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Delay-Bounded Wireless Network Based on Precise Time Synchronization Using Wireless Two-Way Interferometry

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ABSTRACT The importance of reliable information transfer in wireless networks, especially regarding communication delay, is drastically increasing to fulfill safe and high-quality communication in the 5G and post-5G era. However, conventional media access control (MAC) protocol for wireless networks, notably Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), sometimes yields unexpectedly significant delay due to its complex arbitration mechanism assuming asynchronous communication among terminals. As the delay cannot be strictly bounded by a deterministic value, this causes a vulnerability of systems relying on wireless networks. This paper utilizes precise time synchronization achieved by Wireless Two-way Interferometry (Wi-Wi), enabling all terminals to be time-synchronized via wireless signals. We show that by an appropriate periodic assignment of each terminal's data transmission timing, named Arbitration Point (AP), a simple arbitration algorithm obtains a strictly bounded maximum value for the delay while ensuring equalities among all participants. Furthermore, we demonstrate that the total number of terminals manageable in a star-topology wireless network significantly increases by densely packing AP timings, taking into account the spatial geometry information of terminals, which is another feature delivered by Wi-Wi measurement. In the meantime, we experimentally constructed a star-topology wired network where all terminals are time-synchronized via Wi-Wi to confirm the fundamental properties identified in the proposed arbitration protocol. This study paves a new way for future wireless networks where the delay is strictly bounded and provides the basis for ultra-reliable and high-quality information transfer functionalities by utilizing precise time synchronization and space localization (space-time synchronization).

INDEX TERMS Bounded delay, CSMA, MAC protocol, precise time synchronization, space-time synchronization, wireless two-way interferometry, wireless networks.

I. INTRODUCTION

With the increasing demand for wireless communications anywhere at any time, local wireless networks are overwhelmingly deployed. Besides, the demand for low-latency or strictly bounded delay communication dramatically increases in 5G and beyond 5G society [1]. Low latency is mandatory in various large-scale, industrial applications such as healthcare, transport, entertainment, manufacturing, and so on [2]. In the manufacturing industry, latency requirements are particularly stringent [2]. From the perspectives of high-quality information transfer, a strictly bounded delay is a primary need for both real-time (i.e., extremely low-latency) operations of systems, in the sense of hard real-time where the maximum value of delay is strictly bounded, and predictable real-time where its value is predicted deterministically prior

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to the operations with high reliability and reproducibility. In particular, Industrial Wireless Sensor Network (IWSN) is a demanding area for industrial automation with strict latency requirements such as embedded sensor systems for industrial robots [3]. Hence, the technology enablers for managing such delay-bounded wireless communications are essential to realizing the future intelligent society referred to as Industry 4.0 [4], IoE [5], among others.

In the current wireless communications, a complex arbitration mechanism is necessary to deal with the collision or interference caused by simultaneous multiple accesses; therefore, communication overhead is inevitable. For example, Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) is a widely used arbitration method in wireless networks. Although CSMA/CA exhibits good performances, such as throughput, when the traffic is less loaded, its performance decreases drastically with increasing the traffic [6]. Moreover, the successful data transmission wait time can be unexpectedly long in CSMA/CA; in fact, the delay cannot be bounded by an exact deterministic value due to its random access scheme. As a result, although the data body transmission duration can be short often, communication overhead inhibits the improvement of effective throughput and delay for data transfer when the traffic load is high [7].

In the literature, on the other hand, Time Division Multiple Access (TDMA) is one of the well-known approaches as a Media Access Control (MAC) protocol for the bounded delay in Wireless Sensor Networks (WSNs), including IWSN [3]. However, TDMA also needs complex arbitration, including routing and additional data transfer for time synchronization, except for actual data content transmission. Besides, TDMA is not tolerant of dynamic changes in wireless networks' topology due to the assignment of time slots. Therefore, we consider that it is challenging to meet the demands of future wireless communications with the current MAC protocols assuming asynchronous communication between terminals.

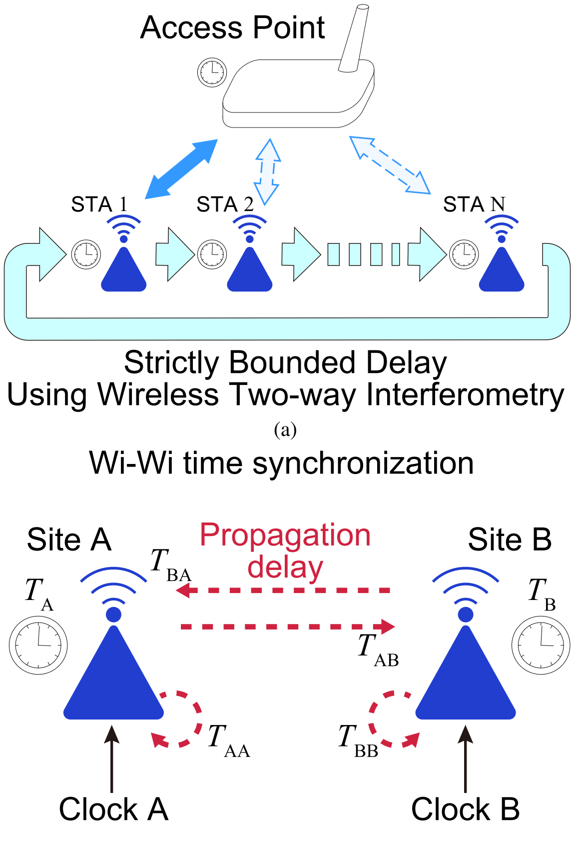
The growing importance of time synchronization technology also stems from the latest communication methods that employ space division technology and time division multiplexing, such as Massive Multiple-Input Multiple-Output (MIMO) [8]–[12], among others. These kinds of techniques enable a higher data transmission rate and effective resource usage. One widely used time-synchronization method is based on Global Navigation Satellite System (GNSS) signals [13]. However, its synchronization performance is sometimes unavailable or degraded in indoor environments, in addition to high cost of updating the satellite equipment or technology. Precision time protocol (PTP) [14] is another technique for precise time synchronization. However, its precision and applicability are limited due to its inability to manage dynamically changing, uncertain network structures. Therefore, given the expected interconnectedness and adaptability of our future society, technology enablers are required for precise time synchronization among distributed and versatile wireless devices in indoor and outdoor environments.

With such background, Shiga *et al.* have developed the so-called Wireless Two-way Interferometry [15], also called Wi-Wi, which enables local terminals to be time-synchronized with each other with high precision. Wi-Wi is implemented at a low cost by using standard wireless communication devices. Its principle relies on two-way time transfer, initially developed for precise comparison of the standard time of different nations via satellite signals. In Wi-Wi, this principle is practically implemented in commercial, inexpensive wireless communication devices instead of the satellite; picosecond-accuracy time synchronization is realized. Besides, as introduced in Section III, Wi-Wi measures propagation delay or distance between terminals, meaning that the two-dimensional position information of terminals can be grasped. Hence, not just time synchronization but also space localization is made possible by Wi-Wi. We define here the term "space-time synchronization (time and space synchronization)" used throughout this paper, where the internal clock of devices is synchronized and the position of devices is mutually recognized in the local area.

Ultimately, suppose precise space-time synchronization capability is ensured over all given devices. In that case, we can think of a paradigm shift in wireless communications towards the Wi-Wi paradigm from the current standards that are inevitably dominated by asynchronous communications. We consider whether this new paradigm, where all terminals are time-and-space synchronized via Wi-Wi, is suitable for ultra-reliable information transfer, potentially ensuring low-latency and effective wireless communications.

As a step in such a direction, the subject of the present study is to achieve strictly bounded delay in wireless networks. According to the previous work, the Wi-Wi paradigm can provide a new MAC protocol for the bounded delay in information transfer. Koyama *et al.* proposed a new arbitration dedicated to optical ring network based on precise time synchronization via Wi-Wi where the maximum value of delay is strictly bounded. In the article [16], the notion of Arbitration Point is introduced as a periodic timing shared by all terminals, such that the proposed protocol provides an equal opportunity for all nodes connected to the optical ring.

The present work aims to establish such an arbitration based on this new paradigm for wireless communications for the first time. Specifically, we examine a single star-topology wireless network based on precise time-space synchronization using Wi-Wi. The proposed protocol utilizes carrier sense and allows multiple access, as discussed in detail in the following sections. In this regard, the proposed method fits into the category of arbitration named CSMA; however, it should be emphasized that what is unique is that a periodic timing named Arbitration Point (AP) is assigned to each terminal based on precise time synchronization. At the timing of AP, each terminal can obtain a communication opportunity, which realizes absolute collision-free CSMA with constraints regarding the assignment period. Thus, we call the proposed protocol CSMA/AP to represent such features. Fig. 1(a) shows a schematic diagram of our proposed



(a)

(b)

FIGURE 1. Design principle of the proposed arbitration based on precise time synchronization. (a) Schematic diagram of the proposed arbitration using wireless two-way interferometry (Wi-Wi). Bounded delay in wireless communication for each terminal is accomplished thanks to precise time synchronization by Wi-Wi. (b) Schematic diagram of Wi-Wi time synchronization. The principle of two-way time transfer provides the time difference and the distance information between two terminals via the same physical route. Wi-Wi realizes space-time synchronization by utilizing this technique.

arbitration based on precise synchronization using Wi-Wi where communication opportunity is periodically circulating among N stations (STAs) to be connected to the access point without missing. Fig. 1(b) schematically depicts the principle of Wi-Wi time synchronization.

We demonstrate that CSMA/AP provides a simple arbitration by which the delay is strictly bounded by a deterministic value. More specifically, this paper proposes two types of CSMA/AP; one is CSMA/AP with Time synchronization, CSMA/AP-T in short; the other is CSMA/AP with Time and Space (space-time) synchronization, abbreviated as CSMA/AP-TS. In both protocols, we exploit the fact that Wi-Wi precisely synchronizes the timing of all terminals for the assignment of AP. Each terminal experiences the timing of AP in a periodic manner. In CSMA/AP-T, the time difference between APs for successive terminals is an identical time duration; indeed, the time difference, referred to as time offset, is set to be long enough to avoid a collision regardless of the spatial position of the terminals. In CSMA/AP-TS, on the other hand, the time offset is not identical and adaptably configured depending on the spatial configuration of terminals. By utilizing the spatial position information obtained by Wi-Wi measurement, the time offset is set to be a smaller value, just large enough so that the collisions are surely avoided. In CSMA/AP-TS, the geometry information obtained by Wi-Wi enables APs to be temporally compactly packed in a shorter time than CSMA/AP-T, allowing to accommodate a larger number of terminals and to improve the channel utilization efficiency.

Furthermore, we examine the technical feasibility of the proposed arbitration protocol for future application purposes. This paper experimentally constructed a star-topology wired network consisting of one access point and two terminals, wherein all of them are time-synchronized thanks to Wi-Wi. Consequently, we demonstrate a reduced time difference among devices using Wi-Wi, which is necessary for information transfer based on CSMA/AP-T to achieve collision-free communications while providing equal performances between terminals.

This paper is organized as follows. In Section II, we review the related works about bounded delay wireless communications. Section III summarizes the principle of Wi-Wi, which is the critical resource of the proposed arbitration method. Sections IV and V describe the proposed arbitration of CSMA/AP-T and CSMA/AP-TS protocols, respectively, based on the Wi-Wi paradigm. Section VI shows the results of an experimental demonstration using Wi-Wi. In Section VII, we describe a few remarks about the present and future studies. Finally, Section VIII concludes the paper.

