An Efficient Terminal Selection Method for Multi-Hop Synchronization in Direct Communication Networks

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In direct communication, in order to deliver synchronization information to mobile terminals outside the coverage area of the base station, some terminals should propagate the synchronization signal through the synchronization channel. In general, a mobile terminal transmits a synchronization signal based on the received synchronization signal. If the received signal strength is below the propagation threshold, the mobile terminal sends a synchronization signal to extend the coverage of the direct communication network. Therefore, the propagation threshold value is closely related to the performance of direct communication networks. If the threshold value is too low, only a minimal number of terminals transmit synchronization information. Thus, the coverage of that direct communication network is limited. On the other hand, if the threshold value is too high, most terminals will transmit synchronization messages, triggering collisions. However, it is difficult to find the optimal propagation threshold value over the entire direct communication network. Therefore, we propose a heuristic method for finding the most efficient threshold value after declaring the decision variables. The proposed method minimizes the probability of collisions between the mobile terminals’ signals on the synchronization channel. By comparing our simulation results with the numerical ones, we show the validity of the proposed synchronization method.

Keywords: synchronization, collision, direct communication, PPDR, IEEE 802.16n

1. INTRODUCTION

National calamities and disasters, such as the September 11 terrorist attacks and Boston marathon bombings in the U.S., or the Fukushima Daiichi nuclear disaster in Japan, continue to take place. Therefore, emergency communication networks, which are aimed at lifesaving and catastrophe recovery, are considered important. Moreover, the sinking of the MV Sewol, which occurred in Korea in April 2014, brought into relief the...
limitations of previous emergency communication networks, such as the Terrestrial Trunked Radio (TETRA) [1] and Association of Public-Safety Communications Officials (APCO) [2]. Therefore, it is clearly urgent to conduct research to complement and improve them [3].

Europe and Korea have used a European standard, called TETRA, as an emergency communication network for responding to national disasters or calamities [1, 4, 5]. However, when an emergency occurs, ordinary people have difficulty gaining access to such disaster communication networks [4]. In order to overcome this problem, ongoing research is focused on making such disaster communication networks compatible with existing open communication networks [4-6]. For example, research into using 3GPP LTE [7] and IEEE 802.16 [8] technologies as special-purpose broadband wireless networks is actively being conducted. One of the representative standards for disaster communication is IEEE 802.16n [5].

To employ special-purpose wireless communication networks, both the 3GPP LTE and the IEEE 802.16 technologies must support direct communication. The direct communication communicates between terminals without a base station. In direct communication, it is important to obtain time synchronization to reduce the interference between the user signals and the subcarriers. The performance of OFDMA systems, such as the 3GPP LTE and IEEE 802.16, is especially very sensitive to the synchronization. Thus, the OFDMA system requires highly precise synchronization.

In direct communication, the terminal located within the base station coverage area achieves time synchronization with the base station by using synchronization channels. A synchronization channel delivers preamble and synchronization messages. Through the synchronization channel, the terminal may also transmit time synchronization information periodically to maintain direct communication between the terminals.

In the process of obtaining inter-terminal time synchronization, the number of synchronization channels is limited. Thus, when too many terminals periodically send synchronization signals, collisions occur between them. To resolve this problem, only the necessary terminals must transmit the synchronization signal. In general, the necessary terminal is selected based on the received signal strength. If the received synchronization signal is below a propagation threshold, the terminal sends the synchronization signal to extend the coverage of the direct communication range. Therefore, the propagation threshold value is deeply related to the performance of the direct communication network. However, finding the optimal value of the propagation threshold over an entire direct communication network triggers a considerable time delay. Therefore, we propose a heuristic method of efficiently finding the propagation threshold value in the process of obtaining inter-terminal time synchronization for multi-hop direct communication. By considering a single terminal, rather than the entire network, the proposed method solves the terminal selection problem without incurring a large amount of overhead.

