Direction Finding Method for Fast Beam Alignment in Wireless Communication Systems

Seon-Ae Kim and Heesang Chung
Mobile Communication Research Division, ETRI
Daejeon, Korea
sun0811@etri.re.kr, hschung@etri.re.kr

Young-Hoon Kim
Satelite Communication Research Division, ETRI
Daejeon, Korea
yhkim23@etri.re.kr

***Abstract*—This paper proposes a simple direction finding (DF) method which aims to realize efficient beam management in mm-wave and THz frequency-band communications where a beamforming is essential. In the proposed method based on the DF built by the synthesis of two pre-designed beam patterns, the relative angle difference of direction-of-attention (DoA) between the beam direction formed by transmitting array antenna and the receiving antenna can be estimated. Accordingly, the receiving device having a DoA value within a specific range can be recognized as being in the main direction of a transmission beam. Also, we design the beam measurement method that is immune to implementation issues such as the imperfect frame synchronization in OFDM systems. Simulation results show the performance of angular filtering of the proposed method in the line-of-sight (LOS) environment.**

Keywords*—*beam alignment, direction of attention, direction finding, 5G/6G communications

I. Introduction

Recently, in a wireless communication system such as IEEE Wi-Fi 802.11 or 3GPP 5th generation new radio (5G NR) mobile communication standard technology, a technology for expanding coverage or increasing capacity by forming a beam in a specific direction using multiple antennas is a key. In particular, since millimeter wave (mmWave) communication to support high data rate has a short communication range and radio waves are frequently blocked by obstacles, so multiple beams being able to cover the entire service area must be operated [1-3].

In general, in order to form a beam between two wireless devices, direction finding technologies are used to estimate the angle-of-arrival (AOA) of radio waves transmitted using multiple antennas on the receiving side or to define the direction of a terminal through beam switching [4]. Beam switching method has been used successfully in 5G NR of above 6GHz and IEEE 802.11ad Wi-Fi of 60GHz frequency band. However, the technology of finding the direction of a desired beam by selecting and sweeping one of several pre-formed beams in a certain search period has a problem in that a complicated procedure of exchanging and finding the measured value of the beam between two devices is required. In [5], a spatial beamforming called random jitter beamforming (RJBF) method that can estimate the relative angle between the transmission beam and the target device by simply measuring the transmission beam in the receiving device was proposed. This method determines the correlation of the transmitted weight vector by multiplying to the known sequence, and the measured value in received side is mapped to a function of a deviation angle from line-of-sight (LOS) direction of transmitting beam. Although RJBF can be effectively applied as an OFDM system, it is vulnerable to the timing offset issues arising from implementation such as the mismatch of FFT window region.

In this paper, we analyze an influence on correlation property of received weight vector by the timing offset at FFT starting point and propose a method to maintain DOA characteristics while ignoring timing offset in OFDM system, which makes a main function for angular filtering based on correlation coefficient between transmitted two sequences with same FFT duration. Compared to the conventional received signal strength (RSS) based beamforming method, in this method not only the measured value can be obtained simply, but also the direction of the incident beam within a specific angle can be fairly accurately caught.

The rest of this paper is organized as follows. In section II, we derive the impact of synchronization timing offset on pre-defined beam pattern and describes the proposed direction finding method, which is more feasible for implementation, in section III. Section IV displays some simulation results showing the angular filtering performance of the proposed method. Finally, Section 5 concludes this paper.

II. Impact of Synchronization Timing Offset on Designed Beam Pattern

Fig. 1 shows the configuration of beam pattern applied for the OFDM transmitter in the proposed DF method. In Fig. 1, a known sequence grouped by Φ_n pre-defined beam pattern for jittering is mapping to sub-carriers of IFFT, where this sequence is already known in the transceiver to detect the correlation property of beam pattern. Pre-defined beam jittered pattern w_k^m is expressed as the weighted array vectors for groups of Φ_n at the k-th sub-carrier and m-th antenna. Assume that the OFDM transmitted signal with the weight vector of the beam pattern group for a 4-element uniform linear array (ULA) antenna at the k-th subcarrier is X_k and the weight vector for the pre-defined beam pattern is $\mathbf{w}_k$ when $\Phi_n = 2$.