II. RELATED WORKS

This section clarifies the scope of the present work by reviewing conventional MAC protocols for wireless networks. There are two types of these protocols, one based on CSMA/CA, and the other based on TDMA. CSMA/CA is widely used and excels in autonomous and distributed operations [17]. However, it cannot guarantee a deterministic upper bound of delay since it is a contention-based approach. Meanwhile, in dedicated applications such as Wireless Sensor Network (WSN), TDMA is an approach, which can provide bounded delay [3]. However, it needs additional overhead for time synchronization and routing algorithm using the same bandwidth as for the data transfer. In addition, TDMA is not cost-effective in low traffic because of its fixed communication resource allocation that caps the available throughput at the same value for each device no matter the traffic.

Power Efficient and Delay Aware Medium Access Control Scheme (PEDAMACS) [18] is one of the MAC protocols based on TDMA providing a bounded delay. The protocol utilizes network topology information for time slots assignment; hence, exchanging local topology information is needed prior to the time slot assignment. However, topology estimation is ambiguous due to dynamic topological changes in actual wireless networks, causing redundant assignments for different terminals. Therefore, actually, there is no actual guarantee to provide a deterministic upper bound of delay. Indeed,

TABLE 1. MAC protocol comparison.

MAC protocol	CSMA/CA	TDMA	CSMA/AP
Control method	Distributed	Centralized	Distributed
Bounded delay	No	Deterministic	Deterministic
High-traffic performance	Not-good	Good	Better
Low-traffic performance	Good	Not-good	Better

in the article [19], when exploring the path to optimize energy efficiency in WSN before arbitration, the bounded path length enables the delay to be bounded. If the minimum length path is beyond the constraint, the node cannot send a packet to the destination with the end-to-end delay being bounded. A delay guaranteed routing and MAC protocol (DGRAM) [20], which also focuses on routing in WSNs, achieves higher energy efficiency and provides a deterministic delay bound for each terminal. In contrast, the layout of the network needs to be shared among all terminals before arbitration, requiring significant overhead that is not appropriate for dynamic allocation. Moreover, it does not take into account the effect of scaling. SS-MAC [21] guarantees that emergency data transmission will be accomplished within a deterministic value. However, it lacks equality because it enables sporadic emergency data to be transmitted at the others' time slot. As reviewed in the aforementioned works, the identical bandwidth usage for different purposes causes unavoidable communication overhead, which hinders strictly bounded delay.

On the contrary, the proposed method is intended to effectively use the communication resource regardless of traffic and yet ensure a strict maximum delay. The proposed protocol employs the contention-based and absolute collision-free approach using precise time synchronization. The key concept here is that two frequency bandwidths are allocated: one low-frequency band for Wi-Wi synchronization, one high-frequency band for data transmission. A practical reason for this separated allocation is because Wi-Wi can cover a wider area, if it is operated at the lower frequency bandwidth, thanks to the diffraction of radio waves, while not disturbing the data transmission band. In other words, precise time synchronization is assured in a given area; that is, a dedicated bandwidth allocation for Wi-Wi synchronization provides a solid foundation to accomplish the bounded delay. Table 1 summarizes comparisons of different MAC protocols.

III. WIRELESS TWO-WAY INTERFEROMETRY (WI-WI)

Wi-Wi employs Two-Way Time Transfer (TWTT) [22] to provide precise time synchronization between two remote sites. TWTT has been initially introduced for Two-Way Satellite Time and Frequency Transfer (TWSTFT) [22], which provides standard time comparison via geostationary satellite signals. Carrier-Phase Two-way satellite frequency transfer (TWCP) [23] has been introduced to improve the synchronization precision of TWSTFT. Thus, Wi-Wi is a technology that substitutes satellite signals for wireless signals to realize precise time synchronization even indoors with lower costs.

A. TWO-WAY TIME TRANSFER

We first review the principle of time synchronization using TWTT [22]. TWTT provides time synchronization between terminals at sites A and B assuming that both terminals exchange their time information via two-way communication through the same physical route. The times at sites A and B are respectively denoted by T_{A} and T_{B} and the time difference between the two sites is denoted by $t_c (:= T_{\mathrm{B}} - T_{\mathrm{A}})$. Then, the time difference calculated when the terminal at A receives the time information of T_{B} after the propagation delay t_d is given as follows:

$$t_{\mathrm{A}} := T_{\mathrm{BA}} - T_{\mathrm{BB}} = -t_c + t_d, \tag{1}$$

where t_{A} denotes the time difference calculated at A. T_{BB} and T_{BA} are the time when the time information of T_{B} arrive at B and A respectively, which means T_{BB} is equivalent to T_{B}. Thus, the time at B is obtained in the same way as follows:

$$t_{\mathrm{B}} := T_{\mathrm{AB}} - T_{\mathrm{AA}} = t_c + t_d, \tag{2}$$

where t_{B} denotes the time difference calculated at B. T_{AB} and T_{AA} are the time when the time information of T_{A} arrive at B and A respectively, which means T_{AA} is equivalent to T_{A}. Assuming a single round trip time for exchanging the information is sufficiently small and the propagation delay from A to B is the same as from B to A, the time difference t_c and the propagation delay t_d can be obtained as follows:

$$t_c = \frac{t_{\mathrm{B}} - t_{\mathrm{A}}}{2}, \tag{3}$$

$$t_d = \frac{t_{\mathrm{B}} + t_{\mathrm{A}}}{2}. \tag{4}$$

Therefore, the time difference t_c given by (3) makes the synchronization of both terminals possible.

Secondly, we describe a technique based on the carrier phase of the transmitted signal. TWCP is a technique to provide the precise time difference based on the exchange of the phase information instead of the time. We can rewrite t_c by using the phase information as follows:

$$t_c := \frac{\phi_c}{4\pi f_0} = \frac{1}{4\pi f_0}\left(\phi_{\mathrm{B}} - \phi_{\mathrm{A}} + 2\pi M_c\right), \tag{5}$$

where f_0 is the carrier frequency, $\phi_c := \phi_{\mathrm{B}} - \phi_{\mathrm{A}}$ is the phase difference between two terminals and M_c is a natural number. ϕ_{A} and ϕ_{B} are obtained from a measured phase likewise (1), (2). Equation (5) shows an ambiguity with the value of M_c since the measured phase can only be obtained as modulo 2π. Therefore, the offset M_c cannot be determined by phase measurement, so it should be determined in a separate way to get t_c. Note that we can track the variation of t_c from the beginning of the measurement if the variation of ϕ_{A} and ϕ_{B} between the successive measurements is smaller than π,

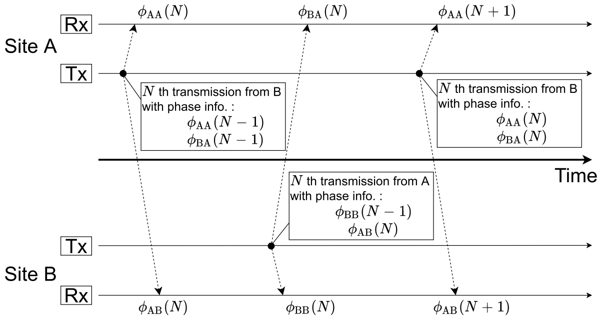


FIGURE 2. **Schematic diagram of Wi-Wi calculation mechanism. In calculating the true time difference, each terminal transmits its phase information while almost simultaneously receiving the phase information from the other and from itself.**

which corresponds to the requirement of a sufficiently short roundtrip time. The successful phase unwrapping has already been demonstrated in [15].

B. WI-WI PRINCIPLE

Based on the technique described above, Wi-Wi can synchronize terminals at two remote sites via wireless communication. Each terminal has to calculate (3), (4) to get the accurate time difference, meaning that 1.5 roundtrip exchanges are needed. Fig. 2 schematically shows the information exchanges between two terminals. Specifically, $\phi_{\mathrm{AA}}(N-1)$ and $\phi_{\mathrm{BA}}(N-1)$ are received by terminal B at the N-th transmission from terminal A. At the same time, terminal A and B obtain $\phi_{\mathrm{AA}}(N)$ and $\phi_{\mathrm{AB}}(N)$ respectively. Likewise, $\phi_{\mathrm{BB}}(N-1)$ and $\phi_{\mathrm{AB}}(N)$ are received by terminal A at the N th transmission from terminal B whereas terminals A and B can obtain $\phi_{\mathrm{BA}}(N)$ and $\phi_{\mathrm{BB}}(N)$ respectively. Finally, $\phi_{\mathrm{BA}}(N)$ is received by terminal B, which allows terminal B to calculate $\phi_c(N)$ from $\phi_{\mathrm{AB}}(N)$, $\phi_{\mathrm{AA}}(N)$, $\phi_{\mathrm{BA}}(N)$ and $\phi_{\mathrm{BB}}(N)$.

Notably, Wi-Wi is a technique to synchronize not only time but also space; indeed, it has been successfully utilized to monitor horizontal distance variations [24], [25]. On the process of t_c calculation, one can also obtain t_d as shown in (4). Hence, the propagation distance between two sites l_d can be obtained as the product of t_d and light speed c:

$$\begin{aligned} l_d &:= c \cdot t_d = -\frac{c}{4\pi f_0}\left(\phi_{\mathrm{A}} + \phi_B + 2\pi M_c\right) \\ &= -\left(\frac{\phi_{\mathrm{A}} + \phi_{\mathrm{B}}}{2\pi} + M_c\right)\frac{c}{2f_0}. \end{aligned} \tag{6}$$

where l_d is the propagation distance between the two terminals. Equation (6) also has the ambiguity of the choice of M_c, but this can be resolved in the same way as for the measurement of t_c in (5).

A compact electronic module implementing such Wi-Wi principles has been developed; PID feedback control is utilized for its built-in internal crystal oscillator to achieve precise time synchronization based on the calculation described above [24]. The current device can be synchronized with up to seven others simultaneously, and the expansion to larger numbers of devices is in progress.

IV. ARBITRATION FOR WIRELESS COMMUNICATIONS BASED ON PRECISE TIME SYNCHRONIZATION: CSMA/AP-T

This section demonstrates the details of CSMA/AP-T designed for a star-topology wireless network where all terminals can send information definitely within a guaranteed bounded delay time based on precise time synchronization by Wi-Wi. We show the derivation of the formula for the maximum delay, as well as the necessary constraints to achieve collision-free CSMA.

As introduced in Section I, CSMA/AP is a contention-based approach. Here, the idea is that by using precise time synchronization among all terminals, the absolute collision-free property is realized by periodic assignments of designated time duration shared among all terminals, called Arbitration Point (AP) [16]. Each terminal receives the timing of AP in chronological order while the time difference between successive APs is kept equal to a constant value. This approach is based on the Wi-Wi paradigm, unlike CSMA/CA, which cannot guarantee bounded delay because of its random access protocol [17] while assuming asynchronous wireless communications.

A. PRINCIPLE

Here we describe the basic principle of CSMA/AP-T, as well as the following adopted assumptions for the proposed arbitration. A single star-topology wireless network consists of one access point and several terminals within the access point's sensitivity limit. The access point has enough power to transmit to all terminals. Each terminal tries to transmit a fixed-length packet on the same channel and has the transmission queue whose capacity is infinite. All terminals are time-synchronized via Wi-Wi and their identities are randomly assigned prior to operations. In addition, we assume there is no so-called hidden terminal problem, which means each terminal can detect others' transmission via carrier sense. Based on these assumptions, the arbitration is detailed as follows.

