Time-Frequency Synchronization Effect on 5G Multicarrier Systems

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Abstract
Synchronization in the time-frequency domain for the fifth-generation (5G) new radio (NR) takes the fundamental steps as in all mobile networks to have user equipment (UE) properly receive and transmit data. The corresponding synchronization for 5G has various challenges due to the wide range of frequencies. This is more so when it comes to applications that would need accurate oscillators to reduce the large values of the frequency offset. This paper presents challenges and issues within the 5G NR synchronization specifically on the pilot-based time and frequency synchronization for OFDM and UFMC systems. It also compares cyclic prefix (CP) based synchronization as it applies to OFDM systems with UFMC noting that no CP is inserted in UFMC system. The effect of timing and frequency offset on OFDM and UFMC systems is then presented with two approaches, CP-based and pilot-based synchronization. Simulation results of the synchronization performance shows that the UFMC out performs OFDM making it more adaptable to 5G considerations.

Keywords: Time-Frequency, Waveforms, Cyclic Prefix, Carrier Frequency Offset.

1.0 INTRODUCTION

For the fifth generation (5G) new radio (NR) mobile communication standard as presented by the 3rd generation partnership project (3GPP) Release 15, the major improvement of the long term evolution-advance (LTE-A) standard is in the area of enhanced mobile broadband, ultra-reliable and low latency communications, and massive machine-type communications. For these to be achieved, there has to be unified network architecture with new physical layer design that supports very high carrier frequencies (mmWaves), large frequency bandwidths and new techniques such as massive multiple-input and multiple-output (mMIMO) and beam forming [5G NR(a), 2018; 5G NR(b), 2018 and 5G NR(c), 2018].

These modifications increase the synchronization challenges, complicating the very high demand for carrier frequencies which results in large values of frequency and time offsets. These need accurate and expensive oscillator to align a transmitter and a receiver for interference free communications. It should be noted that the sources of interference are mainly related to the imperfections of orthogonal frequency-division multiplexing (OFDM) systems which suffer from the time and frequency offsets that result in inter-carrier interference (ICI) and inter-symbol interference (ISI) [Alvarez and Spagnolini, 2018; Li et al, 2012]. Correspondingly, the time offset is due to the transmission delay, where the transmitted signal reaches the receiver delayed in time [Huynh, 2017; Hamza and Mark, 2015]. Generally, the receiver does not know when the transmitter sent a new burst and usually the normalized timing offset is considered, which is equal to the number of samples between the transmitted signal and the received signal. If the normalized timing offset is larger than the cyclic prefix (CP) length, then a misalignment of the fast Fourier transform (FFT) window can be observed, which results in ISI and ICI. Otherwise, only a phase offset can be observed. The estimation and correction of the time offset should be done in the pre-FFT synchronization stage, by using specific synchronization algorithms. In the literature, the auto-correlation and cross-correlation algorithms are well known and used in wireless communication systems [Alvarez and Spagnolini, 2018; Shamaei and Sabbaghian 2015; Zeng et al, 2018].

In the first algorithm, the received signal is correlated with a delayed version of the same signal. In the second algorithm, the received signal is correlated with a stored pattern known to the receiver to estimate the time offset. Beside the time offset, the errors in the transmitter and the receiver oscillators result in frequency offset, which is a linear phase over the time domain samples and it causes ICI over the subcarriers. In contrast to the time offset, this phase offset increases in time as it is directly proportional to the discrete time index. The frequency offset in OFDM is usually normalized to the sub-carrier spacing as the ratio between the frequency error and the sub-carrier spacing [Zeng et al, 2018; Salim et al, 2017; Chen et al, 2018].

This paper looks at pilot-based time and frequency synchronization for OFDM and UFMC systems, compares it with cyclic prefix (CP) based synchronization as it applies to OFDM systems, since no CP is inserted in UFMC system. The effect of timing and frequency offset for OFDM and UFMC systems are then presented with two approaches, CP-based and pilot-based synchronization. The simulation results of the synchronization performance show that the UFMC out performs the OFDM making it more adaptable to 5G considerations.