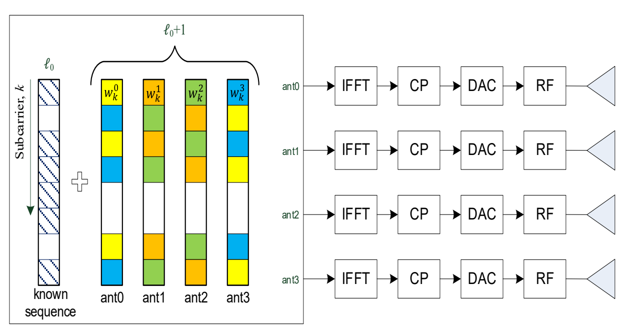


Fig. 1. Transmission method of beam pattern in OFDM system.

Then, the transmitted baseband signal for m-th antenna path is followed as

$$x_m[n] = \sum_{k=0}^{N-1} X_k w_k^m e^{-j\frac{2\pi kn}{N}}. \quad (1)$$

where w_k^m is one of the element of pre-defined beam pattern group. The $\mathbf{w}_k$ group of pre-defined beam pattern is given by

$$\mathbf{w}_k = \begin{cases} \mathbf{w}_{G1}, & k \in 2i+1 \\ \mathbf{w}_{G2}, & k \in 2i \end{cases} \quad (2)$$

where i is a non-negative integer, and two groups of pre-defined beam pattern applied for 4 ULA antenna are defined as follows,

$$\mathbf{w}_{G1} = \left[e^{-j2\pi\frac{d}{\lambda}\varphi_1^0}, e^{-j2\pi\frac{d}{\lambda}\varphi_1^1}, e^{-j2\pi\frac{d}{\lambda}\varphi_1^2}, e^{-j2\pi\frac{d}{\lambda}\varphi_1^3} \right]^T$$

$$\mathbf{w}_{G2} = \left[e^{-j2\pi\frac{d}{\lambda}\varphi_2^0}, e^{-j2\pi\frac{d}{\lambda}\varphi_2^1}, e^{-j2\pi\frac{d}{\lambda}\varphi_2^2}, e^{-j2\pi\frac{d}{\lambda}\varphi_2^3} \right]^T$$

where the antenna spacing d is equal to 0.5λ and α is a scaling factor. φ is the null location of two beam patterns given by $\varphi_1^m = \left(m - \frac{M+1}{2}\right)\sin\theta_1$ and $\varphi_2^m = \left(m - \frac{M+1}{2}\right)\sin\theta_2$, $m = 0, \ldots, M-1$.

The baseband signal received by a single omni- directional antenna is written by

$$\mathbf{y} = \mathbf{hs} + \mathbf{v}, \quad (3)$$

where $\mathbf{s} = [s_0, \ldots, s_m]^T$ and is the $M \times 1$ beam-steered vector of RJBF signal, $\mathbf{h}$ is the $1 \times M$ wireless channel vector, and $\mathbf{v}$ is gaussian noise. s_m is the outputs of multi-antenna for the baseband signal model in transmitter, $s_m = \phi_m x_m$ ($m = 0, \ldots, M-1$), where ϕ_m is a component of beam-steered vector $\boldsymbol{\phi}$. M is the number of transmit antenna.

Generally, an OFDM system is more sensitive for timing synchronization of received frame. Let Y_k be the RJBF sequence performed FFT with imperfect synchronization timing synchronization (STO) as shown in Fig. 3. If the synchronization timing offset δ is defined as a number of shifted samples from the perfect synchronization, the recovered signal with beam pattern Y_k at the k-th sub-carrier after FFT is calculated as

$$Y_k = \sum_k \mathbf{\Theta}_k X_k e^{-j2\pi k\delta/N} + V, \quad (4)$$

where $\mathbf{\Theta}_k$ is combined with channel vector, beam-steered vector and weight vector at k-th subcarrier by matrix operation of (3), respectively, $\mathbf{\Theta} = \mathbf{H\Phi w} = \sum_{m=0}^{M-1} H_m \phi_m w_m$. $\mathbf{H}$ and $\mathbf{\Phi}$ are the expression of vector $\mathbf{h}$ and $\boldsymbol{\phi}$ in frequency domain, respectively, and $\mathbf{w} = [w_0, \ldots, w_m]$, is the vector of pre-defined beam pattern w_m related to the antenna index for w_k^m. The STO is a positive integer number within the cyclic prefix (CP) duration.