We first introduce the set time interval shared among all terminals, named Arbitration Point (AP), which has a designated time length depending on the data rate. Each terminal is periodically assigned to a completely distinct AP for absolute collision-free arbitration while detecting the timing of AP autonomously thanks to precise time synchronization by Wi-Wi.

Each terminal must sense the channel continuously during AP when it has certain information to be transmitted. If the terminal senses the channel idle for AP duration, it can start transmission. If the terminal senses the channel busy during AP, it has to wait for the next assigned AP. The terminal repeats such a procedure until successful data transmission. The remarkable feature of the proposed CSMA/AP-T is that such a transmission opportunity is assuredly available within the deterministically given number of postponements; that is, the maximum value of delay is strictly specified.

To deterministically guarantee an upper-bound to the delay, the assignment period T_{ap} and time offset are determined as follows:

$$T_{i,i+1} = \max\{\Delta t, \frac{2r_{\mathrm{S}}}{c}\}, \quad i = 1, \ldots, N-1, \tag{7}$$

$$T_{N,1} = \max\{\Delta t, \frac{2r_{\mathrm{S}}}{c}\}, \tag{8}$$

$$T_{i,j} = \sum_{k=i}^{j-1} T_{k,k+1} = (j-i) \times \frac{2r_{\mathrm{S}}}{c}, \tag{9}$$

$$T_{\mathrm{tot},N} := \sum_{i=1}^{N-1} T_{i,i+1} + T_{N,1} = N \times \frac{2r_{\mathrm{S}}}{c}, \tag{10}$$

$$T_{\mathrm{ap}} = T_{\mathrm{packet}}, \tag{11}$$

where N is the number of terminals in a wireless network and i (for $i = 1, \ldots, N$) represents the ordered index of terminals. r_{S} is the radius of the sensitivity limit, c is the propagation speed of radio waves and Δt is the designated time length for AP. T_{packet} denotes the time length to transmit a packet, including the propagation time from each terminal to the access point. Fig. 3(a) shows an example of the assignment of AP when N is ten and its chronological order is illustrated, as schematically shown in Fig 3(b). Indeed, the propagation distance between each pair of terminals is up to $2r_{\mathrm{S}}$ as shown in Fig. 3(c). Therefore, the time offset needed to avoid interference is determined by following (7) and (8). Algorithm 1 shows the detail of the arbitration.

Algorithm 1 Overview of CSMA/AP-T

```
Condition: Each terminal can detect AP based on precise time synchronization via Wi-Wi.
1) When terminal $i$ wants to transmit a packet to the access point (i.e., the transmission queue is not empty), the terminal has to wait for its assigned AP.
2) If terminal $i$ finds the channel idle via carrier sense until the end of AP,
    a) The terminal starts transmission at the end of AP.
    b) A radio wave from the terminal definitely arrives at terminal $j (\forall j \neq i)$, which derives from time offset $T_{i,j}$.
    c) The others can listen to the transmission from terminal $i$ and will not disturb it.
3) If terminal $i$ finds the channel busy via carrier sense by the end of its assigned AP,
    a) At the end of AP, the terminal decides to postpone transmission until its next AP, i.e., return to Step 2.
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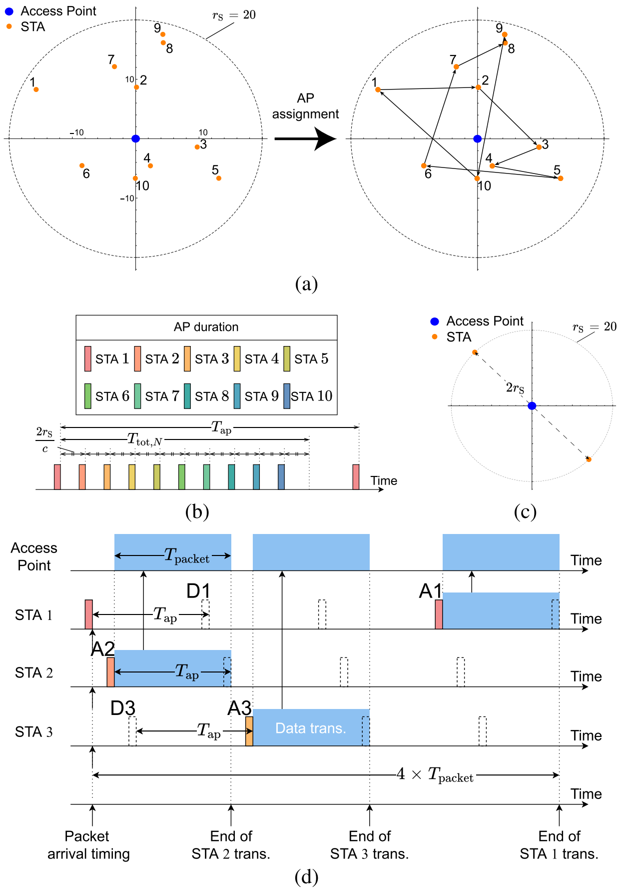


FIGURE 3. Contention-based and absolute collision-free arbitration based on CSMA/AP-T. (a) Schematic diagram of assignment of AP in a star-topology wireless network consisting of one access point and ten terminals. Each terminal is assigned to a designated AP following the order based on its designated index, noting that the successive terminal is given by a chronological order and terminal 1 follows after terminal N. (b) Schematic time axis represents the chronological order of assignment. The assignment of AP for each terminal is periodic, and its period is identical among terminals. Each duration represents the assigned AP whose timing is shared among all terminals thanks to precise time synchronization by Wi-Wi. (c) Example of a pair of terminals with the longest propagation distance $2r_{\mathrm{S}}$ apart: by design, the propagation distance between every pair of terminals within star wireless network is less than or equal to $2r_{\mathrm{S}}$. Therefore, the time offset between successive terminals in chronological order is identical and set based on sensitivity limit for collision avoidance, as shown in (b). (d) Example of the arbitration based on CSMA/AP-T when N is three. Each terminal transmits its packet within a delay bounded by $N \times T_{\mathrm{packet}} + T_{\mathrm{ap}} = 4 \times T_{\mathrm{packet}}$ when T_{ap} equals T_{packet}.

After terminal $i (i = 1, \ldots, N-1)$ completes transmission, the next terminal $i+1$ can start communication if it has a certain packet to transmit. Note that after transmission from terminal N, terminal 1 is the next designated terminal to obtain a data transmission chance. The assignment period T_{ap} needs to satisfy the following inequality in order to guarantee the chronological assignment order;

$$T_{\mathrm{ap}} \geq T_{\mathrm{tot},N}. \tag{12}$$

Otherwise, inequality of opportunity among terminals will appear. Moreover, there is no guarantee for exclusive data transmission. For these reasons, we assume (12) is always satisfied.

Consequently, each terminal can definitely start transmission after passing through at most $N-1$ consecutive APs; that is the maximum number of potentially available chances for data transmission. More specifically, all terminals can transmit a packet at the head of the queue within

$$N \times T_{\text{packet}} + T_{\text{ap}}. \tag{13}$$

Fig. 3(d) shows an example of the arbitration when N is three, where the colored or dashed rectangular bars indicate corresponding APs. The filled ones represent the available chance for data transmission and occupied slots for the dashed ones. We assume that all terminals, denoted by STAs 1, 2, and 3, want to start data transmission at the packet arrival timing, which is just after the end of AP assigned to STA 1. Here, STA 2 detects its AP at the timing marked by A2 and perceives that the channel is idle. Hence, STA 2 starts its data transmission, which is marked by a sky blue colored rectangle followed after AP denoted by A2. Subsequently, STA 3 cannot start data transfer at the following AP timing, denoted by D3, since the channel is busy due to STA 2's transmission. Similarly, STA 1 cannot use the subsequent AP timing marked by D1. STA 3 receives its next AP marked by A3, where STA 3 can now start data transmission because the channel is idle. Similarly, STA 1 starts data transmission at the end of AP marked by A1 after passing through two consecutive assigned AP. What should be emphasized is that the maximum wait time, or delay, is bounded by (13). Thus, CSMA/AP-T provides equal opportunity for data transmission for all terminals within a bounded delay.

B. EVALUATION

We conducted the performance evaluation of the proposed arbitration protocol through the comparison of CSMA/AP-T with CSMA/CA.

1) DETAILS OF SIMULATION METHODS

The primary feature of CSMA/AP-T is that it provides a deterministically determined upper bound of delay. To verify this property, we evaluate the following two kinds of delay. The first one, called "Wait time 1" hereafter, is the time length between the arrival of a packet at the tail of the transmission queue and its reception by the access point. The second one, called "Wait time 2" hereafter, is the time length between the arrival of a packet at the head of the transmission queue and its reception by the access point. In CSMA/AP-T, it is expected that Wait time 2 is strictly bounded by (12), which allows us to predict the maximum value of Wait time 1. In addition, in order to evaluate the communication throughput in a wireless network, we define the effective throughput as follows:

$$\text{Effective throughput} := \frac{T_{\text{packet}}}{\text{Wait time 2}}. \tag{14}$$

These metrics are calculated with respect to successfully transmitted packets.

Secondly, we specify the details of the wireless network under study. A single star-topology wireless network is composed of one access point and N terminals. The wireless network layout is fixed during the consideration time since the time offset only depends on N, not the layout. Assuming all terminals are time-synchronized via Wi-Wi, there is no hidden terminal problem in the wireless network. By referring to the specifications of typical wireless networks, we determine network parameters as follows. All terminals use the same designated 2.4 GHz bandwidth for data transmission, where the data rate is 54 Mbps, the radius of the sensitivity limit r_S is 20 m, and the propagation speed of radio waves c is 3.0×10^8 m/s. To analyze the delay dependency on N, we change N from ten to fifty with steps of ten.

Thirdly, we illustrate the implementation of CSMA/CA, which is described in Algorithm 2 in detail. The parameters of CSMA/CA are as follows. DIFS (Distributed Inter-Frame Space) is 50 µs, SIFS (Short Inter-Frame Space) is 10 µs, and SLOT is 20 µs. CW denotes the size of contention window and its maximum and minimum values are referred to $CW_{\max}$ and $CW_{\min}$ respectively.

Algorithm 2 Overview of CSMA/CA