2.0 LITERATURE REVIEW

Feng et al 2020, considered the filtered orthogonal frequency division multiplexing (F-OFDM) which has inherit technical advantages of OFDM as well as outstanding advantages in system flexibility and spectrum efficiency. The multi-carrier technology however suffers from extreme sensitivity to sample timing offset (STO) and carrier frequency offset (CFO). The paper proposed an improved Park frequency domain training sequence (FS-Park) to complete STO and CFO estimation of F-OFDM system. Firstly, a real-value pseudorandom number (PN) sequence was sent to each subcarrier as training sequence in frequency domain and the corresponding time domain training symbol has a conjugate symmetry structure. Secondly, the training symbol was utilized for timing synchronization, then the fractional frequency offset was estimated based on the cyclic prefix in time domain. Finally, the integer frequency offset was estimated in frequency domain based on the auto-correlation of PN sequence. The simulation results showed that the FS-Park algorithm not only has a single pulse timing metric curve and great STO estimation accuracy, but also has better performance of CFO estimation than classical Park algorithm and Liang Xiao’s method.

Aminjavaheri et al 2015, presented a study of the candidate waveforms for 5G when they were subjected to timing and carrier frequency offset (CFO). The waveforms treated are: orthogonal frequency division multiplexing (OFDM), generalized frequency division multiplexing (GFDM), universal filtered multicarrier (UFMC), circular filter bank multicarrier (C-FBMC) and linear filter bank multicarrier (FBMC). The interest was on the multiple access interference (MAI) when a number of users transmit their signals to a base station in an asynchronous or a quasi-synchronous manner. The source of the waveforms presented various numerical analysis which includes reduction in sensitivity and irregular performance when window with smooth edge is applied at both the transmitter and receiver sides. Of all the waveforms, only the linear FBMC had better performance with MAI.

Wang et al 2015, worked on the Universal Filtered Multi-Carrier (UFMC) multi-carrier modulation technique which was seen as a generalization of filtered OFDM and filter bank based multicarrier (FBMC-FMT). As a candidate waveform technology for 5G wireless systems, UFMC combines the simplicity of OFDM with the advantages of FBMC. The FIR-filter, used in UFMC to filter a group of subcarriers, was seen as a key design parameter to gain more robustness in relaxed synchronization conditions (in time-frequency misalignment). It was then shown that very significant SIR improvement could be achieved for UFMC by optimizing the FIR-filter, taking carrier frequency offset into account. Further, an optimization of the FIR-filter design in UFMC taking both carrier frequency and timing offset into account in an uplink multi-user FDMA scenario was considered. The simulation results showed that up to 3.6 dB SIR improvement could be achieved with the optimized FIR filter compared to UFMC with non-optimized Dolph-Chebyshev filter and 15.1 dB SIR gain against classical CP-OFDM system respectively, provided that the normalized carrier frequency and timing offset were uniformly distributed in the interval 5%.

3.0 TIMING AND FREQUENCY SYNCHRONIZATION

OFDM is very sensitive to carrier frequency offset (CFO) due to high side-lobe levels of the rectangular symbol shape. However, it is robust against positive timing offset (where signal arrives later than receiver expected) due to CP as long as the timing offset is within the CP duration. Compared to OFDM, UFMC can achieve more robustness against time-frequency misalignment with the Finite Impulse Response (FIR) filter [Li et al, 2012]. The reason for robustness against CFO is because of the reduced out-of-band radiation. Robustness against timing offset is achieved by soft protection of filter ramp-up and ramp-down. Receive side synchronization becomes more important when discarding the closed-loop synchronized operation mode of LTE with the timing advance adjustments.