In [5], the cross-correlation (XCR) between a known sequence vector $\vec{x}$ and received RJBF signal vector $\vec{r}$ for a function $f(\rho)$ for angular distance is expressed as follows,

$$\rho = \langle \vec{x} \cdot \vec{r} \rangle / \sqrt{\langle \vec{x} \cdot \vec{x} \rangle \langle \vec{r} \cdot \vec{r} \rangle}, \quad (5)$$

where $\langle a \cdot b \rangle$ is an inner product of two vectors. Since $|\rho|$ is monotonically decreased corresponding to only a deviation angle from a target except for low value, it can be simplified to a function for angular filtering.

To detect the angular distance, the cross correlation coefficient between a known sequence vector $\vec{X}$ and the received sequence $\vec{Y}$ in frequency domain can be calculated using (5). According to (5), the inner product $\langle \vec{X} \cdot \vec{Y} \rangle$ of two vectors for received OFDM symbol with synchronization error δ is following as

$$\langle \vec{X} \cdot \vec{Y} \rangle = \sum_k X_k^* Y_k = \sum_k X_k^* X_k \sum_k \mathbf{\Theta}_k e^{-j2\pi k\delta/N}. \quad (6)$$

Then, the cross-correlation coefficient is calculated as follows,

$$\rho_\delta = \sum_k \frac{|X_k|^2 \mathbf{\Theta}_k e^{-j2\pi k\delta/N}}{\sqrt{|X_k|^2 \cdot |X_k|^2 |\mathbf{\Theta}_k|^2}} = \sum_k \frac{1}{\sqrt{|\mathbf{\Theta}_k|^2}} \mathbf{\Theta}_k e^{-j2\pi k\delta/N}. \quad (7)$$

Assume that the wireless channel is a frequency-flat, $H \simeq 1$, the phase rotation of ρ_δ can be calculated as follows

$$\vartheta = \sum_k \sum_{m=0}^{M-1} 2\pi \left(\frac{md}{\lambda} (\sin\theta_1 + \sin\theta_2) + \frac{k\delta}{N} \right). \quad (8)$$

If the timing synchronization of the OFDM receiver is ideal, the beam pattern with the set of (2) have the identically fixed array response in the direction of 0°, i.e., fixed gain at the direction of LOS, and the varied gains in other directions. Due to the phase rotation, however, all of the devices with the different timing synchronization have different $|\rho|$ even 0° as shown in Fig. 2.

Fig. 2 shows the performance of pre-designed beam-based BF method with respect to the STO of a received OFDM signal under the spatial channel model (SCM) [6] of 3GPP. If the threshold for device filtering is 0.14, the device with $\delta = 3$ in the direction of 0° cannot be filtered as the target, but the device with $\delta = 1$ in the direction of 10°. Therefore, in order to use $|\rho|$ as the common cost function for angular filtering, the OFDM-based BF with specific beam pattern requires the algorithm to compensate the STO. In a general OFDM system, the timing synchronization error within CP duration can be eliminated by the channel equalization. But it is difficult to use the channel equalization in the beamforming-based OFDM system in which the characteristic of a beam pattern must be maintained.

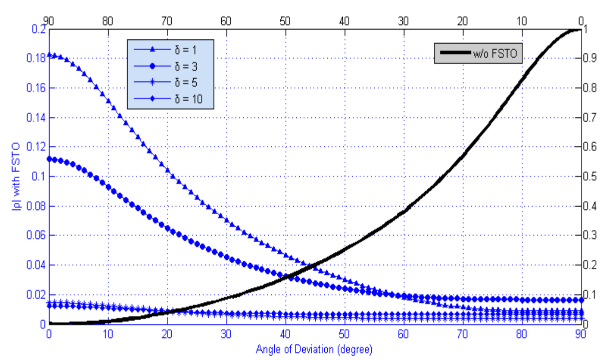


Fig. 2. XCR-based beam measurment performance.

III. PROPOSED DIRECTION FINDING METHOD FOR OFDM SYSTEM

Fig. 3 illustrates the concept of proposed direction method to disregard the impact of STO in the OFDM system. As shown in Fig. 3, the transmit frame of proposed method consists of the pre-designed beam pattern as well as the known sequence used to generate it, that is, these two sequences shared a same binary sequence. In this paper, as a known sequence, the binary sequence of the long training field for preamble of IEEE 802.11 is used.

