# Efficient Cooperative OFDM Localization


Pablo Martinez Grande, MSc TU Delft Exchange Student

IRCTR department at the TU Delft

ETSIIT department at the UPNA

Student number: 4105184

Mentor: Hao Lu

Supervisors: H. Nikookar and Miguel A. Gómez Laso


Delft, 26th October 2011

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# Preface

I've been working on the topic of cooperative OFDM localization for one year in the TU Delft as an exchange student. Nowadays there are many potential uses for cooperative localization in places in which the common systems like GPS could not provide an accurate estimation. It is an advantage to join into a wireless network with a mobile device and be able to navigate and know your position. Two critical points in this topic are the accuracy of the localization, that is required to be high, and the power consumption of the mobile devices, which is a critical resource. Existing indoor cooperative localization methods require big battery consumption for the mobile relays, and the accuracy in low SNR situations is not good enough. The scope of this thesis is to estimate the localization of an unknown mobile device in an efficient way, being accurate even in low SNR situations, with low power consumption. One first approximation and the reference [11] suggested me the idea of the "feature method" which is a bandwidth efficient cooperative ZP-OFDM localization method. After testing different features and conclude that the peak to average power ratio has the best performance another new idea came to me. A new simple relay is proposed, called trigger relay, which consists of forwarding a known signal when the incoming signal is received. With this new idea it is solved the bandwidth and computational problem, being the most efficient method to estimate the TDOA. This brilliant idea was published in the PIMRC conference in September, 2011.

# 0. Abstract

This thesis mixes together three important concepts which are the orthogonal frequency multiplexing (OFDM) technology with cooperative communication to provide localization of an unknown device.

Global Positioning System (GPS) provides worldwide localization but it requires line of sight (LOS) to multiple satellites. Indoor scenarios or other situations in which GPS is ineffective need to be covered.

Other cooperative localization methods have been proposed. Mobile devices that are connected into a wireless network with known position act as cooperative relays to estimate the localization of a new mobile station which joins the system. Time difference of arrival (TDOA) measurements are calculated by the cross correlation of large signals that are forwarded by the cooperative relays. With three TDOA values it is possible to estimate the position of the unknown device solving the hyperbolic equations. In this conventional process it is employed a large bandwidth and a high power consumption, which are inconvenient facts for the mobile relays because their battery life is a critical resource.

The scope of this thesis is to provide an accurate and efficient cooperative OFDM localization method in order to solve those two problems that the conventional method has.

The contribution of this thesis is the proposal of two new efficient and accurate cooperative OFDM localization methods.

The first method is called “Feature Method” and it is based on the idea of the reference [11] which provides a bandwidth efficient method for CP-OFDM.

Our feature method works with ZP-OFDM, takes advantage of the block structure of the OFDM technology and requires the devices involved on the localization process to extract a statistical feature of each received symbol. After that they join all these values together in order to create the "feature signal" which will be the signal cross correlated to estimate the TDOA. Bandwidth and power consumption on the signal transmitted are saved with this new method, because it is only needed to transmit and process a small feature signal compared with the large raw data of the conventional method. Peak to average power ratio (PAPR) is the feature which best performance provides as a consequence of having the highest values for the feature signal, being the most robust of all the feature signals compared against the noise. This new method provides a better TDOA estimation in low SNR conditions with respect to the conventional method.

And the most important contribution of this thesis is the "Trigger Relay with Pilot Signal Method" which provides high accurate TDOA estimation for the cooperative OFDM localization being the most efficient method. A new kind of relay is proposed called trigger relay, which transmits a known OFDM signal at the moment when receives the signal from the source. The pilot signal is a well known OFDM signal, with a simple shape and usually with one OFDM symbol length, which implies a bandwidth and computational efficiency with respect to the other methods. Some parameters could be changed in order to improve the accuracy of the TDOA estimation with a tradeoff of losing efficiency and increasing the power consumption. The most important parameter is the amplitude. In low SNR conditions it is possible to have an acceptable TDOA estimation with this new method only increasing the amplitude of the pilot signal. That implies more power consumption but it is a tradeoff which deserves it.

# 1. Introduction

Wireless localization technology is an interesting topic with a wide range of novel applications. Outdoor environments are usually covered by the global positioning system (GPS) technology, but in some critical environment conditions, such as indoor areas, urban canyons, under tree canopies, etc. this technology doesn't work properly.

Different measurements are used to estimate the location of a device, like angle of arrival (AOA), received signal strength (RSS), time of arrival (TOA) or time difference of arrival (TDOA).

Outdoor navigation error usually could be around tens of meters, without having a critical impact on the performance of the application. On the other hand, indoor location requires a high accuracy because the different areas are separated by few meters.

To perform a system that could provide that precision it is worked with ultra wide band (UWB), which allows accuracy on the range of centimeters. Orthogonal frequency division multiplexing (OFDM) technology is a multicarrier technique with block structure which has a good time resolution due to wideband transmission, is the technology used on the communication protocol.

Cooperative communications allow different nodes in a wireless network to share resources and to collaborate to improve the communication obtaining spatial diversity.

The nodes are located in different positions and the retransmission of the information by the cooperative nodes provide a spatial diversity that could avoid the effect of the selective fading or the non line of sight (NLOS) situations, improving the communication if the direct path between the source and the receiver is not good enough. There are essentially two different relays depending on how they forward the received signal. Amplify and forward (AF) receives the signal, amplifies it and retransmits the amplified copy. Decode and forward (DF) first tries to decode the original signal, and then retransmits that estimation.

The scope of this thesis is to mix together those three important concepts in order to implement a cooperative OFDM localization system. The aim of this scheme is to locate an unknown device while it is having a communication in a wireless network.

The following figure depicts how could be a generic scheme to perform this scenario:

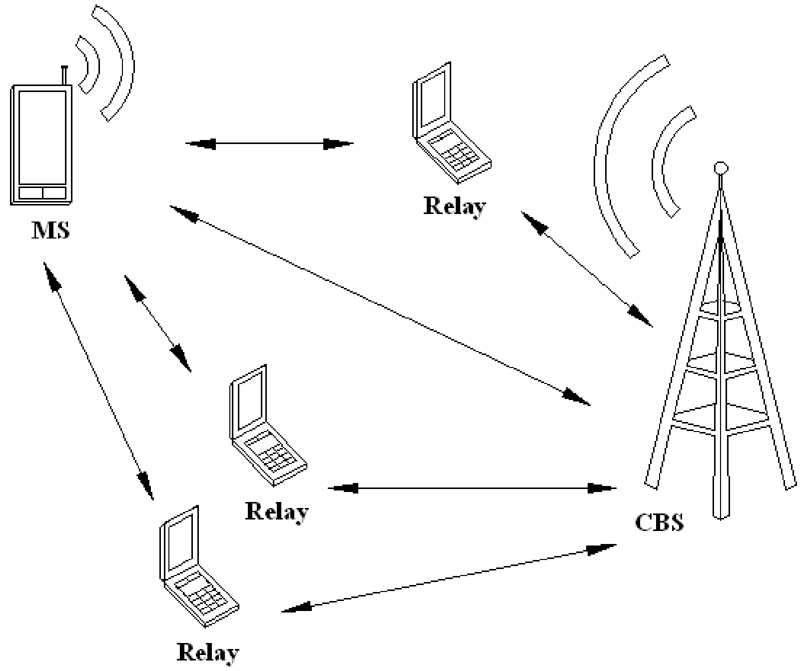


*Figure 1.1 Scheme of the system model for the cooperative localization*

where MS is the mobile station which is wanted to be located, the relays are mobile devices with known position which help on the localization process and CBS is the central base station which computes the positioning estimation.

A central base station (CBS) provides the wireless network, every device connected to the network has a communication with it. Initially the CBS has at least three relays with known position in the system. An unknown mobile device could enter on the scenario and join the wireless network. The work of this thesis is to create a method which could be able to locate the position of this unknown mobile station. To locate an unknown device which is having a communication on an indoor system it is needed at least three nodes to do the triangulation and the TDOA measurements to estimate its position. The CBS is the device designed to do the position estimation, helped by the relays of the system. Taking advantage of the cooperative communications it is possible to employ the located users as relays which help to locate the new unknown mobile stations which enter on the system. The relays which collaborate on the localization process are mobile devices, with limited power. For that reason other feature that is required for the new proposed cooperative OFDM localization method is to be bandwidth and computational efficient in order to save power consumption.

The measurement chosen to estimate the localization is the TDOA. TDOA is a time measurement and working together with UWB technology, which warranties high time resolution, could provide accurate measurements with small errors around the range of centimeters, which are acceptable for indoor localization. Other advantage of working with TDOA is that the localization process doesn't need to have a global clock because it works with the difference of time.

The conventional method to locate a device using TDOA implies the reception of the signal sent by the unknown device by the relays and the central base station. Each relay involved on the localization process needs to retransmit the whole received signal to the central base station. That implies a big bandwidth used, being an inefficient transmission of data, and high power consumption for the devices, which is a critical and limited resource for the mobile users.

Indoor localization is a potentially useful topic in a growing up stage. Several applications could be done while a mobile device is having a communication in a wireless network, ranging from navigation to source localization. The current methods that are available to estimate the TDOA for the indoor localization (based on AF and DF relays) employ a big bandwidth and compute several operations. Also the performance of the error on the localization is not good enough in low SNR conditions.

It is wanted to create a new method to estimate the position of an unknown mobile device in an efficient way, reducing the amount of bandwidth needed to transmit and the number of operations that are required to do the cooperative relays. To approach this problem it is needed to take advantage of the properties of the ZP-OFDM technique and to mix them together with the cooperative communications based on the known position devices which are on the network. The aim of the new method is to estimate the TDOA to compute the localization algorithm with low power consumption and try to estimate the position as accurately as possible.

Reference [11] provides a CP-OFDM bandwidth efficient method to estimate the TDOA. In this scheme it is proposed for the relays to calculate a feature (mean, variance…) of each CP-OFDM symbol, taking advantage of the OFDM block structure, and retransmit a "feature signal", which is a signal composed by the feature values extracted from each OFDM symbol, instead of the whole signal, like the traditional method. The analysis of this reference concludes that the feature which provides the best performance of the TDOA estimation is the mean of the cyclic prefix (CP).

In this thesis there are proposed two new methods to estimate the position of an unknown device in an efficient way.

The first method is called "feature method", and it is based on the idea of the reference [11]. In our method it is worked with zero padding (ZP)-OFDM instead of CP-OFDM, because ZP requires less power to transmit each symbol than the CP, and other advantages, which are explained on the chapter two, that are getting ZP-OFDM a good candidate for UWB communications. But in ZP-OFDM has no sense to calculate the feature of the ZP (the method of [11] extracts the feature from the CP). It is proposed other way to approach this problem, and to do the localization with a feature signal, being bandwidth efficient. An unknown mobile device broadcasts an OFDM signal which is received by the relays and the central base station. The relays extract one feature per each OFDM symbol received, taking a percentage of it in order to be more efficient than processing the full symbol, and send the feature signal to the CBS. The CBS also generates its own feature signal in order to cross correlate it with each feature signal received from the cooperative relays. The performance of the TDOA estimation gets more accurate when the percentage increases, but the optimal percentage to extract the feature depends on the SNR of the system. For that reason there is a tradeoff between the efficiency and the accuracy of the TDOA estimation. After testing different statistical features, the feature employed in our method is the peak to average power ratio (PAPR), because it has the best performance as a consequence of having the feature signal with the highest values. PAPR feature's signal is robust against noise and provides a better TDOA estimation than the conventional method in low SNR situations. With this new method it is wanted to reduce the number of computational operations and the bandwidth employed by the relays in order to save power consumption. The detailed results are shown on the third chapter.

Other new method is proposed to improve the estimation in an efficient way in the cooperative localization. It is called "Trigger relay with pilot signal method". It is proposed a new type of relay which is called "Trigger relay" (TR). When the TR receives the signal sent by the unknown mobile station, instantaneously forwards a known signal called "pilot signal" to the central base station. The pilot signal is an OFDM signal of one symbol length with a known shape. When the signal sent by the MS arrives at the CBS, the CBS also stores the pilot signal in order to do the cross correlation between this signal and the pilot signals received from the different trigger relays.

This method is bandwidth efficient because it is only needed to transmit one OFDM symbol. At the same time it is also computational efficient because the relay only needs to generate and transmit this simple pilot signal, and doesn't need to calculate features or retransmit the whole received signal.

The performance of this method is the best in the TDOA estimation, and also in bandwidth and computational efficiency, which is really important for saving the power consumption of the mobile devices which act as relays, and is their critical resource.

One important advantage of this new method is that changing different parameters it is possible to improve the TDOA estimation, with a tradeoff of decreasing the efficiency and consuming more power. The most important parameter to vary is the amplitude of the pilot signal. The pilot signal could be considered independent from the SNR suffered on the link between the MS and the relay, and the performance only depends on the SNR of the relay-CBS link. If the SNR is low, it is possible to increase the amplitude of the pilot signal, obtaining a good TDOA estimation with low error even in harsh environments in which there were impossible to have a good performance. The trade off is that the relay is required to transmit with more power, and the battery consumption of the mobile device increases so much, decreasing the battery life of the relay.

In the chapter four are shown the results, features and analysis of this new and enhanced OFDM cooperative localization method.

The analysis provided on those new methods is focused on the signal processing in order to compute the TDOA and to minimize the error of the estimation. With three TDOA values it is possible to estimate the position of the unknown device in two dimensions, with the hyperbolic localization algorithm.

The thesis is organized as follows. In chapter 2 it is explained the background information of the three pillars of this work which are the cooperative communications, OFDM and the localization. Chapter 3 describes the feature method and shows the simulation results comparing the performance of the different feature signals. In chapter 4 the Trigger relay with pilot signal method is shown. It is outlined the new idea and are commented the performance results varying different parameters. In chapter 5 it is compared the performance of the conventional methods and the new proposed ones. Finally chapter 6 draws the conclusions and provides the recommendations for the future work.

# 2. Background Information

## 2.1. Orthogonal Frequency Division Multiplexing (OFDM)

### 2.1.1. Introduction

OFDM is a special case of multicarrier transmission technique, where a single datastream is transmitted over a number of lower rate subcarriers. OFDM can be seen as either a modulation technique or a multiplexing technique.

The basic principle of OFDM is to split a high rate datastream into a number of lower rate streams that are transmitted simultaneously over a number of subcarriers. Because the symbol duration increases for the lower rate parallel subcarriers, the relative amount of dispersion in time caused by multipath delay spread is decreased. Intersymbol interference (ISI) is eliminated almost completely by introducing a guard time in every OFDM symbol [1].

One of the main reasons to use OFDM is to increase the robustness against frequency selective fading or narrowband interference [1]. OFDM also provides a multiple access with high data rates.

The following figure shows a basic block equivalent model of an OFDM system:

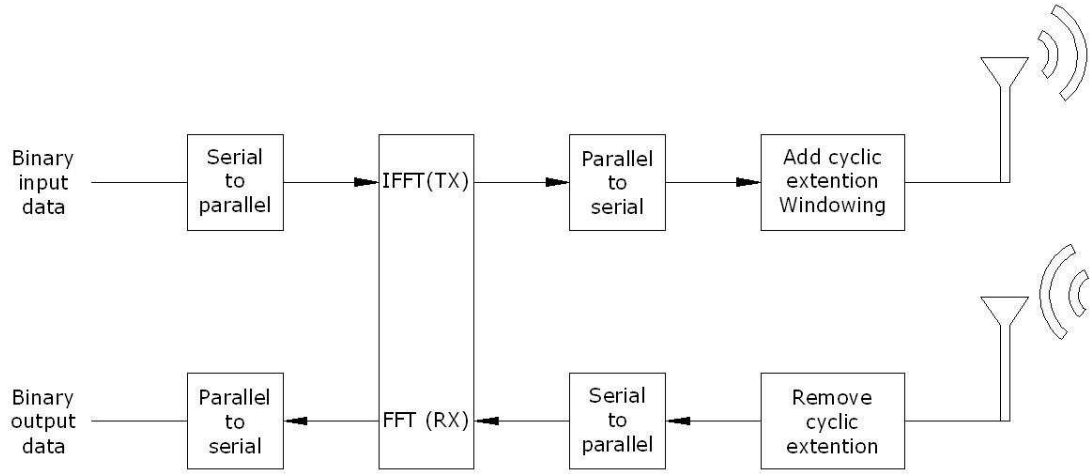


*Figure 2.1 Block equivalent model of an OFDM system*

### 2.1.2. Generation of an OFDM signal

The binary input data of $M$ bits is transposed from serial to parallel, obtaining a $M \times 1$ information block $s_M$ which is precoded by the IFFT matrix. It is obtained the time domain block vector $\tilde{s}_M = F \cdot s_M$, where $F$ is the IFFT matrix. After transposing the vector again to convert from parallel to serial, it is added the guard time, of length $D$, by zero padding or by cyclic prefix. The guard time provides robustness against the ISI effect, and is chosen larger than the expected maximum delay spread [1]. The number of time domain samples per transmitted block is $P = M + D$, and it will be sent sequentially through the channel.

The frequency-selective propagation will be modeled as a FIR filter with channel impulse response (CIR) column vector $h := [h_0 \cdots h_{M-1}]^T$ and additive white Gaussian noise (AWGN) $\tilde{n}_n(i)$ of variance $\sigma_n^2$. In practice, the system is designed such that $M \geq D \geq L$, where $L$ is the channel order. No Channel State Information (CSI) is assumed available at the transmitter. The expression of the $i-th$ received symbol block is given by [3]:

$$\tilde{x}_{cp}(i) = HF_{cp}s_M(i) + H_{IBI}F_{cp}s_M(i-1) + \tilde{n}_P(i) \qquad \text{(for CP-OFDM)} \qquad (2.1)$$

$$\tilde{x}_{zp}(i) = HF_{zp}s_M(i) + H_{IBI}F_{zp}s_M(i-1) + \tilde{n}_P(i) \qquad \text{(for ZP-OFDM)} \qquad (2.2)$$

Where $H$ is the $P \times P$ lower triangular Toeplitz filtering matrix with first column $\left[h_0 \cdots h_{L-1} 0 \cdots 0\right]^T$. $H_{IBI}$ is the $P \times P$ upper triangular Toeplitz filtering matrix with first row $\left[0 \cdots 0 h_L \cdots h_1\right]$ which captures the Inter Block Interference (IBI), and $\tilde{n}_P(i) := \left[\tilde{n}(iP) \cdots \tilde{n}(iP+P-1)\right]^T$ denotes the AWGN vector [3].

### 2.1.3. CP-OFDM

After removing the CP at the receiver, and since the channel order satisfies $D \geq L$ the (2.1) expression reduces to [3]:

$$\tilde{x}_M(i) = C_M(h)F \cdot s_M(i) + \tilde{n}_M(i) \tag{2.3}$$

Where $C_M(h)$ is $M \times M$ circulant matrix with first row $C_M(h) := Circ_M(h_0 0 \cdots 0 h_L \cdots h_1)$ and $\tilde{n}_M(i) := \left[\tilde{n}(iP+D) \cdots \tilde{n}(iP+P-1)\right]^T$. Therefore, after demodulation with the FFT matrix, the “frequency domain” received signal is given by[3]:

$$x_M(i) = D_M(\tilde{h}_M)s_M(i) + n_M(i) \tag{2.4}$$

where $\tilde{h}_M = \left[H_0 \cdots H_{M-1}\right]^T = \sqrt{M} F_M h$, with $H_k \equiv H(2\pi k / M) := \sum_{l=0}^{L} h_l e^{-2j\pi kl/M}$ denoting the channel's transfer function on the *k*th subcarrier; $D_M(\tilde{h}_M)$ standing for the $M \times M$ diagonal matrix with $\tilde{h}_M$ on its diagonal; and $n_M(i) := F_M \tilde{n}_M(i)$ [3].

This CP-OFDM property derives from the fast convolution algorithm based on the overlap–add (OLA) algorithm for block convolution. It also enables one to deal easily with ISI channels by simply taking into account the scalar channel attenuations. However, it has the obvious drawback that the symbol $s_k(i)$ transmitted on the $k-th$ subcarrier cannot be recovered when it is hit by a channel zero ($H_k = 0$). This limitation leads to a loss in frequency (or multipath) diversity but can be overcome by a ZP precoder [3].

### 2.1.4. ZP-OFDM

The received symbol is $\tilde{x}_{zp}(i) = HF_{zp}s_M(i) + H_{IBI}F_{zp}s_M(i-1) + \tilde{n}_P(i)$. The key advantage of ZP-OFDM lies in the all zero $D \times M$ matrix 0, which eliminates the IBI, since $H_{IBI}F_{zp} = 0$. Thus, letting $H := \left[H_0, H_{zp}\right]$ denote a partition of the $P \times P$ convolution matrix H between its first M and last D columns. The received $P \times 1$ vector becomes [3]:

$$\tilde{x}_{zp}(i) = HF_{zp}s_M(i) + \tilde{n}_P(i) \tag{2.5}$$

Corresponding to the first M columns of H, the $P \times M$ submatrix $H_0$ is Toeplitz and is always guaranteed to be invertible, which assures symbol recovery regardless of the channel zero locations. In other words, ZP-OFDM is capable of recovering the diversity loss incurred by CP-OFDM [3]. The trade off of this improvement is to have a more complex receiver.

### 2.1.5. Features

#### 2.1.5.1. Orthogonality

The subcarriers are orthogonal in frequency:

$$\int_{T_0}^{T_0+t} f_1(t) f_2(t) dt = 0 \tag{2.6}$$

Comparing with other multicarrier modulations the property of orthogonality implies a better spectral efficiency. The following figures show this feature:

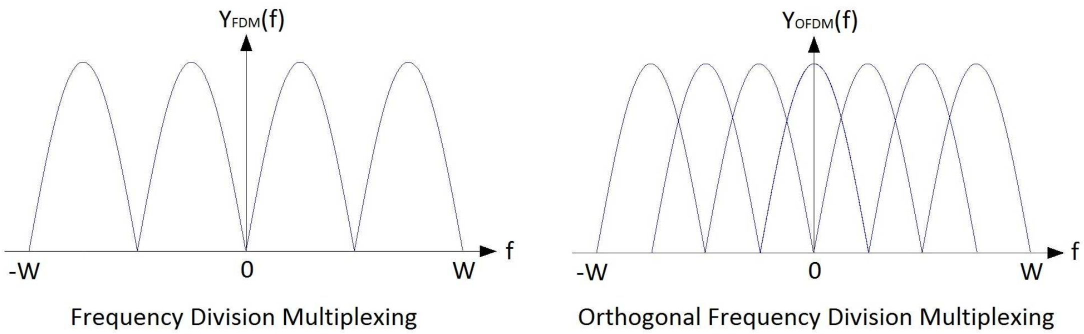


*Figure 2.2 Comparison between a modulation with and without orthogonality*

The figure 2.2 compares FDM with OFDM. Both are multicarrier modulations, but it is clearly depicted, that in the same bandwidth, there are more subcarriers (more information) on the orthogonal one.

Figure 2.3 shows the property of orthogonality, and how being overlapped the subcarriers, there is no interference.

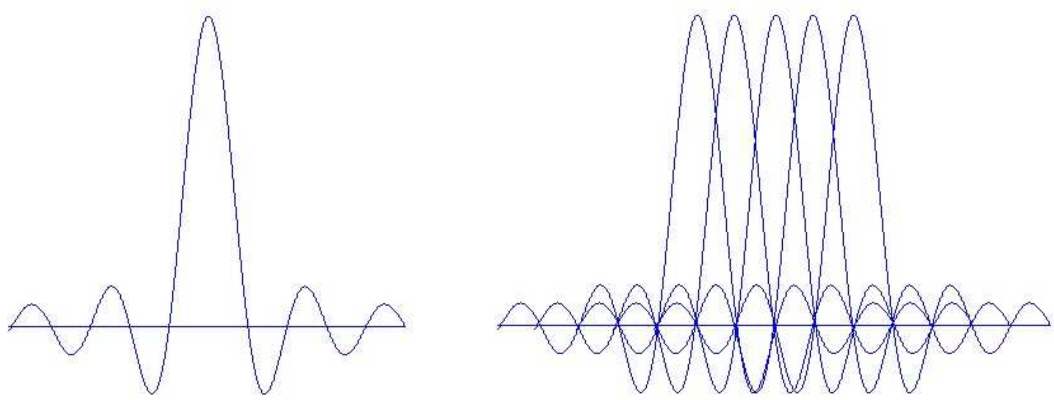

*Figure 2.3 Single carrier and multiple orthogonal subcarriers.*

#### 2.1.5.2. Multicarrier

A delimited bandwidth with different orthogonal subcarriers has better spectral efficiency than a single carrier system. It is needed to take into account the subcarrier spacing because if the number of subcarriers is increased in a fixed bandwidth, the subcarrier frequencies could be very close to each other, and then, the BER increases and the receiver synchronization needs to be very accurate.

Multicarrier property can avoid different problems that suffer other single modulation techniques, as ISI, or the frequency selective fading, which means a degradation of the system performance.

High data rates are limited by ISI in systems with single carrier. This problem could be solved decreasing the data rate, but it implies a slower communication. Other solution is to employ multiple subcarriers instead of using a single one. Having multiple subcarriers could enhance the symbol period on each carrier, being higher than the delay spread of the channel. Finally the effective rate could be high.

The frequency selective fading exists when the delay spread is longer than the guard time.

#### 2.1.5.3. Guard time

A guard time is introduced for each OFDM symbol to eliminate ISI. The guard time is chosen larger than the expected spread delay [1]. But the larger the guard time is, the less efficiency you will have.

Guard time can be filled either with CP or ZP.

The cyclic prefix is a periodic extension of the last part of an OFDM symbol that is added to the front of the symbol in the transmitter, and is removed at the receiver before demodulation. The cyclic prefix has two important benefits; acts as a guard space between successive OFDM symbols preventing ISI, and ensures orthogonality between the sub-carriers by keeping the OFDM symbol periodic over the extended symbol duration, avoiding inter-carrier interference (ICI).

### 2.1.6. COMPARISON BETWEEN CP-OFDM AND ZP-OFDM

If the length of the zero padding equals the length of CP, then the ZP-OFDM will achieve the same spectrum efficiency as CP-OFDM[4].

In ZP-OFDM, full symbol recovery is guaranteed, and equalization can be carried out by finite impulse response (FIR) filter regardless of the channel zeros or close to carrier frequencies [4].

When the ZP prefix replaces the CP in OFDM symbols, the ripples in the power spectral density (PSD) can be reduced significantly [4].