3.1 Timing Offset Estimation

Figure 1 illustrates the timing offset between transmitted and received signal due to propagation delay. The underlying timing offset degrades system performance by introducing ISI and destroying the orthogonality between subcarriers. This should be estimated and corrected at the receiver. The inserted pilot symbols at the transmitter can also be used to estimate the timing offset.

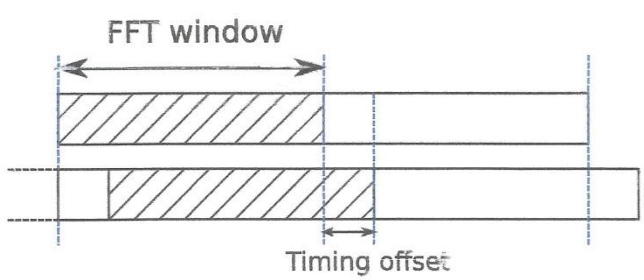


Figure 1: Timing Offset between Transmitter and Receiver

As the pilots are already known by the receiver, the Cross Correlation Function (XCF) *A(k)* between the known pilots in time domain *s(n)* and the received signal *r(n)* can be calculated [Lee et al, 2004]:

$$A(k)=\sum_{n} s^{*}(n-k)r(n)=\sum_{n} s^{*}(n-k)y(n)+\sum_{n} s^{*}(n-k)w(n) \qquad (1)$$

where (‘)* is conjugate complex. The peak position *k* of the XCF indicates the timing offset. Consider a Transmission Time Interval (TTI) of one sub-frame, which contains two pilot symbols and the time lag between these two pilots are known. Then the XCF *A(k)* should have two peaks with the known sample distance l_d. However, the peak position can be wrongly estimated due to noise and ISI.

To increase robustness of the algorithm the sum of two peak amplitude instead of a single peak for one pilot was considered. Hence the final timing offset estimator can be written as:

$$\Lambda n = \arg\max_k (|A(k)| + |A(k+l_d|) \qquad (2)$$

If the N_{pilot} pilot symbols are contained in the TTI, then the estimator can be given as:

$$\Lambda n = \arg\max_k \sum_{n=0}^{N_{pilot}-1} |A(k+(n-1)l_d)| \qquad (3)$$

It has to be noted that the performance of this method depends very much on the auto-correlation (AC) properties of the pilot symbol.

3.2 Timing and Carrier Frequency Offset Estimation

There is need for timing and frequency offset estimation due to the Doppler-Effect and frequency mismatch of local oscillator and frequency error. To extend the timing offset estimator to cover the timing and carrier-frequency offset estimation, hypotheses tests for various frequency offsets. It is assumed that the normalized CFO ε is within the interval -0.5 and 0.5 subcarrier spacing. The normalized CFO is then quantized between -0.5 and 0.5 subcarrier spacing into l_q levels. These quantized discrete normalized CFOs form a set Sq_{CFO}. Hence for every CFO from this set $\varepsilon_q \in Sq_{\text{CFO}}$, the timing offset estimation algorithm is performed and the peak amplitude and estimated timing offset is recorded. Instead of using the conjugate complex originally known pilot sequence in time domain s*(k), the CFO compensating version of the known pilot $s*(k).e^{-j2\pi\varepsilon_q k/N}$ is used to perform timing offset estimation. Among all the peak values, the largest peak is selected. The frequency and timing offset can be estimated by the corresponding indexes of the largest peak where the estimator can be formulated as [Lee et al, 2004]:

$$(\varepsilon, \Lambda n) = \arg\max_{k,\varepsilon_q} \sum_{n=0}^{N_{pilot}-1} |A(k+n(n-1)l_d| \qquad (4)$$

with $$A(k) = \sum_n \bar{s}*(n-K)r(n) \qquad (5)$$

hence $$\bar{s}(n) = e^{-j2\pi\varepsilon_q n/N} s(n) \qquad (6)$$

The estimator’s performance therefore dependents on the used pilot sequences, SNR and number of pilots N_{pilot} within the considered TTI. Invariably, the inserted CP in OFDM systems is also a redundant information that can be used to estimate timing and frequency offset. First, there is an observation window *r(k)* of the length $2N + L_{CP}$ that is selected, where L_{CP} is the length of the CP. It is also assumed that one complete symbol of $N + L_{CP}$ length is always contained in the observation window so that a correlation peak exists between the copied CP and the data symbol.