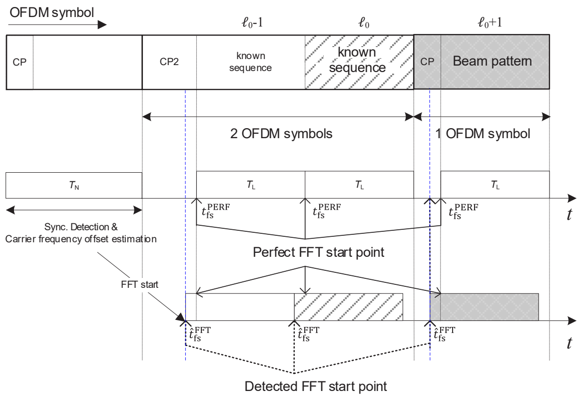


Fig. 3. Frame configuration and transmsssion concept of the proposed method.

The timing synchronization for receiving these two sequence symbol can be obtained from several OFDM symbols received in T_{N} interval. Thereafter, the received OFDM symbols are demodulated based on the synchronization detected in the T_{N} interval. Although the timing synchronization was slightly swayed, in the proposed method, two symbols have a common FFT window start point in Fig. 3.

Once again, let Y_k be the recovered sequence with beam pattern corresponding to (4) and let Z_k be the received known sequence with the synchronization timing offset δ at the k-th subcarrier. Then, the received sequence is expressed as

$$Z_k = \sum_k \boldsymbol{\Psi}_k X_k e^{-j2\pi k\delta/N} + V, \tag{9}$$

where $\boldsymbol{\Psi}_k$ is composed to the channel vector and beam-steered vector at k-th subcarrier, $\boldsymbol{\Psi} = \mathbf{H}\boldsymbol{\Phi} = \sum_{m=0}^{M-1} H_m \Phi_m$. $\mathbf{H}$ and $\boldsymbol{\Phi}$ was defined in section II.

Then, the new function of angular-distance is generated from the auto-correlation of these two sequences in the direction of target by basics of the proposed method. The new function of angular-distance by received the given sequence $\vec{Z}$ and the beam pattern-based sequence $\vec{Y}$ in frequency domain can be reconstructed by (5). If the inner product $\langle \vec{Z} \cdot \vec{Y} \rangle$ of two vectors is defined as $\langle \vec{Z} \cdot \vec{Y} \rangle = \sum_k Z_k^* Y_k$. The inner product of three components of at k-th subcarrier is calculated to

$$\alpha = \langle \vec{Z} \cdot \vec{Y} \rangle$$
$$= \sum_k \left(X_k \boldsymbol{\Psi}_k e^{-\frac{j2\pi k\delta}{N}} \right)^* X_k \boldsymbol{\Theta}_k e^{-\frac{j2\pi k\delta}{N}} = \sum_k |X_k|^2 \boldsymbol{\Psi}_k^* \boldsymbol{\Theta}_k$$

$$\beta = \langle \vec{Z} \cdot \vec{Z} \rangle$$
$$= \sum_k \left(X_k \boldsymbol{\Psi}_k e^{-\frac{j2\pi k\delta}{N}} \right)^* X_k \boldsymbol{\Psi}_k e^{-\frac{j2\pi k\delta}{N}} = \sum_k |X_k|^2 |\boldsymbol{\Psi}_k|^2$$

$$\gamma = \langle \vec{Y} \cdot \vec{Y} \rangle$$
$$= \sum_k \left(X_k \boldsymbol{\Theta}_k e^{-\frac{j2\pi k\delta}{N}} \right)^* X_k \boldsymbol{\Theta}_k e^{-\frac{j2\pi k\delta}{N}} = \sum_k |X_k|^2 |\boldsymbol{\Theta}_k|^2.$$

Accordingly, a function of angular-distance based on auto-correlation coefficient is following as

$$\rho_{\mathrm{new}} = \frac{\alpha}{\sqrt{\beta \cdot \gamma}} = \sum_k \frac{\boldsymbol{\Psi}_k^* \boldsymbol{\Gamma}_k}{|\boldsymbol{\Psi}_k|^2 |\boldsymbol{\Gamma}_k|^2}.$$

Compared to (8), in the above equation, it can be seen that the term δ related to the timing offset disappears and the DF effect by the weight vector of (1) and (2) is maintained. Therefore, the proposed DF method is a more feasible solution than for OFDM implementation.