Actually ZP-OFDM is a good candidate for ultra wide band (UWB) communications. Its implementation requires less power than the CP-OFDM scheme, and as a consequence of the zero padding the interference is lower than with the cyclic prefix.

## 2.2. COOPERATIVE COMMUNICATIONS

### 2.2.1. INTRODUCTION

The motivation of the cooperative communications comes from the multiple input multiple output (MIMO) technology, which improves the received signal quality and increases the data communication speed by using digital signal processing techniques to shape and combine the transmitted signals from multiple wireless paths created by the use of multiple receive and transmit antennas.

Mobile devices are small and battery limited, being not possible to have an array of antennas inside them. It is possible to create a virtual MIMO system in a multi-user scenario, sharing their single antennas, cooperating together. This is the essence of the cooperative communications.

Cooperative communications allow different users or nodes in a wireless network to share resources and to create collaboration through distributed transmission/processing, in which each information is sent out not only by the transmitting user (source), but also by the collaborating users, called relays. It also realizes a new form of space diversity to combat the detrimental effects of severe fading.

MIMO's communication is done by different antennas, which are close to each other. As a consequence of the proximity, the channels aren't independent. On a cooperative communications scheme, the relays are located in different positions obtaining independent channels, which imply spatial diversity.

In a wireless environment, the signal transmitted or broadcasted by a source to a destination node (each one employing a single antenna), is also received by other terminals. Those terminals can act as a relay processing and retransmitting the signals they receive. The destination then combines the signals coming from the source and the partners, thereby creating spatial diversity by taking advantage of the multiple receptions of the same data at the various terminals and transmission paths. In addition, the interference among terminals can be dramatically suppressed by distributed spatial processing technology.

### 2.2.2. PERFORMANCE OF THE COOPERATIVE COMMUNICATIONS

The performance of the cooperative communications depends on the relaying strategy. There are basically two important protocols, amplify and forward (AF), and decode and forward (DF).

As shown in the figure below [5] the simplified cooperation model is composed of one relay (it would be more), one source and one destination. $P_1$ is the power which is transmitted by the source and $P_2$ is the power transmitted by the relay. $h_{s,r}$ is the channel coefficient between the source and the relay, $h_{r,d}$ is the channel coefficient between the relay and the destination and $h_{s,d}$ is the channel coefficient between the source and the destination. All the coefficients are modeled as Rayleigh flat fading channels.

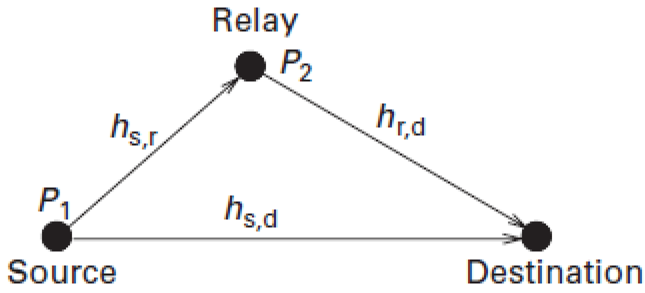


*Figure 2.4 Simplified cooperative communication model* [5].

The source transmits a signal '$x$' to the relay and to the destination. The signal received will be different in each node because of the different channel coefficients:

$$y_{s,r} = \sqrt{P} h_{s,r} x + n_{s,r} \tag{2.7}$$

$$y_{s,d} = \sqrt{P} h_{s,d} x + n_{s,d} \tag{2.8}$$

The terms $n_{s,r}$ and $n_{s,d}$ denote the additive white Gaussian noise with zero-mean and variance $N_0$ and independent one from each other.

This is the same for every strategy. The difference will be the amount and the quality of information that the destination receives.

### 2.2.3. AMPLIFY AND FORWARD (AF) RELAY

The amplify and forward scheme is a simple cooperative method in which each node of the network receives a noisy version of the signal transmitted by the source. As the name implies, the relay then amplifies and retransmits this noisy version. The base station combines the information sent by the source and relay, and makes a final decision on the transmitted bit (Fig. 2.5) [6].

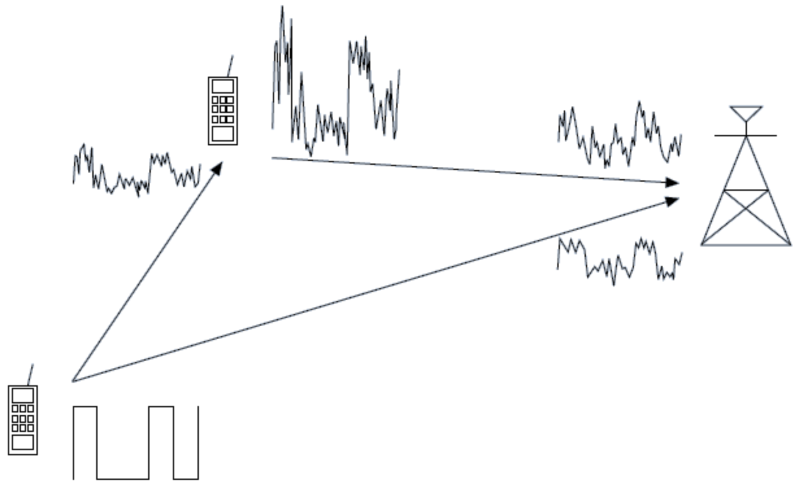

*Figure 2.5 Amplify and forward scheme* [6]

Although noise is amplified by cooperation, the base station receives two independently faded versions of the signal and can make better decisions on the detection of information [6].

In this protocol, the relay amplifies the signal from the source and forwards it to the destination ideally to equalize the effect of the channel fade between the source and the relay [5].

$$\beta_r = \frac{\sqrt{P}}{\sqrt{P\left|h_{s,r}\right|^2 + N_0}} \tag{2.9}$$

The relay transmits the signal $x_r = \beta_r y_{s,r}$ and has power $P$ equal to the power of the signal transmitted from the source.

### 2.2.4. DECODE AND FORWARD (DF) RELAY

The figure 2.6 [6] shows the scheme of a DF performance:

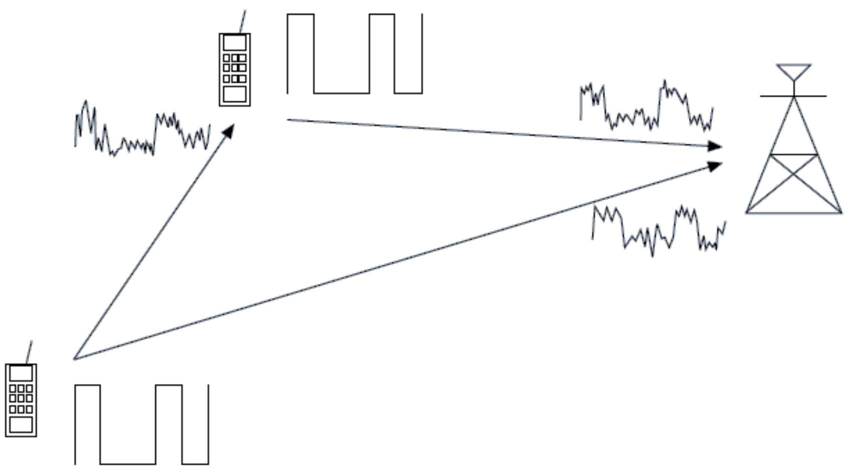

*Figure 2.6 Decode and forward scheme* [6]

There are two different decode and forward schemes, fixed and selective.

#### 2.2.4.1. Fixed-DF

In fixed DF the relay decodes the received signal '$x$' and retransmits it. But if the signal is wrong the cooperative communication will be worse than the direct transmission. That protocol depends strongly of the quality of the source-relay link and relay-destination link.

#### 2.2.4.2. Selective DF

The selective DF relaying protocol is an adaptive cooperation strategy that bases its operation in function of the SNR threshold received. If the signal that arrives at the relay is over that level, the relay decodes the received signal and forwards the decoded information to the destination. If the level is less than threshold, the relay idles. If the SNR is under the threshold probably the retransmit signal will be incorrect, for that it is inefficient to transmit it.

## 2.3. LOCALIZATION

### 2.3.1. INTRODUCTION

Localization is an interesting topic which has a potential use in different environments. Global Positioning System (GPS) is widely used, but, in critical environment conditions, such as indoor areas, urban canyons, under tree canopies, etc. This technology doesn't work properly. Thus, alternative methods can be implemented.

A general location system consists of three major elements: location-sensing module, positioning algorithm module, and the display module. The location-sensing part which is used in multiple sample modules due to trianglization, receives the RF signal, extracts appropriate features and delivers them to the positioning algorithm part. Trianglization is a technique that finds the position of the mobile terminal (MT) from its relative distances to the reference points (RP). Furthermore, the accuracy of the MT positions can be enhanced by increasing the number of RPs which increases the number of circles [7].

For the device localization problem different measurements like angle of arrival (AOA), received signal strength (RSS), time of arrival (TOA), time difference of arrival (TDOA), etc. can be used. This thesis is focused on time measurement based methods, especially TDOA.

### 2.3.2. Time of arrival (TOA)

TOA is the measured time at which a signal first arrives at a receiver. The measured TOA is the time of transmission plus a propagation-induced time delay. This time delay, between transmission at sensor $i$ and reception at sensor $j$, is equal to:

$$t_{delay}(i,j) = \frac{d_{i,j}}{v} \qquad (2.10)$$

where $d_{i,j}$ is the transmitter-receiver separation distance and $v$ is the propagation velocity [8].

With one TOA measurement it is possible to estimate a sphere in which is located the unknown device. With two different TOA, the spheres intersect on a line in which is the source that it is wanted to locate. Finally with three TOA measurements ideally there is a single point in which the unknown device is. On a real situation this point become an area.

### 2.3.3. Time difference of arrival (TDOA)

TDOA techniques are based on estimating the difference in the arrival times of the signal from the source at multiple receivers. This is usually accomplished by taking a snapshot of the signal at a synchronized time period at multiple receivers. The cross-correlation of the two versions of the signal at pairs of base stations is done and the peak of the cross correlation output gives the time difference for the signal arrival at those two base stations [9].

A particular value of the time difference estimate defines a hyperbola between the two receivers on which the mobile may exist, assuming that the source and the receivers are coplanar. If this procedure is done again with another receiver in combination with any of the previously used receivers, another hyperbola is defined [9]. The intersection of three hyperbolas results in the position location estimation of the source.

The following figure shows the scheme of the TDOA hyperbolic localization:

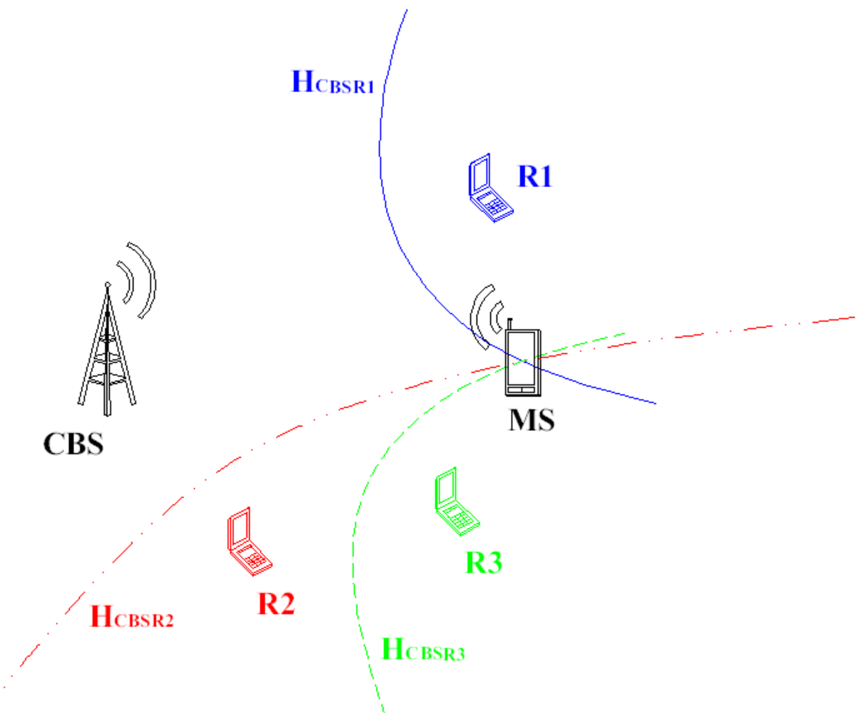


Figure 2.7 2D hyperbolic position location solution

## 2.4. COOPERATIVE LOCALIZATION WITH OFDM

It has been commented the features of the three important concepts that are the cooperative communications, the localization and the OFDM technology. In this master thesis it is wanted to mix them together to take advantage of their properties.

One main drawbacks of using TDOA methods for source localization and navigation is that it requires centralization of multiple copies of a signal, which wastes bandwidth and power. For OFDM sources, the amount of required centralization of data can be greatly reduced by comparing the temporal locations of the Cyclic Prefix (CP) rather than comparing the entire signals. However, since CPs occurs at regular intervals, this leaves an integer ambiguity in each TDOA (any integer times the OFDM block length). There are different methods for solving the ambiguity, transmitting a small amount of data per block, or using integer least squares methods [10].

TDOA measurements are often determined from the generalized cross correlation of the two received signals, which requires that one of the two sensors involved in each TDOA computation retransmit a long portion of the signal it receives to the other sensor involved in the computation [11].

Exploiting the structure of the multicarrier transmission, much less information is needed to be exchanged between sensors compared to the standard cross correlation approach.

Multicarrier systems use a more highly structured transmission format than many single carrier schemes. Of particular note, the beginning and end of each block of data are identical, due to the presence of a cyclic prefix inserted before each block. Thus, each node can identify block boundaries by looking for this repetition, which does not require knowledge of the transmitted signal. The nodes can independently locate the block boundaries without any cooperation amongst them, and then can each calculate some statistical feature (e.g., the sample mean or variance) of each block [11].

Taking advantage of the properties of the block structure of the OFDM technology, reference [11] proposes a bandwidth efficient cooperative localization method.

The proposed efficient TDOA computation is a two-step process [11]:

S1) (block boundaries): The relay uses the CP to locate the block boundaries within the signal that it receives. Simultaneously and independently, the base station performs the same task on its received signal.

S2) (feature extraction): The relay and the base station each compute a single, scalar statistical feature from each block. The relay transmits the feature values and boundary times of the associated blocks to the base station, which then correlates the sets of feature values in order to line them up.

Note that S1) is what makes the proposed method specific to OFDM. For non-block-based methods, there would be no way to predefine times at which one could measure features.

Some of the features that are considered include the first four normalized central moments (mean, variance, skewness, and kurtosis), the "mini-mean" (mean of the cyclic prefix), the average symbol's phase, and the peak-to-average power ratio. The formulas of each parameter can be shown at the reference [11]. At that reference, they found that the "mini-mean" feature yielded the best performance.

But this method is no available working with ZP-OFDM.

Comparing with CP-OFDM, ZP-OFDM requires less power to transmit and has less interference between symbols.

UWB signaling is especially suitable in the time based approaches for localization because it allows centimeter accuracy in ranging, as well as low power and low cost implementation of communication systems.

Multipath is considered deleterious for localization because it introduces interference in estimating the received data signals. However, the scattering objects can be regarded as the virtual cooperative nodes and can forward the copies of the transmitted signals to the receiver. Thus, with the proper design of the transceivers, the signal detection at the receiver side can be improved by gaining from multipath diversity.

This thesis is focused on the efficient estimation of an unknown device working with ZP-OFDM and the cooperative communications. The following chapters will show the new proposed methods to obtain that goal and the analysis of the performance of each one.

# 3. Feature Method. A Bandwidth and Computational Efficient Method in the ZP-OFDM Cooperative TDOA estimation

## 3.1. ABSTRACT

In this chapter, it is proposed a bandwidth and computational efficient localization method, using cooperative communications with ZP-OFDM. It is based on the transmission of block features to compute the cross correlation to estimate the TDOA, instead of transmitting the whole signal, as the conventional way does. It is proposed a method to calculate those features with less computational operations using a portion of the symbol for its extraction.

## 3.2. CONVENTIONAL TDOA-BASED LOCALIZATION

Accurate position measurement is important for many source localization and navigation problems. In source localization it is wanted to determine the position of the source of a wireless transmission. In the navigation problem, the premise is to use existing wireless infrastructure, such as radio and television towers at known locations, to determine the position of a mobile receiver [11].

For either the source localization or the navigation problem, the intent is to determine the relative position of the transmitter and the receiver [11].

This thesis is focused on TDOA-based methods. It is possible to directly determine a position estimate from the received data signals. In TDOA-based methods, there must be either two transmitters sending the same signal or two spatially separated receivers measuring the same transmission. Usually only one transmitter is available, hence multiple sensors or receivers must cooperate by sharing data. One drawback that arises from this is that the sharing of data requires significant bandwidth. Specifically, TDOA measurements are often determined from the generalized cross correlation of the two received signals, which requires that one of the two sensors involved in each TDOA computation retransmits a long portion of the signal it receives to the other sensor involved in the computation. However, this may require a large amount of bandwidth and power, which are limited resources for mobile, wireless devices [11].

## 3.3. INTRODUCTION

Reference [11] provided a feature based localization method in which the TDOA is calculated reducing the amount of data that must be shared between relays and the central base station (CBS) in order to perform TDOA computation, working with CP-OFDM.

It is called "feature" at the statistical characterization procedure of one OFDM block. One feature is calculated per each OFDM symbol. The signal which contains all those feature values is called "feature signal". Each node calculates this signal, the cooperative node sends its signal to the CBS, and the latter does the cross correlation of both, to estimate the TDOA.

Reference [11] uses the cyclic prefix to locate the symbols and then extract a feature of each one. Then the relays only send the feature of each symbol, instead of the whole symbol, saving bandwidth, computational operations, and battery consumption, which are critical resources for the mobile wireless devices.

The contribution of this method is to estimate the TDOA measurements in a bandwidth and computational efficient way.

## 3.4. SYSTEM MODEL

It is wanted to locate a mobile station (MS) while it is having a communication with the central base station (CBS). We consider a scenario which includes a MS, one relay (R) and the CBS, to compute the TDOA between R and CBS. The computation of the TDOA is done on the CBS.

This is a scheme which depicts the scenario of the simulation model:

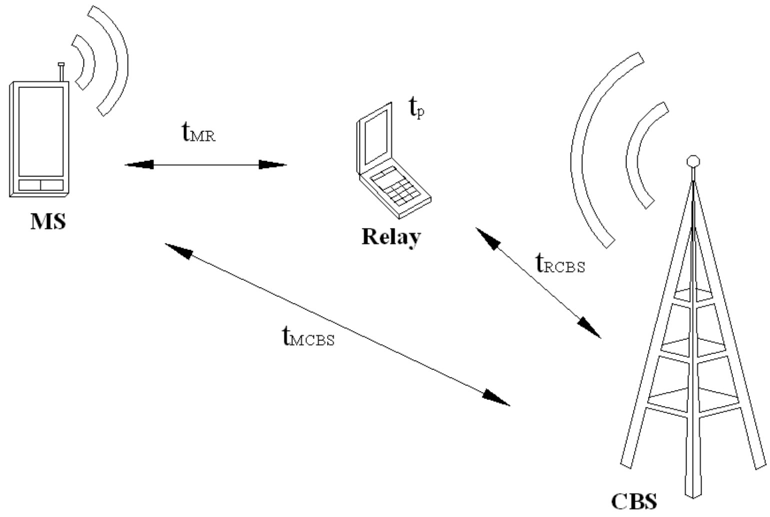


*Fig. 3.1 Scheme of the simulation model.*

where $t_{MR}$ is the propagation time between the MS and the relay, $t_{MCBS}$ is the propagation time between the MS and the CBS, $t_p$ is the process time and $t_{RCBS}$ is the propagation time between the relay and the CBS.

The MS is the element which is wanted to know its location. The relay collaborates sharing with the CBS the information received from the MS. For localization, additional relays are required in order to obtain more TDOA measurements, but for simplicity we only show one. The CBS has the communication with the MS, and receives the other signal from the relay. It processes the whole data, and makes an estimation of the MS location. We assume that the MS, the relay and the CBS have a line of sight (LOS) between each other. The location of the relay and the CBS are perfectly known.

The communication adopts ZP-OFDM technique, which is a block based and spectrum efficient technology. The MS sends a signal which is received by the relay and the CBS. To estimate the location of the MS, it is needed to calculate the time difference of arrival (TDOA), between the relay and the CBS. At least three TDOA measurements are required between different cooperative nodes. But this chapter is focused on calculate the TDOA in a bandwidth and computational efficient way, and for simplicity we only show one pair of MS, relay and CBS to describe the TDOA.

## 3.5. FEATURE BASED COOPERATIVE ZP-OFDM TDOA ESTIMATION

The first step for the proposed cooperative localization system is to know which could be the best feature to transmit. In the reference [11] it is provided that the best feature is the "mini-mean", which is the mean of the cyclic prefix.

For the ZP-OFDM is not possible to use this method. As the guard time is zero padding, the statistic features could have no relevant meaning.

The concept of calculating the mean of the CP, gave the idea of taking a percentage of the symbol in order to extract the feature of this part, instead of the whole symbol, with the aim of reducing the amount of operations, and, at the end, save battery for the mobile devices, which is a limited resource.

In the proposed cooperative ZP-OFDM system, we considered the block features include the first four normalized central moments (mean, variance, skewness and kurtosis) by using the first P samples of the *k*-th block effective OFDM symbol:

Mean:

$$\mu_{rx}(k)=\frac{1}{P}\sum_{i=1}^{P}y_{rx}(k)_i \qquad (3.1)$$

Variance:

$$\sigma_{rx}^2(k)=\frac{1}{P}\sum_{i=1}^{P}\left(y_{rx}(k)_i-\mu_{rx}(k)\right)^2 \qquad (3.2)$$

Skewness:

$$\lambda_{rx}=\frac{1}{P}\sum_{i=1}^{P}\left(\frac{y_{rx}(k)_i-\mu_{rx}(k)}{\sigma_{rx}(k)}\right)^3 \qquad (3.3)$$

Kurtosis:

$$\varepsilon_{rx}=\frac{1}{P}\sum_{i=1}^{P}\left(\frac{y_{rx}(k)_i-\mu_{rx}(k)}{\sigma_{rx}(k)}\right)^4 \qquad (3.4)$$

where the subscript "rx" denotes received signal either from the mobile station or relay. $y_{rx}(k)_i$ refers to the *i*-th sample of the *k*-th OFDM block.

It is also considered the average symbol's phase:

$$\Phi_{rx}(k)=\frac{1}{P}\sum_{i=1}^{P}\arctan\left(\frac{\mathrm{Im}(y_{rx}(k)_i)}{\mathrm{Re}(y_{rx}(k)_i)}\right) \qquad (3.5)$$

the variance of the symbol's phase:

$$\Psi_{rx}(k)=\frac{1}{P}\sum_{i=1}^{P}\left(\arctan\left(\frac{\mathrm{Im}(y_{rx}(k)_i)}{\mathrm{Re}(y_{rx}(k)_i)}\right)-\Phi_{rx}(k)\right)^2 \qquad (3.6)$$

and the Peak to Average Power Ratio (PAPR):

$$PAPR_{rx}=\frac{Max\left(\left|y_{rx}(k)_i\right|^2,\ldots,\left|y_{rx}(k)_p\right|^2\right)}{\frac{1}{P}\sum_{i=1}^{P}\left|y_{rx}(k)_i\right|^2} \qquad (3.7)$$

as the block features, where $\mathrm{Im}(\cdot)$ and $\mathrm{Re}(\cdot)$ stand for the imaginary and real part of the complex value, respectively. $Max(\cdot)$ denotes the maximum element of a vector.

The development of the scheme starts when the MS sends a signal which is received by the relay and the CBS in different times $t_{MR}$ and $t_{MCBS}$ respectively, as shown in Fig. 3.1.

The relay processes this signal and extracts one feature per symbol received. It is elapsed a process time, $t_p$, which is known. After that, the relay sends the "feature signal", which contains the feature values of each symbol received, to the CBS. The flying time is $t_{RCBS}$ which is possible to calculate because the position of the relay and the CBS are known.

The CBS receives the signal from the MS at the time $t_{CBS}$, in that moment the CBS processes that signal, and extracts its own feature signal in the same way as the relay. The CBS does the cross correlation between the two feature signals:

$$R_y(d) = \sum_{i=1}^{K} y_R(i) y_{CBS}^*(i+d) \qquad (3.8)$$

where $y_R(i)$ is the feature signal sent by the relay, $y_{CBS}(i)$ is the feature signal made by the CBS, and $(\cdot)^*$ denotes the complex conjugate function. The CBS must compute (3.8) for all values since there is received the first signal (from MS or relay), until the end of the latest arrival signal:

$$Min\left\{t_{MCBS}, \left(t_{MR} + t_p + t_{RCBS}\right)\right\} \le d \le Max\left\{t_{MCBS}, \left(t_{MR} + t_p + t_{RCBS}\right)\right\} + L \qquad (3.9)$$

where $L$ is the length of the feature signal.

The cross correlation value will be:

$$XCORR = t_{MR} + t_p + t_{RCBS} - t_{MCBS} \qquad (3.10)$$

Calculating the TDOA by its definition:

$$TDOA_{MCBS-MR} = t_{MCBS} - t_{MR} \qquad (3.11)$$

Mixing (3.10) and (3.11), it is calculated the TDOA known the processing time, the flying time and the cross correlation:

$$TDOA_{MCBS-MR} = t_{MCBS} - t_{MR} = t_p + t_{RCBS} - XCORR \qquad (3.12)$$

With three TDOA measurements and the hyperbolic equations, it is possible to estimate the location.

## 3.6. SIMULATION RESULTS

In the simulation it is considered the MS sending a signal of 50 symbols with a binary phase shift keying (BPSK) modulation in ZP-OFDM, with 64 subcarriers. The bandwidth of the signal is 500MHz, having a time resolution of 2ns. The emitter generates the BPSK signal with a random Gaussian distribution with zero mean and variance equal to one.

In this system, we assume additive white Gaussian noise (AWGN), and a Rayleigh flat fading channel.

In the scenario there is a fixed and well-known position relay, which extracts the feature of every symbol received from the mobile station in order to send the feature signal to the CBS, and also a fixed and well-known position central base station which computes the cross correlation between its own feature signal and the feature signal received from the relay. With the result of that operation the CBS makes the TDOA estimation.

In each simulation it is changed randomly the position of the mobile station through the area of the scenario (100x100 meters).