### 2. RELATED WORKS

#### 2.1 Time Synchronization Methods

The methods of time synchronization between the terminals can be classified into
two approaches: the sender-receiver and receiver-receiver approaches [9]. The sender-receiver approach is a method that exchanges synchronization messages between a sender and a receiver. This approach is generally used for synchronization of ad hoc networks such as sensor networks. Representative methods of the sender-receiver approach include the flooding time synchronization protocol [10, 17] and time-sync protocol for sensor networks [11, 18]. In contrast, the receiver-receiver approach is widely used in network infrastructures such as BS or AP-based mobile communication systems. In the receiver-receiver approach, the terminals are time-synchronized by exchanging synchronization messages between those terminals that received the same reference broadcast messages. Reference Broadcast Synchronization (RBS) [12, 19] is known as a representative receiver-receiver approach. It is also widely adopted as the direct communication method for many emergency communication networks.

In RBS, a reference beacon is broadcasted by the reference node. Those nodes that receive it maintain synchronization and share this time with their neighboring receiving nodes. However, because the distance between the reference node and the neighboring receivers is not constant, it is difficult to use RBS in an environment with high propagation delay times. In order to overcome this limitation, protocols using loops existing in the network have been proposed [13-15], including Rate Adaptive Time Synchronization (RATS), Routing Integrated Time Synchronization (RITS), and Control Time Protocol (CTP) [9, 16]. The RATS and the RITS utilize one-way message exchange and the CTP uses two-way message exchange.

However, even though such methods are utilized, the number of synchronization channels used to obtain inter-terminal time synchronization is limited. It is not a good idea for an arbitrary terminal to periodically transmit synchronization signals in multi-hop direct communications. To resolve this problem, a terminal on the synchronization channel can be selected as a representative of all of the terminals in the network. However, the process of integrating the information from countless terminals, deriving a result, and delivering it to all of the terminals in the network is time-consuming.

The contention collision probability is an important issue not only in time synchronization but also in data delivery. Especially, in the VANET, there have been many related works that were talking about how to select the proper node for propagating the data packets [20-23]. However, for the efficient discussion, we will focus on time synchronization in this paper.

2.2 Problem Definition of Multi-hop Synchronization

Based on Fig. 1, the process of multi-hop synchronization is described as follows. Terminal A obtains synchronization by directly approaching the frame of the base station. But terminal B obtains synchronization indirectly by receiving the synchronization messages delivered by terminal A through the synchronization channel. In the same way, terminal C obtains synchronization through terminal B. Ultimately, the synchronization channel is used for terminals that cannot directly receive the preamble from the base station. Instead, they receive the preamble through multi-hops.
Fig. 1. Multi-hop synchronization.

Fig. 2. Impetus for multi-hop synchronization.

Fig. 2 shows an example of collision between terminals when a terminal located outside the base station’s cell and another one situated within the base station’s cell without time synchronization. Direct communication between terminals B and C interferes with the communication between the base station and terminal A. To avoid such a collision, it is necessary for terminals located outside the base station’s cell to be synchronized by a multi-hop synchronization mechanism. For this purpose, the general direct communication networks reserve the synchronization channel, which is a control block used for the delivery of the synchronization message.

The delivery of synchronization messages can succeed by the contention access method. That is, dispersed terminals competitively occupy and use a synchronization channel at the proper time through carrier sensing. When a synchronization channel is indiscriminately abused, message collision is inevitable. In this case, a bottleneck phenomenon occurs in the synchronization channel. Thus, terminals located outside the base station’s communication range fail to synchronize. For instance, terminals E, F, and G within the base station’s cell directly obtain synchronization through the base station’s preamble. They also intend to deliver synchronization messages to terminal H outside the cell. If terminals E, F, and G attempt to deliver messages concurrently whenever the synchronization channel is allocated, terminal H does not receive a single message due to collision. In order to preempt such a collision and prevent the abuse of the synchronization channel, it is a good idea that only a single terminal among terminals E, F, and G to participate in the multi-hop synchronization process.