```
Condition: Each terminal follows Distributed Coordination Function (DCF) [17].
Initialization: $CW$ is initialized to $CW_{\min}$ for all terminals.
1) When terminal $i$ wants to transmit a packet to the access point (i.e., the transmission queue is not empty), the terminal has to listen to the channel for DIFS.
2) If terminal $i$ finds the channel idle via carrier sense,
    a) The terminal tries contention-based transmission based on a binary exponential back-off algorithm.
    b) If there are no back-off slots to carry over from the previous contention, the terminal chooses the SLOT index from [0, $CW$]. If there is, the terminal follows the previous one.
    c) If the terminal finds the channel idle via carrier sense for SLOT, decrement the SLOT index; otherwise, the SLOT index will be carried over to the next contention and move to Step 3)a).
        i) When the SLOT index reaches 0, the terminal starts its transmission.
        ii) After its transmission, the terminal waits for ACK from the access point for SIFS. If there is, its transmission is successfully completed and $CW$ is updated to $CW_{\min}$. If there is no ACK, its transmission is regarded as failure and $CW$ is updated to $2CW + 1$ as long as $CW$ is smaller than $CW_{\max}$.
3) If terminal $i$ finds the channel busy via carrier sense,
    a) The terminal waits until the channel has been idle for consecutive DIFS.
    b) Return to Step 2)a).
```

Finally, we refer to the traffic model. We consider the time length to transmit a fixed-length packet, which is 1512 Byte, meaning that T_{packet} is 224 µs including propagation time from each terminal to the access point. These variables are also based on the typical specifications of commercially deployed wireless apparatus. With these parameters, we defined the identical assignment period T_{ap} equivalent to T_{packet}, meaning that (13) always holds. The simulation time duration is 20 s. The packet arrival time distribution at each terminal follows the exponential distribution whose parameter λ is given by:

$$\lambda = \frac{R}{10 \times T_{\mathrm{packet}}}, \tag{15}$$

where R is referred to as the traffic rate. In the following analysis, R ranged from 0 to 1 with steps of 0.01. The larger the traffic rate, the shorter the mean. We average the results over ten different simulations obtained by changing the seed of pseudorandom numbers.

2) PERFORMANCE ANALYSIS

We first evaluate the performance of low-latency packet transmission provided by the proposed protocol. We compare the Wait time 1 of CSMA/AP-T and CSMA/CA; Figs. 4(a) and (b) represent the Wait time 1 as a function of traffic rate obtained by CSMA/CA and CSMA/AP-T, respectively. Each symbol represents the mean of the proportion of Wait time 1 distribution of all packets successfully sent within the indicated interval proportion for each traffic rate. In the case of CSMA/CA, Wait time 1 increases dramatically the delay when the traffic rate is larger than 0.5, even with respect to the lower 10% delay. By contrast, with CSMA/AP-T, even when the traffic rate is around 0.8, Wait time 1 becomes smaller by a factor of at least ten compared with CSMA/CA, which demonstrates better performance in low latency by CSMA/AP-T. One remark here is that the drastic increase of Wait time 1 is also observed in CSMA/AP-T when the traffic rate is 0.9 or more. We clarify such a rapid increase in Wait time 1 later below based on queuing analysis.

Secondly, we illustrate bounded delay in CSMA/AP-T. We evaluate Wait time 2 in both protocols; Figs. 4(c) and (d) show the Wait time 2 as a function of traffic rate by CSMA/CA and CSMA/AP-T, respectively. Each symbol in these figures denotes the mean of the proportion of Wait time 2 distribution. The black dashed line in Fig. 4(d) represents the theoretical upper bound of Wait time 2 in CSMA/AP-T, which derives from (12). Wait time 2 significantly increases, as shown in Fig. 4(c), when the traffic rate is 0.5 or more by CSMA/CA. By CSMA/AP-T, in contrast, the maximum value of Wait time 2 is strictly bounded by 11 × T_{packet} even with a high traffic rate.

Thirdly, we evaluate the efficiency of the proposed method; Fig. 4(e) summarizes the effective throughput and the mean of Wait time 2 obtained by CSMA/CA and CSMA/AP-T. The effective throughput decreases when the traffic rate is greater than 0.53, whereas, with CSMA/AP-T, the effective throughput is strictly lower bounded. Likewise, the mean of Wait time 2 by CSMA/CA dramatically increases when the traffic rate is greater than 0.5, whereas that by CSMA/AP-T is smaller than about 2.5 µs even when the traffic rate is beyond 0.9. In addition, the traffic rate that signals a drastic change in effective throughput or Wait time 2 is about 0.5 in the case of CSMA/CA, and about 0.9 in the case of CSMA/AP-T.

We apply the queueing theory to scrutinize these observations. Here, we consider that each terminal in the wireless network can be denoted as the M/G/1 queue, known as Kendall notation [26] in the queueing theory. The service time is equivalent to Wait time 2. We can obtain the utilization rate ρ as follows:

$$\rho := \frac{\lambda}{\mu}, \tag{16}$$

where λ is the mean arrival rate, which is defined in (15), and μ is the mean of service rate, which derives from the inverse of the service time. If $\rho \geq 1$, the length of the queue or the wait becomes infinity, meaning that the traffic is beyond its capacity. Therefore, $\rho < 1$ is the requirement for stability.

In CSMA/AP-T, the utilization rate is strictly bounded:

$$\rho = \frac{\lambda}{\mu} \leq \frac{R(N+1) \times T_{\mathrm{packet}}}{10 \times T_{\mathrm{packet}}} = \frac{N+1}{10} R, \tag{17}$$

with equality if and only if all terminals send their packets in chronological order without missing. When ρ is 1 or more, the equality requirement (17) is definitely satisfied, which means ρ equals $(N+1)R/10$. Thus, instability occurs if the following condition is verified:

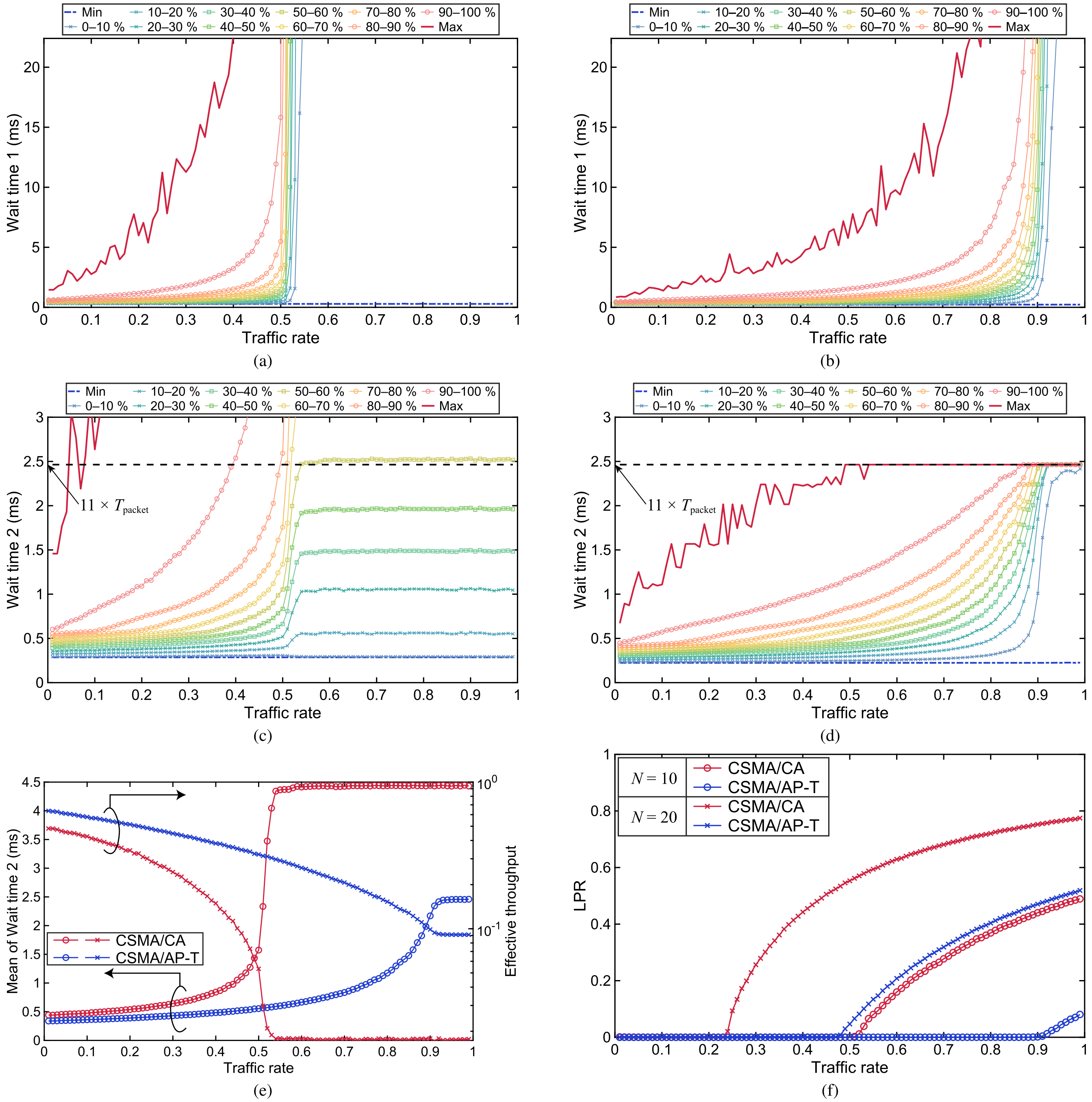
$$\frac{10}{N+1} \leq R. \tag{18}$$

In CSMA/CA, an upper bound of service time cannot be analytically obtained because of its random back-off algorithm. On the other hand, an expected mean of the service time can be explicitly expressed by the collision rate p, described in the article [27], [28]. The critical assumption behind this is as follows: if $\rho \geq 1$, "at each transmission attempt, and regardless of the number of retransmissions suffered, each packet collides with constant and independent p" [27]. Hence, the estimation value explicitly expressed by p may converge to a constant. In our experiments, Wait time 2 indeed converged to a constant value as the traffic rate increases as shown in Fig. 4(e); thus, we can substitute Wait time 2 obtained from the simulation for $1/\mu$ in (16). Then, the condition for instability in CSMA/CA is given by:

$$\frac{10 \times T_{\mathrm{packet}}}{\frac{1}{\hat{\mu}}} \leq R, \tag{19}$$

where $\hat{\mu}$ is an approximation of the service rate. When N is ten or twenty, $1/\hat{\mu}$ is equivalent to about 19.8 × T_{packet} or 44.7 × T_{packet}, respectively.

When ρ is one or more, some of the arrival packets get stuck in the queue, which is a crucial factor representing efficiency in wireless communications. We define the ratio of the number of packets that have not been transmitted over the total number of packets arrived within a given time as the Lost Packet Rate (LPR); the variation of LPR obtained by CSMA/CA and CSMA/AP-T when N equals ten and twenty



(a)

(b)

(c)

(d)

(e)

(f)