To compare the quality of the results it was used different criteria:

- Average of the time error:

  $$\mu_e = \frac{1}{N}\sum_{i=1}^{N} e_i \tag{3.13}$$

  where the time error is $e = \left|TDOA_{true} - TDOA_{estimation}\right|$ and $N$ is the number of iterations per simulation.

- Probability of having an error bigger than 1.5 meters (an error bigger than 5ns.):

  $$p_e = P\left(e > 5x10^{-9}\right) \tag{3.14}$$

  where $P(\cdot)$ is the probability estimator and $e$ is the time error.

  With this parameter it is possible to show how successful the estimation is, comparing the error with a threshold of 5 nanoseconds (1.5 meters), which is a reasonable error for indoor localization.

- Probability distribution function of the relative error, being the relative error:

  $$e_{rel} = \frac{\left|TDOA_{true} - TDOA_{estimation}\right|}{TDOA_{true}} \tag{3.15}$$

  With this parameter it is possible to show the impact of the error and the probability of having this value.

- Variance of the error:

  $$\sigma_e^2 = \frac{1}{N}\sum_{i=1}^{N}\left(e_i - \mu_e\right)^2 \tag{3.16}$$

  where $e$ is the time error, $\mu_e$ is the average of the time error and $N$ is the number of iterations per simulation.

  Shows how different the errors are. Is a good criterion to complement the average of the time error.

- Cumulative distribution function (CDF) of the error:

  $$CDF\left(X\right) = P\left(x \le X\right) = \int_{-\infty}^{X} f\left(x\right)dx \tag{3.17}$$

  where the probability density function is the vector which contains the 1000 times error values of the simulation and $x$ is the value in time which is wanted to know the probability of having an error lower than that value.

### 3.6.1. PERFORMANCE WITH DIFFERENT SNR

There are compared the performances of the different feature signals (mean, variance, skewness, kurtosis, symbol phase and PAPR) in different SNR conditions, large SNR (20dB), medium SNR (0dB) and low SNR (-20dB).

The simulations are done with different percentages taken from the OFDM symbol to extract the feature. The less percentage taken the most bandwidth and computational efficient the method is. It is wanted to find the best performance with the less percentage of the symbol taken.

#### 3.6.1.1. SNR=20dB

The following plot shows the average of the time error for each feature:

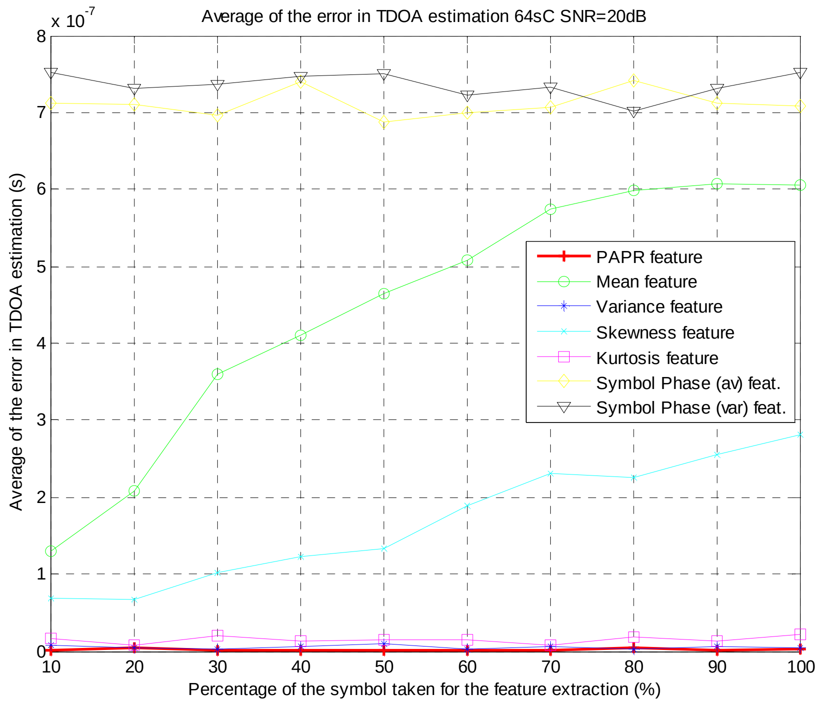


*Figure 3.2 Average of the time error with SNR=20dB*

Looking at the figure it is noticed the first conclusion, there are some features that have a big error in average, and won't be chosen as the feature for the feature method. Those features rejected are the variance of the symbol phase, average of the symbol phase, mean and skewness. They couldn't be used for indoor localization because they have an error on the order of $10^{-7}s$ which implies errors on the order of tens of meters, that are unacceptable in this environments.

Symbol phase has each value bounded between '0' and '1', and it's more sensitive to small variances on the received values disturbed by the noise, obtaining the worst performance. Mean and skewness have their best performance with small percentage of the symbol taken. The signal is generated randomly with zero mean and variance equal to one, for that reason, when the percentage of the symbol increases, the amount of data taken to extract the feature tends to have that zero mean, obtaining a feature signal with low values, and finally easy to be disturbed by the noise.

Features related with the power of the signal like variance and PAPR have the best performance, because the values obtained on the feature extraction are bigger. Variance values are around one, and the PAPR even bigger. For that reason, the feature signal is more powerful and more robust against the detrimental effects of the noise.

Next graph shows the performance looking at other criterion, which is the probability of having an error bigger than 1.5 meters (5ns) of all the features:

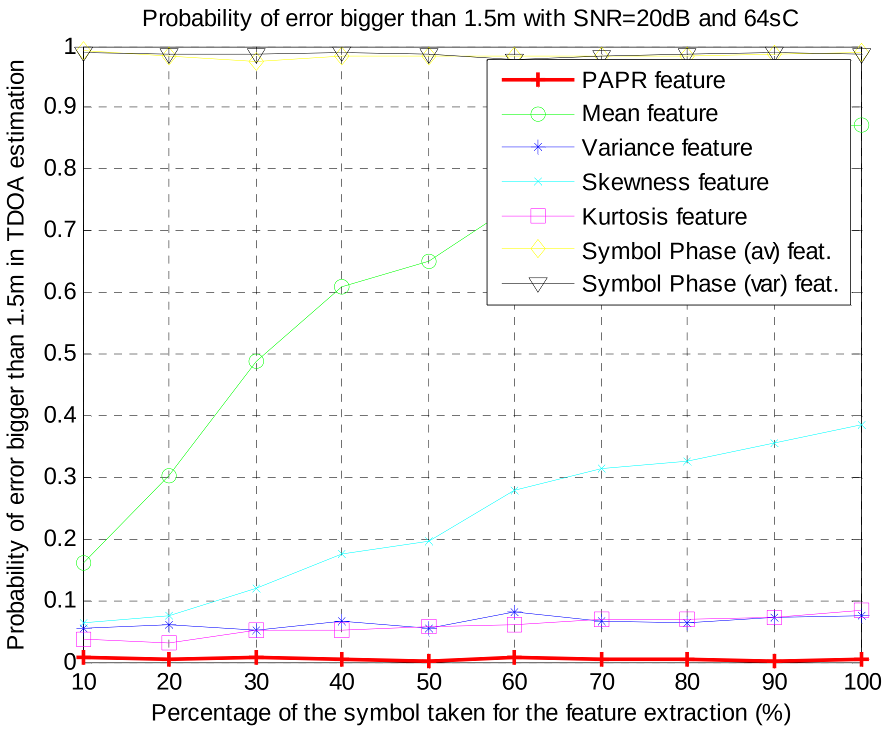


*Figure 3.3 Probability of error with SNR=20dB*

PAPR feature has TDOA estimation with an error below of 1.5 meters almost in the 100% of the times in a 20dB SNR situation, even with small percentage taken to extract the feature. Variance and Kurtosis also have a good enough performance, having a good TDOA estimation more than the 90% of the times.

The cumulative distribution function (CDF) of the PAPR feature is:

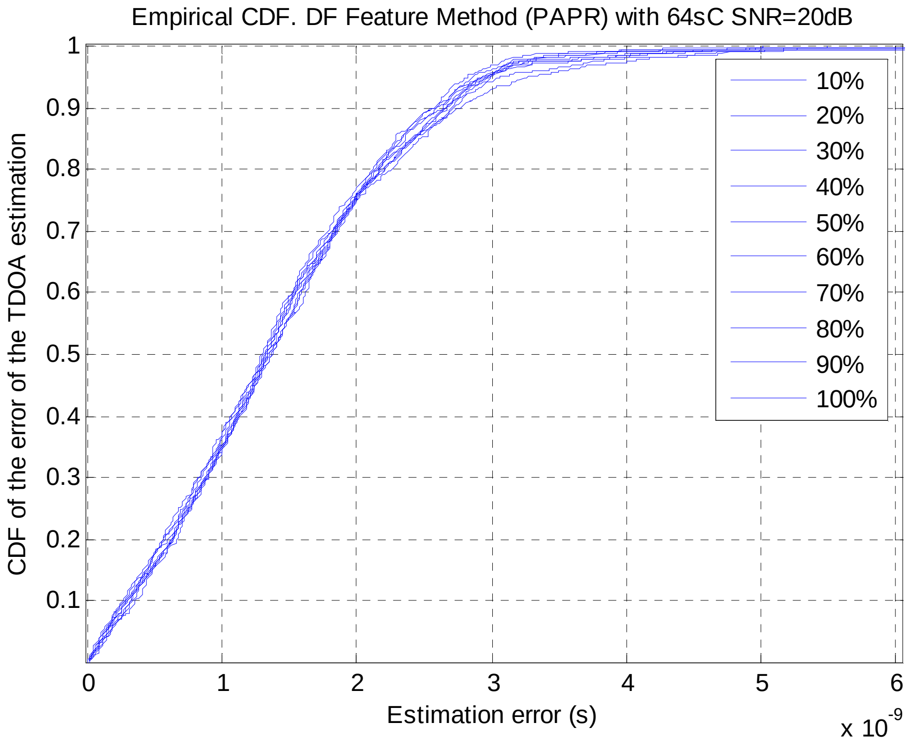


*Figure 3.4 CDF of the PAPR feature with SNR=20dB*

This figure shows how is distributed the error for the PAPR feature signal. All the curves are almost overlapped, that means that the percentage taken to extract the feature is not a critical issue for the performance of the system. For been the most efficient as possible, it will be choose the minimum percentage. The CDF plot also shows that the 90% of the simulations with this feature signal, the error is below 3ns.

PAPR feature signal is related with the power of the signal and its values are bigger than one, being robust against the noise effect, and obtaining a powerful signal that arrives without a big distortion when it is sent by the relay, obtaining a good cross correlation calculation.

To compare with other power related feature, the following plot shows the CDF of the variance feature:

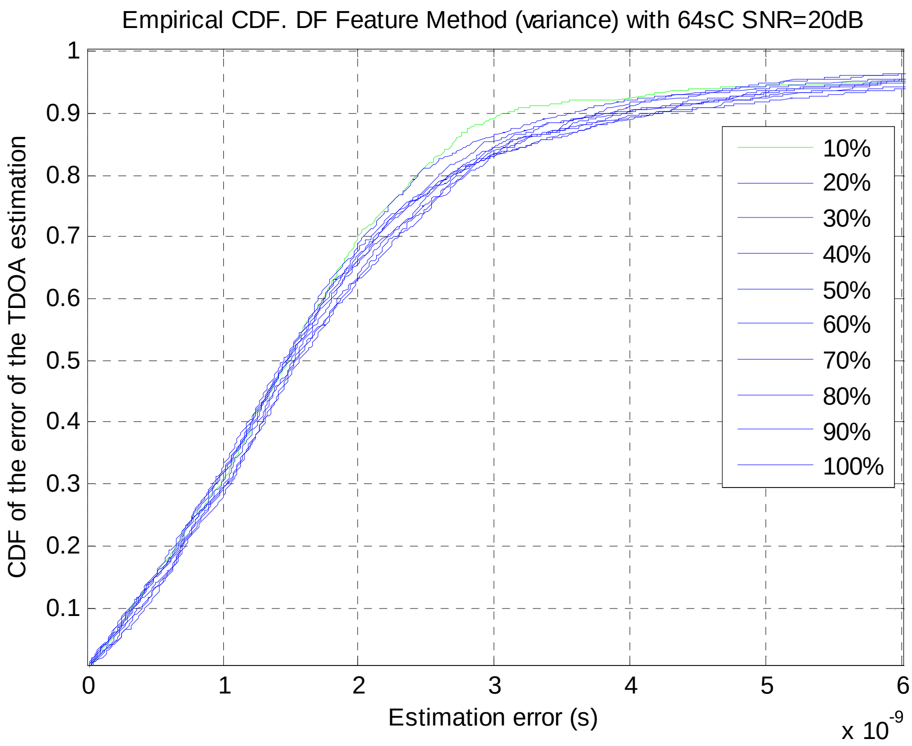


*Figure 3.5 CDF of the variance feature with SNR=20dB*

Figure 3.5 shows how is distributed the error of the TDOA estimation with the variance as feature signal. With the 10% taken to extract the feature is the best performance, and the 90% of the times, the error is below 3ns.

#### 3.6.1.2. SNR=0dB

Decreasing the SNR of the system, the results obviously turn worse. It is wanted to check the behavior of the different feature signals when the quality of the system conditions decreases.

The following graph shows the average of the time error for each feature:

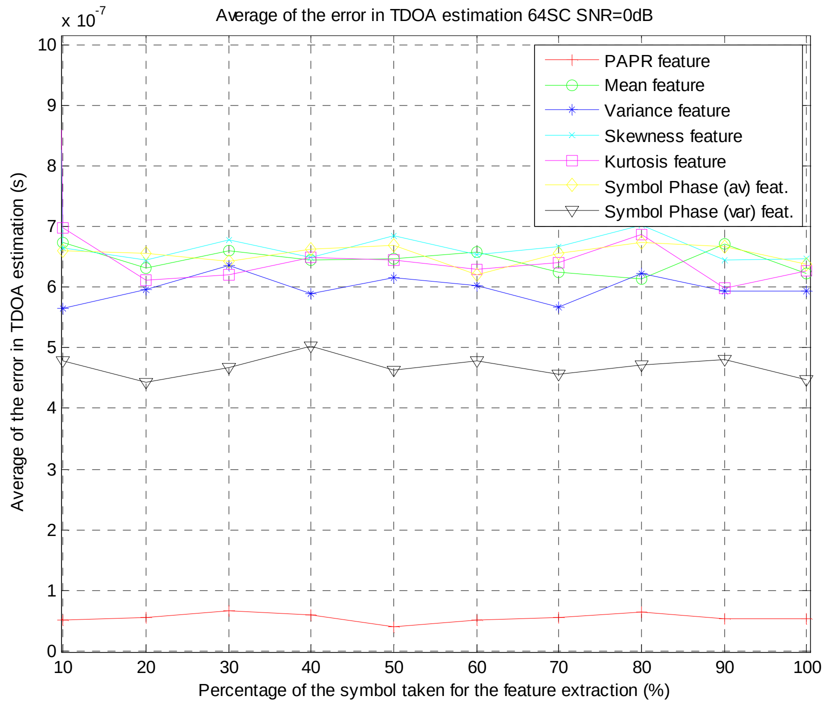


*Figure 3.6 Average of the time error with SNR=0dB*

When the SNR gets worse, PAPR is the only feature which has an acceptable performance, because the other feature signals have big errors in time average on the order of $5 \cdot 10^{-7}\, s$ that implies a location error of tens of meters.

The probability of having an error bigger than 1.5 meters (5ns) of all the features:

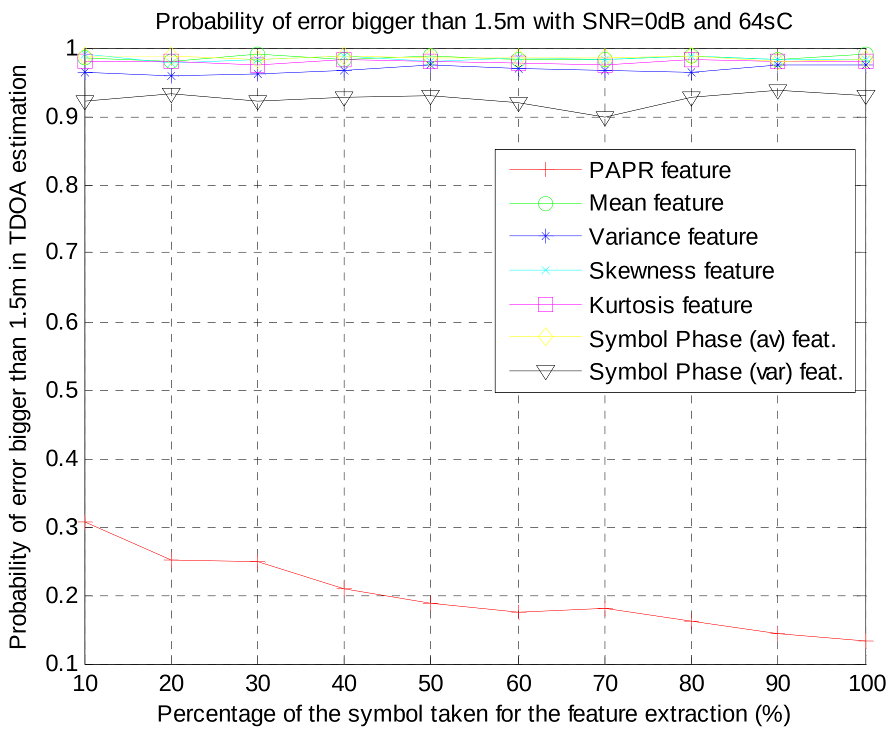


*Figure 3.7 Probability of error with SNR=0dB*

Except PAPR feature, all the features have big errors in more than the 90% of the times. Increasing the length to extract the PAPR feature the performance gets better. In 0dB SNR conditions there is a tradeoff between the computational efficiency and the accuracy of the TDOA estimation.

In 0dB SNR, the noise has more impact than the previous situation (20dB), implying a worse performance. Features which have a bad performance even in large SNR conditions now they have unacceptable errors, being impossible to use them for the TDOA estimation. Even the variance, that is a feature related with the power and in 20dB SNR has a good performance, with 0dB SNR has big error on the TDOA estimation. Having a feature signal with values around one, is not enough to survive the effect of the noise. PAPR feature signal has values bigger than one, and for that reason its feature signal is robust against the noise even in this SNR conditions.

The following graph shows the CDF of the PAPR feature signal:

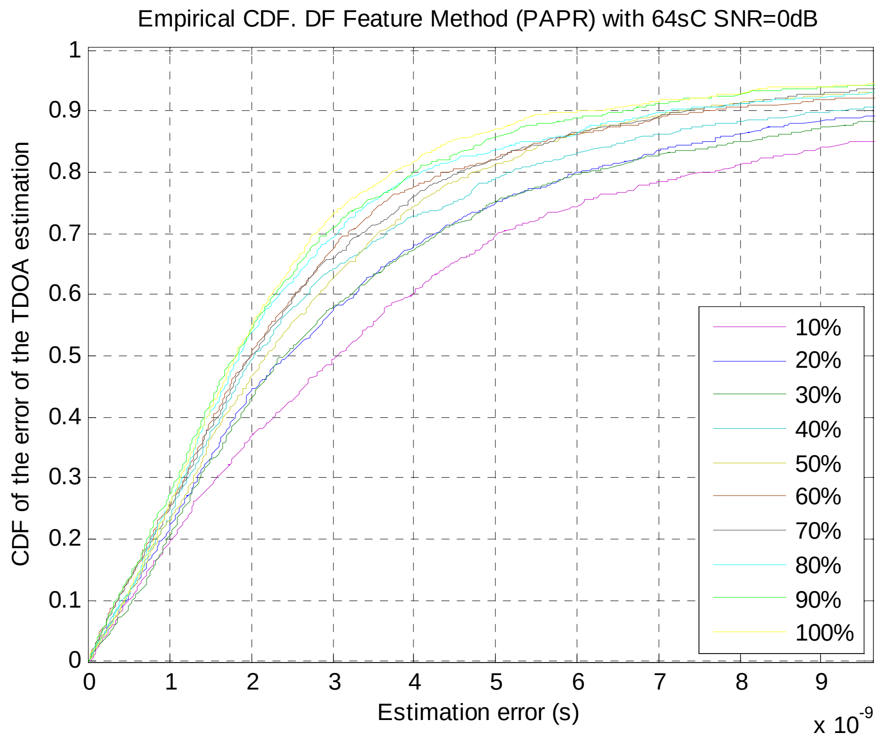


*Figure 3.8 CDF of the PAPR feature with SNR=0dB*

Figure 3.8 shows clearly the different behavior depending on the percentage taken to extract the feature. Obviously is worse than the SNR=20dB situation, but taking more than the 30% of the symbol at least the 80% of the times the error is under 5ns.

The next plot shows the CDF of the variance feature, in order to compare the different performance of this two power related features:

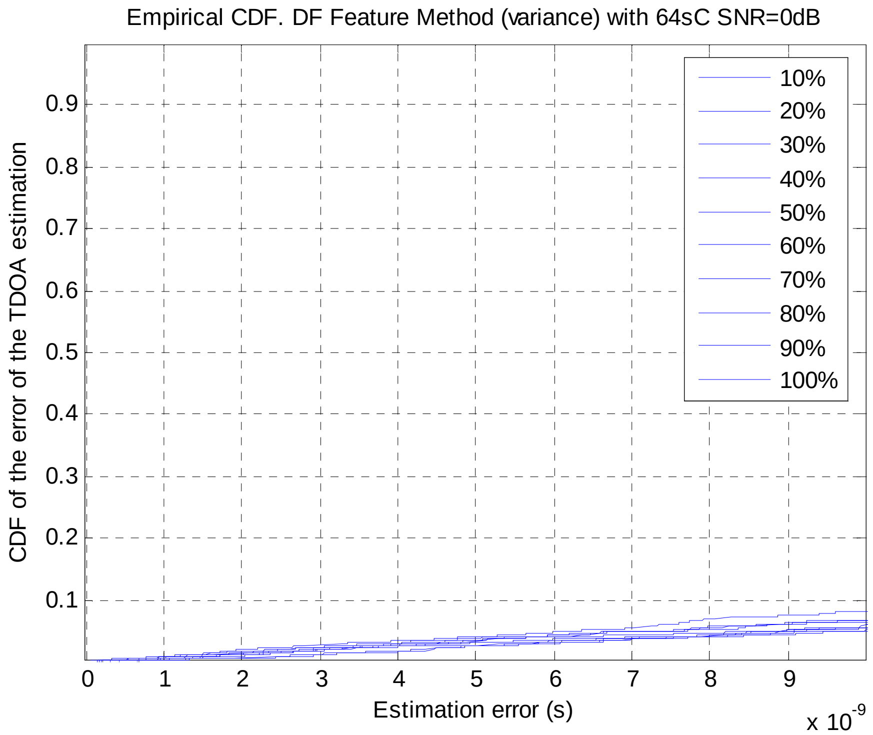


*Figure 3.9 CDF of the variance feature with SNR=0dB*

The other feature signals have a poor performance, for example the figure 3.9 shows the CDF of the variance feature, which in SNR=20dB has a good performance, and with SNR=0dB even neither the 10% of the simulations is below 10ns.

#### 3.6.1.3. SNR=-20dB

The following plots show the performance in low SNR conditions. The probability of having an error bigger than 1.5 meters (5ns) of all the features:

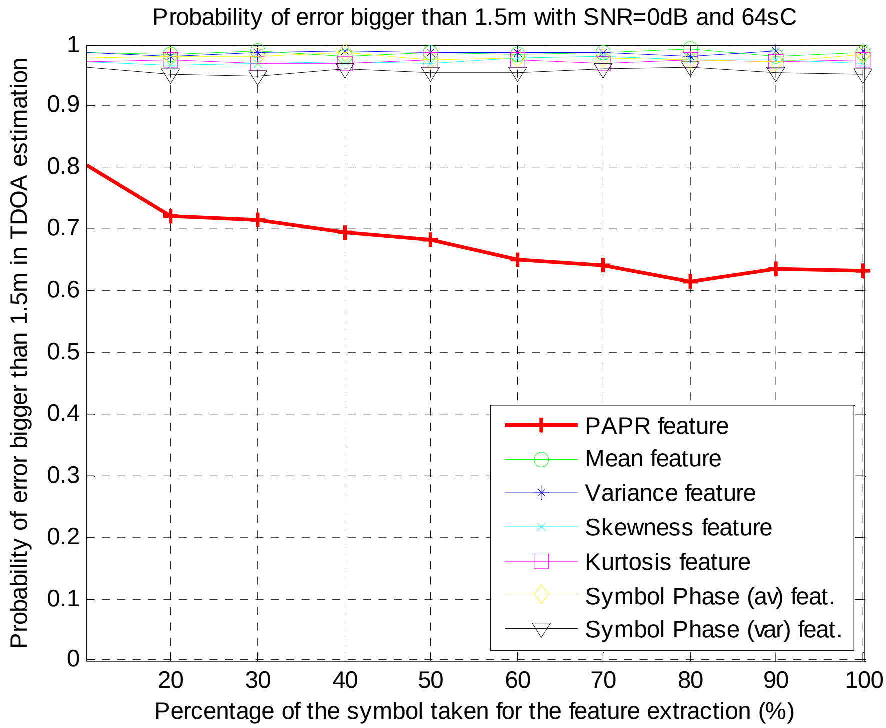


*Figure 3.10 Probability of error with SNR=-20dB*

It is shown that in low SNR conditions, even increasing the percentage of the symbol taken to extract the feature, the probability of having an error bigger than 1.5m. is high, more than the 60%.

