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Improved autocorrelation method for time synchronization in filtered orthogonal frequency division multiplexing

Suyoto[1,2], Agus Subekti[1,2], Arief Suryadi Satyawan[1,3], Mochamad Mardi Marta Dinata[1], Arumjeni Mitayani[1], Purwoko Adhi[1]
[1]Research Center for Telecommunication, National Research and Innovation Agency, Bandung, Indonesia
[2]Information Technology Department, Universitas Nusa Mandiri, Jakarta, Indonesia
[3]Electrical Engineering Department, Nurtanio University, Bandung, Indonesia

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ABSTRACT

Time synchronization is essential in multicarrier systems such as filtered orthogonal frequency division multiplexing (F-OFDM) because it determines the whole system's performance. Differ with OFDM, where subcarrier allocation is not flexible. In F-OFDM, the subcarrier allocation is more flexible, and the whole subcarrier in one symbol can be grouped into several subbands. The use of subcarriers that are limited to only one subband can reduce the performance of time synchronization based on autocorrelation (AC) methods. In this study, we first compare the performance of the AC-based time synchronization algorithms used in F-OFDM when training symbols are limited to one subband. Secondly, we made improvements to the AC-based time synchronization with the averaging technique of its timing metric, thus increasing the accuracy of time estimates in the F-OFDM system. The averaging technique of the timing metric improved the performance of the AC method in cases where the training symbol is limited to one subband, as shown in the simulation results.

Corresponding Author:

Suyoto
Research Center for Telecommunication, National Research and Innovation Agency
Bandung, Indonesia
Email: suyo004@brin.go.id

1. INTRODUCTION

The high growth of interconnected communication devices and the multiple data transfer rates make 4G technology less feasible. Therefore, a new technology based on 5G is designed to meet this demand [1], [2]. Several things must be fulfilled from this request, including ultra-reliable and low latency communications (URLLC), massive machine type communication (mMTC), and enhanced mobile broadband (eMBB) [3]–[5].

To accomplish this requirement, the design of the 5G waveform must be flexible and adaptive [6]. As shown in [7], the filtered orthogonal frequency division multiplexing (F-OFDM) waveform has many advantages for 5G compared to the other waveforms. This advantage is due to the lower level of complexity, such as requiring a simple equalizer in the receiver, and the better spectral efficiency than that of OFDM.

Like OFDM, F-OFDM has some drawbacks, such as sensitivity to symbol timing errors (errors in picking up the starting point of the symbol) and carrier frequency mismatch. One of the applications, such as the internet of vehicles (IoV) [8], requires tight synchronization because high device mobility makes channel communication change rapidly and increases the Doppler frequency shift. Time synchronization performance can also affect the overall OFDM/F-OFDM system performance [9], [10]. The synchronization method based on autocorrelation (AC) is used not only for synchronization but also for data detection, where the results are better than those of the match filter method [11].

Many studies have been conducted on time synchronization techniques, especially using training symbols as shown in [12]–[22]. Methods in [12]–[20] are AC methods, while methods in [21], [22] are statistical methods, which are the development of AC methods to improve the accuracy of their estimates, especially in multipath fading channels. The metric used to measure time synchronization performance is usually expressed in mean squared error (MSE). One OFDM symbol is used as training by Schmidl and Cox (SC) [12], which is done by inserting the complex-valued pseudonoise sequence (PNs) on odd subcarriers and inserting zeroes on even subcarriers. In the time domain, the resulting correlator is in the form of two identical halves. Park *et al.* [14] also use one OFDM symbol as in the simplified conformal (SC) method, but only the real-valued PNs are used. In the time domain, the resulting correlator is in the form of a symmetric correlator. Yi *et al.* [18] also use one OFDM symbol by inserting the real-valued PNs in the middle of the subcarrier index and zeros on the sides of the subcarrier index. Like the PK method, this method also produces a symmetric correlator. In research [23], a new preamble design for different numerology for OFDM systems is proposed to overcome the interference in time synchronization due to different numerology. This method still uses one block OFDM symbol for time synchronization. Feng *et al.* [24] proposed a symbol training in which real values are sent to all subcarriers in one F-OFDM symbol. This method resembles the YI method.