FIGURE 4. **Delay analysis by the proposed method where the number of terminals is ten. (a), (b) Wait time 1 distribution respectively obtained by CSMA/CA and CSMA/AP-T when *N* is ten. Low-latency communications are realized by CSMA/AP-T. (c), (d) Wait time 2 distribution respectively obtained by CSMA/CA and CSMA/AP-T when *N* is ten. The most striking result is that Wait time 2 is strictly bounded by the deterministic value in CSMA/AP-T. (e) Mean of Wait time 2 and effective throughput obtained by CSMA/CA and CSMA/AP-T when *N* is ten. Even when the traffic rate is high, effective throughput is strictly lower bounded in CSMA/AP-T thanks to bounded Wait time 2. (f) Lost packet rate (LPR) obtained by CSMA/CA and CSMA/AP-T when *N* is ten and twenty. Besides, ∘ indicates LPR obtained from *N* = 10 and × does *N* = 20. Simulation results are shown to be consistent with queuing analysis from the threshold at which LPR rises in the figure.**

is shown in Fig. 4(f). The traffic rate threshold at which LPR is greater than zero agrees well with the requirement for the traffic rate R given by (18) and (19). When LPR is greater than zero (i.e., the length of the queue becomes gradually greater over time), Wait time 1 seems to increase rapidly, corresponding to the wait time in the queue. The threshold of a rapid increase of Wait time 1 observed in Figs. 4(a) and (b) also shows good agreement with the rise of LPR.

In summary, we propose the CSMA/AP-T method, where all terminals can send a packet within a deterministic delay-bounded time, relying on precise time synchronization performed by Wi-Wi. A periodic assignment of AP for each terminal achieves bounded delay where the time offset between the successive terminals in the chronological order is set to be identical. In addition, we explicitly give the requirement on the assignment period to avoid collisions safely. Secondly, we have conducted the performance analysis on the proposed method to verify its property. As a result, low-latency packet transmission with bounded delay is demonstrated with CSMA/AP-T for ten terminals. Moreover, the delay for both proposed and conventional methods is defined analytically and shown to be consistent with the simulation results, based on queueing analysis.

V. ARBITRATION FOR WIRELESS COMMUNICATIONS BASED ON PRECISE SPACE-TIME SYNCHRONIZATION: CSMA/AP-TS

In this section, we describe the details of CSMA/AP-TS as an extension of CSMA/AP-T based on precise time-space synchronization by Wi-Wi. Once the two-dimensional geometry information of the network is appropriately identified through Wi-Wi synchronization, the time offset to avoid collisions can be as small as the propagation time between terminals. Therefore, APs can be densely packed, which allows the assignment period for collision-free arbitration to be shorter than that of CSMA/AP-T. Consequently, CSMA/AP-TS can accommodate a significantly larger number of terminals than CSMA/AP-T in many configurations.

Simultaneously, however, CSMA/AP-TS poses a certain additional cost because the order assignment mechanism is required to determine the appropriate chronological order.

A. PRINCIPLE

We first describe the basic principle of CSMA/AP-TS. The primary condition is the same as with CSMA/AP-T: a star-topology wireless network consisting of one access point and terminals, no hidden terminal problem, unlimited queue capacity for each terminal, and a fixed-length data packet to send. In addition to time synchronization, CSMA/AP-TS utilizes relative position detection achieved by Wi-Wi. The main difference between CSMA/AP-T and CSMA/AP-TS is the set of time offsets of the assignment period for successive terminals. We determine the time offset as follows:

$$T_{i,i+1} = \max\{\Delta t, \frac{d_{i,i+1}}{c}\}, \qquad i = 1, \ldots, N-1, \tag{20}$$

$$T_{N,1} = \max\{\Delta t, \frac{d_{N,1}}{c}\}, \tag{21}$$

$$T_{\mathrm{tot},N} := \sum_{i=1}^{N-1} T_{i,i+1} + T_{N,1}, \tag{22}$$

$$T_{\mathrm{ap}} = T_{\mathrm{packet}}, \tag{23}$$

where N is the number of terminals in the wireless network, assuming that all terminals are ordered. $d_{i,j}$ is the geometric propagation distance in a direct path between terminal i and terminal j, c is the propagation speed of radio waves and Δt is the designated time length for AP. T_{packet} denotes the time length to transmit a single data packet, including the propagation time from each terminal to the access point. Figs. 5(a) and (b) show examples of the assignment of AP and its chronological order based on CSMA/AP-T and CSMA/AP-TS, respectively. Algorithm 3 shows the details of the arbitration.

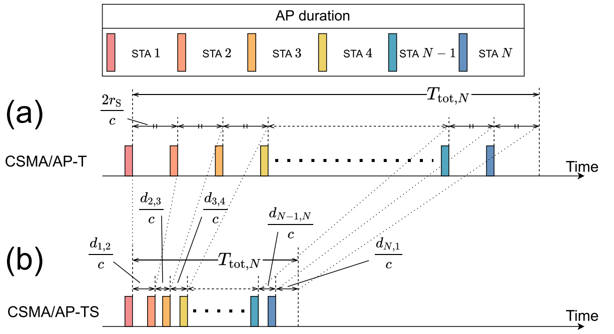


FIGURE 5. **Schematic time axis of CSMA/AP-T and CSMA/AP-TS. Time offset should be long enough to detect transmission from the successive terminal (i.e., propagation time in a direct path). Time offset in CSMA/AP-TS can be shorter than CSMA/AP-T.**

Algorithm 3 Overview of CSMA/AP-TS

Condition: Each terminal can detect AP based on precise time synchronization via Wi-Wi.

1) When terminal i wants to transmit a packet to the access point (i.e., the transmission queue is not empty), the terminal has to wait for its assigned AP.
2) If terminal i finds the channel idle via carrier sense until the end of AP,
    a) The terminal starts its transmission at the end of AP.
    b) A radio wave from the terminal assuredly arrives at terminal $j (\forall j \neq i)$, due to the setting of the time offset. *Proof:* Based on triangle inequality, $d_{i,j} (\forall j \neq i)$ is upper bounded as follows:

$$d_{i,j} \leq \begin{cases} \sum_{k=i}^{j-1} d_{k,k+1} \\ \sum_{k=i}^{N-1} d_{k,k+1} + d_{N,1} + \sum_{k=1}^{j-1} d_{k,k+1} \end{cases}, \tag{24}$$

where the former is given when $j \in [i+1, N]$, the latter is otherwise. ■

    c) The other terminals can listen to the transmission from terminal i and will not disturb it.
3) If terminal i finds the channel busy via carrier sense by the end of AP,
    a) At the end of AP, the terminal decides to postpone its transmission until its next AP, i.e., return to Step 2).

The main benefit of CSMA/AP-TS is that the lower limit of the assignment period can be smaller than that of CSMA/AP-T; thus, T_{ap} is given by $T_{\mathrm{tot},N}$ and increases the maximum potential communication bandwidth usage efficiency. The constraint to guarantee the deterministic delay is given by:

$$\exists m \in \mathbb{N}, 0 \le T_{\mathrm{packet}} - T_{\mathrm{tot},N} \times m \le \min_{\substack{i,j\in\mathbb{N}^* \\ 1\le i<j\le N}} T_{i,j}, \qquad (25)$$

If T_{ap} is set to $T_{\mathrm{tot},N}$, a terminal has to wait consecutive APs at most m times when it senses the channel as busy.

With the arbitration described above, CSMA/AP-TS guarantees equal opportunity for all terminals with a bounded delay, whose maximum is still given deterministically by (12). All terminals can send a packet within $N \times T_{\mathrm{packet}} + T_{\mathrm{ap}}$, thanks to the assignment of AP in chronological order.

B. ORDER ASSIGNMENT ALGORITHM

We assumed that the order of periodic assignment of AP had been determined prior to the arbitration. The order significantly impacts on CSMA/AP-TS; this is because the smaller $T_{\mathrm{tot},N}$ is, the more we can benefit from its temporally densely packed APs. Therefore, the order assignment algorithm is necessary for CSMA/AP-TS. Finding the best order to minimize $T_{\mathrm{tot},N}$ is equivalent to solve the traveling salesman problem (TSP); in general, finding the optimal solution is hard in polynomial time. Heuristic algorithms are known to obtain approximate solutions for TSPs, such as genetic algorithm and Nearest Neighbor (NN) [29]. In this study, we adopt NN.

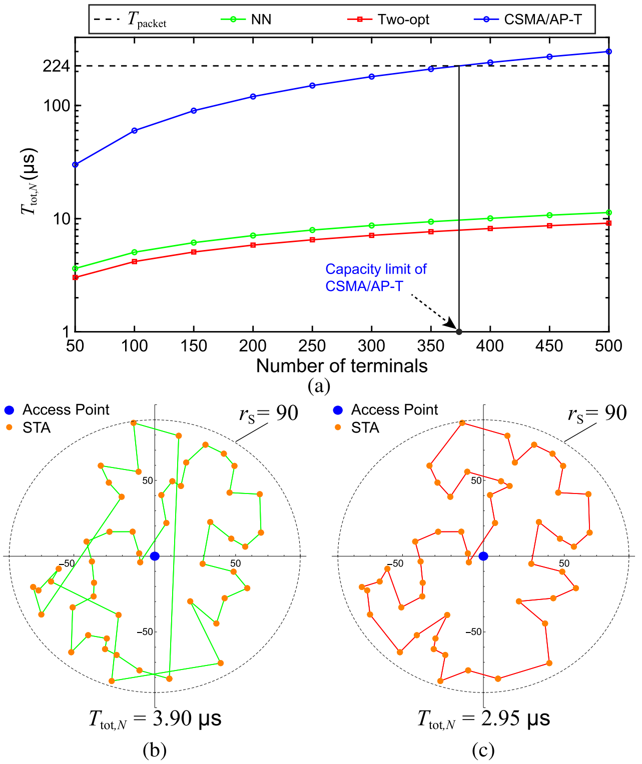
The TSP under study regarding a star-topology wireless network is formulated as follows:

$$\begin{aligned}
&\text{maximize } \sum_{i\in V}\sum_{j\in V} d_{ij}x_{ij} \\
&\text{subject to } x_{ij} \in \{0,1\} \quad (\forall i,j \in V) \\
&\qquad \sum_{i\in V} x_{ij} = 1 \quad (\forall i \in V) \\
&\qquad \sum_{j\in V} x_{ij} = 1 \quad (\forall j \in V) \\
&\qquad \sum_{i\in T}\sum_{j\in V\setminus T} x_{ij} \ge 1 \quad (\forall T \subset V, T \ne \emptyset) \qquad (26)
\end{aligned}$$

where N is the number of terminals, V is the set of terminals, and $d_{i,j}$ is the distance between terminal i and terminal j. The detail of NN for a star-topology wireless network is described in Algorithm 4.

Algorithm 4 Overview of NN for CSMA/AP-TS