CDF of the PAPR feature:

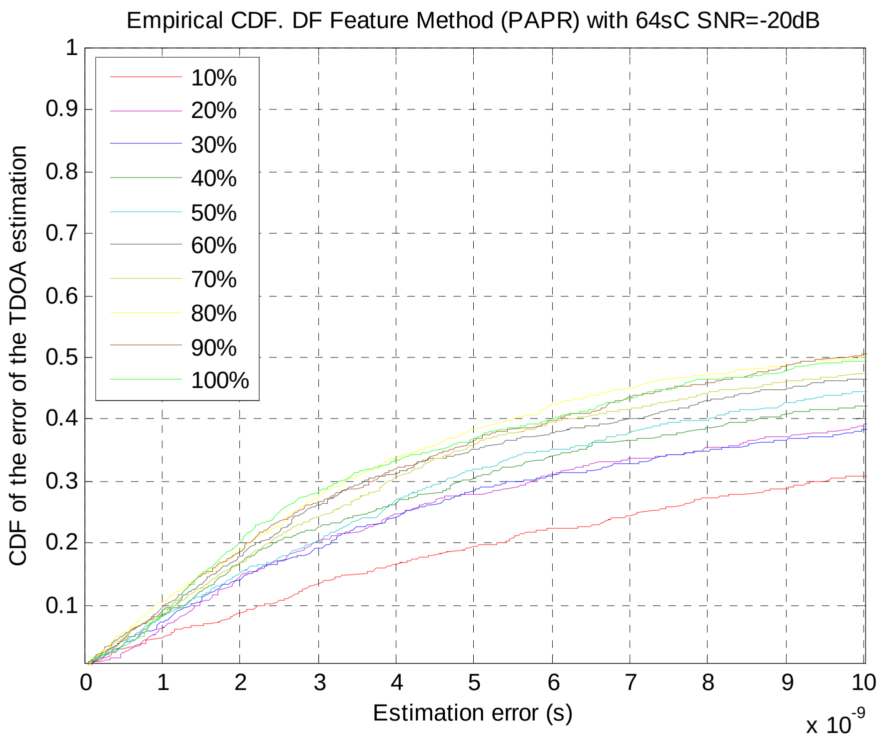


*Figure 3.11 CDF of the PAPR feature with SNR=-20dB*

In low SNR conditions it is needed to increase the percentage of the taken symbol to extract the feature in order to obtain a better performance, but looking at the figure 3.14 it is depicted that only the 50% of the times the error is below 10ns. Other features have even worse performance, that implies being always in error. For example looking at the CDF of the variance feature:

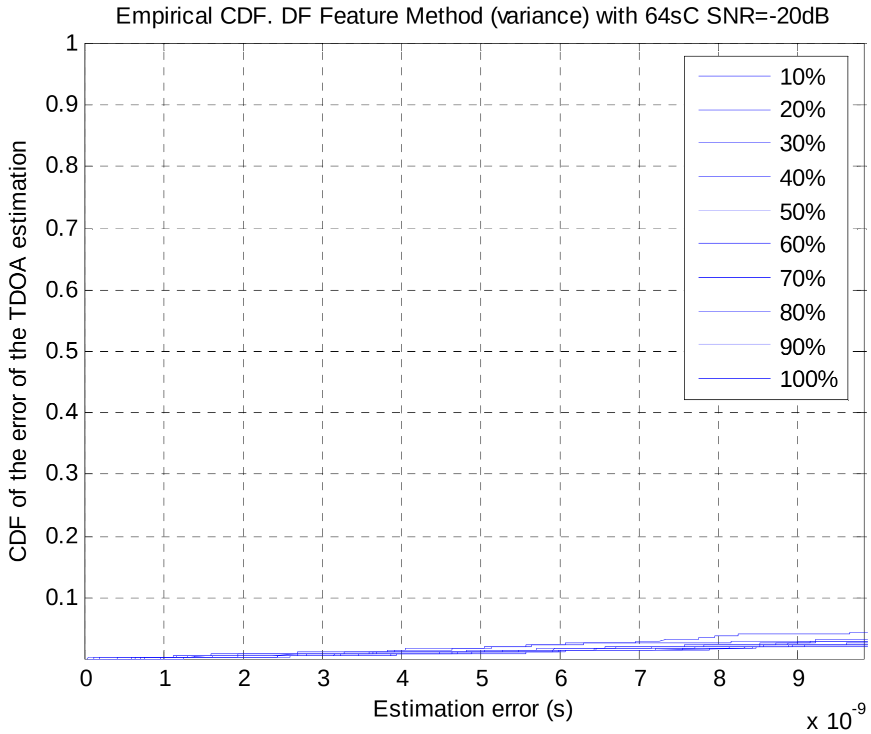


*Figure 3.12 CDF of the variance feature with SNR=-20dB*

The feature method doesn't work properly in low SNR conditions (around -20dB), but it is a bandwidth and computational efficient method with a good performance in middle and large SNR situations. It is wanted to study if varying other parameters it is possible to improve the performance in that low SNR conditions in order to have a good TDOA estimation even in harsh environments.

### 3.6.2. EFFECT OF THE NUMBER OF SUBCARRIERS

It is wanted to vary the number of subcarriers of the ZP-OFDM system in order to know how they affect on the performance. It has been simulated the same scenario with 32, 64 and 128 subcarriers with 10dB SNR.

The probability of having an error bigger than 1.5 meters for different number of subcarriers:

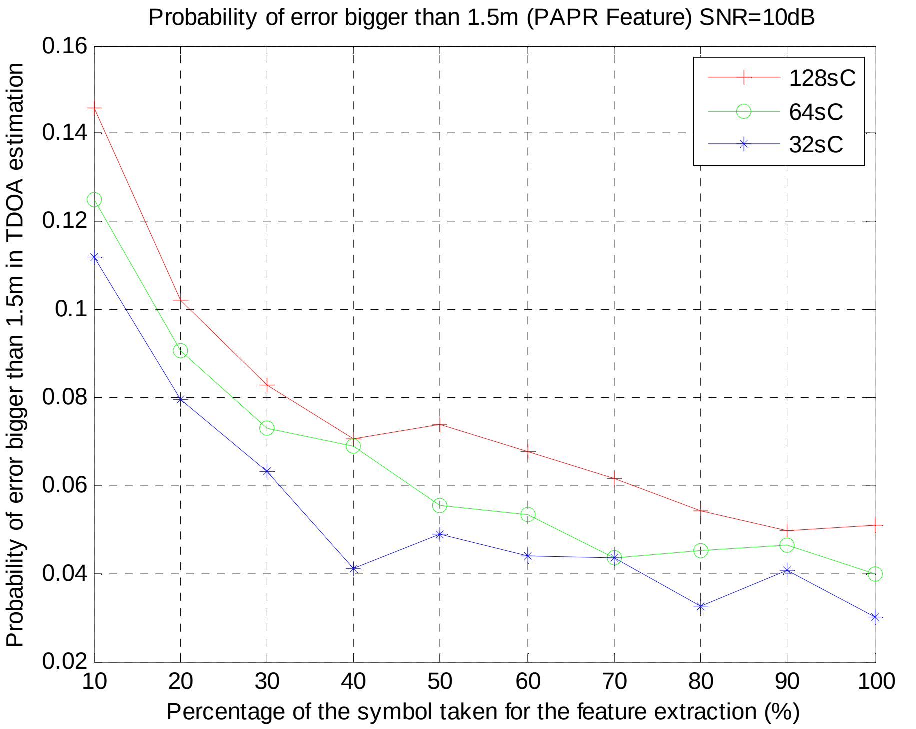


*Figure 3.13 Probability of error with different subcarriers in a SNR=10dB*

Figure 3.13 shows the different performance varying the number of subcarriers. It is shown that decreasing the number of subcarriers, the performance turns better, but the difference is small.

There are plotted also the CDF with different subcarriers showing three different percentages of the symbol taken, 10%, 50% and 100% to show the results clearer:

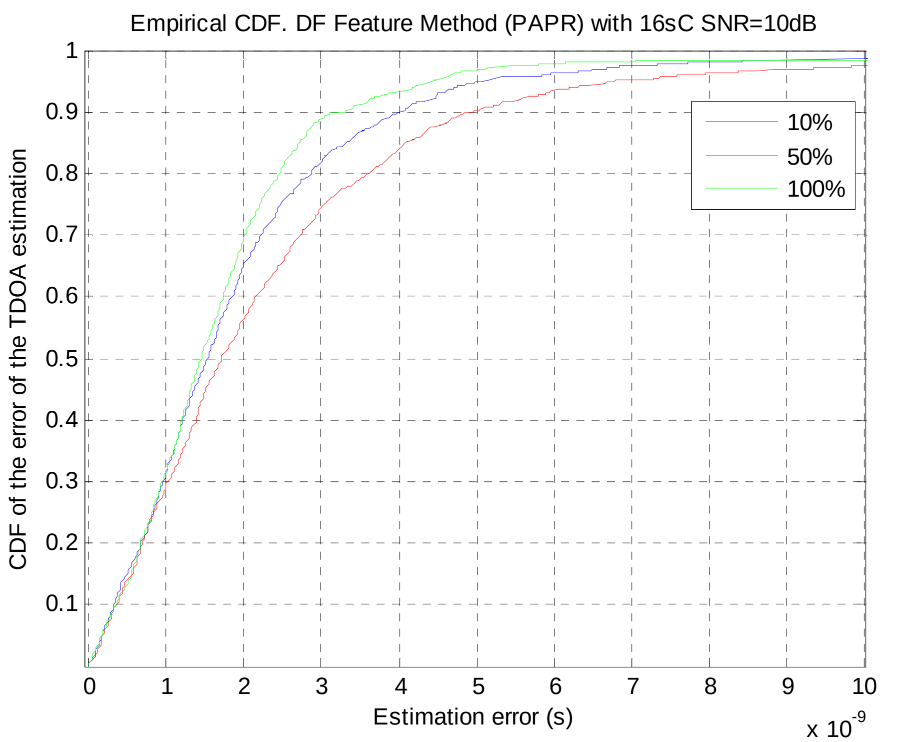


*Figure 3.14 CDF of PAPR feature signal with 16sC and SNR=10dB*

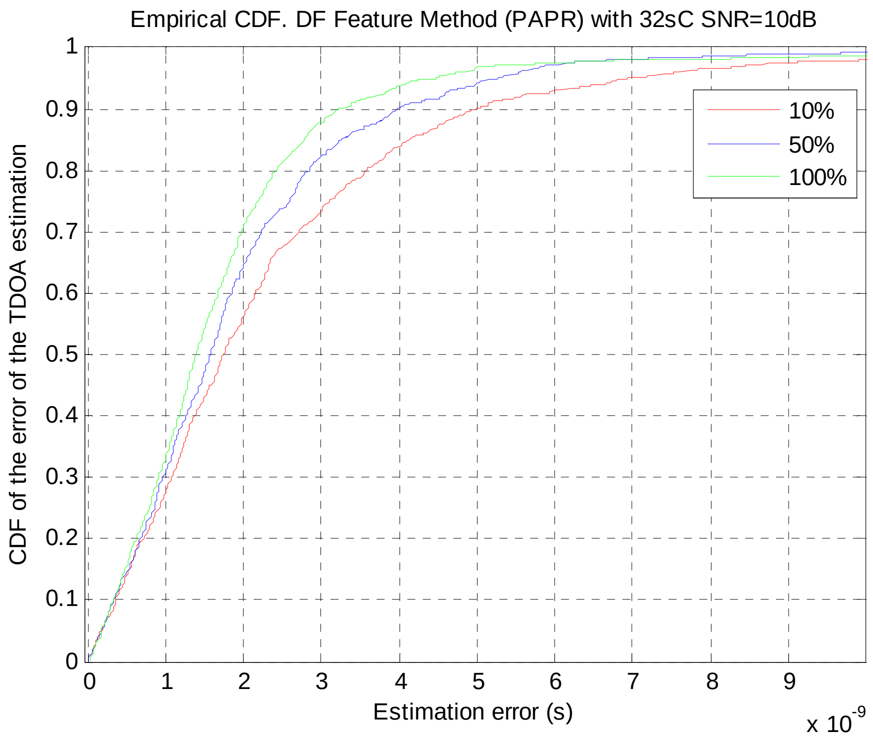


*Figure 3.15 CDF of PAPR feature signal with 32sC and SNR=10dB*

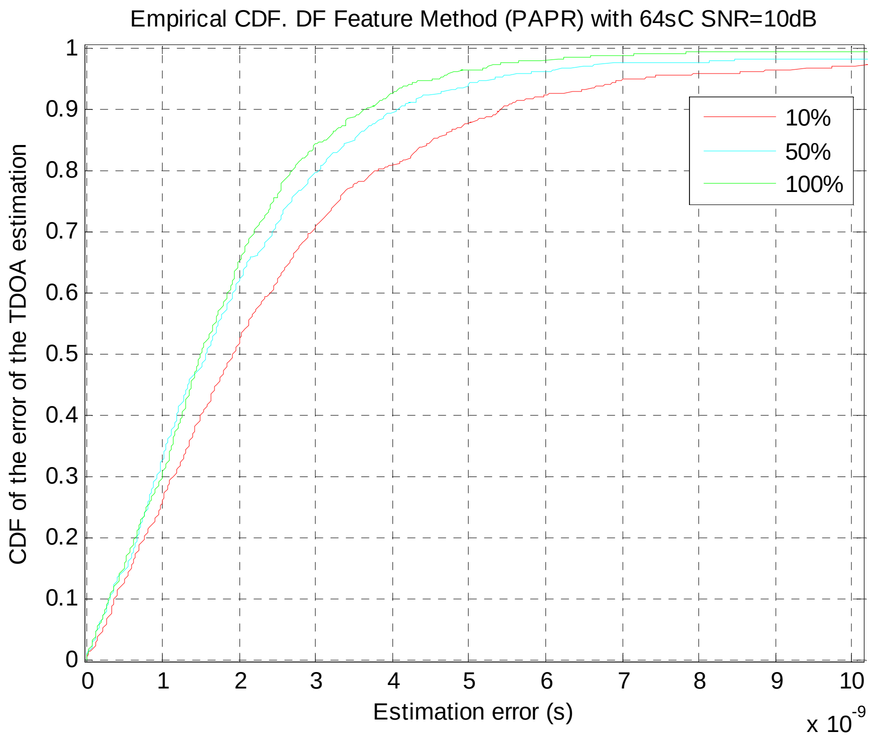


*Figure 3.16 CDF of PAPR feature signal with 64sC and SNR=10dB*

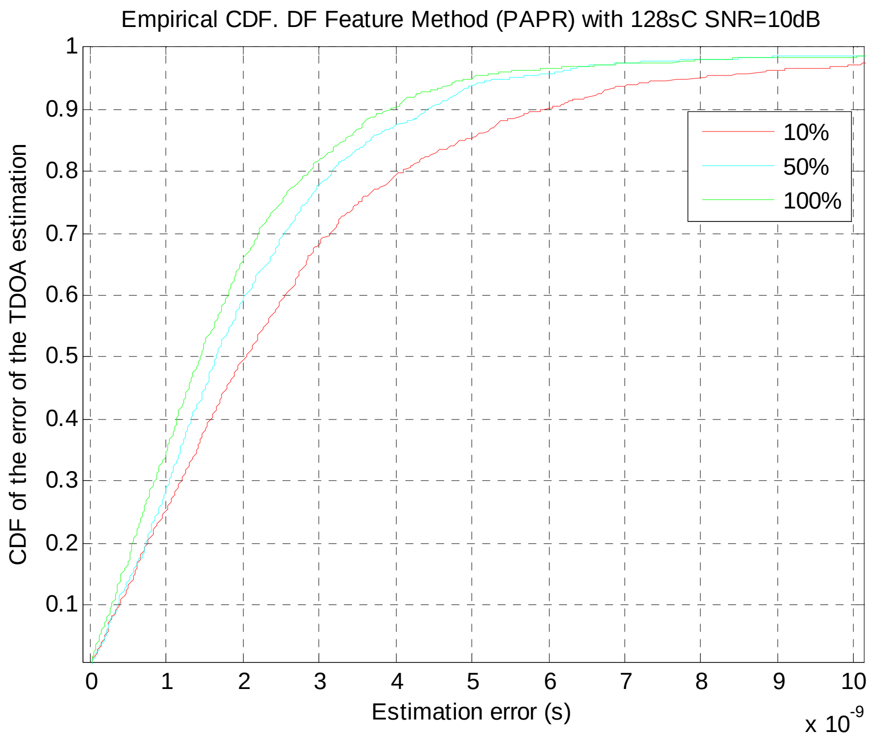


*Figure 3.17 CDF of PAPR feature signal with 128sC and SNR=10dB*

With a small number of subcarriers the performance gets a little bit better. It happens because with less subcarriers there are less data on the same symbol length of a transmitted signal. For instance, one OFDM signal of 50 symbols is larger with 64 subcarriers than with 16. As it is needed to wait the full length of the received signal to extract the feature of each symbol received, the temporal signal stored to do the cross correlation becomes larger, but the feature signal has the same 50 bits. Proportionally the useful percentage (the proportion which is the feature signal respect the whole signal to do the cross correlation) will be bigger when the transmitted signal has less number of subcarriers, obtaining a better cross correlation result, and finally a better TDOA estimation.

It is easier to demonstrate it with a graph, showing the shapes of the signals and their behavior:

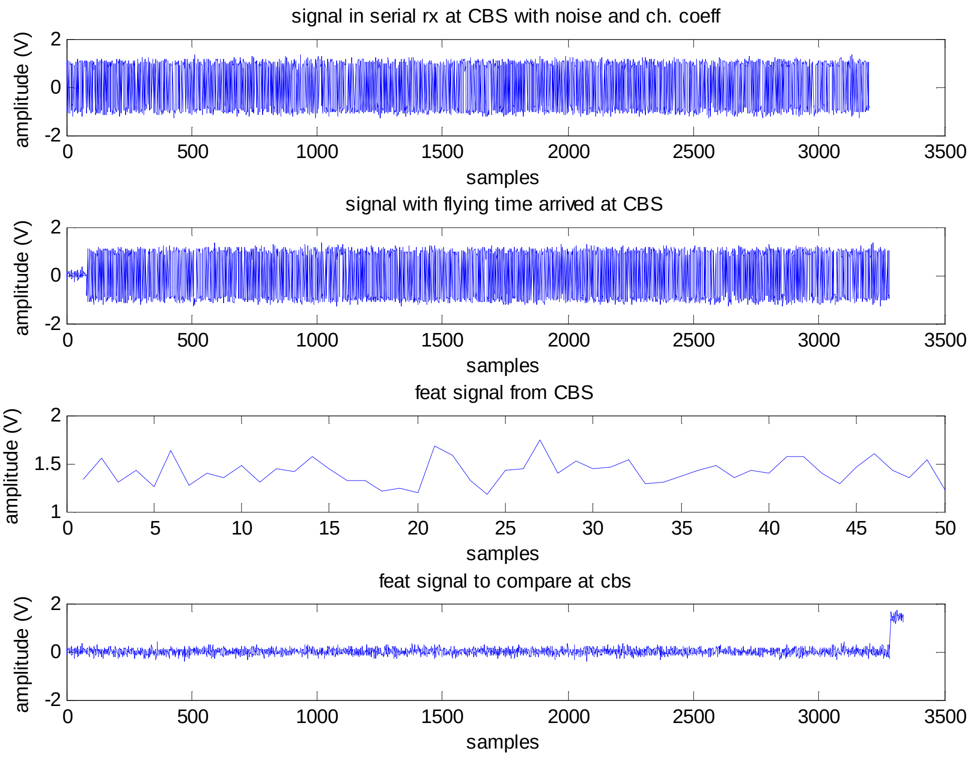


*Figure 3.18 Signal shapes for the feature method with 64 subcarriers*

The first plot of the figure 3.18 shows how arrives the signal sent by the mobile station under the effect of the noise and the channel coefficients. This plot is with a SNR of 20dB, and as a consequence of that, the signal hasn't suffered a big variation. The second plot of the figure 3.18 shows the previous signal arriving at the CBS. The first samples which appear with less amplitude are the flying time between the MS and the CBS. The third plot is the extracted feature signal, with 50 samples, one sample per each symbol of the OFDM signal sent by the MS. And finally the fourth plot of the figure 3.18 is the feature signal which will be cross correlated with the received feature signal coming from the relay. The first samples centered on zero values are the "elapsing time" since the MS sent the original signal, and they have included the flying time (first samples of the second plot), the processing time, and the total time of the whole signal sent by the MS (50 symbols multiplied by 64 subcarriers per symbol are 3200 samples), and after those samples there is the feature signal.

The following figure shows the same results and under the same simulation conditions (same SNR, channel gain, number of OFDM symbols sent), but changing the number of subcarriers from 64 to 16:

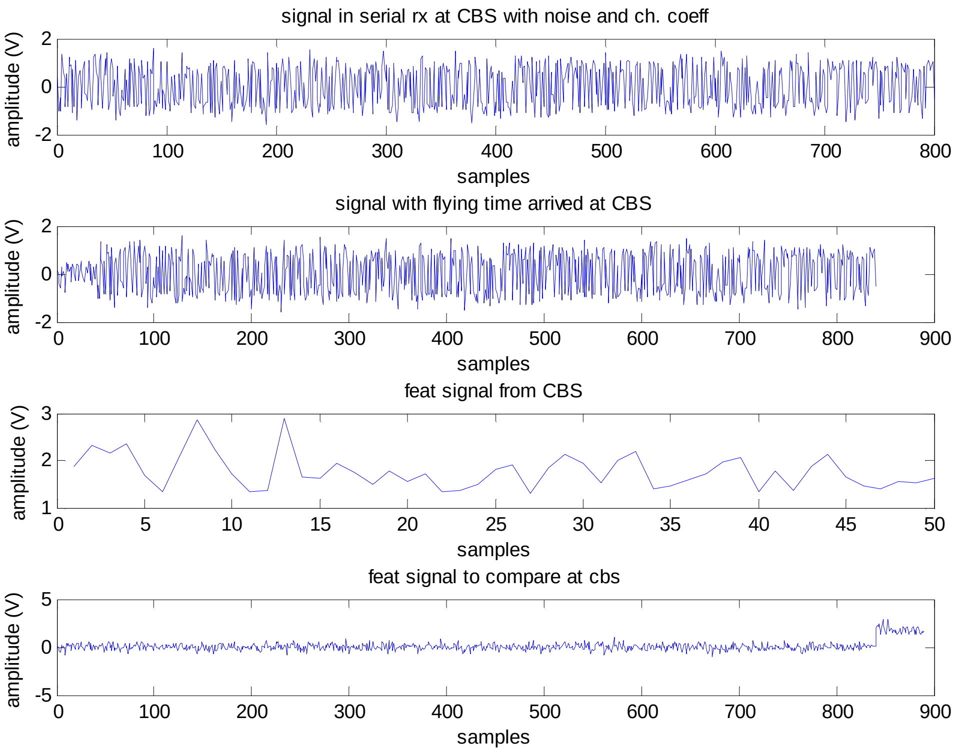


*Figure 3.19 Signal shapes for the feature method with 16 subcarriers*

The difference between the two situations is the number of samples which has the signal sent by the MS. With 16 subcarriers, and 50 OFDM symbols, there are 800 samples for the signal. The fourth plot shows how in this case, the elapsed time is 800 plus the flying time and plus the process time, and then there is the feature signal of 50 samples. The proportion of useful samples, being the useful samples the feature signal ones, working with a system with less subcarriers is bigger than other which works with more subcarriers, implying a better cross correlation result, as the simulation results show.

## 3.7. JUSTIFICATION OF THE RESULTS AND CONCLUSIONS

In this chapter, it is proposed a bandwidth and computational efficient cooperative ZP-OFDM TDOA estimation scheme. This system is based on reducing the amount of information which needed to be shared between the nodes to compute the TDOA. A statistic feature is computed in a portion of the effective OFDM symbol. The cross correlation is done by the features instead of the raw data, reducing the necessary bandwidth and the number of operations to compute the TDOA.

PAPR is the feature which has the best performance on the TDOA estimation.

The signal generation is Gaussian distributed with zero mean and variance of one. As a consequence of that, features like mean, skewness and kurtosis have values closer to zero, for that reason the noise can easily disturb these feature signal values, which implies an error on the cross correlation and on the TDOA estimation. The feature signal, sent by the relay, arrives at the CBS with different values than the original one. The bits of the received signal are corrupted by the noise, causing a wrong cross correlation result as a consequence of the two different signals compared.

On the other hand, the power features, like variance or PAPR are more robust against noise. Their feature signal values are higher (PAPR the highest), and not centred on zero, for that reason the feature signal arrives at the CBS almost with the same values of the original one. The impact of the error in both cases is lower than the rest, having values in their feature signal below the unit.

It is also remarkable that in large SNR conditions, it could be possible to have a very good performance with a small percentage of the symbol to calculate the feature. It implies less computational operations, and as a consequence of that, energy saving, which is a very important issue for the mobile devices which have limited battery.

In order to look for the most efficient way to do the TDOA estimation with the feature method, it has been studied how to extract the feature with less computational operations. Instead of analyse the full symbol, it is selected only a percentage of it. It has been simulated the performance employing different percentages. Increasing the percentage improves the TDOA estimation, but decreases the computational efficiency. There is a trade off between the computational efficiency and the improvement on the error. It A percentage of 20% could be a good candidate to have a good performance in different SNR situations, and also been computational efficient. But this choice could be modified depending on the SNR conditions of the system, increasing the percentage in the situations of low SNR in order to help the system to improve the TDOA estimation.

The number of subcarriers employed on the OFDM transmission technique affects on the performance of the TDOA estimation with the feature method. The signals employed to calculate the cross correlation have a part of noise (useless) with a number of samples equal to the sum of the flying time plus the processing time plus the length of the signal sent by the MS, and the useful part which is the feature signal. The useless part is proportional to the number of samples per symbol, and this is related with the number of subcarriers per symbol. For that reason, with more number of subcarriers per symbol, the useless part increases with respect the useful part in the signal designated to do the cross correlation, implying a worse result.

# 4. Trigger Relay with Pilot Signal Method for Cooperative ZP-OFDM Bandwidth and Computational Efficient TDOA Estimation

## 4.1. ABSTRACT

In this chapter, it is investigated the relaying issue of Zero-Padding (ZP) Orthogonal Frequency Division Multiplexing (OFDM) technique to estimate Time Difference of Arrival (TDOA) for locationing applications. In order to benefit from the easy processing of Amplify-and-Forward (AF) relay as well as the noise and interference cancellation of Decode-and-Forward (DF) relay schemes, it is introduced the trigger relay technique for TDOA estimation. The trigger relay possesses the merit of bandwidth efficiency, since only a short pilot or preamble needs to be sent. Compared to its counterparts AF and DF relays, trigger relay achieves a better performance in terms of system complexity and TDOA accuracy [12].

## 4.2. INTRODUCTION

Cooperative localization is an emerging paradigm that offers additional localization accuracy by enabling the agents to help each other in estimating their positions. Conventionally there are mainly two relaying protocols in cooperative networks: AF and DF. In AF, the received signal is amplified and retransmitted to the destination. The advantage of this protocol is its simplicity and low-cost implementation. However, the noise is also amplified at the relay. In DF, the relay attempts to decode the received signals. If successful, it re-encodes the information and retransmits it. If some relays cannot fully decode the signal, they should be discarded. In this chapter, it is proposed a new relaying technique for cooperative localization, called trigger relay, which combines the advantages of AF relay and DF relay, i.e., less complexity because of no decoding, while removing the noise and interference effect at relay [12].