In this paper, we propose a method of finding an answer to the question, “How will a set of terminals participating in the delivery of synchronization messages be selected?” The proposed method prevents, as much as is possible, message losses resulting from collisions. To accomplish this, it keeps the number of terminals participating in delivering synchronization messages as small as possible, while enabling the multi-hop synchronization of as many terminals as possible. Through the proposed method, we can avoid the negative effects of the indiscriminate abuse of a synchronization channel.
2.3 Overview of Terminal Selection Model

The selection of terminals for transmitting synchronization messages in consideration of the entire network map is extraordinarily difficult and overhead is significant. Calculating an appropriate set of terminals by considering the locations of all the terminals consumes a great deal of time and incurs large transmission overhead. Thus, in this paper, we consider a heuristic terminal selection model of solving the problem of selecting terminals for transmitting synchronization messages. Because the heuristic model solves the problem from the perspective of a single terminal, it does not incur inordinate overhead costs.

In the heuristic model, the propagation threshold value ($P_{BS}$) of the synchronization signals from the base station (BS) and the propagation threshold value ($P_{MS}$) of the synchronization signals from the mobile station (MS) terminals are selected in advance. Through these thresholds, the terminals to use for transmitting synchronization messages are chosen adaptively. In this model, when a MS receives the BS’s synchronization message, the synchronization message is transmitted in the case where the received signal strength of the message is lower than the current BS’s propagation threshold value. When a MS receives the synchronization message of a neighboring MS, it checks the number of hops of that message. If the number of hops of the received message is the same as that of the synchronization message to be transmitted, it checks again the signal strength of the received synchronization message. If the received signal strength is higher than the current MS propagation threshold value, it stops the transmission of the synchronization message. Otherwise, the MS continuously sends the synchronization message on the synchronization channel. The hop count is used to determine if the transmission of the synchronization message is necessary when the received synchronization message has the same hop count of the synchronization message to be transmitted. In such a case, the transmitting the synchronization message may be duplicated and therefore, the MS checks again the signal strength of the received synchronization message to reduce the inefficient transmission.

By using the propagation threshold value of the heuristic model, the number of MSs that transmit the synchronization message can be adaptively adjusted and the message losses caused by collision can be minimized. However, if the propagation threshold value is too low, only a minimal number of MSs transmit synchronization message. Thus, many MSs fail to receive the synchronization information. If the propagation threshold value is too high, most MSs transmit synchronization messages, causing more collisions. Therefore, it is evident that the selection of the transmission MS set is affected by the propagation threshold value and such a selection can be represented as one of determining the optimal propagation threshold value.

3. SOLUTION TO THE TERMINAL SELECTION PROBLEM

To find the optimal propagation threshold value and solve the terminal selection problem, we first define the environment reflection functions for reflecting the operational environment of the terminals. The environment reflection functions consist of contention collision probability function, reachable area function, and connectivity func-
tion. The contention collision probability function represents the probability of a collision caused by the neighboring MSs from the perspective of the central MS. The reachable area function refers to the coverage area outside of the BS for the MS within the BS’s coverage to deliver synchronization messages to MSs outside the BS’s coverage area. The connectivity function refers to the link connectivity required to deliver synchronization messages while forming multi-hops. The objective function is derived from the contention collision probability function to which the decision-making variables $P_{BS}$ and $P_{MS}$ are reflected. The constraint condition formula of $P_{BS}$ is obtained from the derived contention collision probability function and reachable area function. The constraint condition formula of $P_{MS}$ is obtained from the derived connectivity function. These constraints are used to find the optimal solution of the objective function.