As discussed above, the effect of time synchronization has been extensively studied. However, according to the authors' best knowledge, no one has discussed time synchronization in the F-OFDM system using the training symbol, where the subcarriers used are just in one subband. The first contribution of this study is to compare the performance of time synchronization based on AC methods for the F-OFDM system, where the number of subcarriers used for training symbols is limited, in this case to one subband. The results are also compared with the synchronization methods in the OFDM system, where all subcarriers in one symbol are used as training symbols. The second contribution is that we proposed an averaging technique to improve the performance of three AC-based methods. The averaging technique uses an average of timing metrics to improve the performance of time synchronization. The simulation was carried out on the multipath fading channel. From a comparability perspective, the YI method was better than the other methods as measured by MSE. The SC method produces a flat timing metric estimate that produces a wide estimation variance. In contrast, the PK method still has sidelobes, so fewer subcarriers make the noise effect higher and widen the estimated variance. The proposed improvement method uses an averaging of its timing metric, which increases the accuracy of timing estimates.

2. F-OFDM MODEL

The overall subcarriers in F-OFDM are grouped into several subbands [8], as shown in Figure 1. Thus, the parameters in each subband can be configured independently, such as the number of points of fast Fourier transforms (FFT), the number of subcarriers, the cyclic prefix (CP), and the subcarrier spacing. After N_i-point inverse fast Fourier transforms (IFFT) and CP of length NCP_i are added, the output signal for each subband is defined as (1):

$$s_i(a) = \sum_{k=m}^{m+M-1} x_i(k) e^{\frac{j2\pi ka}{N_i}} \quad (1)$$

where s_i is the F-OFDM symbol for subband i on subcarrier a, x_i is the data symbol in subband i, $\{m, m+1, \dots, m+M-1\}$ stands for the designated subcarrier range, and M is the number of data symbol in subband i. The F-OFDM symbol $y_i(a)$ is obtained after filtering each subband as (2):

$$y_i(a) = s_i(a) * f_i(a) \quad (2)$$

where $f_i(a)$ denotes filter impulse response of subband i. To combine several subbands after filtering, for example, we have two subbands (subband 1 and 2). The symbol duration relationship for the two subbands can be given as in (3) [25],

$$C_1 = \frac{C_2}{2^l} \quad (3)$$

with C_1 and C_2 being the symbol durations in subband 1 and subband 2, respectively, and l being a positive integer, the relationship of (3) can be described as one symbol duration in subband 2 equal to 2^l symbols durations in subband 1. Thus, the F-OFDM output signal denotes p becoming:

$$p = \overline{y}_1 + y_2 \quad (4)$$

where $\overline{y}_1 = [y_1(1); y_1(2); \dots; y_1(2^l);]$, y_1 is the vector representation of $y_1(a)$ for length N_1, and y_2 is the vector representation of $y_2(a)$ for length N_2. The F-OFDM signal at the receiver, which is indicated by $\mathcal{R}(a)$, is defined as (5):

$$\mathcal{R}(a) = \psi(a) * \varkappa(a) + \Theta(a) \quad (5)$$

where $\Theta(a)$ is white noise, $\varkappa(a)$ denotes the Rayleigh fading channel, and $\psi(a)$ represents the p vector. Then the signal $\mathcal{R}(a)$ is matched for filtering in conjunction with filter $f_i^*(-a)$, which matches the filter applied at subband i as (6).

$$\mathcal{R}_i(a) = \mathcal{R}(a) * f_i^*(-a) \quad (6)$$

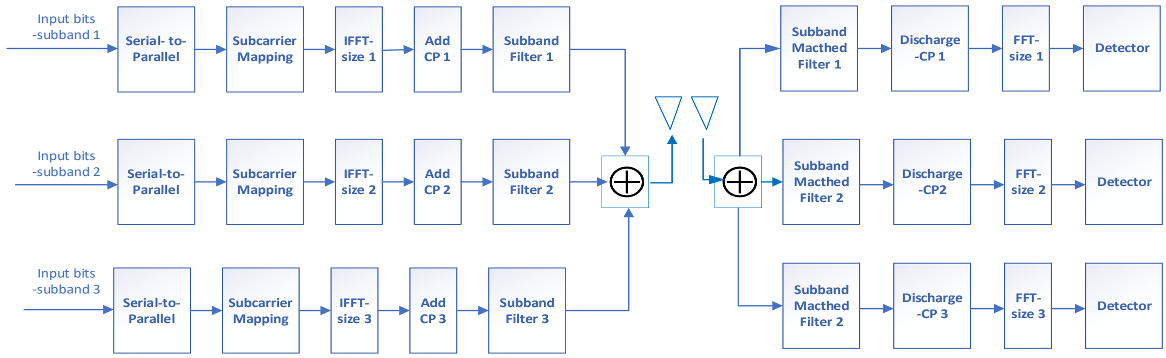

Figure 1. Block diagram of F-OFDM

3. PROPOSED IMPROVEMENT METHOD

We will first go through the synchronization techniques that typically employ one symbol before moving on to those that require only one subband. Methods such as SC, PK, and YI use one OFDM symbol for synchronization. The most common example is the SC method. Inserting PNs (complex-valued) of length $N_i/2$ on odd subcarriers and zeroes on even subcarriers in the frequency domain yields the training sequence. After the N_i-point IFFT process, in the time domain, the training symbol form as shown in Figure 2.