IV. SIMULATION RESULTS

All simulation results performed in 4 elements ULA antenna with antenna spacing 0.5λ for transmitting and a single omni-directional antenna for receiving and two pre-designed beam pattern with $\sin\theta_1 = -0.25$ and $\sin\theta_2 = 0.25$ to have equal gain and phase in the direction of target is considered. An OFDM system for simulation has 64 subcarriers in 20MHz bandwidth with 5GHz center frequency as shown in Fig. 1 and 3. A binary sequence for pre-defined beam pattern occupies 52 subcarrier following the IEEE 802.11n specification. For simulation, the wireless channel model is considered to the modified SCM for 3GPP in [6]. This channel model is fitted to device-to-device communications under the situation of only mobile device with low antenna height unlike original SCM in urban micro environment with LOS. Rician K factor of LOS path for simulation is 6dB and noise figure is -92.97dBm in receiver.

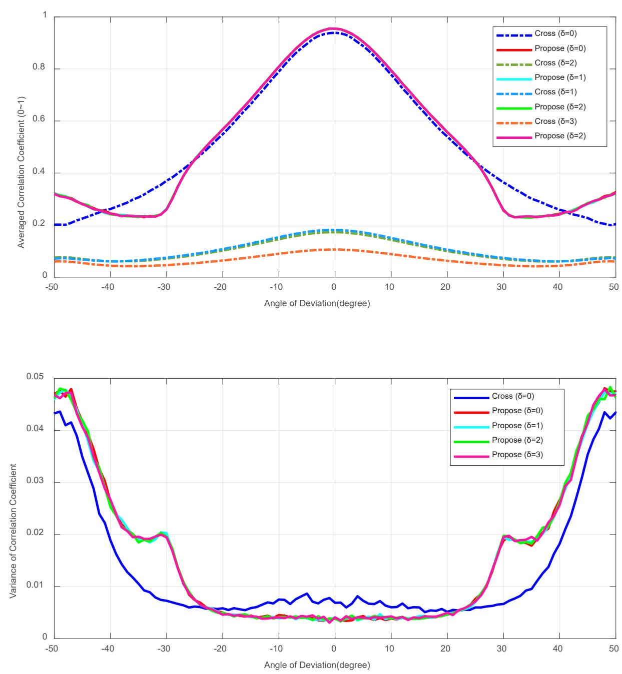
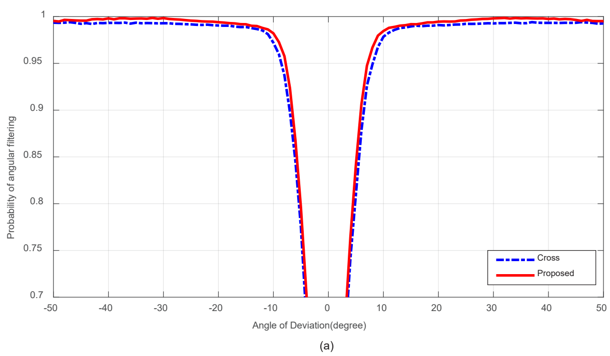


Fig. 4. Average and variance of correlation coefficient at the received device position $-50 \leq \theta < 50$.

Fig. 4 illustrates the correlation coefficient map of the proposed method and the conventional patterned beam method when OFDM system has the STO δ from 0 to 5 samples. These results show the mean and variance of $|\rho|$

obtained from 20,000 independent runs. Note that $|\rho|$ determined by the wireless channel is a random variable because our modified SCM for the simulation has the stochastic model with a WSS (wide sense stationary) random process. As shown in simulation results, $|\rho|$ is expressed as a monotonically decreasing function of the angular distance from the direction of target without the effect of side lobes. If threshold is 0.8 in the conventional patterned beam method, the angular filtering resolution about 9° can be obtained on average. But even though there are STO of just 1 sample in receiving beam jittered symbol, their correlation coefficient was changed to $0 \leq |\rho| \leq 0.2$, and then the threshold for angular filtering must be set differently in all devices. On the other hand, the proposed method serves a function of the angular distance regardless of frame synchronization within CP duration, where nonlinearity at $\pm 30°$ is null position generated by auto-correlation of beam pattern. In the proposed DF, the angular filtering resolution of 10° can be always obtained when threshold 0.8 is used.