3.1 Environment Reflection Functions

3.1.1 Contention collision probability function

Let’s call a MS which gets a synchronization channel and becomes synchronized as a central MS. After synchronized, the central MS may transmit the synchronization message through the synchronization channel. From the perspective of the central MS, contention conflict occurs when a surrounding MS occupies the same synchronization channel as that of the central MS. The surrounding MS includes not only exposed MSs but also hidden MSs. Thus, the probability of contention collision is the same as the possibility that all surrounding MSs do not use synchronization channels, which is different from that of the central MS. Therefore, the possibility for contention collision to happen from the perspective of a central MS is

$$1 - (\frac{T - 1}{T})^D,$$

where $T$ means the number of channels and $D$ means the number of MSs that transmit synchronization messages.

The possibility for contention collision to take place is expressed as the average for all MSs and defined as the contention collision probability function as

$$\frac{1}{N} \sum_{j=1}^{N} (1 - (\frac{T - 1}{T})^{\sum_{i} L_{ij}}),$$

where $N$ is the total number of MSs, $i$ is an ambient MS, and $j$ is a central MS. Here, we note that, when there is a link between $i$ and $j$, the value of the available link matrix $L_{ij}$ is equal to one and when there is no link, $L_{ij}$ is equal to zero.

3.1.2 Reachable area function

For a MS within a BS's transmission range to deliver synchronization information to a MS outside its range, there may be an area not overlapping with the coverage area of
the BS. From the perspective of the entire network map, the larger the area is, the more favorable the conditions become for the spreading of synchronization information. To derive a reachable area function, let us suppose that a MS i exists within the coverage range of the BS, $R_{BS}$, as shown in Fig. 3. And an arbitrary point $p$ exists out of $R_{BS}$ but within $R_{BS} + R_{MS}$ where $R_{MS}$ is the coverage range of the MS. When at least a single MS i, whose distance from an arbitrary point $p$ is shorter than $R_{MS}$ exists, point $p$ becomes a reachable point. Also, the reachable area function is defined as the ratio of the number of reachable $p$s to all $p$s.

When the distance between an arbitrary point $p$ and an arbitrary MS i is smaller than $R_{MS}$, $p$ becomes a reachable point. Depending upon whether $p$ is reachable or not, we compose a matrix $A_p$ whose value is 1 when it is possible to reach $p$ and 0 otherwise. That is, $A_p$ denotes a reachable matrix and $A_p$ is 1 if the distance between an arbitrary point $p$ and a MS is smaller than $R_{MS}$.

Fig. 3. Reachable area.

When the number of arbitrary points $p$s in the area between $R_{BS}+R_{MS}$ and $R_{BS}$ is $M$, the reachability function may be derived as follows:

$$
\sum_{p=1}^{M} A_p
$$

(3)

3.1.3 Connectivity function

Connectivity between MSs is important to ensure that the synchronization information of a BS goes beyond its coverage area and is delivered from MS to MS. Because synchronization channels are delivered while following multi-hops from a BS, the synchronization channel delivered with smaller hops has more priority. Thus, connectivity is defined as the ratio of the number of synchronization channels with a smaller number of hops than the number of hops of the synchronization channels to be transmitted by the MS among the total number of sensed synchronization channels. That is, the connectivity is the number of lower hop links divided by the number of usable links.

Reliability improves when it is insensitive to random variations of the received signal intensity value. The signal intensity is relatively strong and insensitive when the re-
receiving MS is close to the sending MS. Thus, reliability is affected by the distance between the sending MS and the receiving MS. That is, the shorter the distance, the higher the reliability, and vice versa. Thus, reliability is calculated by integrating the probability density function of the normal distribution from the distance where the signals are receivable to infinity, given that the random variation of the received signal intensity has normal distribution characteristics.

\[
\int_{dist-R}^{\infty} \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{x^2}{2\sigma^2}} dx.
\]

(4)

Here, the connectivity function is derived by multiplying the ratio of synchronization channels with a smaller number of hops than that of synchronization channels to be transmitted reliably by the MS, as follows:

\[
\frac{1}{N} \sum_{j=1}^{N} \frac{r_j H_{ij}}{\sum_{i=1}^{N} L_{ij}},
\]

(5)

where \(r_j\) is the reliability and \(H_{ij}\) is the matrix representing those links with a smaller hop count than that of the synchronization channels to be transmitted reliably by the MS.