4.0 RESULTS AND DISCUSSION

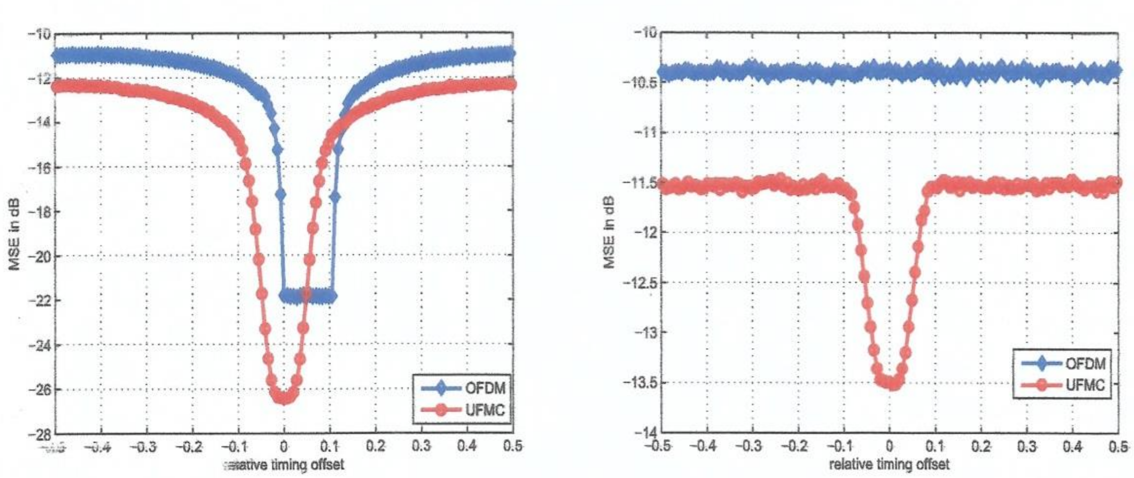
i. Relative Timing and CFO

The relative timing offset and relative CFO (rCFO) is normalized to total number of samples per symbol and subcarrier spacing respectively. The simulation settings are shown in table 1. For the simulation, it was considered that one sub-band with a User of Interest (UoI) is perfectly synchronized at the receiver and all other nine sub-bands interfere with the UoI.

Table 1: Simulation Settings to Evaluate the Effect of Timing and Frequency Offset in OFDM and UFMC Systems

MultiCarrier Scheme	OFDM	UFMC
FFT size	128	128
Subband size	12	12
Number of Subbands	10	10
CP-length	15	0
FIR-filter type	none	Chebyshev (40 dB side lobe attenuation)
Filter length	-	16

Figure 2 shows the Mean Square Error (MSE) of symbol estimates plotted over relative timing offset with relative CFO (rCFO) 0.1 (figure 2a) and 0.5 (figure 2b) subcarrier spacing. The result shows that UFMC clearly has a symmetric effect of timing offset rather than the non-symmetric effect on OFDM systems.



(a) Effect of timing offset in UFMC and OFDM under rCFO 0.1 subcarrier spacing

(b) Effect of timing offset in UFMC and OFDM under rCFO 0.5 subcarrier spacing

Figure 2: The System Performance Comparison of OFDM and UFMC under Timing and Frequency Offset

ii. Cross Correlation Function

Figure 3 show the XCF for a TTI of 2 slots in a UFMC system with SNR 0 dB. It is observed that two peaks correspond to the pilot position. In order to increase robustness of the algorithm, the sum of the peak amplitude was considered instead of a single peak for one pilot.