```
Initialization: Choose terminal $i (i \in V)$ as the initial terminal at random, then add it to $U$.
1) As long as $|U| < N$ is satisfied, follow two steps.
    a) Choose terminal $j (j \in V \setminus U)$, which minimizes $d_{i,j}$.
    b) Update parameters: $U \leftarrow U \cup j, i \leftarrow j$.
2) Choose the path between the current terminal and the initial terminal.
```



(a)

$T_{\mathrm{tot},N}$ = 3.90 μs

(b)

$T_{\mathrm{tot},N}$ = 2.95 μs

(c)

FIGURE 6. **Performance comparison of TSP solutions from different algorithms. (a) $T_{\mathrm{tot},N}$ as a function of the number of terminals. $T_{\mathrm{tot},N}$ in CSMA/AP-TS is derived from the total length of the closed path found by NN or Two-opt. In the case of CSMA/AP-T, we calculate $T_{\mathrm{tot},N}$ following (10). (b), (c) Example of solution and $T_{\mathrm{tot},N}$ respectively obtained by NN and Tw-opt.**

We examine the impact of TSP algorithms on $T_{\mathrm{tot},N}$ with the following method for the simulations. The terminals are randomly and uniformly located within the sensitivity limit of the access point whose radius r_S is 90 m. $T_{\mathrm{tot},N}$ derives from dividing the total length of the closed path by c, except for CSMA/AP-T: $T_{\mathrm{tot},N}$ follows (10) in CSMA/AP-T. To examine the dependency of $T_{\mathrm{tot},N}$ on N, we change N from fifty to five hundred by steps of fifty. The seed of pseudorandom numbers used to specify the terminal layout is changed a thousand times for each given N, and the evaluation is averaged over them.

We first compare $T_{\mathrm{tot},N}$ obtained by CSMA/AP-T and CSMA/AP-TS; Fig. 6(a) shows $T_{\mathrm{tot},N}$ as a function of N. It is apparent that $T_{\mathrm{tot},N}$ from CSMA/AP-T increases linearly because of its definition (10); in this configuration, the capacity limit of CSMA/AP-T is 373. On the other hand, $T_{\mathrm{tot},N}$ provided by CSMA/AP-TS is approximately ten times smaller than the one from CSMA/AP-T; that is, we observed that CSMA/AP-TS allows more terminals than CSMA/AP-T and preserve equality between terminals. The maximum capacity of CSMA/AP-TS is derived by dividing T_{packet} by Δt; in this configuration, it amounts to about sixty times as many terminals as for CSMA/AP-T.

Secondly, we compare two approximation algorithms; the closed paths shown in Fig. 6(b) and (c) show the shortest paths obtained by NN and Two-opt [29], respectively.

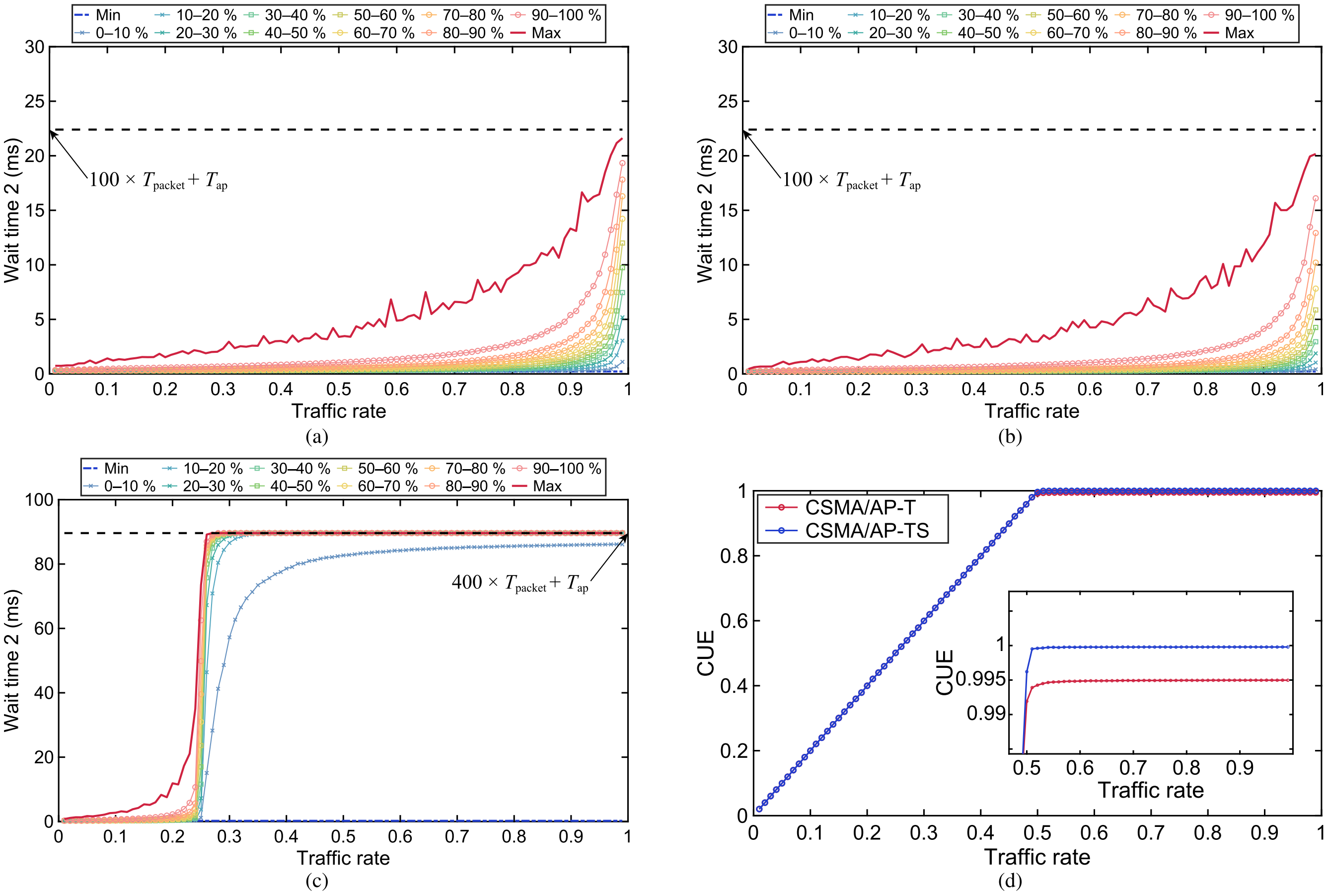


FIGURE 7. **Delay analysis of the proposed method. (a), (b) Wait time 2 distribution obtained by (a) CSMA/AP-T and (b) CSMA/AP-TS when *N* is 100. Both protocols provide bounded delay and low-latency communications. (c) Wait time 2 distribution respectively obtained by CSMA/AP-TS when *N* is 400. CSMA/AP-TS provides bounded delay even with a large number of terminals, whereas CSMA/AP-T cannot. (d) CUE with traffic rate evolution obtained by CSMA/AP-T and CSMA/AP-TS when *N* is 200. Although CUE obtained by CSMA/AP-TS is greater than the one by CSMA/AP-T when the waiting queue becomes infinite, the difference is marginal.**

Two-opt finds a shorter path than NN; however, an increase of $T_{\text{tot},N}$ is at most 24% of the one obtained by Two-opt as observed in Fig. 6(a). Therefore, sufficient performance can be obtained by NN with its simple calculations.

C. EVALUATION

We conducted the performance evaluation of CSMA/AP-TS through the comparison with CSMA/AP-T.

1) DETAILS OF SIMULATION METHODS

We first introduce some evaluation items. Following the discussion in Section IV, we evaluate Wait time 2 to verify the upper boundedness of the delay provided by the proposed method. To compare the efficiency in communication, we define the Channel Utilization Efficiency (CUE) as the ratio of the time length used for packet transmission over the consideration time. Here we assume the order assignment is completed prior to the arbitration; this is because our interest regards evaluating the pure performance improvement of CSMA/AP-TS over CSMA/AP-T.

The specifications of the wireless network are given as follows; the terminal layout is fixed during consideration time, there is no hidden terminal problem, all terminals use the same designated 2.4 GHz bandwidth for packet transmission, the data rate is 54 Mbps, the radius of the sensitivity limit r_{S} is 90 m, and the propagation speed of radio waves c is 3.0×10^8 m/s. To examine the delay dependency on N, we change N from 100 to 500 by steps of 100; indeed, CSMA/AP-T cannot control terminals more than 400 as shown in Fig. 6(a).

Secondly, the traffic model is specified as follows. As introduced in Section IV, a fixed-length data packet of 1512 Byte or T_{packet} of 224 µs is assumed. The time duration considered in the simulation lasts 20 s. The packet arrival time distribution at each terminal follows an independent exponential distribution with parameter λ:

$$\lambda = \frac{R}{100 \times T_{\text{packet}}}, \tag{27}$$

where R is the traffic rate. The seed of pseudorandom numbers is changed ten times.

For the sake of simplicity, we define the identical assignment period T_{ap} equivalent to the estimation value of $T_{\text{tot},N}$

instead of the true value, where (25) is always satisfied:

$$\hat{T}_{\mathrm{tot},N,m} = \min_{m\in\mathbb{D}}\{\frac{T_{\mathrm{packet}}}{m}\}, \tag{28}$$

where D is the set of divisors of T_{packet} and the estimation value should be greater than true $T_{\mathrm{tot},N}$ to satisfy (13).

2) PERFORMANCE ANALYSIS

We first evaluate the delay provided by two protocols; Figs. 7(a) and (b) show the Wait time 2 as a function of the traffic rate for CSMA/AP-T and CSMA/AP-TS, respectively. Each symbol in these figures deciles Wait time 2 distribution and the black dashed line shows the bounded delay value derived from (12). We observe clearly that both protocols successfully provide a delay with a deterministically defined maximum. In Fig. 7(c), the number of terminals is 400, which is greater than the capacity limit of CSMA/AP-T as shown in Fig. 6(a), demonstrating the high-capacity ability offered by CSMA/AP-TS.

Secondly, we compare these protocols from the perspective of CUE. The red and blue circular markers in Fig. 7(d) show CUE as a function of the traffic rate obtained by CSMA/AP-T and CSMA/AP-TS, respectively. CUE reaches its maximum value because of induced contentions in all terminals when the traffic rate is greater than 0.5; that is equivalent to the threshold leading to the rise of LPR according to the analysis in Section IV. The maximum value of CUE in both protocols is equally delivered by:

$$\frac{N \times T_{\mathrm{packet}}}{N \times T_{\mathrm{packet}} + T_{\mathrm{ap}}}. \tag{29}$$

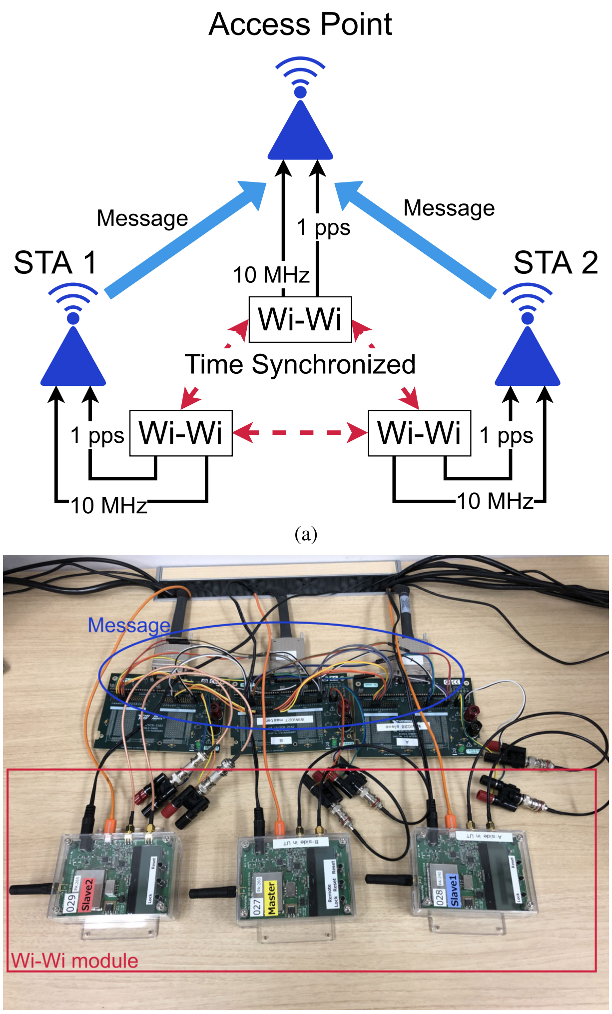
Since T_{ap} for CSMA/AP-TS is surely smaller than for CSMA/AP-T, CSMA/AP-TS uses the bandwidth more efficiently even when the traffic rate is high, as compared with CSMA/AP-T, as long as T_{ap} is equivalent to $T_{\mathrm{tot},N}$. However, the difference is only about 0.5% beyond 0.5 traffic rate, as demonstrated in the inset of Fig. 7(d); this is because the first term of the denominator is larger than the difference of T_{ap} between two protocols when N is sufficiently large.

VI. EXPERIMENTAL DEMONSTRATION

This section describes the experiment conducted to verify the principle of CSMA/AP-T with specific wireless devices implementing the Wi-Wi principle, which are called Wi-Wi in the following. In order to verify the basic principle of information transfer based on CSMA/AP-T, the experiment is based on a star-topology wired network wherein all terminals are connected with individual Wi-Wi modules to accomplish the precise time synchronization among the entire network. Note that the information is transferred over electrical cables whereas Wi-Wi time synchronization is delivered in wireless, as the primary goal of the experiments is to give a proof-of-concept based on CSMA/AP-T.

A. EXPERIMENTAL DETAILS

A schematic diagram of the experiment is shown in Fig. 8(a). We have constructed a star-topology system with three terminals, wherein one of those is operated as the access point, whereas the other two work as the transmitters called STA 1 and STA 2. Each terminal comprises a personal computer with a dedicated digital I/O device which is coupled with a Wi-Wi module.

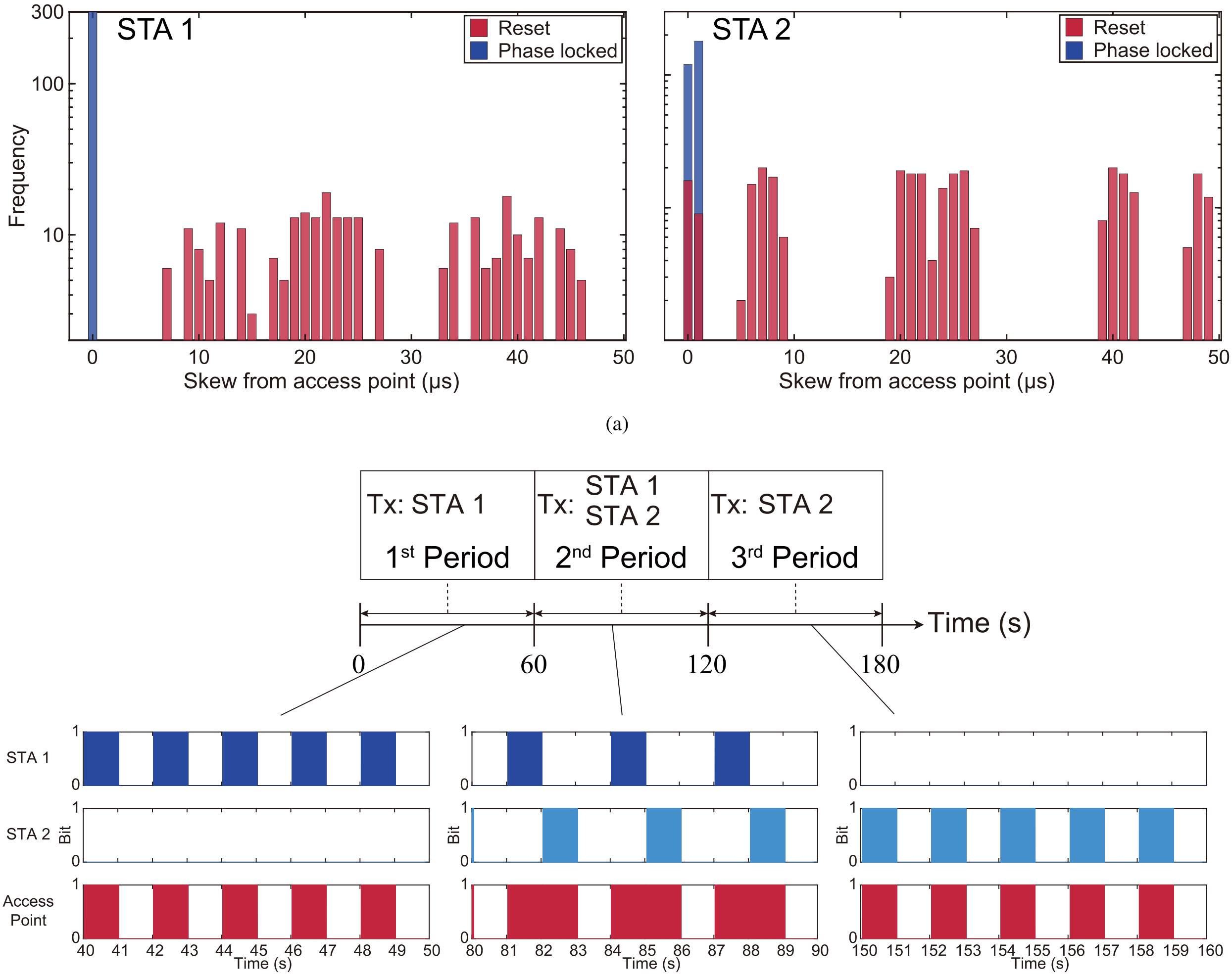


(a)

(b)

FIGURE 8. Design of the experimental setup used to verify the principle of CSMA/AP-T. (a) Schematic diagram of the experiment. The wired network is composed of three digital I/O devices, each equipped with a dedicated Wi-Wi module. One of the three terminals is considered an access point. The other two work as edge terminals, called "STA 1" and "STA 2", respectively. Wi-Wi provides each device with a 10 MHz reference signal and a 1 pps time-based clock one, which are synchronized via wireless communications at the 920 MHz band. (b) Overview of the experimental setup.