### 3.2 Decision-Making Variables

The propagation threshold values \((P_{BS}, P_{MS})\) can be used as decision-making variables. The effects of the decision-making variables are different based on where the synchronization channels originate from. When the synchronization channel messages originate from the BS, the distance between the BS and the MS should be longer than the reference distance of \(P_{BS}\). Simultaneously, in order to receive the signals, the distance between the BS and the MS should be smaller than the radius of the BS coverage, \(R_{BS}\). Therefore, only those MSs that exist between the reference distance of \(P_{BS}\) and \(R_{BS}\) transmit synchronization messages.

When the synchronization channels originate from other MSs and the synchronization channels have the same number of hops as those that the MS intends to transmit, the MS identifies whether it retransmits the synchronization channel messages or not by using the decision-making variable, \(P_{MS}\). If the distance between the two MSs is shorter than the reference distance of \(P_{MS}\), the MS stops transmitting synchronization messages. Otherwise, the MS continues sending them.

### 3.3 Objective Function

An objective function is derived by reflecting the two decision-making variables \((P_{BS}, P_{MS})\) on the earlier defined contention collision probability function. In this paper, we assume that there is a BS and MSs are uniformly distributed with a constant density. Prior to inducing the objective function, we derive the ratio of MSs that transmit syn-
chronization messages in order to calculate the probability of contention conflict.

3.3.1 Ratio of MSs transmitting synchronization messages

If we focus on MSs that transmit synchronization messages, only those MSs existing between \( P_{MS} \) and \( R_{MS} \) send synchronization messages. Here, the ratio of MSs that transmit synchronization messages, except for the central MS, can be expressed as the ratio of the area between \( P_{MS} \) and \( R_{MS} \) to the MS coverage area, as follows:

\[
\text{txRatio} = \frac{\pi R_{MS}^2 - \pi P_{MS}^2}{\pi R_{MS}^2} = \frac{R_{MS}^2 - P_{MS}^2}{R_{MS}^2} = 1 - \left( \frac{P_{MS}}{R_{MS}} \right)^2. \tag{6}
\]

By the way, from the perspective of the network as a whole, Eq. (6) does not make sense because the MSs that transmit synchronization messages affect the transmission of the synchronization messages of the other MSs. By considering the dependency between the MSs, Eq. (6) can be modified as follows:

\[
\text{txRatio} = \frac{\left( \pi R_{MS}^2 - \pi P_{MS}^2 \right) \times \pi R_{MS}^2 - \pi P_{MS}^2}{\pi R_{MS}^2} \times \frac{R_{MS}^2 - P_{MS}^2}{R_{MS}^2} = \left( 1 - \left( \frac{P_{MS}}{R_{MS}} \right)^2 \right)^2. \tag{7}
\]

3.3.2 Induction of an objective function

If a BS is assumed to exist at the center of the network, the network may be divided into the exterior and interior parts of \( P_{BS} \). The contention collision probability of the MSs existing in the interior area of \( P_{BS} \) almost converges to zero. The contention collision probability of the MSs existing at the exterior area of \( P_{BS} \) can be calculated as follows where \( k \) is the radius of the entire network:

\[
\frac{\pi k^2 - \pi P_{BS}^2}{\pi k^2} \times \left( 1 - \left( \frac{T - 1}{T} \right)^2 \right). \tag{8}
\]

In Eq. (8), by replacing the term \( D \), which refers to the number of MSs transmitting synchronization messages near the central MS, into \( \text{txRatio} \) in Eq. (6) multiplied by \( d \), which is the number of MSs existing within the MS coverage, the following objective function is derived:

\[
\frac{k^2 - P_{BS}^2}{k^2} \times \left( 1 - \left( \frac{T - 1}{T} \right)^2 \right) d\left( 1 - \left( \frac{P_{MS}}{R_{MS}} \right)^2 \right). \tag{9}
\]
3.4 Constraint Function

In this section, the constraints on the $P_{BS}$ and $P_{MS}$, which are decision-making variables, are derived from the basic network environment and the environment reflection function. The constraint condition equations of $P_{BS}$ and $P_{MS}$ are derived from the reachable area function and connectivity function, respectively.