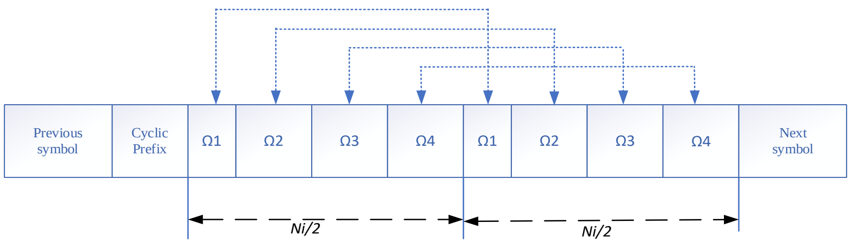

Figure 2. Time-domain form for the SC method with the $N_i/2$ sequence in the frequency domain

3.1. Synchronization method using one subband in F-OFDM

In this section, we discuss three types of AC methods used for time synchronization. In general, training sequences are obtained by inserting a PN in the frequency domain. Then, IFFT is used to transform that training into a time domain. The three methods are SC, PK, and YI, which will be explained as follows:

3.1.1. SC method

The mechanism for generating the training symbols is described above, but the number of subcarriers is limited to only one subband. Let's define the number of subcarriers in one subband as X, which is used for training, and X, which is much smaller than N_i. Then, as depicted in Figure 2, the IFFT of N_i-point may be used to get the training symbol form in the time domain. The timing metric of SC (M_{SC}) is obtained by using the AC method at the receiver side as defined in (7).

$$M_{SC}(a) = \frac{|Z1(a)|^2}{(A1(a))^2} \tag{7}$$

with

$$Z1(a) = \sum_{n=0}^{\frac{N_i}{2}-1} \mathcal{R}_i^*(a+n)\mathcal{R}_i\left(a+n+\frac{N_i}{2}\right) \tag{8}$$

and

$$A1(a) = \sum_{n=0}^{\frac{N_i}{2}-1} \left|\mathcal{R}_i\left(a+n+\frac{N_i}{2}\right)\right|^2 \tag{9}$$

3.1.2. PK method

The training sequence is obtained in the frequency domain by inserting the real value of PNs of length $X/2$, where X is the number of subcarriers in one subband with $X < N_i$. Figure 3 displays the training symbol form in the time domain that was produced using N_i-point IFFT. At the receiver, the PK (M_{PK}) timing metric is defined as (10).

$$M_{PK}(a) = \frac{|Z2(a)|^2}{(A2(a))^2} \tag{10}$$

with

$$Z2(a) = \sum_{n=1}^{\frac{N_i}{2}-1} \mathcal{R}_i(a+n)\mathcal{R}_i(a+N_i-n) \tag{11}$$

and

$$A2(a) = \sum_{n=1}^{\frac{N_i}{2}-1} \left|\mathcal{R}_i\left(a+n+\frac{N_i}{2}\right)\right|^2 \tag{12}$$

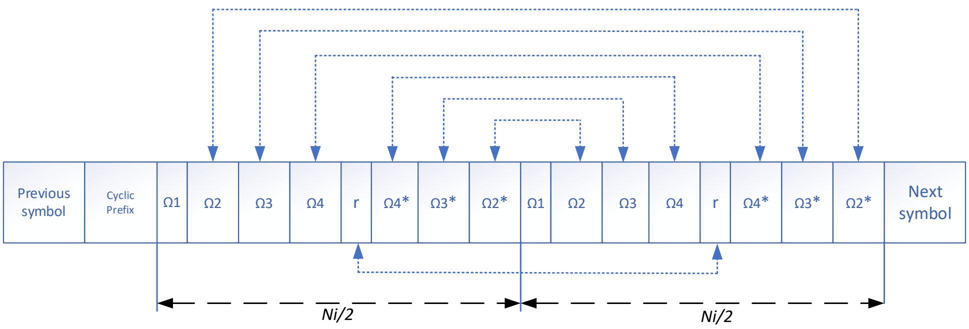

Figure 3. Time-domain form for the PK method with the $X/2$ sequence in the frequency domain