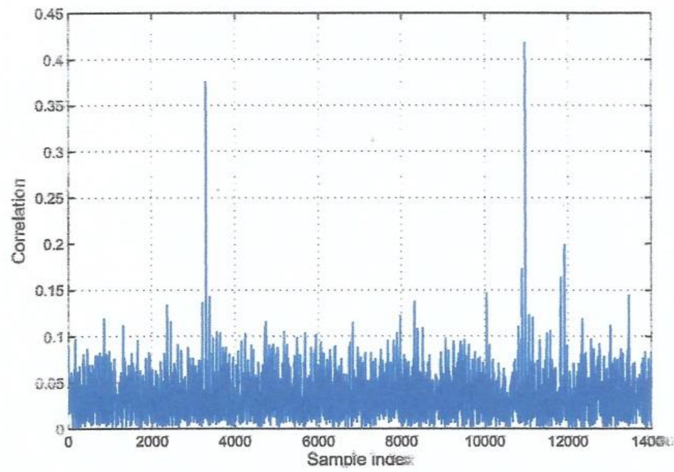


Figure 3: XCF for TTI of 2 Slots in UFMC with SNR of 0dB.

iii. Pilot-Based Timing Estimator

The performance of the pilot-based timing offset estimator is evaluated with the basic simulation settings of table 2.

Table 2: Simulation Parameters

FFT Size	Filter/CP Length	PRB Size	No. of PRBs	Timing Offset (TO)	TTI
1024	74/73	12	10/2	10 samples	2 slots

The Dolph-Chebyshev FIR filters are used with its center frequency shifted to that of every physical resource block (PRB). The side-lobe attenuation of Dolph-Chebyshev filters are set to 40 dB. Timing offset is set to be of length 10 samples. At the transmitter, one sub-frame which contains 12 data symbols and 2 pilot symbols are transmitted. At the receiver, a timing synchronization algorithm is performed. The number of allocated PRB for users affects the system performance in such a way that it affects the SNR. The larger the number of allocated PRB for a user, the larger the SNR is for constant power spectral density of data symbols. A pilot sequence of “allones” was introduced to show the influence of the pilot sequences in the simulation as a reference. The allones pilot refers to a pilot which contains only ones in all the allocated subcarrier positions. LTE standard compliant pilots were evaluated for comparison and the user is assumed to move at the speed of 50 kmh (resulting in Jake’s Doppler spectral power density). The probability density function (PDF) of the estimated timing offset is calculated in order to evaluate the performance of the pilot-based timing estimator.