3.4.1 Constraint condition of the BS propagation threshold value

We note that $P_{BS}$ is commonly smaller than $R_{BS}$. Furthermore, the environmental reflection function, which is the reachable area function, is strongly related to $P_{BS}$. Thus, in this paper, we derive the constraint condition of $P_{BS}$ from the reachable area. Even though we aim at minimizing the number of MSs that transmit synchronization messages, if the number of MSs transmitting synchronization messages is very small, the reachable area is reduced. Thus, we derive the constraint condition equation by finding the maximal $P_{BS}$ value that does not reduce the reachable area.

The Marginot Line is a condition where the MSs at the edges of the BS coverage are arranged at certain intervals. If we divide the circumference of the BS coverage by the average interval between the MSs, the number of MSs existed at the edges of the BS’s coverage area can be calculated. First, the circumference of the BS’s coverage area is derived by using the circle’s circumference formula. Next, the average interval between the MSs is derived using the number of MSs existing within the MS coverage area $(d)$ and the radius of the MS coverage area. We note that the ratio of the number of MSs to the MS coverage is approximately equal to the ratio that just two MSs exists in a square made by the average MS distance, $x$. Thus, the average MS distance can be derived as follows:

$$\frac{d}{\pi R_{MS}^2} \approx \frac{2}{x^2} \Rightarrow x \approx \sqrt{\frac{2\pi R_{MS}^2}{d}}. \quad (10)$$

By dividing the circumference of the BS’s coverage area by $x$, the number of MSs existed at the edge of the BS’s coverage area is derived as follows:

$$\frac{2\pi R_{BS}}{\frac{2\pi R_{MS}^2}{d}}. \quad (11)$$

In an actual operating environment, the number of MSs arranged at the edge of the BS’s coverage area should be smaller than the number of MSs existing between the actual $P_{BS}$ and $R_{BS}$. Therefore, the actual number of MSs can be calculated by multiplying the area between $P_{BS}$ and $R_{BS}$ by the ratio of the number of MSs to the MS coverage area as follows:

$$(\pi R_{BS}^2 - \pi P_{BS}^2) \times \frac{d}{\pi R_{MS}^2}. \quad (12)$$
Because the number of MSs laid out at the edges of the BS’s coverage area is smaller than the number of MSs actually existing between $P_{BS}$ and $R_{BS}$, the following equation is deprived:

$$2\pi R_{BS}^2 < (R_{BS}^2 - P_{BS}^2) \times \frac{d}{R_{MS}^2}.$$ \hspace{1cm} (13)

By rearranging Eq. (13) to focus upon $P_{BS}$, the constraint condition of the BS propagation threshold value is expressed as:

$$P_{BS} < \sqrt{R_{BS}^2 - R_{BS}^2 \times \frac{2\pi R_{MS}^2}{d}}.$$ \hspace{1cm} (14)

### 3.4.2 Constraint condition of the MS propagation threshold value

The $P_{MS}$ has a positive value and is smaller than $R_{MS}$. In addition, $P_{MS}$ is deeply related to the connectivity. From the perspective of MSs transmitting synchronization messages, at least one lower hop link should exist. This is because the synchronization information should be continuously delivered and maintained. The number of lower hop links needed is approximately equal to half the number of MSs that transmit synchronization messages. In this paper, only the MSs that reside in the area between $P_{MS}$ and $R_{MS}(R_{MS}^2 - P_{MS}^2) \times d/ R_{MS}^2$ can send synchronization messages. So, the number of MSs that transmit the synchronization message can be calculated by multiplying $txRatio$ (Eq. (7)) by the area between $P_{MS}$ and $R_{MS}$. Therefore, the constraint condition is derived as follows:

$$1 < \frac{1}{2} ((R_{MS}^2 - P_{MS}^2) \times \frac{d}{R_{MS}^2} \times (1 - P_{MS}^2 / R_{MS}^2)^2).$$ \hspace{1cm} (15)