3.1.3. YI method

The training sequence is obtained in the frequency domain by inserting the real value of PNs of length X, where X is the number of subcarriers in one subband with $X < N_i$. Figure 4 displays the training symbol form in the time domain that was produced using N_i-point IFFT. At the receiver, the YI (M_{YI}) timing metric is defined as (13):

$$M_{YI}(a) = \frac{|Z3(a)|^2}{(A3(a))^2} \tag{13}$$

with

$$Z3(a) = \sum_{n=1}^{\frac{N_i}{2}-1} \mathcal{R}_i(a+n)\mathcal{R}_i(a+N_i-n), \quad (14)$$

and

$$A3(a) = \sum_{n=1}^{\frac{N_i}{2}-1} \left|\mathcal{R}_i\left(a+n+\frac{N_i}{2}\right)\right|^2 \quad (15)$$

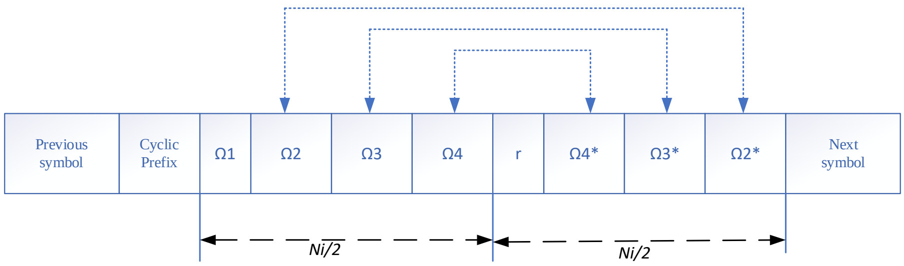

Figure 4. Time-domain form for the YI method with the X sequence in the frequency domain

3.2. Improvement method

The comparison of YI, SC, and PK methods as shown in the above section experienced performance degradation when using subcarriers that were limited to only one subband. This is because the sidelobe effect increases when the subcarriers used are limited to one subband. Therefore, we proposed an averaging method to improve the performance of the three AC methods. This method works by taking the average value of the timing metric of YI, PK, and SC in the F-OFDM system. For the YI and PK methods, the averaging method is carried out, respectively, as (16), (17):

$$AVG\_YI(a) = \sum_{k=1}^{K1} M_{YI}(a+k-1) \quad (16)$$

$$AVG\_PK(a) = \sum_{k=1}^{K1} M_{PK}(a+k-1) \quad (17)$$

where $K1$ is the sample length for averaging, which is set to 8 for the YI and PK methods, while for the SC method, it is carried out as (18):

$$AVG\_SC(a) = \sum_{k=1}^{K2} M_{SC}(a-k+1) \quad (18)$$

where $K2$ is set to 32. This was done because of the timing metric characteristic of the SC method, which has more sidelobes compared with the YI and PK methods. Likewise, with the initial sampling for averaging values, in the YI and PK methods, it is taken at the beginning of the sample, while in the SC method, it is taken at the end of the sample. This is because the sidelobe position in the YI and PK methods is at $0 \leq a \leq L$, where 0 is stated as the beginning of the F-OFDM symbol and L is stated as channel length. While the SC method is at $NCP \leq a \leq L$. Without losing the generality of all the above methods, to calculate the beginning of the F-OFDM symbol, find the maximum value (Γ) of the timing metric as (19):

$$\Gamma = \underbrace{argmax}_{a}(TM) \quad (19)$$

where TM is the timing metric and Γ is the estimate of the correct timing point.

4. RESULTS AND DISCUSSION

All simulations for the F-OFDM system use two subbands with the parameters shown in Table 1. For the first subband, we use a subcarrier spacing of 20 kHz, a number of subcarriers of 50, and 512 FFT points. For the second subband, the subcarrier spacing is 10 kHz, the number of subcarriers is 100, and there are 1,024 FFT points. The length of CP, data modulation, and sampling rate used in both subbands are the same, namely $N/8$, 4-QAM (quadrature amplitude modulation), and 10 MHz, respectively. The multipath fading channel contains six paths with a delay of $[0, 3, 7, 10, 17, 25]$ and an average gain for each path of $[1, 0.7943, 0.1259, 0.1, 0.031, 0.01]$. The Hanning windowed sinc filter with a length half of the FFT size is used for filtering.