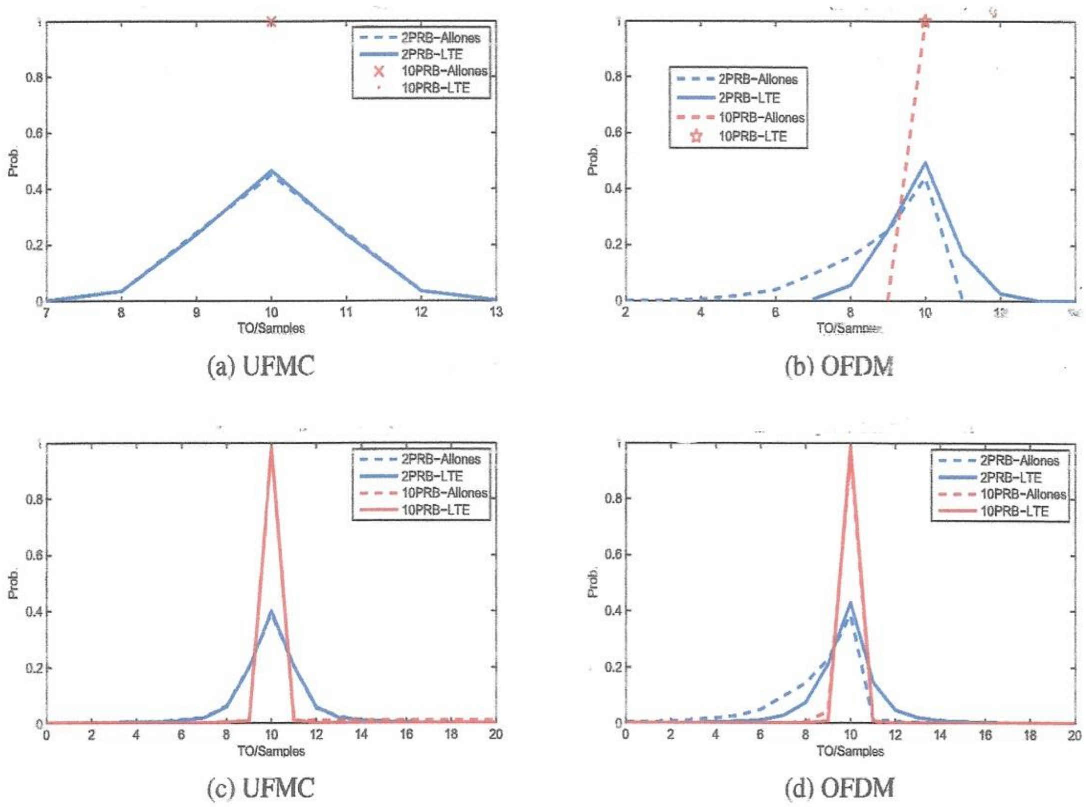


Figure 4: UFMC and OFDM Timing Offset Estimator Performance.

With the SNR fixed at 10dB for both UFMC and CP-OFDM and used pilot are allones vector and pilots according to LTE standard, the PDF of estimated timing offsets are plotted for UFMC (figure 4a,c) and OFDM (figure 4b,d) under the three considered channel models separately. From the simulation results it is seen that the method works well under AWGN and flat fading channel model with quite satisfying detection probability. The allones and LTE standard compliant pilot sequences have almost the same performance in UFMC systems, while the LTE standard compliant pilot sequences outperform the simple allones pilot in OFDM systems. The reason is that the auto-correlation properties of the pilot standardized in LTE is optimized for OFDM systems and these properties are again destroyed in UFMC systems. The optimal autocorrelation properties are destroyed by the filtering approach, since the symbols are not equally weighted in different subcarrier positions in UFMC. Furthermore, it is noteworthy to mention that UFMC has more tolerance on negative timing errors than OFDM if residual timing offset remains after synchronization.

iv. CP-Based and Pilot-Based Timing-Frequency Estimator

Carrier frequency offset is also to be estimated using the timing and frequency estimator based on pilot and CP. For OFDM systems, both CP-based and pilot-based method can be used to jointly estimate timing and frequency offset. Only pilot-based method can be used for UFMC systems since it does not have CP.

For the pilot-based method, the normalized CFO is quantized into l_q = 21 levels from -0.5 to 0.5 with quantization accuracy of 0:05. Since there is quantization error, the estimation is expected to be biased. Also, the larger the quantization level l_q is, the more accurate the estimation can be. This however results in higher computational complexity, since the number of hypotheses increases. There is then a compromise between the estimation accuracy and computational complexity. The quantization accuracy of 0:05 with $l_q = 21$ is sufficient to neglect the quantization errors. The rCFO is set to 0:1 subcarrier spacing and timing offset of 10 samples. The allocation size is 10 PRBs and standard compliant pilot sequences are used in pilot-based estimation method.

The PDFs of the estimated timing offset are shown (figure 5) for OFDM with CP-based and pilot-based method for different SNRs. From the results for timing offset estimation, it is obvious that pilot-based method is more robust for frequency unselective channel (AWGN and flat fading channel). Satisfying performance can be achieved under -10 dB SNR and good performance from 0 dB SNR for the pilot-based synchronization. The CP-based method requires SNR larger than 10 dB to achieve the same performance of pilot-based synchronization. The obtained results for UFMC systems using pilot-based approach are similar to that for OFDM.