By rearranging Eq. (15) to focus upon $P_{MS}$, the constraint condition of the MS propagation threshold value is expressed as:

$$P_{MS} < \sqrt{R_{MS}^2 - \sqrt{2} R_{MS}^2 / \sqrt{d}}.$$ \hspace{1cm} (16)

### 3.5 Optimal Solution

In this section, we derive an optimal solution from the objective function reflecting decision-making variables and the constraint conditions of the decision-making variables.
The number of MSs participating in the delivery of synchronization messages is obtained from the optimal solution where the value of the objective function is minimized. However, from Eq. (17), we note that, the objective function is not a linear one so that the problem is interpreted as a non-linear optimization problem. The non-linear optimization problem is ordinarily solved by finding the maximum or minimum value of the objective function. However, the objective function of our problem decreases as the decision-making variables increase, because the differential values of $P_{BS}$ and $P_{MS}$ are all negative values. Therefore, there is no maximum and minimum values as shown in Fig. 4. This means that the minimum or maximum value in the objective function is meaningless and the optimal solution should be derived from the constraint conditions. As mentioned earlier, we want the value of the objective function to be minimal. As $P_{BS}$ and $P_{MS}$ increase, the values of the objective function increase and thus, we can determine the optimal solution by finding the maximal $P_{BS}$ and $P_{MS}$ values meeting the constraint conditions.

From the maximal $P_{BS}$ and $P_{MS}$ values of the constraint conditions, the solution for the optimization problem where the objective function becomes minimal is derived as follows:

**Objective Function**

\[
\text{Objective Function} = \frac{k^2 - P_{BS}^2}{k^2} \times \left(1 - \left(\frac{T}{L} - 1\right) \exp\left(-\frac{R_{BS}^2}{R_{BS}^2}\right)\right),
\]

**Constraint 1:** $0 < P_{BS} < \sqrt{\frac{R_{MS}^2 - R_{BS}^2}{2\pi R_{MS}^2}} - \frac{2\pi R_{MS}^2}{d}$, 

**Constraint 2:** $0 < P_{MS} < \sqrt{\frac{\sqrt{2}R_{MS}^2}{\sqrt{d}}}$.

\[(17)\]

![Fig. 4. Influence of $P_{BS}$ and $P_{MS}$ on the objective function.](image)

(a) Influence by $P_{BS}$.

(b) Influence by $P_{MS}$.
where \( P_{rs} = \sqrt{R_{rs}^2 - R_{bs}^2} \) and \( P_{ms} = \sqrt{R_{ms}^2 - \frac{2\pi R_{ms}^2}{d}} \).

4. PERFORMANCE EVALUATION

In this section, we compare the results of the simulation and the optimal solution of the objective function. We implemented a simulator using C++ based on IEEE 802.16 standard. The experiment was conducted by laying out one BS on the middle of a map and the MSs are uniformly on the map. We assumed that the synchronization messages were transmitted from the BS and were connected in multi-hop form. In Table 1, we summarize the values of the simulation parameters.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time Increment Unit</td>
<td>0.02s</td>
<td>Channel Specification</td>
<td>IEEE 802.16n</td>
</tr>
<tr>
<td>Simulation Time</td>
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<td>SYNC Channel Length</td>
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<td>Transmission Power of BS</td>
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<td>SYNC MSG Length</td>
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<td>Cell Coverage of MS</td>
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<td>Frequency BW</td>
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</tr>
<tr>
<td>Error Rate P</td>
<td>0.1</td>
<td>CP ratio</td>
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</tr>
<tr>
<td>Radius of the Entire Network ((k))</td>
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<td>Preamble Length</td>
<td>3 OFDMA symbols</td>
</tr>
</tbody>
</table>

![Reachable Area and Connectivity Functions](image)

(a) Influence of \( P_{bs} \).
(b) Influence of \( P_{ms} \).