With the new trigger relay proposed for TDOA estimation, only a short pilot or preamble signal is sent to the primary receiver, which can achieve bandwidth efficient localization as well. Compared to the AF relay and DF relay with block feature, the trigger relay reduces the system complexity and enhances the TDOA estimation accuracy [12].

## 4.3. TRIGGER RELAY FOR TDOA ESTIMATION

The advantage of AF is that it doesn't need the complicated signal decoding, while the strong point of DF relay relies on that it can get rid of the noise effect and channel interferences. Therefore, we propose a trigger relay technique to take advantage of these two merits [12].

The diagram of signal transmissions in the trigger relay TDOA estimation is shown in Fig. 4.1 A mobile station (MS) with unknown position connects into a wireless network at the moment $t_0$ and starts having a communication broadcasting an OFDM signal at $t_0^{'}$. Immediately after the central base station (CBS) and the relays (for simplicity here we only consider one relay because we focus on the TDOA calculation, but for localization there are required at least three relays) receive the MS signal at $t_1$ and $t_2$ respectively, they generate a predetermined signal, the CBS stores it at $t_1^{'}$, and the relay sends it to the CBS at $t_2^{'}$. This predetermined signal is considered the "pilot signal". We assume that the processing intervals at two relays are the same, i.e., $t_1^{'} - t_1 = t_2^{'} - t_2$. Then, CBS receives the signal from relay at $t_{r2}$.

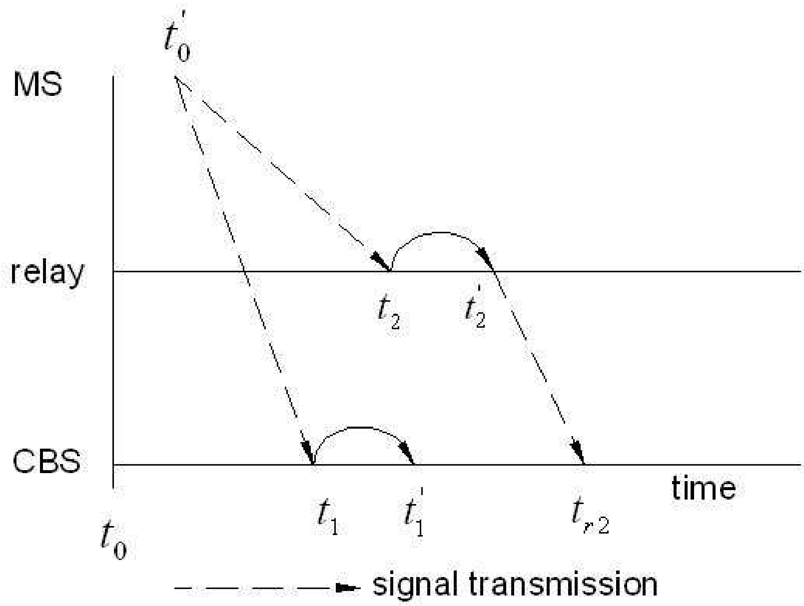


*Figure 4.1 Signal transmissions in trigger relay TDOA estimation scheme*

Subsequently, the TDOA between the relay to MS link and the CBS to MS link $TDOA$ can be calculated by CBS as

$$TDOA = \left|(t_{r2} - t_1^{'}) - t_k\right| \tag{4.1}$$

where $(t_{r2} - t_1^{'})$ can be achieved by correlation of the two signals (from the relay and the CBS), similar to the AF and DF relay case, and $t_k$ is the time duration between the known positions of the CBS and the relay and could be calculated:

$$t_k = \frac{\sqrt{(x_r - x_{CBS})^2 + (y_r - y_{CBS})^2}}{c} \tag{4.2}$$

where $x_r, y_r$ are the coordinates of the relay, $x_{CBS}, y_{CBS}$ are the coordinates of the CBS, and $c$ is the speed of light.

This method doesn't require synchronization. At the moment in which the CBS detects the new unknown MS joining the wireless system it starts storing two signals simultaneously; one for its own pilot signal, which will be generated at the moment in which the CBS receives the signal sent by the MS ($t_1$ in Figure 4.1), and the other stores the pilot signal sent by the relay.

## 4.4. SIMULATION RESULTS

In this thesis we consider the cooperative localization for the wideband communication system in LOS scenario. We assume the locations of the central base station (CBS) and relays are known by the station who will compute the TDOA (CBS). Scatterers are located between the CBS, relays and the mobile station (MS), causing multipath channels. The ZP-

OFDM is adopted as the modulation scheme. In general, by using the TDOA measurements together with the classical hyperbolic intersection searching, the CBS can localize the position of the MS.

The MS first broadcasts the signal. The relays receive the signal and send a known signal called pilot signal to the CBS. The CBS receives the MS original signal, and generates its own pilot signal, which will be cross correlated in time with the different pilot signals received from the cooperative relays. In this simulation for simplicity it is only considered one cooperative relay, the mobile station and the central base station.

In this thesis, we assume that the CBS can distinguish the signals from MS and relay. In order to obtain TDOA estimation, the CBS performs a cross correlation in time between the pilot signal generated by it and the pilot signal received from the relay.

The simulation results are focused on the quality of the TDOA estimation in order to employ those measurements into a localization algorithm to locate an unknown device.

It will be measured and studied the behavior of the error of the TDOA estimation comparing the experimental value with the theoretical one.

TDOA estimation with the Trigger Relay and pilot signal method is a new scheme, for that reason it is wanted to study and analyze every parameter and show how they affect into the performance of the error of the TDOA estimation.

The goal of those simulations is to obtain the best quality TDOA estimation choosing the appropriate parameters which reduce the error and provide the most accurate result.

Other factor that is really important is the efficiency. Cooperative relays are mobile devices, and they have a limited battery life. For that reason our goal is to provide an accurate TDOA measurement, in a bandwidth and computational efficient way, in order to decrease the power consumption, which is a critical resource for the mobile devices.

### 4.4.1. SIMULATION PARAMETERS

In the simulation it is considered the MS sending a signal of 50 symbols with a binary phase shift keying (BPSK) modulation in ZP-OFDM, with 64 subcarriers. The bandwidth of the signal is 500MHz, having a time resolution of 2ns. The emitter generates the BPSK signal with a random Gaussian distribution with zero mean and variance equal to one.

In this system, we assume additive white Gaussian noise (AWGN), a Rayleigh flat fading channel and in some simulations also multipath.

In the scenario there is a well-known position relay (trigger relay), which sends the pilot signal to the CBS when it receives the signal broadcasted by the MS, and also there is a fixed and well-known position central base station which computes the cross correlation between its own pilot signal, generated at the moment in which it receives the signal sent by the MS, and the signal received from the relay. With the result of that operation the CBS makes the TDOA estimation.

In each simulation it is changed randomly the position of the mobile station through the area of the scenario (100x100 meters).

To compare the quality of the results it is used different criteria, as shown in the equations 3.13-3.17 of the previous chapter.

### 4.4.2. THE PILOT SIGNAL

The pilot signal could be a well known OFDM signal which is the key tool in this TDOA estimation method.

Both the relay and the CBS generate the same pilot signal in order to calculate the cross correlation and to do the TDOA estimation.

The following simulation results and analysis compare the performance of different scenarios changing the parameters of the pilot signal and looking for the most efficient and accurate configuration.

#### 4.4.2.1. SHAPE

It is wanted to compare the effect of the shape of the pilot signal. Varying the bits that fill the OFDM symbol, it is possible to play with different shapes and check how it affects on the performance of the TDOA estimation. It is wanted to generate different shapes, changing the number of fluctuations between the value '1' and '-1', or varying the moments of the transitions between those bits… It has been done a comparison between four different shapes that are:

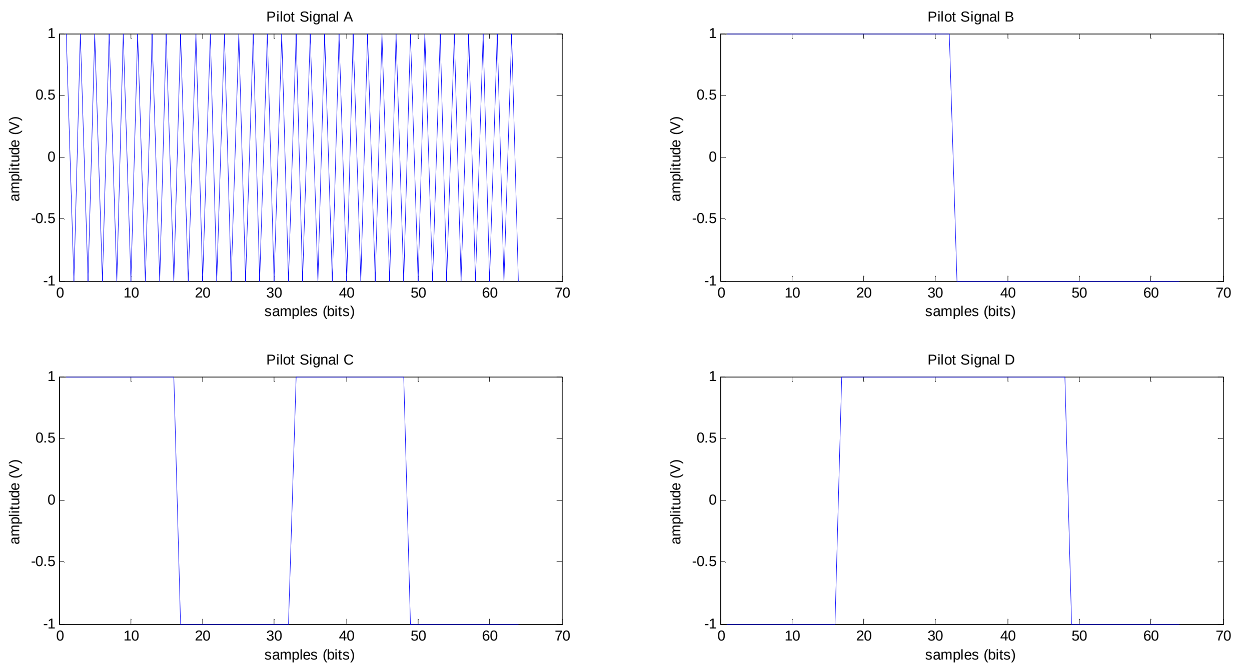


*Figure 4.2 Different shapes for the pilot signal.*

Each pilot signal has the same length, one ZP-OFDM symbol, which has in this case 64 bits. In the following chapter there are also simulations with different pilot signal's lengths to compare the performance.

The following figure shows the "average of the time error" performance:

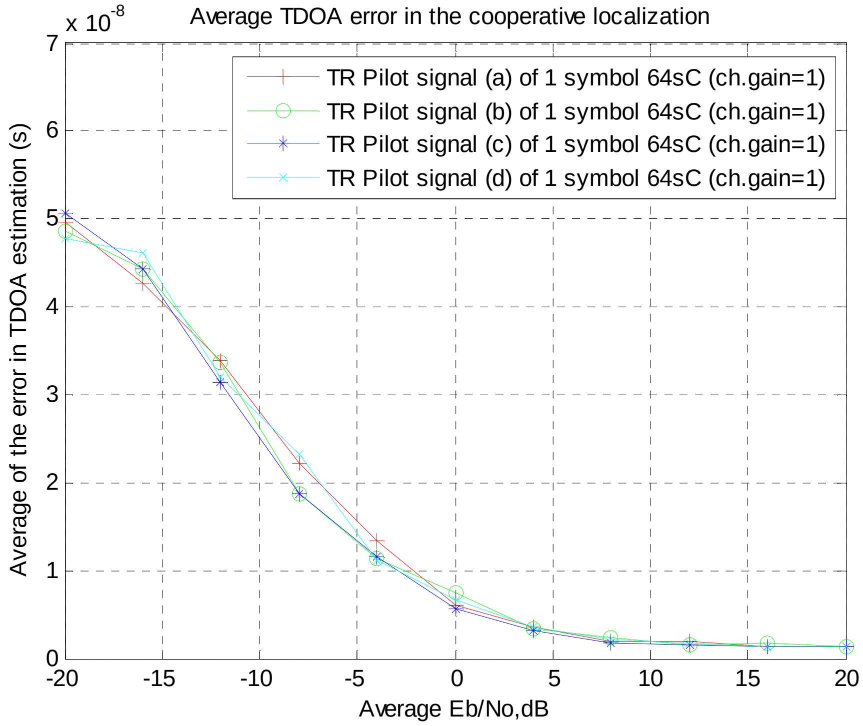


*Figure 4.3 Average of the time error with different pilot signal's shapes*

It is shown that there are not significant differences between the curves. Looking at the criterion of the probability of having an error bigger than 1.5m:

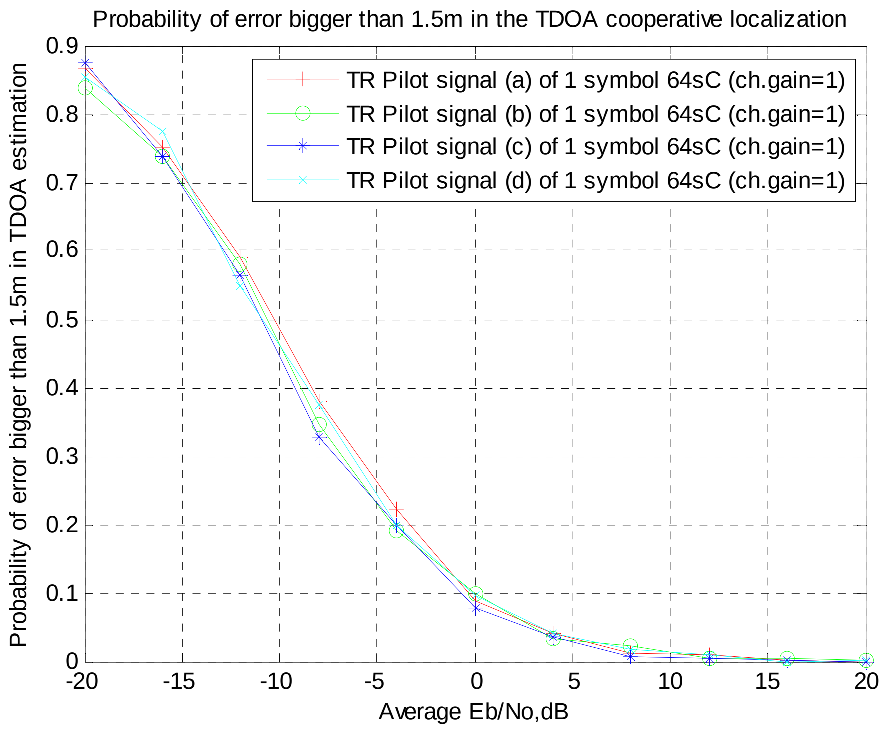


*Figure 4.4 Probability of having an error bigger than 1.5m for the different shapes*

The previous figures show a similar performance for the different shapes of the pilot signal. The following graphs show the cumulative distribution function (CDF) to compare their performance in different SNR situations, from SNR=-20dB until SNR=20dB in steps of 4dB:

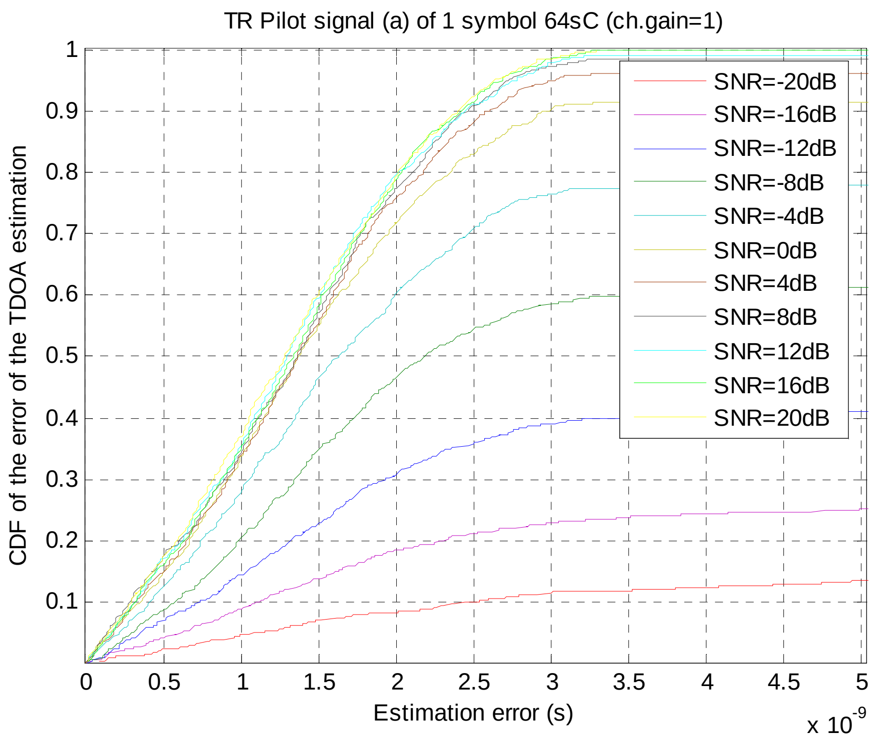


*Figure 4.5 CDF of the TR method with pilot signal 'a'*

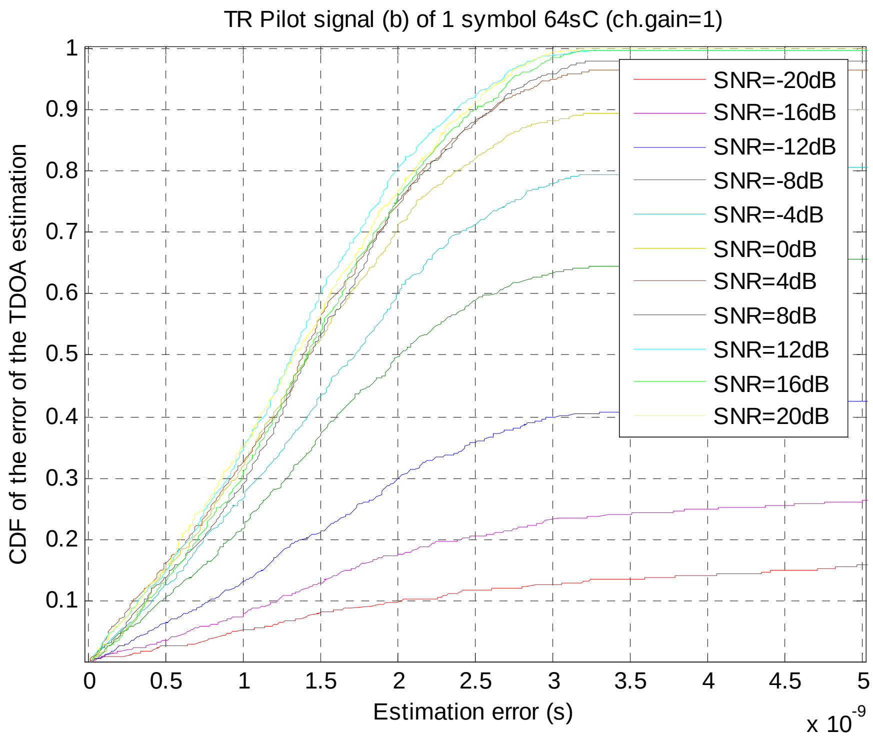


*Figure 4.6 CDF of the TR method with pilot signal 'b'*

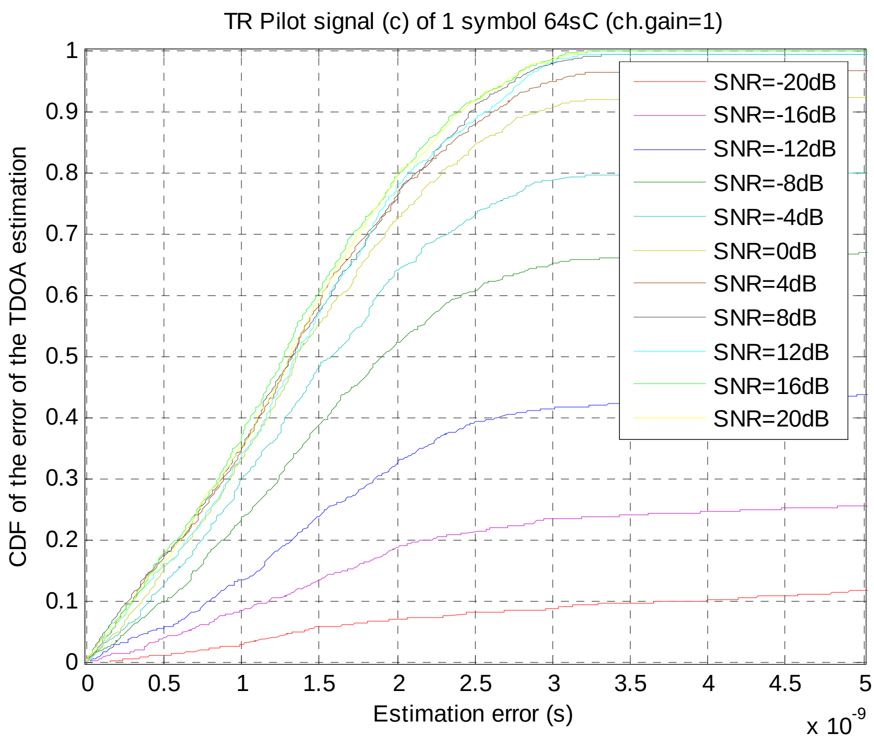


*Figure 4.7 CDF of the TR method with pilot signal 'c'*

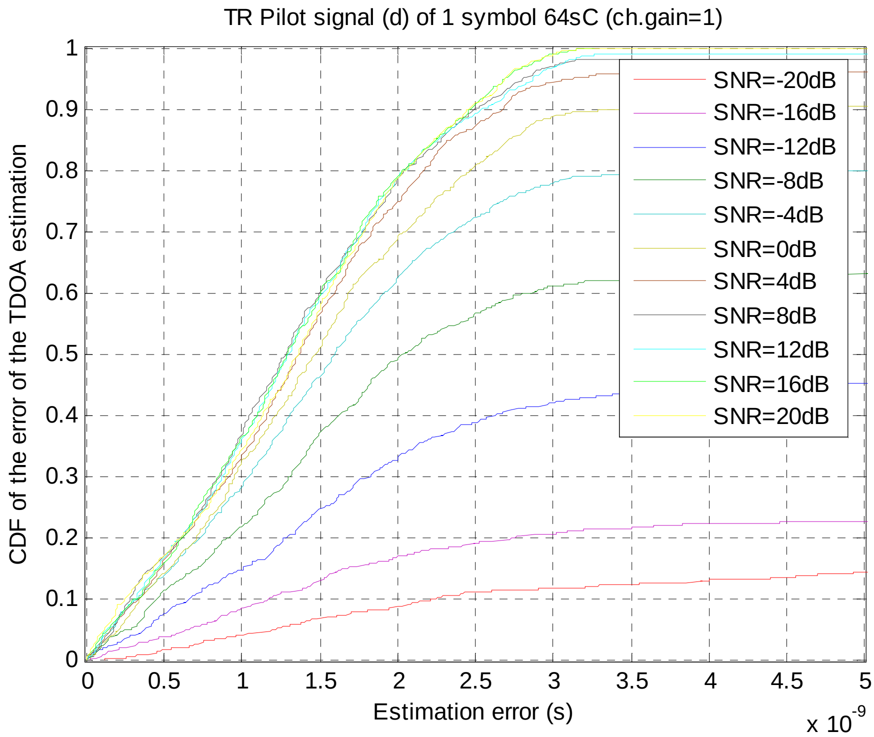


*Figure 4.8 CDF of the TR method with pilot signal 'd'*

It was expected that the shape of the pilot signal could have an important impact on the performance of the system, but the simulation results show the opposite; different shapes of the pilot signal provide similar performance of the TDOA estimation.

But only one concrete shape for the pilot signal is required to work in the trigger relay with pilot signal method to estimate the TDOA. It has been chosen the 'b' shape, because it has has the easiest process to generate it, only needing one fluctuation to create it (one change between '-1' level and '1' level).

#### 4.4.2.2. LENGTH

The pilot signal has an OFDM structure. The most bandwidth and computational efficient pilot signal employed is the shortest one, of one OFDM symbol length, because it implies the less number of operations to generate it and the less bandwidth required to transmit it.

With the following analysis it is wanted to check if the performance improves increasing the length of the pilot signal.

It could be a tradeoff between the improvement on the error and the efficiency of the system.

It has been compared three different lengths for the pilot signal. The minimum length is one OFDM symbol, with the same bits as the ZP-OFDM symbol for the communication. Other lengths considered are 5 OFDM symbols, (5 pilot signals of one OFDM length consecutively), and 10 OFDM symbols (10 pilot signals of one OFDM length consecutively).