Table 1. F-OFDM simulation parameters

Parameter	Subband 1	Subband 2
FFT size (N_i)	512	1024
Number of subcarriers (X)	50	100
CP length (NCP_i)	$N_i/8$	
Sampling rate	10 MHz	
Subcarrier spacing	20 kHz	10 kHz
Data modulation	4-QAM	
Channel model	vehicular A channel	
filter type	Hanning windowed sinc filter	

Figure 5 shows the timing metrics of time synchronization methods in the OFDM system, and Figure 6 shows those in the F-OFDM system. Both simulations were performed using a white Gaussian noise communication channel. For the F-OFDM case, the AC results decrease with the addition of sidelobes, especially in the YI and PK methods.

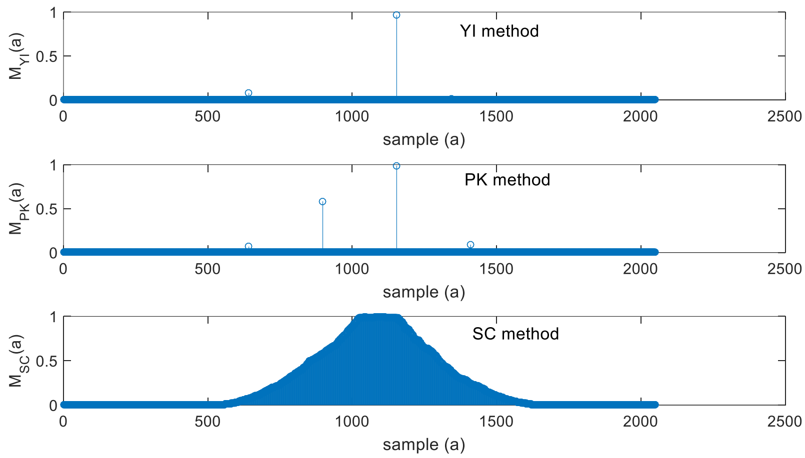

Figure 5. The timing metrics comparison in the OFDM system

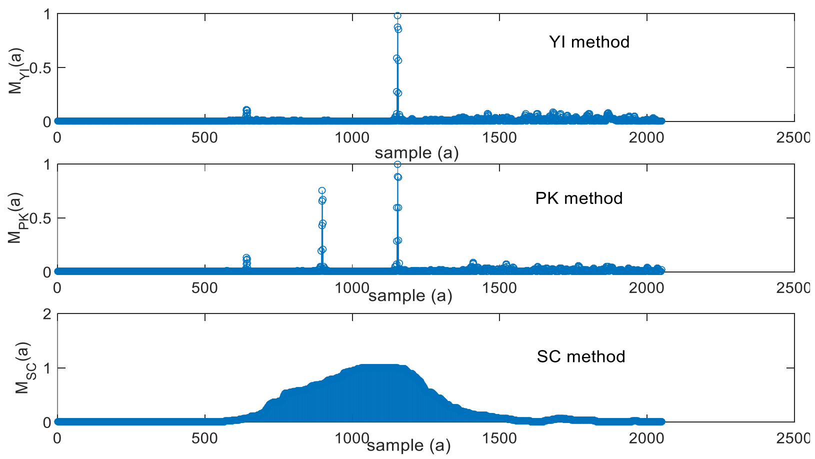

Figure 6. The timing metrics comparison in the F-OFDM system

Figure 7 shows the time synchronization performance of the YI, PK, and SC methods in the OFDM system using all subcarriers in one OFDM symbol as a training symbol and in the F-OFDM system using a limited number of subcarriers in one subband as a training symbol, respectively. The PK method experienced a significant decrease in performance due to the fact that it adds quite a lot of sidelobes, which causes poor performance on all tested signal to noise ratios (SNRs). The YI method has a smaller sidelobe addition than the PK method, so it only experiences a significant decrease in performance at low SNR. In contrast, at a higher SNR, the performance is still good. The SC method undergoes little change in performance, but this method has a large MSE because the timing metric has a plateau, which decreases the precision in estimating the beginning of F-OFDM symbols. Figure 7 also shows the performance of the improvement methods labeled as AVG-YI, AVG-PK, and AVG-SC, respectively, and shows that the averaging technique increased the accuracy of timing estimates for the SC, PK, and YI methods in the F-OFDM system, where training symbols are limited to one subband.