Fig. 5. Experimental results of reachable area and connectivity functions.

In Fig. 5, it is shown that the values of the reachable area function and the connectivity function rapidly decrease at the end. This is because, at the terminus, the \( P_{bs} \) value of the reachable area function and \( P_{ms} \) value of the connectivity function become the maximum values of the constraint conditions. Also, in Table 2, it is shown that the experimental result values are the same as the theoretical ones, confirming that the constraint conditions are valid.
Table 2. Experimental and numerical results of reachable area and connectivity.

<table>
<thead>
<tr>
<th>Function</th>
<th>Experimental Results</th>
<th>Numerical Results</th>
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</thead>
<tbody>
<tr>
<td>Reachable Area</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1226.84 P_{BS}&lt;460</td>
<td>900.89 P_{BS}&lt;440</td>
<td></td>
</tr>
<tr>
<td>484.40 P_{BS}&lt;430</td>
<td>1226.84 P_{BS}&lt;457.84</td>
<td></td>
</tr>
<tr>
<td>Connectivty Function</td>
<td></td>
<td></td>
</tr>
<tr>
<td>900.89 P_{MS}&lt;117</td>
<td>484.40 P_{MS}&lt;90</td>
<td></td>
</tr>
<tr>
<td>484.40 P_{MS}&lt;90</td>
<td>900.89 P_{MS}&lt;105.97</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 6. Experimental results of the contention collision probability function.

Table 3. Experimental and numerical results of the contention collision probability.

<table>
<thead>
<tr>
<th>Function</th>
<th>Experimental Results</th>
<th>Numerical Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contention Collision</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Probability Function</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1226.84</td>
<td>0.056</td>
<td>0.067</td>
</tr>
<tr>
<td>900.89</td>
<td>0.066</td>
<td>0.061</td>
</tr>
<tr>
<td>484.40</td>
<td>0.062</td>
<td>0.051</td>
</tr>
</tbody>
</table>

In Fig. 6 and Table 3, we show the experimental and theoretical values of the objective function, where the values range from 0.05 to 0.06 with slight variations. These results imply that the proposed method minimizes the contention collision probability by maximizing the reachable area and, thus, the synchronization information from the BS may be widely delivered. Furthermore, these results show that the proposed method maximizes the connectivity with which synchronization messages are delivered through multiple hops.

5. CONCLUSIONS

In this paper, we proposed an efficient multi-hop synchronization method, which is necessary for direct communication networks. It has been shown that the proposed method minimizes the synchronization channel interference between the MSs by minimizing the number of MSs transmitting synchronization messages without performance degradation. To accomplish this, those MSs that transmit synchronization messages are
selected by setting the optimal values of the BS and MS propagation thresholds. By comparing the numerical values with those of the simulation, we confirmed that the number of MSs participating in the delivery of synchronization messages is derived from the minimum value of the proposed objective function. Thus, we believe that the proposed method can be used as an efficient multi-hop synchronization method for direct communication networks.

In order to sophisticatedly evaluate the proposed method, the comparison with the others are needed. However, to our best knowledge, there have been no method which appropriately fits in the terminal selection problem for multi-hop synchronization in direct communication networks. Therefore, we leave the comparison with the other methods in the future work.

In the performance evaluation, we used the fixed nodes for the simulation. The fixed nodes were enough to mainly show the performance of multi-hop synchronization. But, for the more sophisticated evaluation, we will extend the simulator to include the mobile nodes in the future.

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