We first describe the details of the devices. The communication band of Wi-Wi modules is 920 MHz. A Wi-Wi module provides a 1 pps trigger signal and a 10 MHz reference signal, which are connected to the input ports of the digital I/O device. Fig. 8(b) shows a photograph of the experimental apparatus. All terminals are time-synchronized via Wi-Wi by phase-locking through the Wi-Wi principle described in Section III, called phase-locked state, accomplished by pressing the lock button on the Wi-Wi module itself. In contrast, pressing the reset button makes the timing asynchronous between modules.



(a)

(b)

FIGURE 9. Experimental demonstration of the proposed arbitration by CSMA/AP-T. (a) The time difference between the beginning of the reception by the access point and the detection by the other transmitter. The left figure shows the skew between the access point and STA 1 and the right one does the skew between the access point and STA 2. We can clearly observe that the phase-locked state given by Wi-Wi reduces the time difference or skew. (b) The data transmission experimental demonstration concerning equality provided by CSMA/AP-T. The upper part schematically depicts the demonstration scenario, whereas the lower part summarizes the experimentally observed data by the terminals. There is no inequality of communication when comparing both transmitters.

The arbitration mechanism of CSMA/AP-T is implemented by software using LabVIEW 2019 to control the digital I/O devices. More specifically, we utilize the following standard desktop computers to be connected to each I/O device: STA 1: Dell Precision 5820 Tower (CPU: Intel Xeon W-2102, 2.9 GHz, RAM: 16GByte, OS: Windows 10 Pro for workstations), STA 2: Dell Precision 5820 Tower (CPU: Intel Xeon W-2104, 3.2 GHz, RAM: 16GByte, OS: Windows 10 Pro for workstations), and Access point: Dell Precision Tower 3620 (CPU: Intel Core i5-6500, 3.2 GHz, RAM: 8GByte, OS: Windows 10 Pro).

The network parameters are determined as follows: the data rate is 1 Mbps, the message includes 40 digits 0 and 1 data and each transmitter transmits the packet for T_{packet}, here 1 s. The other parameters are as follows; AP duration Δt is 1 ms, assignment of AP period T_{ap} is 1 s, and identical time offset is 20 ms.

B. EXPERIMENTAL DEMONSTRATION OF CSMA/AP-T

We first evaluate the impact of precise time synchronization via Wi-Wi. Based on CSMA/AP-T, each transmitter tries to send a packet exclusively during the operation time, here 180 s. The transmitter can start its transmission if the channel is idle during the AP duration, as discussed in earlier sections. To mimic the carrier sense, each terminal detects the other transmission by monitoring the communications between the access point and the other terminal.

It is expected that the time difference between the reception time of the access point and the detection of the other transmitter will diverge without Wi-Wi because time synchronization cannot be established.

Fig. 9(a) shows the measured skew between the access point and each STA. The left figure shows the skew between the access point and STA 1, the right one We observe that the skew is significantly larger without Wi-Wi than with Wi-Wi.

The reduced skew enabled by Wi-Wi is of the essence to verify a fundamental requirement of the proposed arbitration method, because the precise AP time offset among terminals is critical for collision-free arbitration of CSMA/AP-T as well as CSMA/AP-TS.

Secondly, we confirm the validity of exclusive transmission provided by CSMA/AP-T. In the case of CSMA/CA, a particular terminal may continue data transmission even though others are continuously waiting because of its random access scheme. Conversely, CSMA/AP-T provides equal opportunity for each terminal by following the assignment of AP as theoretically and numerically demonstrated in Section IV. To experimentally demonstrate such a feature, we configure the following scenario as schematically depicted in the upper part of Fig. 9(b). In the first 60 s duration, denoted by the 1st Period, only STA 1 wants the data transfer all the time. In the subsequent 60 s duration (the 2nd Period), both STA 1 and STA 2 have the data transmission demands. Finally, in the next 60 s duration (the 3rd Period), only STA 2 wants the data transfer all the time.

Fig. 9(b) summarizes the experimentally observed data transmission by STA 1, STA 2, and the data receipt by the access point during the 1st, 2nd, and 3rd Periods. We observe that STA 1 and STA 2 transmit packets exclusively and alternately, even when both STAs always want to send packets in the 2nd Period. In addition, although the number of transmitters changes at 60 s and 120 s, CSMA/AP-T provides equal opportunity for both terminals without collision at any time. On the other hand, it is also observed that there are periodical idle time durations of the access point. Indeed, we can minimize the dead time of the access point usage when T_{ap} is set to $T_{\text{tot},N}$. However, since there are some technical problems concerning the real-time operation, we cannot set T_{ap} to $T_{\text{tot},N}$; resulting in the periodical dead time duration shown in Fig. 99(b).

VII. DISCUSSION

Before the concluding remarks, we address a few aspects of our study. We first refer to the differences between CSMA/AP-T and CSMA/AP-TS. As discussed in this paper, both can secure the delay bounded by a deterministic value. The main attribute of CSMA/AP-T is that it does not need the order assignments for each and every terminal thanks to its identical time offset. CSMA/AP-TS, on the other hand, can accommodate more terminals than CSMA/AP-T at the expense of cumbersome determination of time offset concerning the spatial information of the terminals. Each of the proposed methods will be beneficial in specific domains; for example, applications to local 5G for CSMA/AP-T by exploiting its straightforward control principle, whereas applications to a fixed massive array of robots for CSMA/AP-TS by taking advantage of its capacity and further short assignment period.

Secondly, we discuss the hidden terminal problem. This study presumes no hidden terminal problem; however, severe electromagnetic environments sometimes exist, such as physical obstacles to prevent the high-frequency radio wave from propagating. In such a case, the CSMA scheme may cause interference even when CSMA/AP is in operation. Meanwhile, since Wi-Wi utilizes a low-frequency bandwidth, which is currently experimentally set at 920 MHz, Wi-Wi signal can widely propagate thanks to diffraction. Therefore, one approach to solve the hidden terminal problem is utilizing the Wi-Wi communication bandwidth also for carrier sense, not just for time synchronization, so that the Wi-Wi signal covers the area of interest without any hidden terminals. This is a noteworthy example symbolizing the potential benefits from the separated bandwidth allocation used for Wi-Wi synchronization. Detailed discussions are expected to trigger fascinating future studies.

Finally, we refer to the effect of the mobility of terminals. To effectively exploit the fact that the CSMA/AP-T provides collision-free arbitration with bounded delay regardless of the layout, the number of terminals should be properly grasped. Therefore, managing the active participants in a given wireless network is an essential future study, also taking into account the mobility of terminals. Besides, the variation in the propagation time from the terminal to the access point is another problem when the terminal's mobility is highly variable. Ultimately, an autonomous and distributed principle is expected to be developed for solving these problems.

VIII. CONCLUSION

This paper demonstrates that, by utilizing precise time and space synchronization among terminals in wireless networks, the communication delay is strictly bounded by deterministically determined value with a simple arbitration mechanism. Wireless two-way interferometry, known as Wi-Wi, realizes the essential time and space synchronization. We utilize the notion of Arbitration Point (AP) to specify the time duration for carrier sense, which is precisely coordinated to avoid collisions. Specifically, we propose and demonstrate two arbitration protocols; one is CSMA/AP-T with an identical time duration for all terminals guaranteed by time synchronization, the other is CSMA/AP-TS with optimized time duration for collision-free arbitration based on space-time synchronization. By exploiting the shared precise timing information, both protocols equally provide chances for data transmission with all terminals; thus, realize the delay-bounded property. Further, we show an analytical formula based on queueing theory to examine the bounded delay in the proposed arbitration.