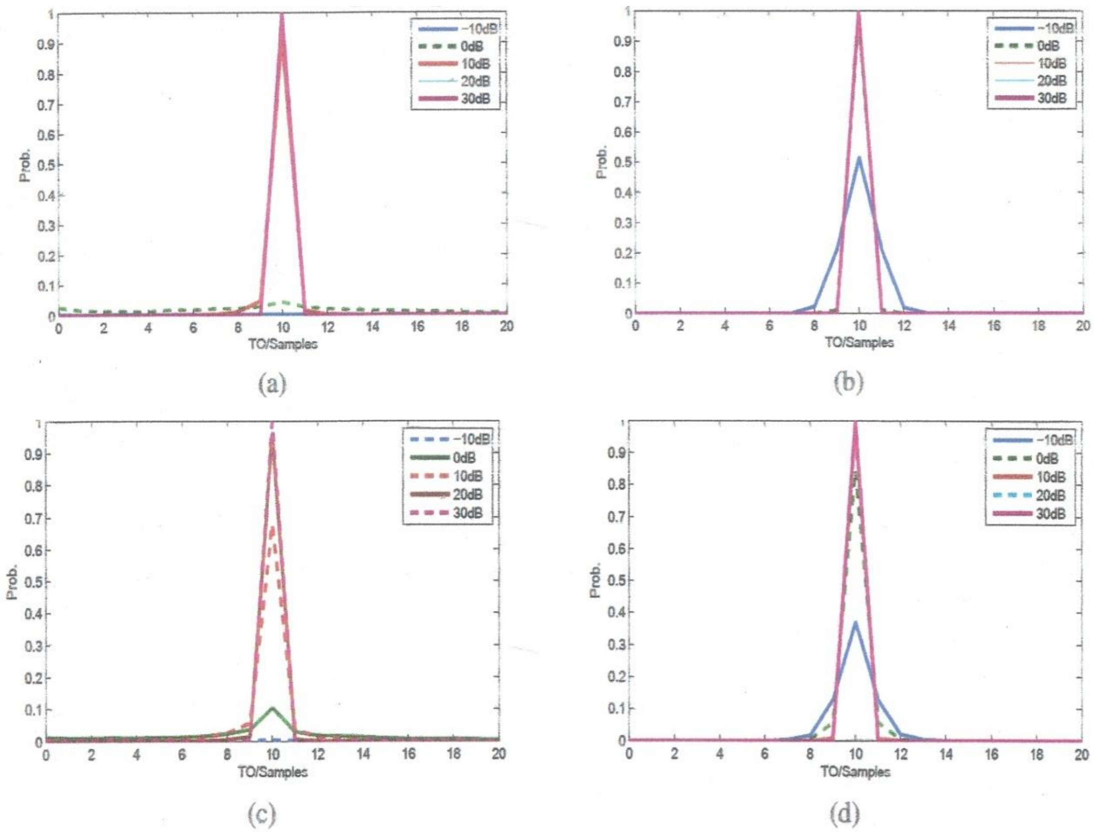


Figure 5: CP-based and Pilot-based Timing Estimator in OFDM

Conclusion

The pilot-based method outperforms CP-based method especially for SNRs which are higher than 5 dB. For flat fading, CP-based method is more robust for SNRs under 0 dB, while the MSE decreases fast for pilot-based method with increasing SNR. The performance of pilot-based method is almost the same for OFDM and UFMC. Although the received signal is impaired with CFO, the performance of timing offset seems not to be affected by CFO. The largest estimation error due to the quantization of CFO occurs if the real CFO value is located exactly between two quantized CFOs. As far as the comparison of OFDM and UFMC for 5G synchronization is concerned, OFDM is more sensitive to quantization errors than UFMC, hence UFMC is more preferred.

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