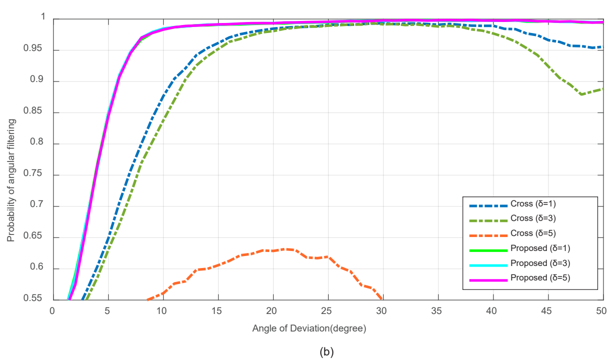


Fig. 5. The probability of angular fitering: (a) XCR vs. Proposed for $\delta = 0$, (b) for $\delta = 1{,}3{,}5$.

Fig. 5(a) and (b) show the probability of successful angular filtering of proposed DF with the perfect synchronization and the several STO case, respectively. For this simulation, the target and interference devices are located at 0° and an interval of 1° in $-50 \leq \theta \leq 50$, respectively, at the radius $r = 70m$ from a user device. A 'successful angular filtering' is defined as the case where the $|\rho|$ of the target has a higher value than the $|\rho|$ of the inference at position (r, θ), e. g. $(70m, 1{\sim}50°)$. By the practical results obtained from 20,000 independent runs, the angular resolution with the probability of 90% and 98% are about 7° and 11° in cross correlation based conventional DF as shown in Fig. 5(a). It means that the interferers outside of 7° can be filtered out with the probability more than 90%. But by the STO inevitably generated in implementing the receiver, the probability of successful angular filtering of cross correlation based conventional DF is degraded to less than 65% for any position interferers in Fig. 5(b) even though only 5 samples were dislocated. On the other hand, the proposed DF method can achieve the angular resolution about 6° and 9.5° with the probability 90% and 98% for any STO within the CP duration.

V. Conclusion

This paper proposed an advanced DF method to make the beam pattern designed for finding the direction of LOS work well despite a timing synchronization error in the OFDM receiver, and represented the performance of proposed method compared to XCR-based conventional one in SCM channel environment. Simulation results show that proposed DF method achieves great angular filtering resolution for any synchronization within 10 samples. With a 4 element ULA, an angular filtering resolution of 9.5° with success rate 98% can be obtained. And even lots of interferences are located up to 42°, the performance of angular filtering is lost just 0.15% by interferences around the filtering resolution in practice.

Acknowledgment

This work was supported by Institute of Information & communication Technology Planning & Evaluation (IITP) grant funded by the Korea government (MSIT) (RS-2023-00216221, Development of service coverage extension technologies for 5G-Advanced mobile communications based on reconfigurable intelligent surface).

References

[1] Dahlman, Erik, Stefan Parkvall, and Johan Skold. 5G NR: The next generation wireless access technology. Academic Press, 2020.

[2] Y.-N. R. Li, B. Gao, X. Zhang, and K. Huang, "Beam Management in Millimeter-Wave Communications for 5G and Beyond," IEEE Access, vol. 8, pp. 13 282–13 293, 2020.

[3] S. Park, S. Kim, J. Sohn, and H. Shin, "Design of a 28 GHz Switched Beamforming Antenna System Based on 4×4 Butler Matrix," The Journal of Korean Institute of Electromagnetic Engineering and Science, vol. 26, no. 10, pp. 876–884, Oct. 2015.

[4] B.-J. Jang, "Direction Finding Technology: Tutorial, Review, and Research Prospects," The Journal of Korean Institute of Electromagnetic Engineering and Science, vol. 30, no. 8, pp. 607–617, Aug. 2019.

[5] B. J. Kwak, S. A. Kim, Y. H. Kim, and N. O. Song, "Random Jitter Beamforming for Point-and-Link Communications," 2012 IEEE Statistical Signal Processing Workshop (SSP'12), pp. 496-499, 5-8 Aug. 2012.

[6] 3GPP TR 25.996 V11.0.0, Spatial channel model for Multiple Input Multiple Output (MIMO) simulations, September 2012.

[7] Dah-Chung Chang, "Effective Compensation of Symbol Timing Offset in OFDM Systems With Channel Interpolation," IEEE Transaction on Broadcasting, vol. 54, No. 4, Dec. 2008.