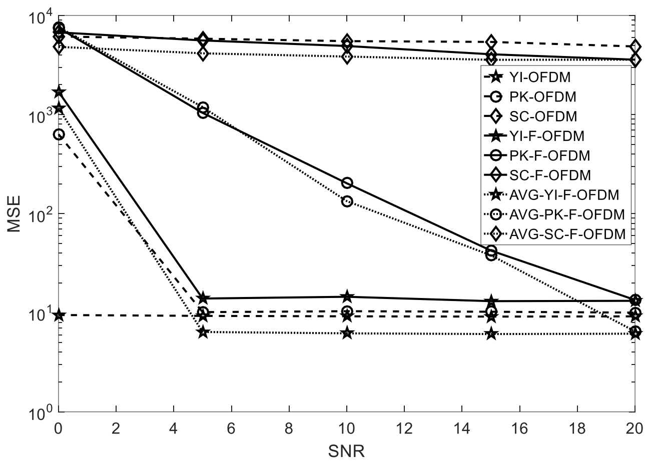

Figure 7. Comparison of time synchronization methods in OFDM and F-OFDM systems under vehicular a channel

5. CONCLUSION

We have tested three types of time synchronization methods based on AC methods in the F-OFDM system. Those methods were tested on the vehicular A channel with the use of subcarriers limited to only one subband for the training symbol and compared to the use of all subcarriers in one OFDM symbol in the OFDM system. From a comparison perspective, it shows that the performance of the YI method experienced only a slight decrease in performance, while the PK method experienced the most significant reduction in performance. Therefore, the YI method can be used in F-OFDM systems where the use of subcarriers for time synchronization is limited to only one subband. However, it is necessary to improve existing synchronization methods so that it becomes feasible to use them, even though they use a few subcarriers, especially in the case where only one subband is used for time synchronization. Therefore, we proposed an improvement method using an averaging of its timing metric, which increases the accuracy of timing estimates.

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BIOGRAPHIES OF AUTHORS

Suyoto has joint the research center of telecommunication BRIN since 2005. Obtained Ph.D., Master's degree, Bachelor's degree all in electrical engineering from the Bandung Institute of Technology, Indonesia in 2019, 2009, and 2002, respectively. His motivation research in the field of synchronization technique in multicarrier systems, signal processing, and wireless communication. He can be contacted at email: suyo004@brin.go.id and suyotofx@gmail.com.

Agus Subekti is researcher at research center of telecommunication BRIN. Obtained Bachelor's degree, master's degree, and Ph.D. all from the Bandung Institute of Technology in 1998, 2001, and 2016, respectively. Currently, he is a researcher with BRIN since 2005. He can be contacted at email: agus.subekti76@gmail.com.

Arief Suryadi Satyawan is researcher at research center of telecommunication BRIN. Obtained Bachelor's degree in electrical engineering in 2000 from Universitas Jenderal Achmad Yani and received his Master's degree in electrical engineering from ITB in 2007. In 2019 he received Ph.D. from Waseda University, Japan. His motivation research in the field of video communication system, and image processing. He can be contacted at email: arief.suryadi@akane.waseda.jp.

Mochamad Mardi Marta Dinata received his Bachelor's degree in electrical engineering from Institut Sains & Teknologi Nasional, Indonesia, in 2011. In 2016, he received his Master's degree in electrical engineering from Universitas Indonesia, Indonesia. He has joined with Research Center for Telecommunication, BRIN, since 2019. Currently, he also preparing himself to pursue his Ph.D. at Osaka University, Japan. He can be contacted at email: mochamad.mardi.martadinata@gmail.com.

Arumjeni Mitayani received her Master's and Bachelor's Degrees from Institut Teknologi Bandung, Indonesia, in 2013 and 2012, respectively. She has joined Research Center for Telecommunication, BRIN, Indonesia since 2019. Her research interests are wireless communication, beamforming, 6G, reconfigurable intelligent surface (RIS), mmWave communication, and non-terrestrial network (NTN). She can be contacted at email: arumjeni.mitayani@brin.go.id.

Purwoko Adhi received his engineering degree in electrical engineering from ESIGELEC France and his master degree in robotics from Pierre and Marie Curie University, Paris, France. He received his PhD in signal processing from Curtin University of Technology, Western Australia. He is currently a senior researcher at Research Center for Telecommunication, BRIN, Indonesia. His motivation research in the field of signal processing, image processing, machine learning, and wireless communications. He can be contacted at email: purwoko.adhi@brin.go.id.