The following graphs show the cumulative distribution function (CDF) for the different length situations:

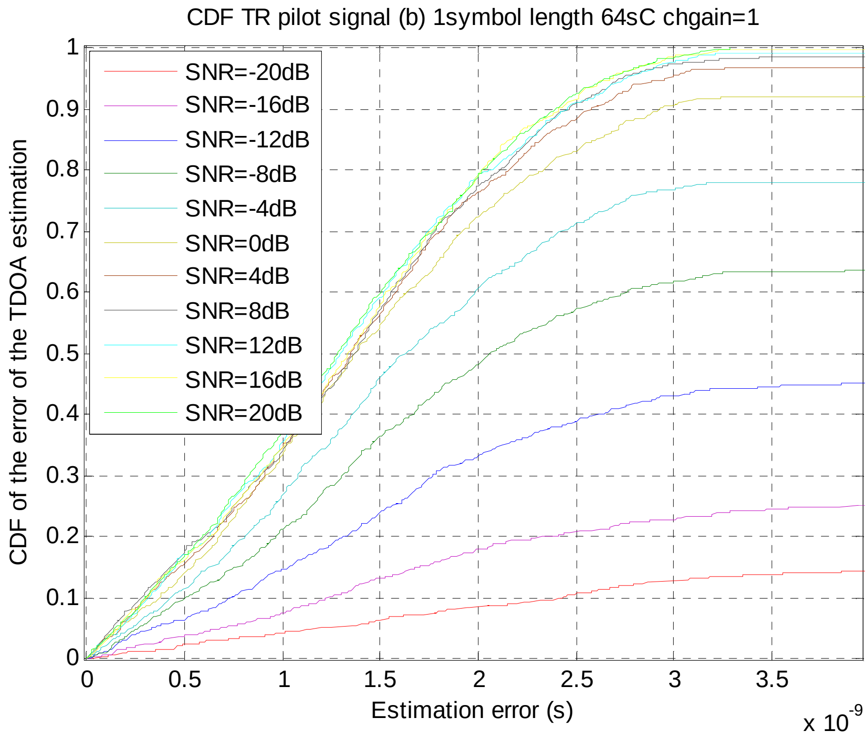


*Figure 4.9 CDF of the TR method with 1 OFDM symbol length pilot signal*

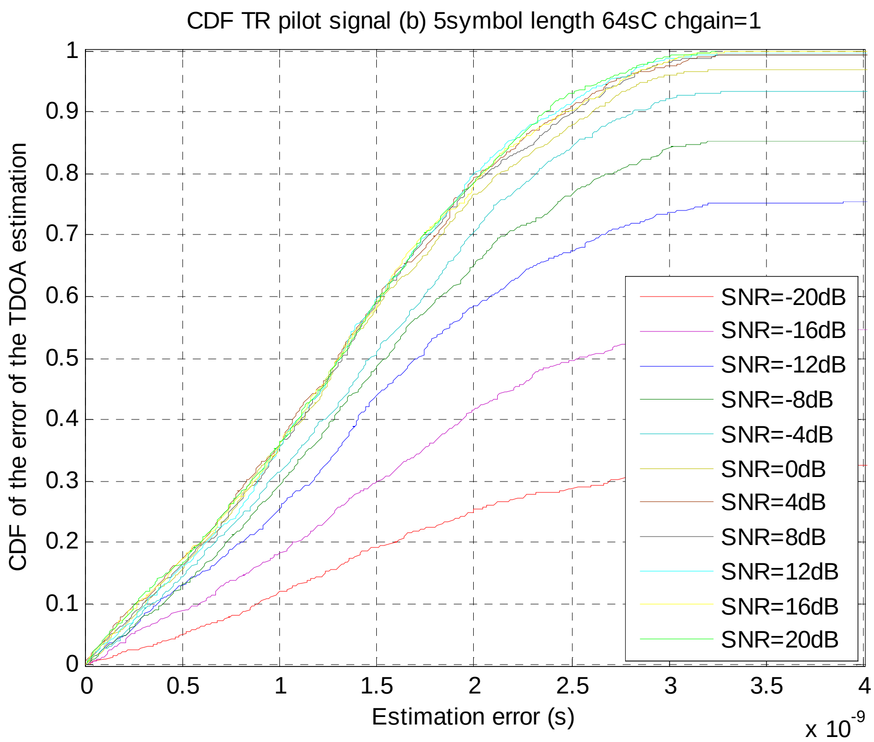


*Figure 4.10 CDF of the TR method with 5 OFDM symbols length pilot signal*

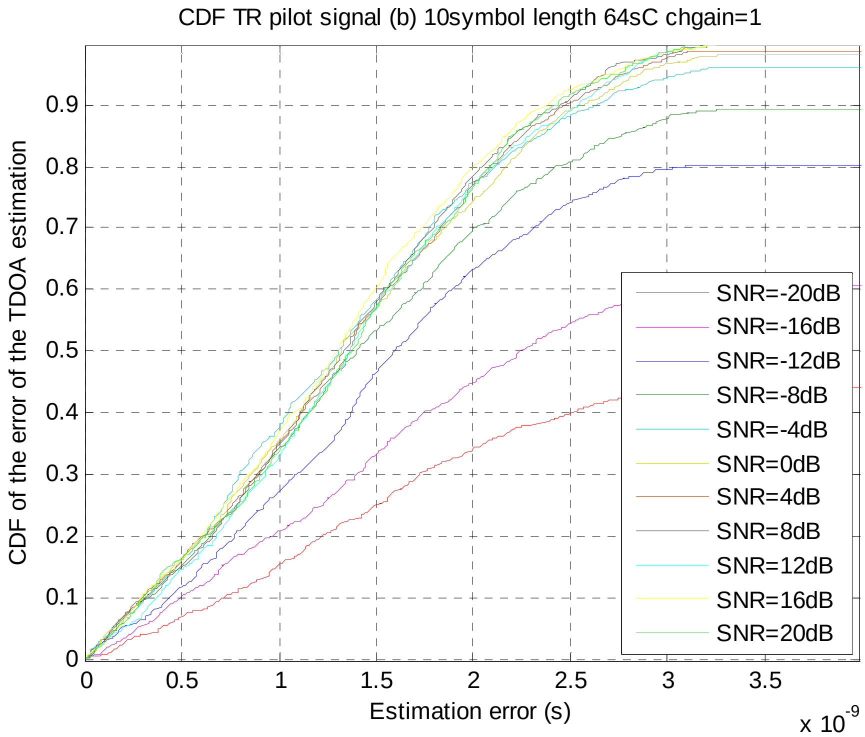


*Figure 4.11 CDF of the TR method with 10 OFDM symbols length pilot signal*

The previous graphs show that if in low SNR conditions we increase the length of the pilot signal, the CDF gets better. Increasing the length of the pilot signal means to have more data to compare and to do the cross correlation process, obtaining better and more robust results than with a pilot signal with fewer bits.

The following graphs show in detail the comparison in different SNR situations:

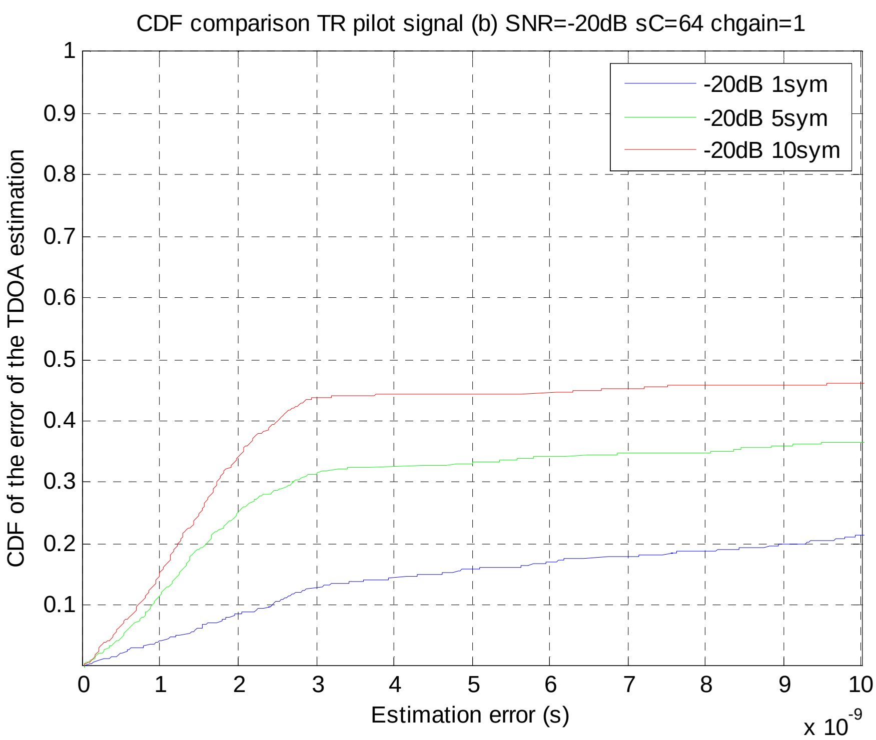


*Figure 4.12 CDF of the TR method in -20dB SNR with different pilot signal's length*

In low SNR situations are the biggest differences between the performances of the different pilot signal lengths. When the pilot signal length increases implies more data to generate and to transmit, which means be less efficient than the one OFDM symbol pilot signal, but on the other hand there are more data to do the cross correlation, obtaining a better result. For that reason in low SNR conditions the longest pilot signal has the best performance.

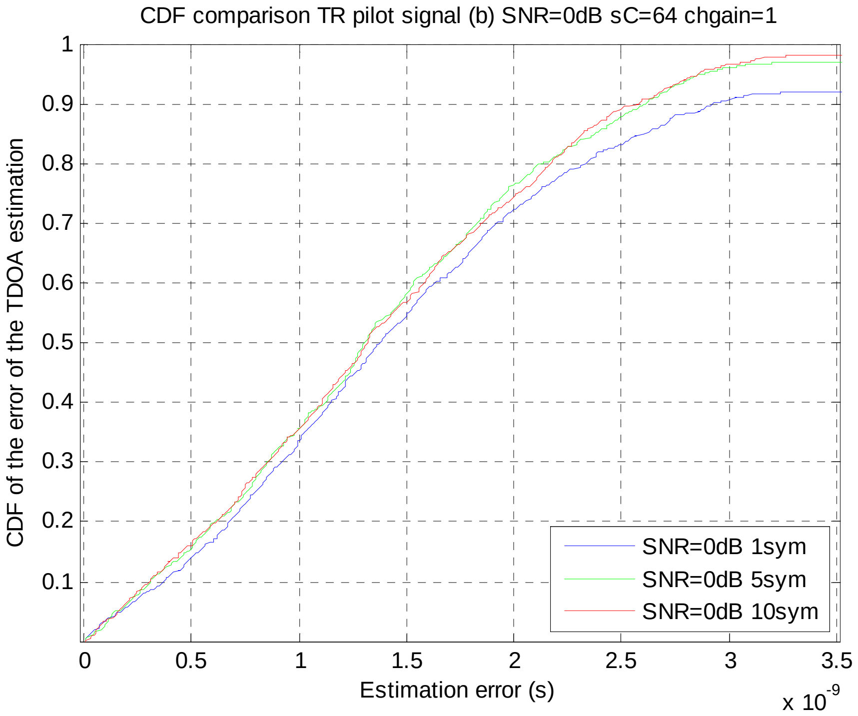


*Figure 4.13 CDF of the TR method in 0dB SNR with different pilot signal's length*

In 0dB SNR, the system which employs a longer pilot signal has better performance comparing with the one OFDM symbol pilot signal. The previous figure shows the improvement of using a longer pilot signal, but now the performance of the five and ten OFDM symbols pilot signal is practically the same, because they are getting their results near the upper bound. In this situation is inefficient to use a pilot signal of ten OFDM symbols because its performance is similar to the five OFDM symbols one. Even it could worth to sacrifice that small improvement on the error provided by the effect of increasing the length of the pilot signal, and change it for the bandwidth and computational efficiency that provides the system which works with one OFDM symbol pilot signal.

With large SNR (20dB) all the pilot signal lengths have almost the same performance:

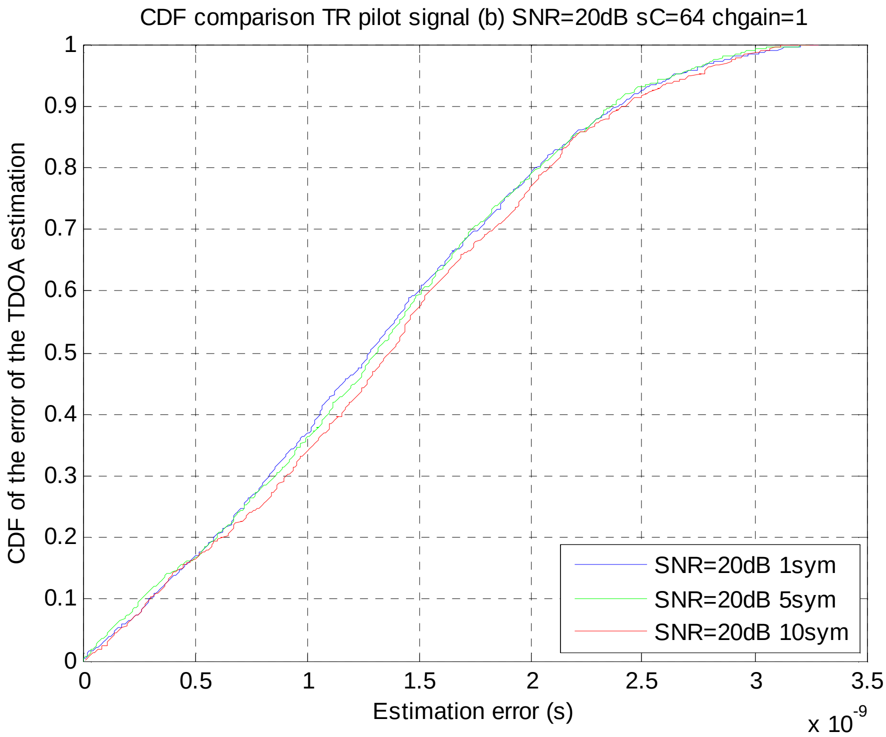


*Figure 4.14 CDF of the TR method in 20dB SNR with different pilot signal's length*

In situations of large SNR the most efficient choice is to work with a pilot signal length of one OFDM symbol.

The effect of changing the length of the pilot signal affects directly to the efficiency, because it is needed to process more data (computational inefficiency) and to transmit more data (bandwidth inefficiency). For those reasons it is only recommended to increase the length of the pilot signal only when we are in low SNR conditions.

The conclusion of this analysis is that increasing the length of the pilot signal improves the performance of the TDOA estimation, because there are more data to process and compute the cross correlation, but reduces the bandwidth and computational efficiency of the system, compared with the one OFDM symbol pilot signal method. That tradeoff worth it in low SNR conditions, but since the SNR is around 0dB or more, it's better to work with a pilot signal of one OFDM symbol.

#### 4.4.2.3. AMPLITUDE

One of the advantages of the trigger relay relies on its independence of the SNR conditions of the MS-CBS path and the MS-Relays link, because the pilot signal is generated when the first bit received from the MS arrives.

The quality of the TDOA estimation depends strongly on the channel Relay-CBS, which is the only path in which the pilot signal could be deteriorated.

If the SNR is low, it is possible to have good performance, despite of the bad conditions, thanks of that independence. In fact, if we increase the power of the pilot signal, it will be more robust against the big noise, obtaining an accurate TDOA estimation, even in bad channel conditions. The trade off is the power consumption of the relay, but the goal deserves it.

The following graphs show the comparison between the performances of the trigger method with different power for the pilot signal:

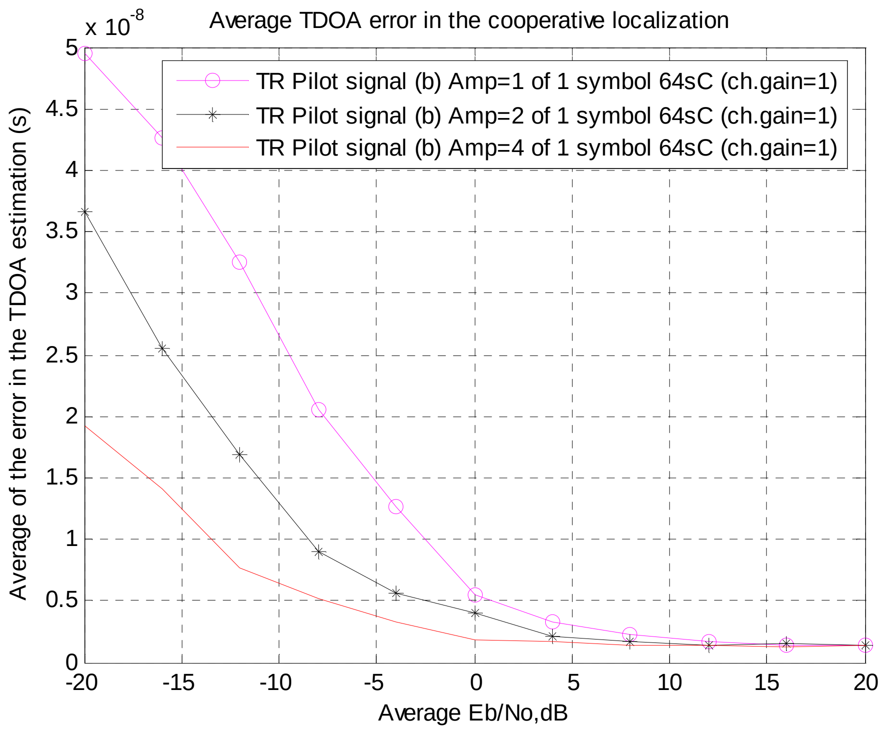


*Figure 4.15 Average of the TDOA error changing the amplitude of the pilot signal*

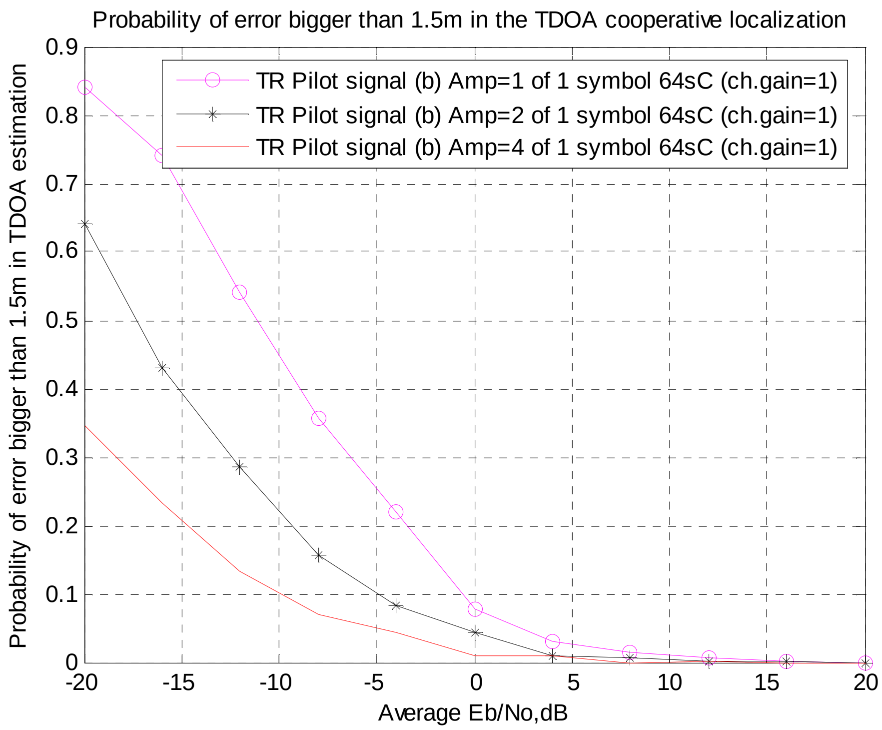


*Figure 4.16 Probability of error changing the amplitude of the pilot signal*

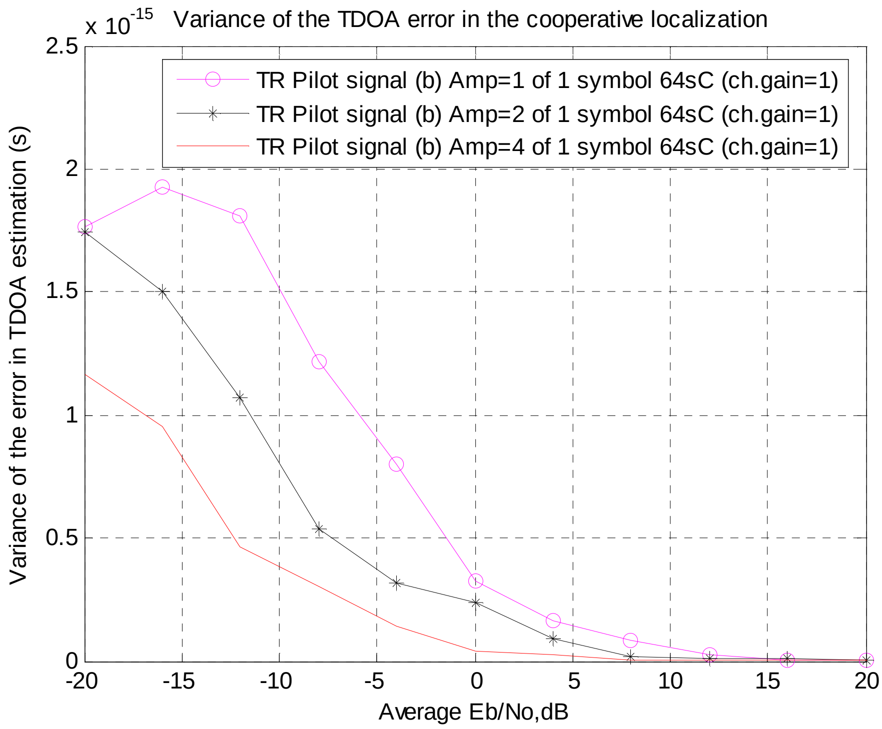


*Figure 4.17 Variance of the TDOA error changing the amplitude of the pilot signal*

The average TDOA error, probability of error and variance of TDOA error graphs show that increasing the amplitude of the pilot signal, in low SNR conditions decreases the error considerably. Taking advantage of this parameter it is possible to have a good performance even in low SNR conditions. Below 0dB the improvement is considerable.

The following graphs show the comparison in detail in different SNR conditions:

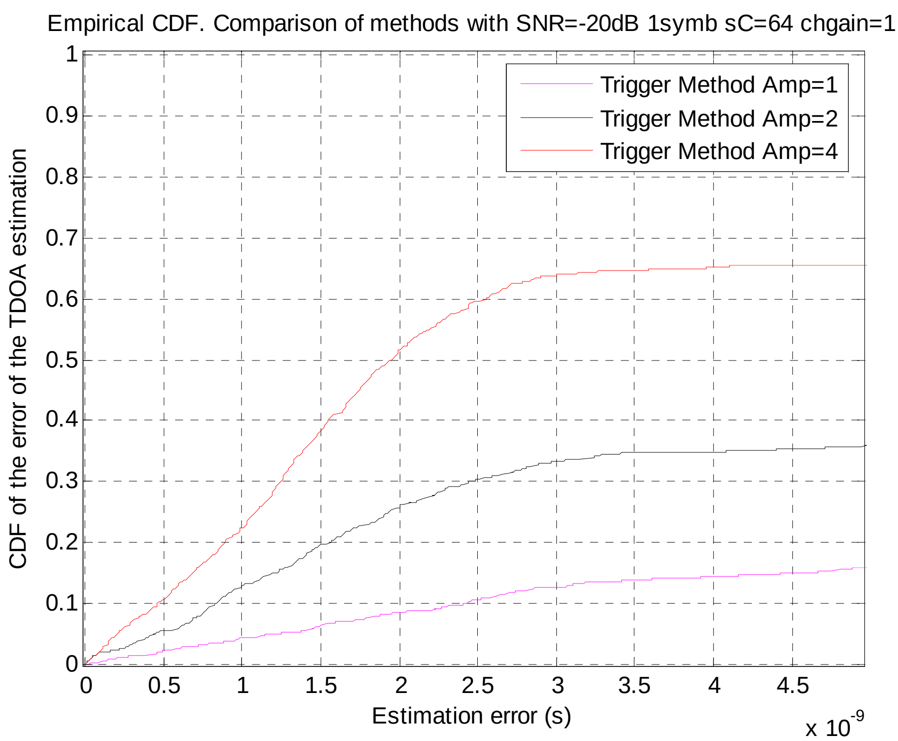


*Figure 4.18 Comparison of the CDF for different pilot signal amplitudes in -20dB SNR*

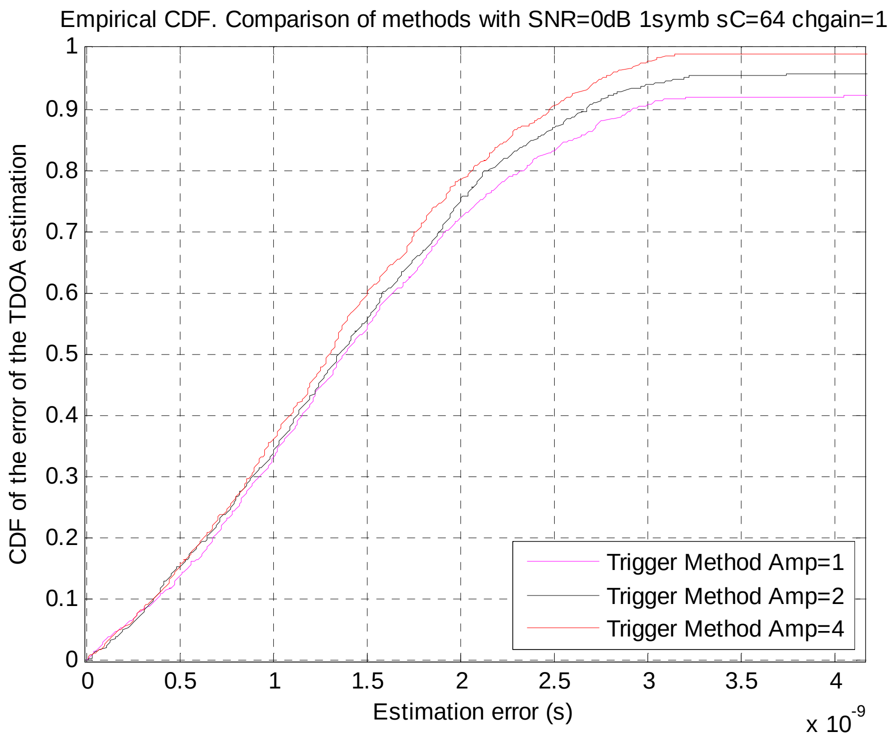


*Figure 4.19 Comparison of the CDF of the TDOA error for different pilot signal amplitudes in 0dB SNR*

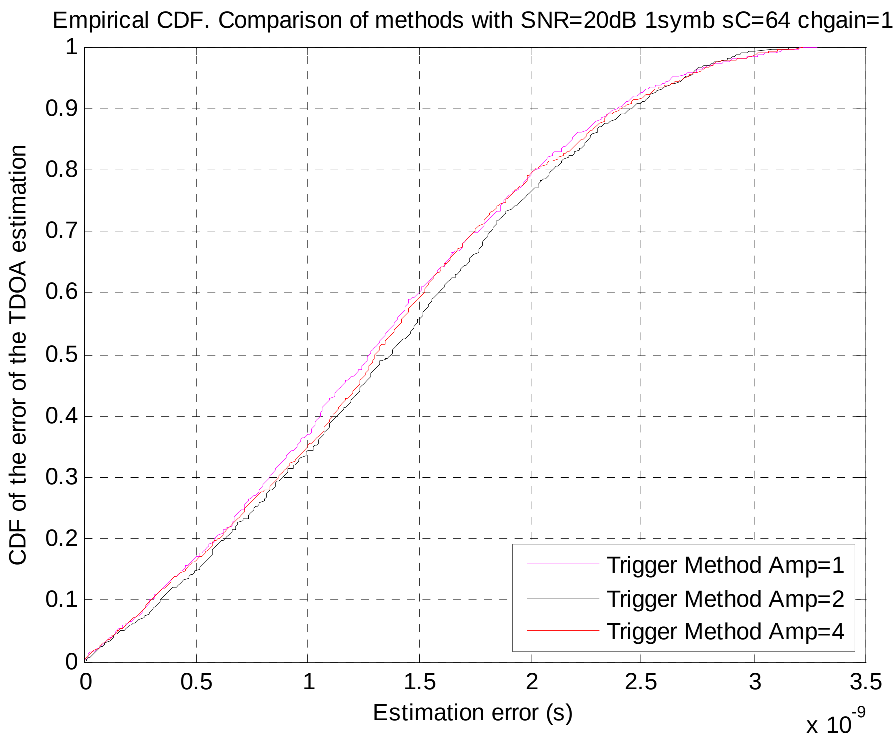


*Figure 4.20 Comparison of the CDF for different pilot signal amplitudes in 20dB SNR*

Increasing the power of the pilot signal, the error decreases, obtaining a better performance robust against the noise.