The precise time synchronization by Wi-Wi enables all participants to share their timing information, meaning that each terminal can autonomously detect its AP. The periodic assignment of AP for each terminal guarantees delay-bounded property in both proposed protocols. Besides, we have formulated explicit conditions and requirements to assure the delay upper boundedness under time and space synchronization. More specifically, the identical time offset in CSMA/AP-T allows all terminals to start their data transmission within the bounded delay regardless of the terminal layout. On the other hand, CSMA/AP-TS benefits from utilizing the two-dimensional geometry information of terminals; that is, the time offset between successive data transmission chances becomes shorter than with CSMA/AP-T. The consecutive APs assigned to each and every terminal are temporally densely packed by appropriately ordering the timing for all terminals in the network. Thus, we demonstrate that CSMA/AP-TS can accommodate approximately 60 times more terminals than CSMA/AP-T in the same configuration. Meanwhile, CSMA/AP-TS presupposes solving a traveling salesman problem (TSP) for the assignment of AP in the appropriate chronological order. We show that a simple heuristic algorithm for TSP can yield sufficiently tolerate performance with limited computation resources.

In addition, we have constructed a star-topology wired network for the experimental demonstration of the proposed arbitration protocol, wherein all terminals are time-synchronized by Wi-Wi. CSMA/AP-T is implemented to confirm its fundamental properties, especially equality in communications. The reduced skew by Wi-Wi time synchronization is clearly observed; as a result, collision-free data transmission is demonstrated based on the precisely controlled timing information provided by Wi-Wi while ensuring performance equality between all contended terminals.

Throughout this paper, we examined the delay bounded wireless communications based on the Wi-Wi paradigm assuming space-time synchronization established via wireless signals. In the meantime, the Wi-Wi paradigm may provide novel directions in innovation for Information and Communication Technology (ICT) development; for instance, improving the conventional asynchronous wireless communication such as slotted-ALOHA [30], or constructing versatile autonomous self-organized networks based on the precise timing information.

In summary, this study paves a new way for wireless communications with upper bounded, which provides the basis of ultra-reliable and high-quality information transfer accomplished by the precise time and space synchronization provided by Wi-Wi.

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REFERENCES

[1] W. Jiang, B. Han, M. A. Habibi, and H. D. Schotten, "The road towards 6G: A comprehensive survey," *IEEE Open J. Commun. Soc.*, vol. 2, pp. 334–366, 2021.

[2] M. A. Lema, A. Laya, T. Mahmoodi, M. Cuevas, J. Sachs, J. Markendahl, and M. Dohler, "Business case and technology analysis for 5G low latency applications," *IEEE Access*, vol. 5, pp. 5917–5935, 2017.

[3] M. Raza, N. Aslam, H. Le-Minh, S. Hussain, Y. Cao, and N. M. Khan, "A critical analysis of research potential, challenges, and future directives in industrial wireless sensor networks," *IEEE Commun. Surveys Tuts.*, vol. 20, no. 1, pp. 39–95, 1st Quart., 2018.

[4] L. D. Xu, E. L. Xu, and L. Li, "Industry 4.0: State of the art and future trends," *Int. J. Prod. Res.*, vol. 56, no. 8, pp. 2941–2962, Mar. 2018.

[5] M. H. Miraz, M. Ali, P. S. Excell, and R. Picking, "A review on Internet of Things (IoT), Internet of everything (IoE) and Internet of nano things (IoNT)," in *Proc. Internet Technol. Appl. (ITA)*, Wrexham, U.K., Sep. 2015, pp. 219–224.

[6] G. Bianchi, L. Fratta, and M. Oliveri, "Performance evaluation and enhancement of the CSMA/CA MAC protocol for 802.11 wireless LANs," in *Proc. 7th Int. Symp. Pers., Indoor, Mobile Commun. (PIMRC)*, Taipei, Taiwan, Oct. 1996, pp. 392–396.

[7] Y. Xiao and J. Rosdahl, "Throughput and delay limits of IEEE 802.11," *IEEE Commun. Lett.*, vol. 6, no. 8, pp. 355–357, Aug. 2002.

[8] T. L. Marzetta, "Noncooperative cellular wireless with unlimited numbers of base station antennas," *IEEE Trans. Wireless Commun.*, vol. 9, no. 11, pp. 3590–3600, Nov. 2010.

[9] E. G. Larsson, O. Edfors, F. Tufvesson, and T. L. Marzetta, "Massive MIMO for next generation wireless systems," *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 186–195, Feb. 2014.

[10] L. Lu, G. Y. Li, A. L. Swindlehurst, A. Ashikhmin, and R. Zhang, "An overview of massive MIMO: Benefits and challenges," *IEEE J. Sel. Topics Signal Process.*, vol. 8, no. 5, pp. 742–758, Oct. 2014.

[11] F. Rusek, D. Persson, B. K. Lau, E. G. Larsson, T. L. Marzetta, and F. Tufvesson, "Scaling up MIMO: Opportunities and challenges with very large arrays," *IEEE Signal Process. Mag.*, vol. 30, no. 1, pp. 40–60, Jan. 2013.

[12] P. Yang, Y. Xiao, M. Xiao, and S. Li, "6G wireless communications: Vision and potential techniques," *IEEE Netw.*, vol. 33, no. 4, pp. 70–75, Jul. 2019.

[13] M. Maróti, B. Kusy, G. Simon, and Á. Lédeczi, "The flooding time synchronization protocol," in *Proc. 2nd Int. Conf. Embedded Netw. Sensor Syst.*, New York, NY, USA, Nov. 2004, pp. 39–49.

[14] J. C. Eidson, M. Fisher, and J. White, "IEEE-1558 standard for a precision clock synchronization protocol for networked measurement and control systems," in *Proc. 34th Annu. PTTI Meeting*, Reston, VA, USA, Dec. 2002, pp. 243–254.

[15] N. Shiga, K. Kido, S. Yasuda, B. Panta, Y. Hanado, S. Kawamura, H. Hanado, K. Takizawa, and M. Inoue, "Demonstration of wireless two-way interferometry (Wi-Wi)," *IEICE Commun. Exp.*, vol. 6, no. 2, pp. 77–82, 2017.

[16] D. Koyama, Y. Wang, N. Shiga, S. Yasuda, N. Chauvet, and M. Naruse, "Low latency information transfer based on precision time synchronization via wireless interferometry," *NOLTA, IEICE*, vol. 12, no. 2, pp. 225–235, 2021.

[17] B. P. Crow, I. Widjaja, J. G. Kim, and P. T. Sakai, "IEEE 802.11 wireless local area networks," *IEEE Commun. Mag.*, vol. 35, no. 9, pp. 116–126, Sep. 1997.

[18] S. C. Ergen and P. Varaiya, "PEDAMACS: Power efficient and delay aware medium access protocol for sensor networks," *IEEE Trans. Mobile Comput.*, vol. 5, no. 7, pp. 920–930, Jul. 2006.

[19] S. C. Ergen and P. Varaiya, "Energy efficient routing with delay guarantee for sensor networks," *Wireless Netw.*, vol. 13, no. 5, pp. 679–690, Oct. 2007.

[20] A. Sahoo and S. Chilukuri, "DGRAM: A delay guaranteed routing and MAC protocol for wireless sensor networks," *IEEE Trans. Mobile Comput.*, vol. 9, no. 10, pp. 1407–1423, Oct. 2010.

[21] H. Farag, M. Gidlund, and P. Österberg, "A delay-bounded MAC protocol for mission- and time-critical applications in industrial wireless sensor networks," *IEEE Sensors J.*, vol. 18, no. 6, pp. 2607–2616, Mar. 2018.

[22] D. W. Hanson, "Fundamentals of two-way time transfers by satellite," in *Proc. 43rd Annu. Symp. Freq. Control*, May 1989, pp. 174–178.

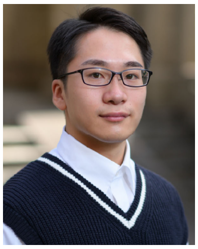
[23] M. Fujieda, T. Gotoh, F. Nakagawa, R. Tabuchi, M. Aida, and J. Amagai, "Carrier-phase-based two-way satellite time and frequency transfer," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 59, no. 12, pp. 2625–2630, Dec. 2012.

[24] S. Yasuda, R. Ichikawa, Y. Hanado, S. Kawamura, H. Hanado, H. Iwai, K. Namba, Y. Okamoto, K. Fukunaga, T. Iguchi, and N. Shiga, "Horizontal atmospheric delay measurement using wireless two-way interferometry (Wi-Wi)," *Radio Sci.*, vol. 54, no. 7, pp. 572–579, Jul. 2019.

[25] B. R. Panta, K. Kido, S. Yasuda, Y. Hanado, S. Kawamura, H. Hanado, K. Takizawa, M. Inoue, and N. shiga, "Distance variation monitoring with wireless two-way interferometry (Wi-Wi)," *Sens. Mater.*, vol. 31, no. 7, pp. 2313–2321, Jul. 2019.

[26] G. Bolch, S. Greiner, H. D. Meer, and K. S. Trivedi, *Queueing Networks and Markov Chains: Modeling and Performance Evaluation With Computer Science Applications*, 2nd ed. New York, NY, USA: Wiley, 2006.

[27] G. Bianchi, ''Performance analysis of the IEEE 802.11 distributed coordination function,'' *IEEE J. Sel. Areas Commun.*, vol. 18, no. 3, pp. 535–547, Mar. 2000.
[28] A. Abdrabou and W. Zhuang, ''Service time approximation in IEEE 802.11 single-hop ad hoc networks,'' *IEEE Trans. Wireless Commun.*, vol. 7, no. 1, pp. 305–313, Jan. 2008.
[29] D. L. Applegate, R. E. Bixby, V. Chvatal, and W. J. Cook, *The Traveling Salesman Problem: A Computational Study*. Princeton, NJ, USA: Princeton Univ. Press, 2007.
[30] L. G. Roberts, ''ALOHA packet system with and without slots and capture,'' *ACM SIGCOMM Comput. Commun. Rev.*, vol. 5, no. 2, pp. 28–42, Apr. 1975.



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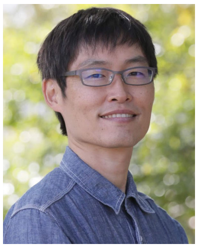

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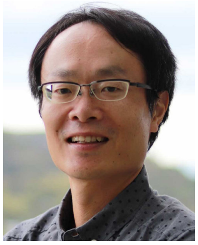

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