection of the previous HBSs’ and ‘propagation delay reduction’ are considered in the multi-hop clock synchronization procedure. The ACD value is found that is increased with more number of ships being deployed due to the increment of beacon collision probability. Consequently, the proposed ATSP-based MCSS is aimed to further decrease the ACD by reducing the collision rate. In the simulation, we trace the clock drift of a ship located in the last hop. The simulation results show that the ACD of the proposed MCSS is smaller than FTSP because the former can efficiently avoid to increase the propagation delay. The ACD of ATSP-based MCSS is less than TSF-based MCSS because the beacon collision probability is further decreased. Finally, the maximum ACD (almost 1 ms) under *Case-3* by the ATSF-based MCSS is considered for the SANET frame structure finalization, where the BCW interval is fixed across 60 data slots in order to avoid the ACD exceeding 60 ms. Note that regarding the spectrum efficiency of the SANET, the beacon interval is adjustable according to the density and deployment of ships.

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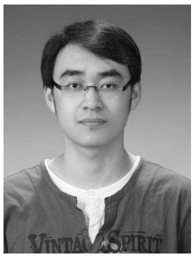

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