Depending on the SNR conditions, is not necessary to increase the power of the pilot signal because with large SNR the results are quite similar. As the power consumption is a critical resource for mobile devices maybe could be better to save battery rather than obtain a small improvement on the TDOA estimation.

This parameter is especially important because it provides a good performance despite the low SNR conditions, where usually the conventional systems (like AF, DF, or DF feature method), are always in error. The tradeoff of this improvement is the power consumption of the cooperative mobile relays.

## 4.4.3. EXTERNAL PARAMETERS

### 4.4.3.1. CHANNEL GAIN

Each received signal which crosses trough the channel suffers the flat fading and the additive noise effects, and could be written as:

$$y_i = h_i x + n_i \tag{4.8}$$

where $h$ is the channel gain, $x$ is the pilot signal sent by the relay, $n$ is the additive white Gaussian noise (AWGN) and the sub index $i$ denotes the different path in which travels the pilot signal when is received by the CBS.
The channel gain multiplies the whole signal, and it implies a weighted shape of the original pilot signal. The AWGN is the parameter which disturbs the original shape of the pilot signal, causing random variances of each bit of this signal.

If the channel gain increases, it makes the pilot signal more robust against the fluctuations of the AWGN, and gives more power to each bit compared with the power of the AWGN, giving a better performance to estimate the TDOA.

To estimate the TDOA it is required to identify the peak of the cross correlation of the signals involved on the localization process, which is the sum of the same segment of the signal included on both signals (in theory, the pilot signal), this value is always positive, being independent if the channel gain factor is positive or negative.

The following graphs show the performance of the TDOA error varying the channel gain:

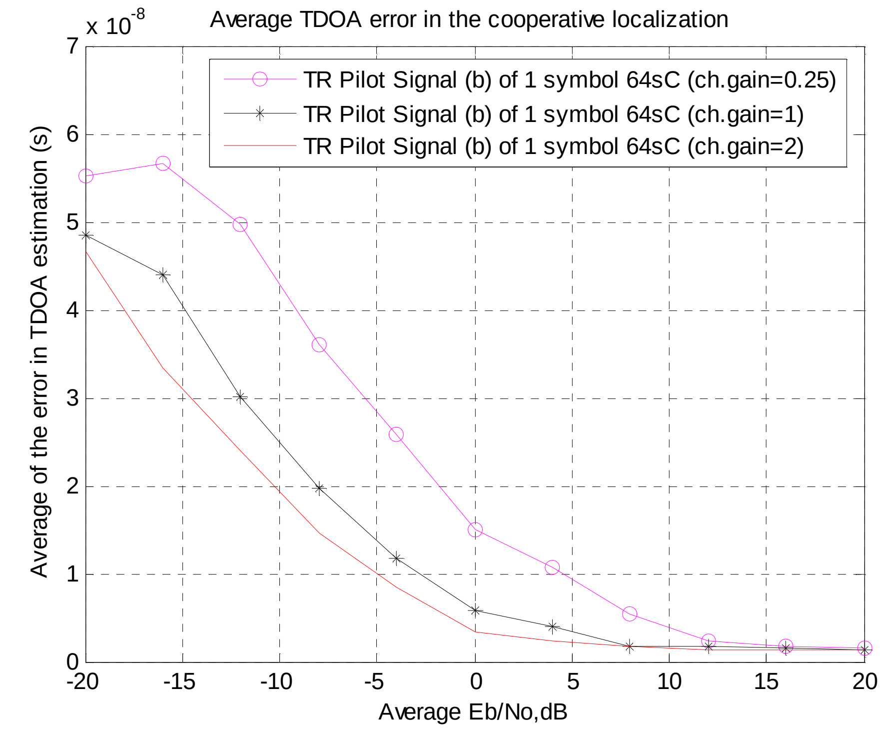


*Figure 4.21 Average of the TDOA error changing the channel gain*

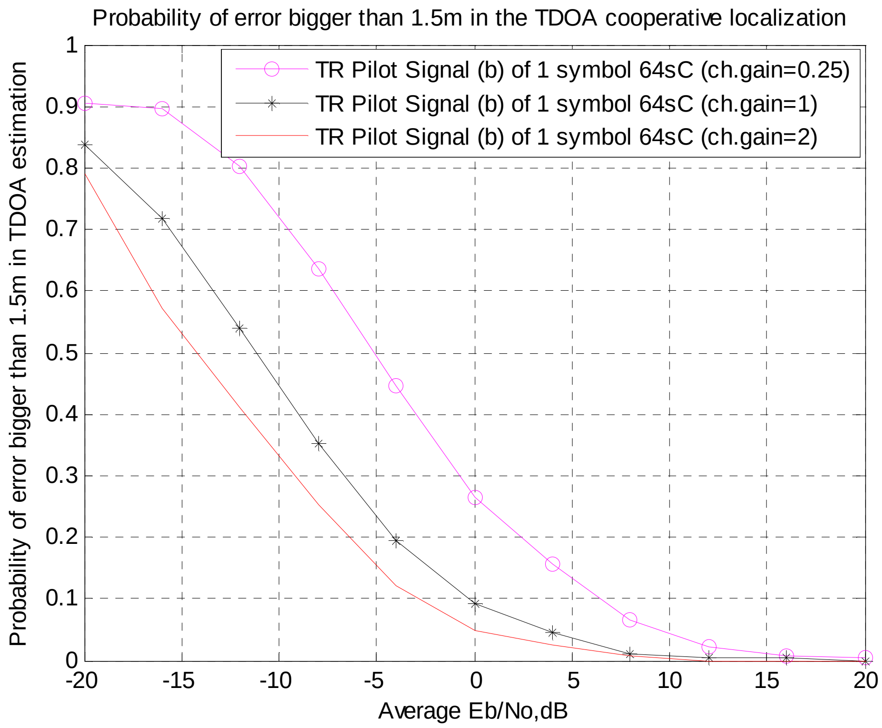


*Figure 4.22 Probability of error with different channel gains*

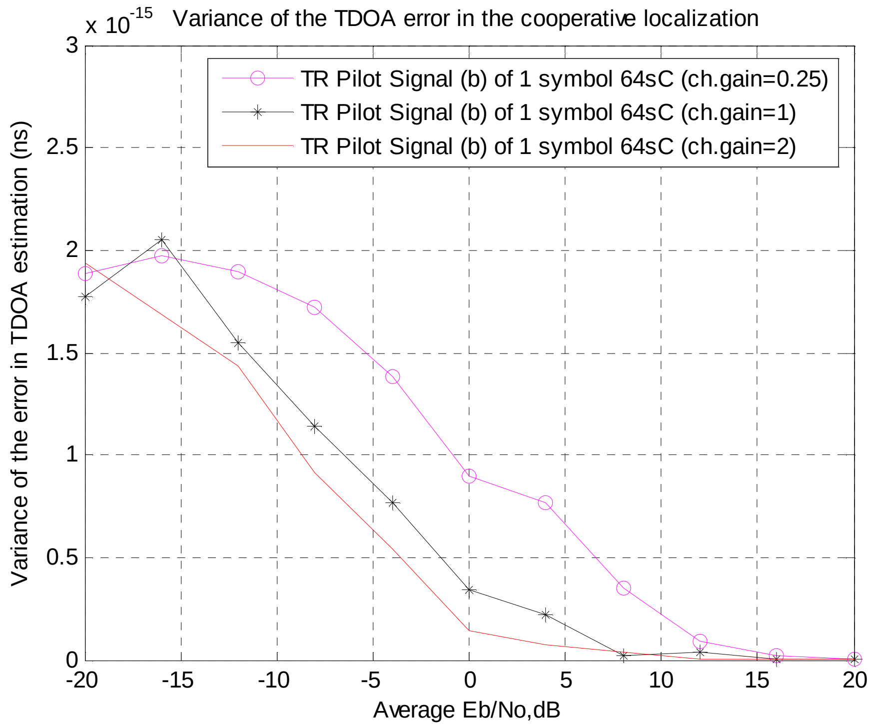


*Figure 4.23 Variance of the TDOA error changing the channel gain*

The previous graphs show that when the channel gain increases, the performance of the TDOA error improves.

The following graphs show the comparison of the different channel gains in different SNR conditions:

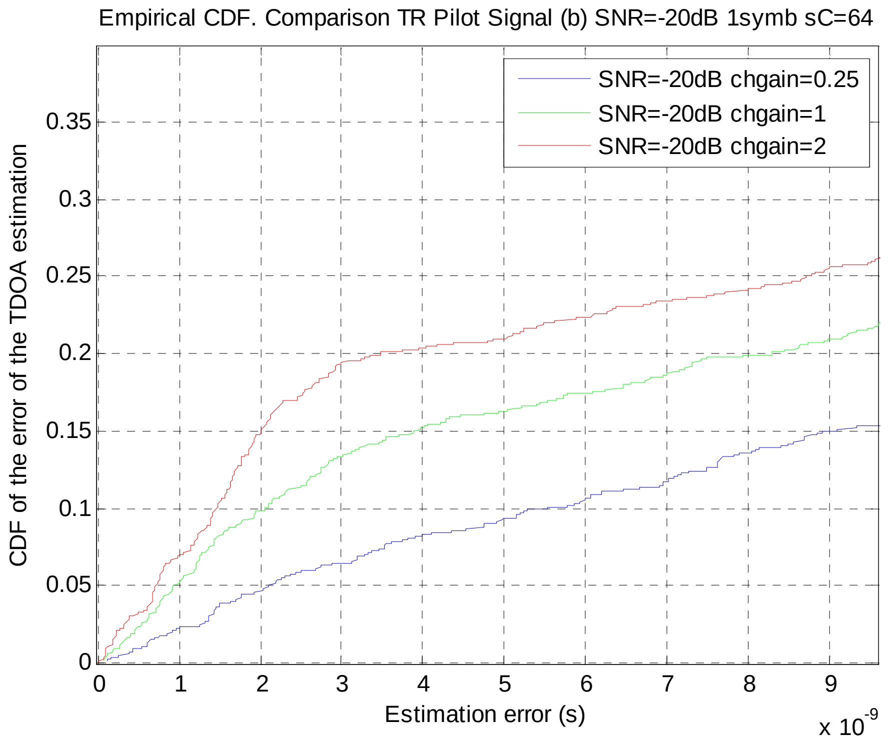


*Figure 4.24 Comparison of the CDF of the TDOA error changing the channel gain in -20dB SNR*

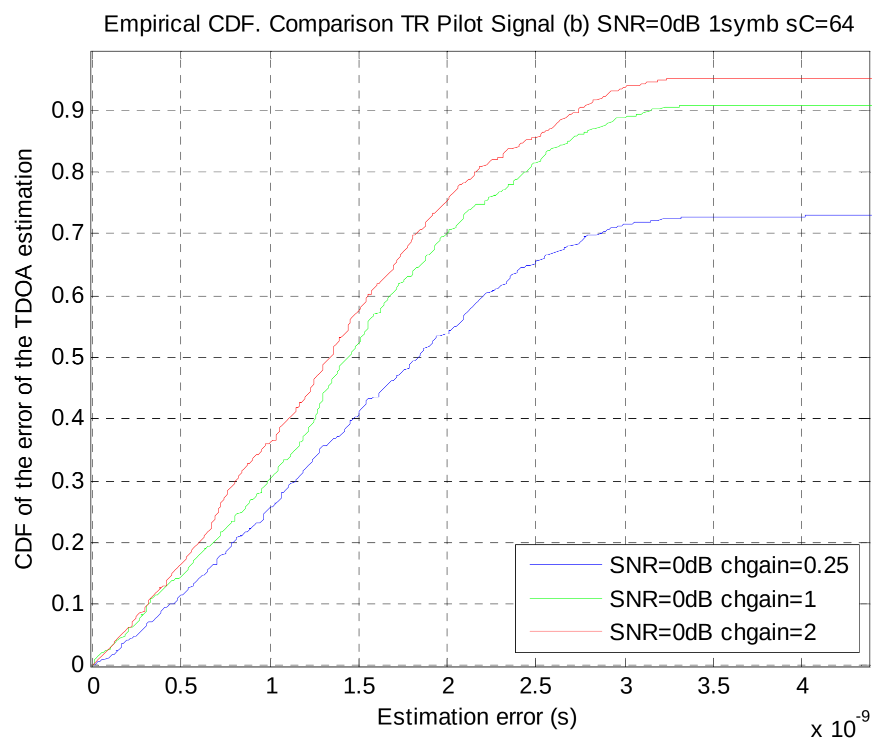


*Figure 4.25 Comparison of the CDF of the TDOA error changing the channel gain in 0dB SNR*

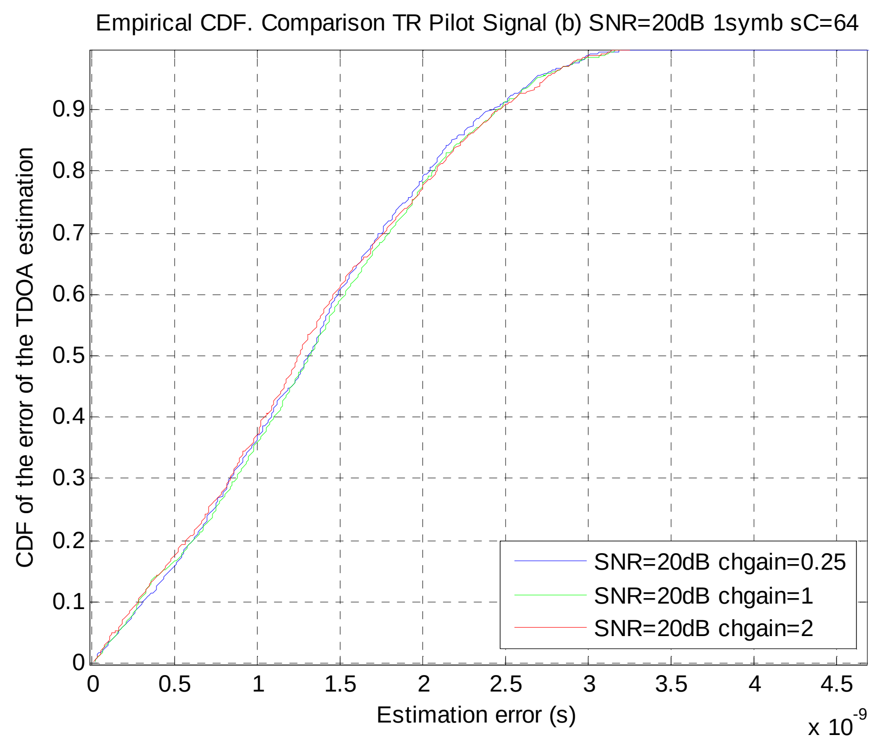


*Figure 4.26 Comparison of the CDF of the TDOA error changing the channel gain in 20dB SNR*

The channel gain affects directly to the performance of the error of the TDOA estimation, having a bigger impact in low and middle SNR situations (below 10dB). It would be desirable to work with a channel gain at least one or bigger than one.

#### 4.4.3.2. NUMBER OF SUBCARRIERS

The number of subcarriers is one parameter of the OFDM transmission technique. The more subcarriers, the more data per symbol is. This parameter affects the pilot signal directly, because its length is related with the length of the OFDM symbol. In terms of efficiency, if the number of subcarriers is increased, the relays need to send a longer pilot signal, which implies more computational cost, and more bandwidth consumption.

The next graph shows the probability of having an error bigger than 1.5 meters with different number of subcarriers:

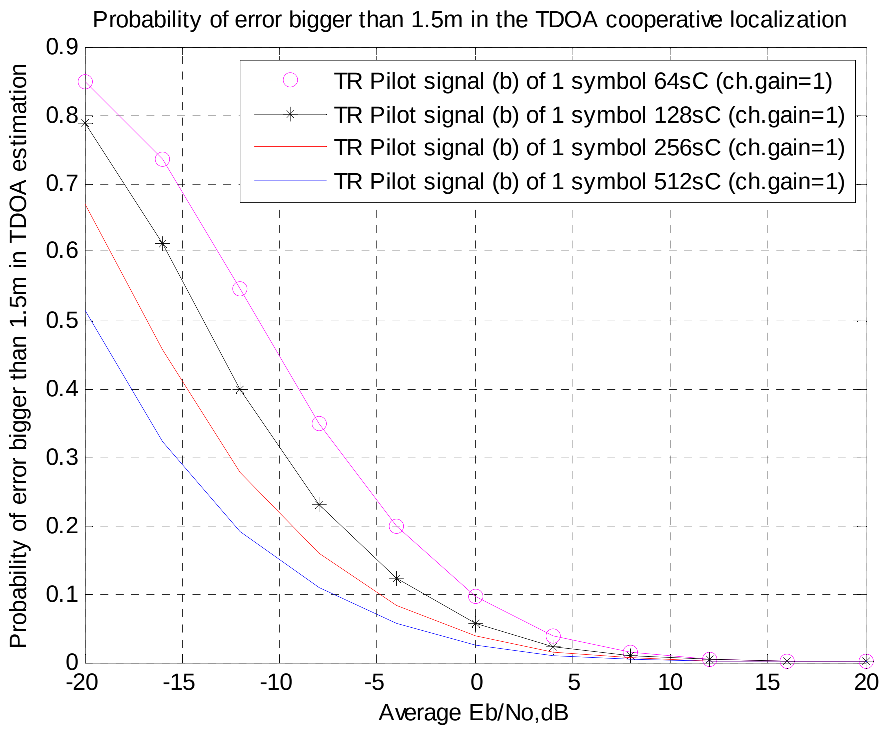


*Figure 4.27 Probability of error changing the number of subcarriers*

More number of subcarriers implies a longer pilot signal, which implies more data to do the cross correlation and obtain a more robust estimation of the TDOA error. For that reason the system with more number of subcarriers has the less probability of having a big error.

The following graphs show the CDF of the error in different SNR conditions for each system with different number of subcarriers:

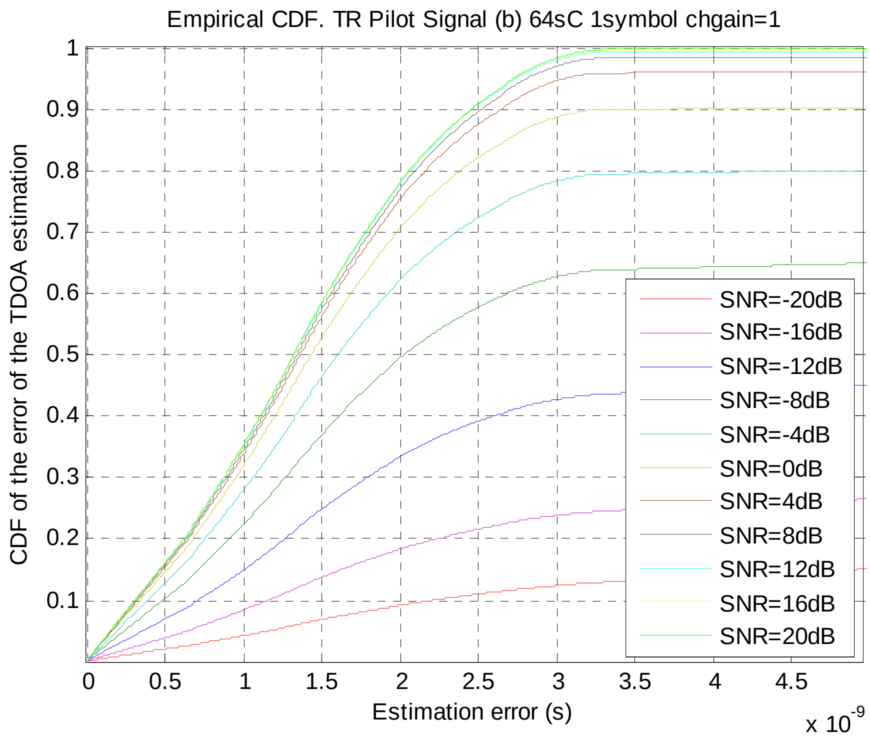


*Figure 4.28 CDF of the TR method with 64 subcarriers*

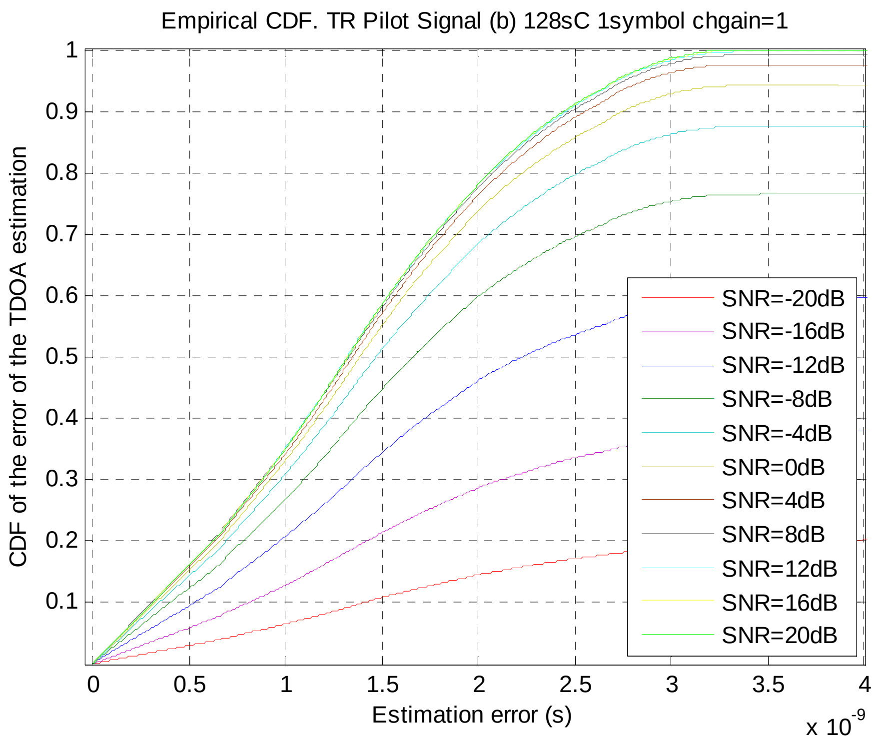


*Figure 4.29 CDF of the TR method with 128 subcarriers*

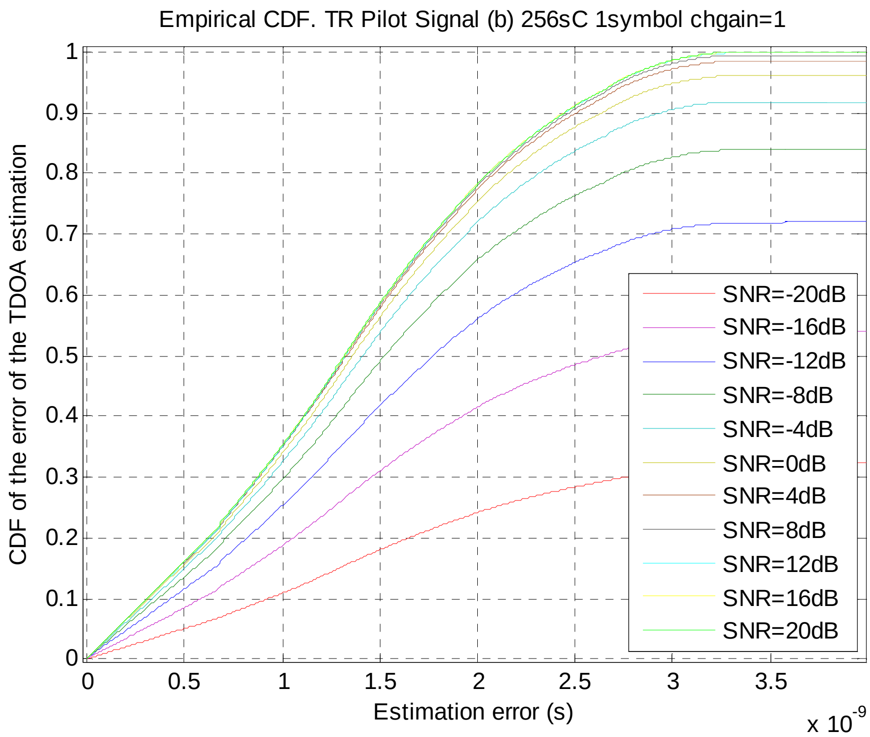


*Figure 4.30 CDF of the TR method with 256 subcarriers*

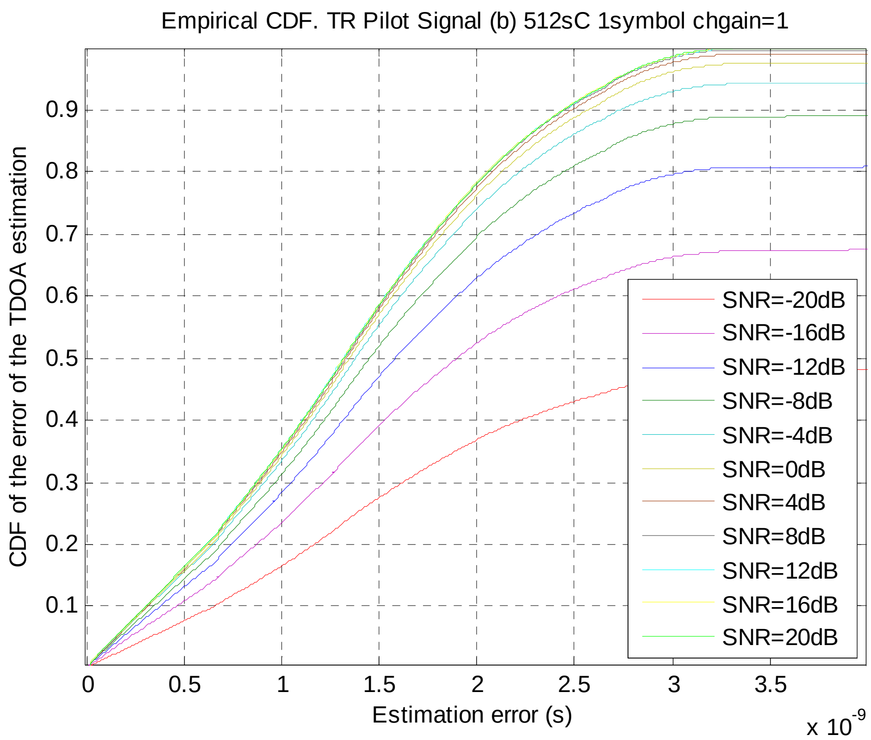


*Figure 4.31 CDF of the TR method with 512 subcarriers*

In large SNR conditions, the CDF curve tends into the higher bound in which converge all the results as a consequence of the physical limits of the system, like the time resolution. It depicts how the curves of low SNR get better on the systems with more subcarriers as well.

The following graphs show the comparison between the different systems in low, medium and large SNR conditions:

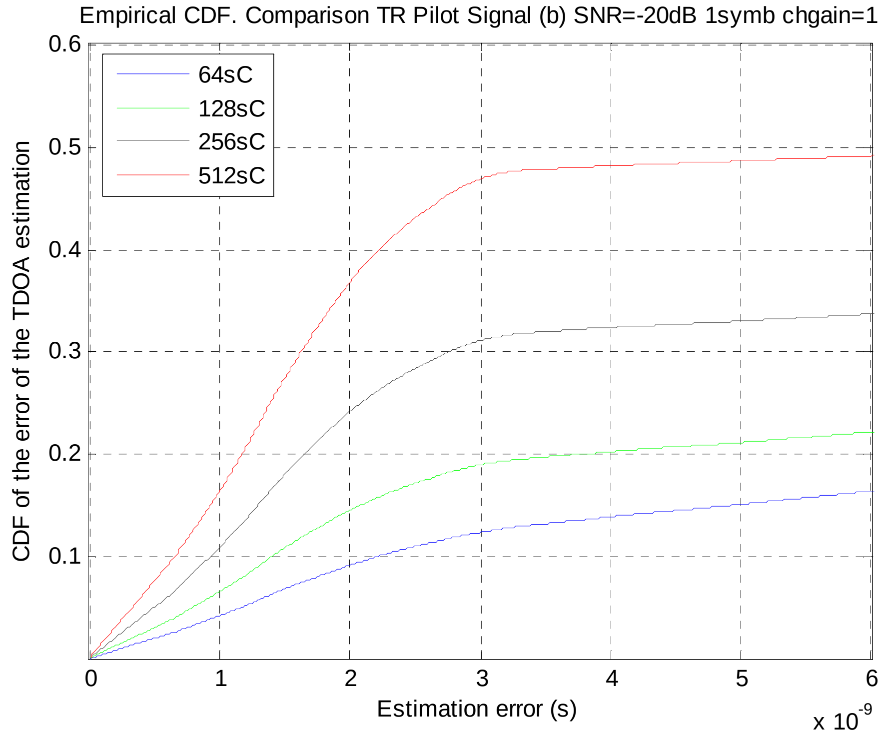


*Figure 4.32 CDF of the TDOA error changing the number of subcarriers in -20dB SNR*

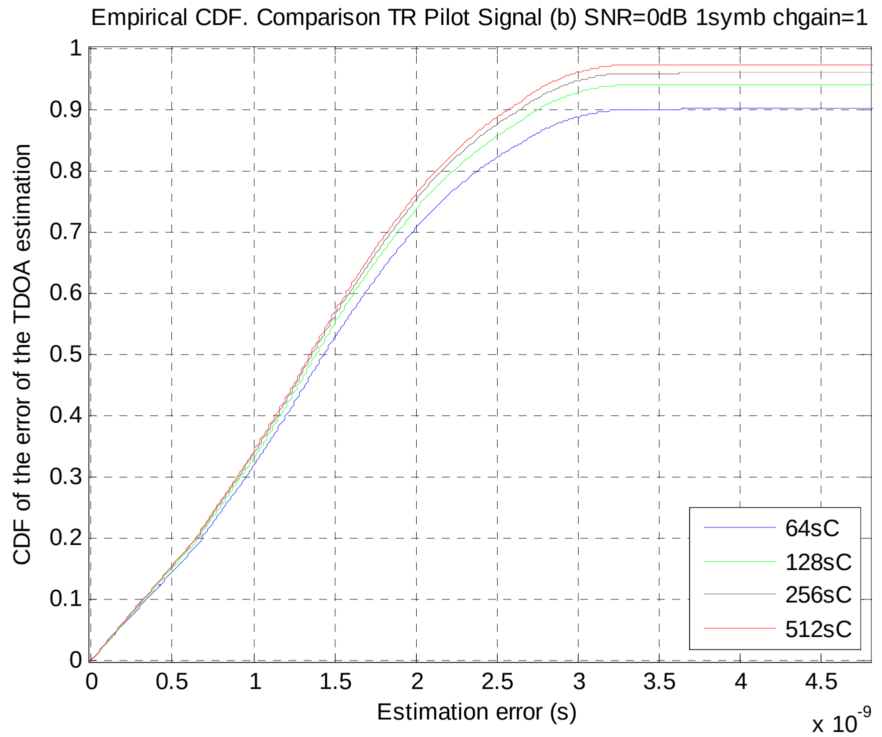


*Figure 4.33 CDF of the TDOA error changing the number of subcarriers in 0dB SNR*

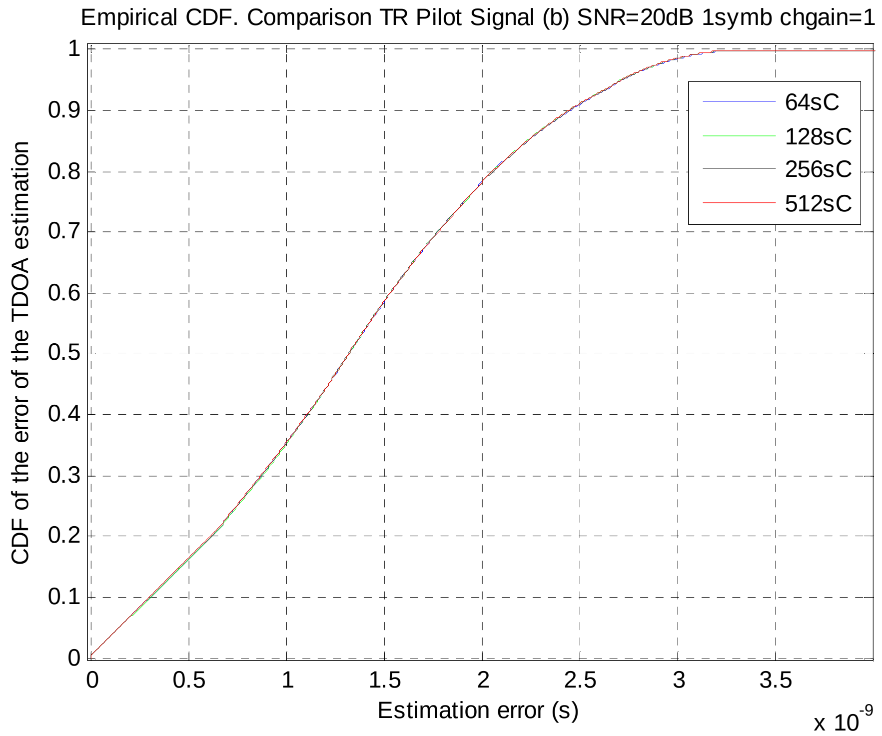


*Figure 4.34 CDF of the TDOA error changing the number of subcarriers in 20dB SNR*

The results show an improvement on the performance when the number of subcarriers increases, especially in low SNR conditions. In this situation is convenient to have a system with more subcarriers despite the trade off of the power consumption and bandwidth employed by the relay.

In 0dB SNR conditions there is also an improvement when the number of subcarriers increases, but maybe it does not worth to work with more subcarriers, trying to be the most efficient as possible.

Working with large SNR, all the results are similar, because the trigger relay method already has a good performance, and the improvement which could add the fact of increase the number of subcarriers does not get any effect.

It has been demonstrated that increasing the number of subcarriers implies an improvement on the performance of the TDOA error. It's because with more subcarriers there is more data on the pilot signal, which is the effective data that is required to do the cross correlation in order to obtain the TDOA estimation. The peak of the cross correlation is more powerful, obtaining a robust estimation which could cope with an accurate estimation in low SNR conditions.

#### 4.4.3.3. MULTIPATH DIVERSITY

In ZP-OFDM transmission with multipath channel, trigger relay TDOA estimation can further gain from multipath diversity, and improve the TDOA accuracy. When adopting the linear transceiver proposed in [3], ZP-OFDM channel holds the linear structure or tall Toeplitz structure, where its full column rank property always guarantees matrix invertibility and signal detection. Meanwhile, the tall Toeplitz ZP-OFDM channel matrix ensures the full multipath diversity gain for the signal detection, only with the linear equalizers, such as Zero-Forcing (ZF) and Minimum Mean Square Error (MMSE) equalizers [13], [14].

Therefore, in the trigger relay TDOA estimation, the above mentioned linear transceiver can be used to achieve the full multipath diversity gain in the relay to primary receiver link, to combat the noise effect, and to improve the signal detection. Utilizing the well detected signal to process the TDOA estimation, it will consequently enhance the TDOA estimation accuracy. Meanwhile, this linear transceiver possesses a lower system complexity, compared to those systems with non-linear maximum-likelihood equalizers [12].

There are considered three scenarios, one without multipath (only the direct path), other with multipath diversity order of two, and the last one with four.

The following graphs show the improvement of the multipath diversity gain on the error of the TDOA estimation:

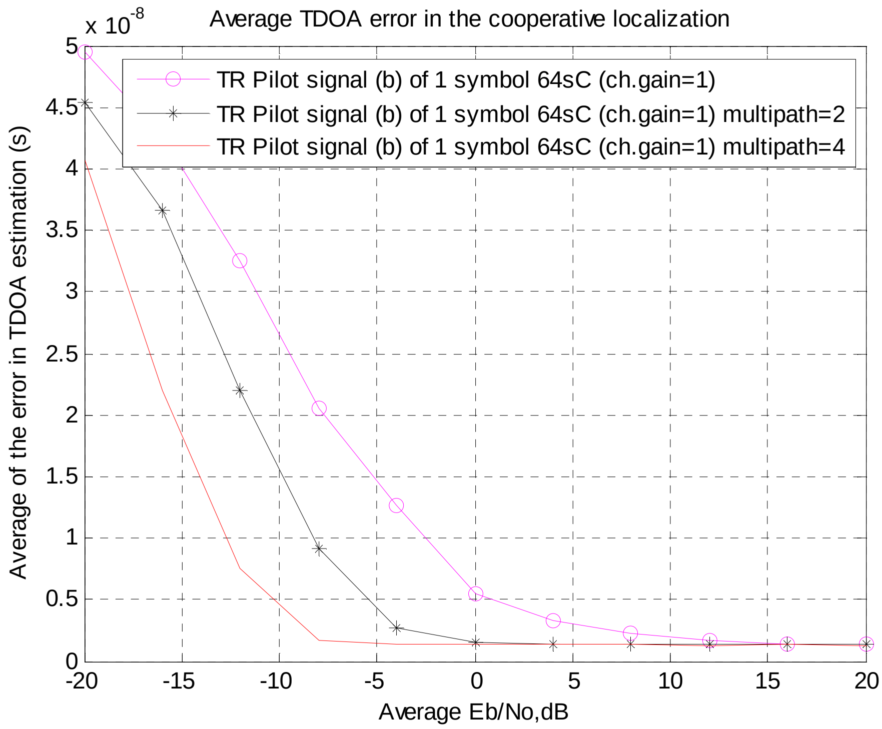


*Figure 4.35 Average of the error of the TDOA estimation with different multipath gain.*

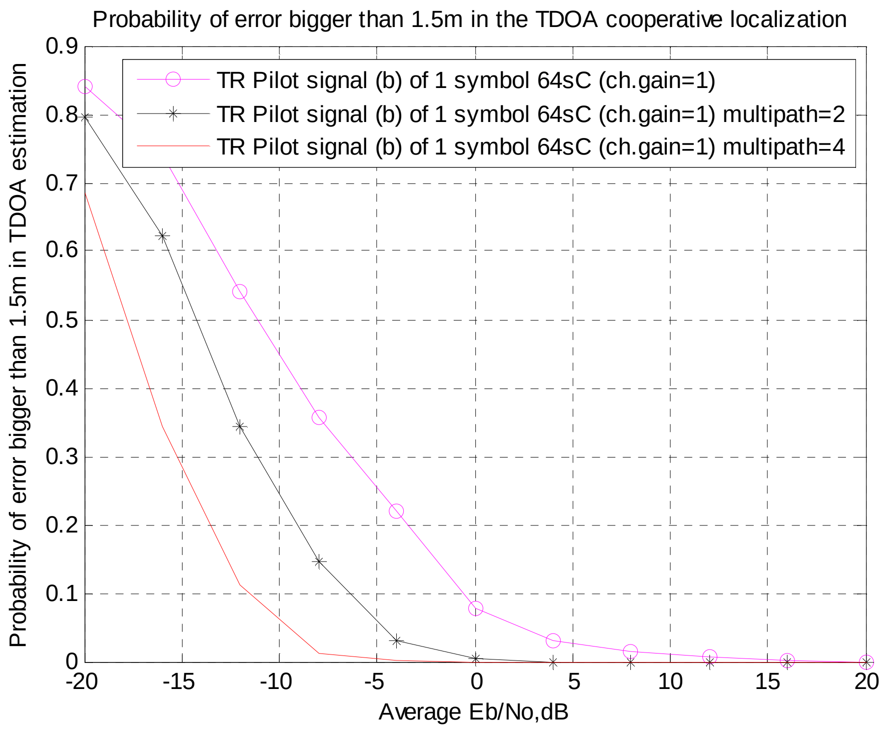


*Figure 4.36 Probability of error of the TDOA estimation with different multipath gain.*

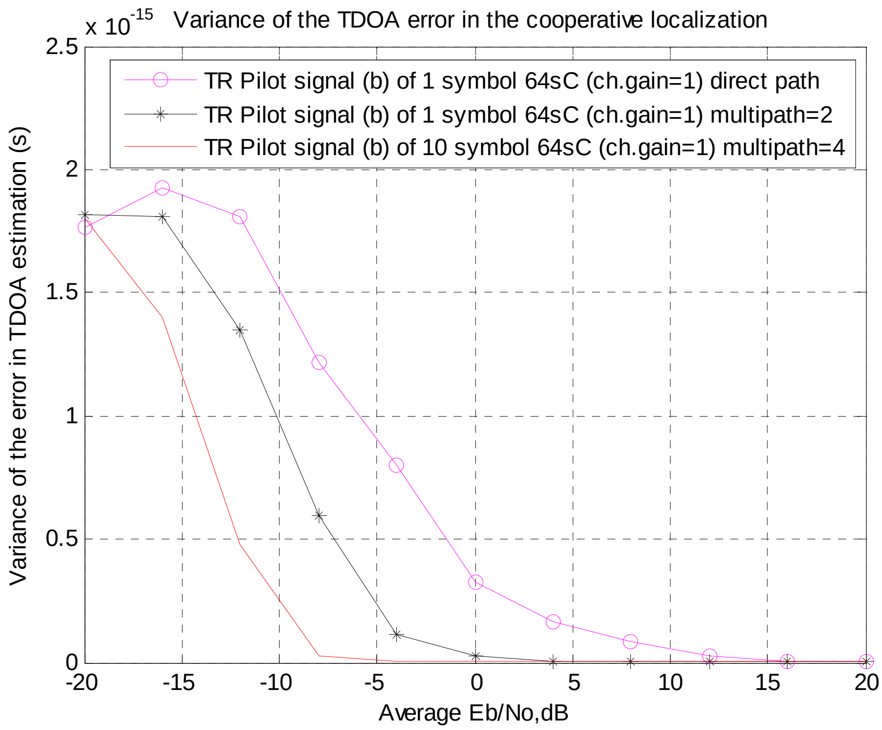


*Figure 4.37 Variance of the error of the TDOA estimation with different multipath gain.*

The figures show how increasing the multipath order, the performance improves.

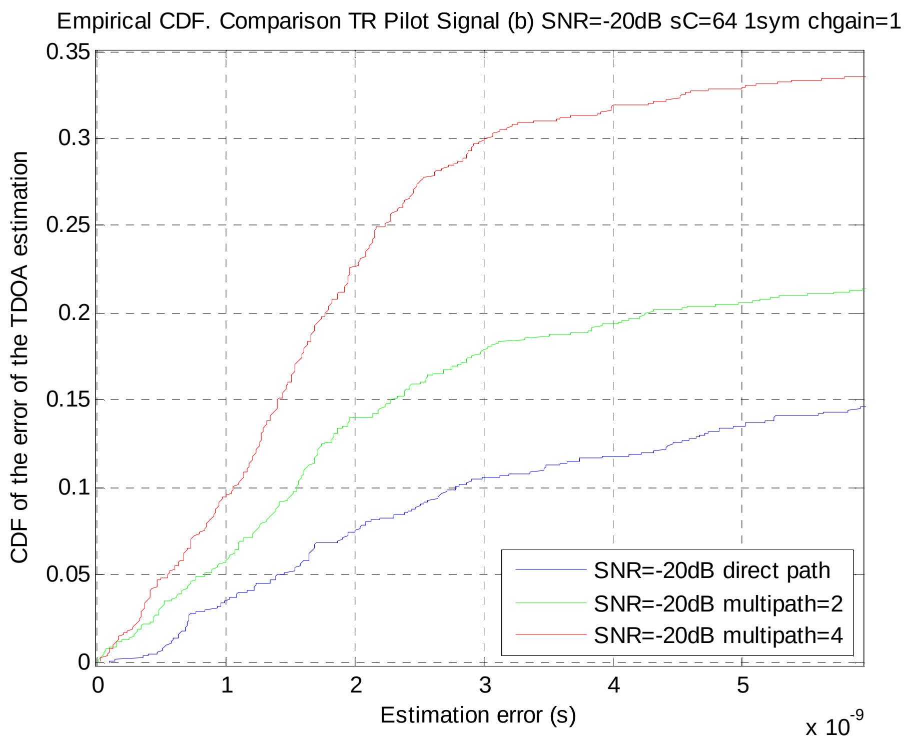


*Figure 4.38 Comparison of the CDF of the TDOA error with in different multipath situations, in a -20dB SNR*

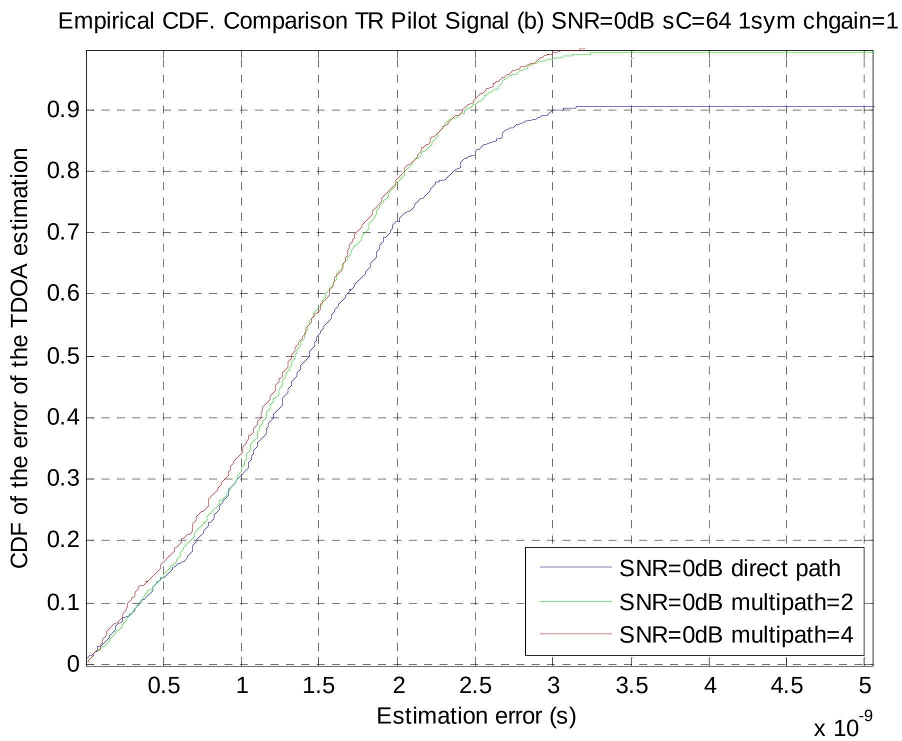


*Figure 4.39 Comparison of the CDF of the TDOA error with in different multipath situations, in a 0dB SNR*

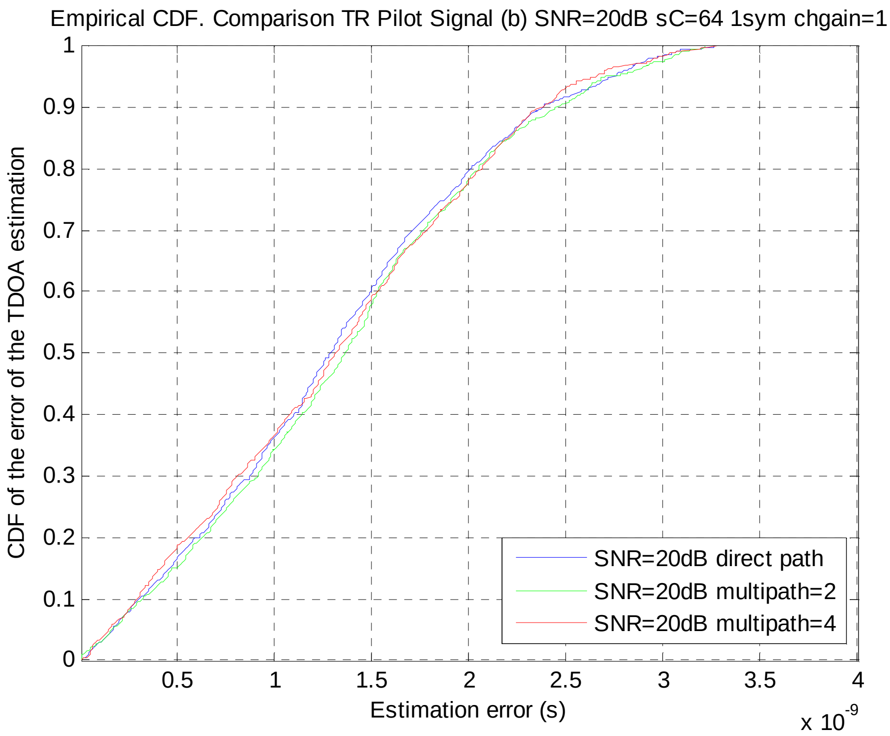


*Figure 4.40 Comparison of the CDF of the TDOA error with in different multipath situations, in a 20dB SNR*

We can see from the figures that in the low SNR region, multipath diversity helps decreasing the TDOA estimation error. The more multipath diversity order, the smaller the TDOA estimation error.

## 4.5. JUSTIFICATION OF THE RESULTS AND CONCLUSIONS

Trigger relay with pilot signal method is a new efficient method proposed to estimate the TDOA for cooperative localization.

It is bandwidth efficient because it only requires the relays to transmit a pilot signal, which usually is one OFDM symbol length. It is computational efficient as well, because the relays only need to generate and transmit one simple OFDM signal, which is the pilot signal. Both advantages make the method appropriate to be used for the cooperative localization, since the power consumption is low, and the relays are mobile devices that are connected to the wireless network being their battery life a critical resource.

This method provides a great accuracy on the estimation of the TDOA, even in low SNR situations, improving the performance of the previous methods and having the extra advantage of being computational and bandwidth efficient.

Different parameters could be changed to improve the performance of this method especially in low SNR situations, having a tradeoff with the efficiency. It must be used the most efficient parameters configuration in the middle and large SNR situations, because the trigger relay with pilot signal method provides a good TDOA estimation, and the tradeoff of loosing efficiency does not worth it.

The shape of the pilot signal is not a critical issue on the performance of the system, for that reason it has been chosen a pilot signal easy to generate and being one with the lowest error.

If the length of the pilot signal increases, the TDOA estimation improves. That is because with more OFDM symbols for the pilot signal it is obtained more data to do the cross correlation, obtaining a stronger peak and a more robust result.

The amplitude of the pilot signal is probably the most important parameter to take into account. The pilot signal is generated directly on the relays, being independent how the signal sent by the MS arrives and how the SNR on the link MS-relay is. For that reason, if the SNR of the system is low, it is possible to increase the amplitude of the pilot signal, to get more robust and to have more probability of success on the TDOA estimation. Obviously it impacts on the power consumption of the relay, because it is required to transmit more power, but is a good tradeoff because it provides a good performance even in low SNR situations, where other methods are always in error.

Other parameters of the system could affect the performance of the TDOA estimation in the trigger relay with pilot signal method.

The channel gain affects directly the performance of the system; if the channel gain is high, it improves the TDOA estimation, and if it is low, the error increases. The channel gain is a random value, and could be either positive or negative. The TDOA is obtained by the cross correlation of two signals, looking for the peak, which is the sum of the power of the common part of both signals, being always a positive value. Channel gain only escalates the signal that passes through the path, preserving the original shape.

The number of subcarriers has a similar effect like the length of the pilot signal. Increasing the number of subcarriers the TDOA estimation gets better, but it is required to the relay to send a larger signal, being less efficient and consuming more power.

Taking advantage of the multipath diversity and with a proper design of the receiver, it is possible to take advantage of the multipath effect and improve the performance of the system.

# 5. Comparison of Methods

## 5.1. INTRODUCTION

In this chapter there are compared the new proposed methods to estimate the TDOA in an efficient way, feature method and trigger relay with pilot signal method, with the existing conventional method of sending the raw data in order to compare the quality of the measurements and the performance of the system.

## 5.2. EFFICIENCY COMPARISON

### 5.2.1. BANDWIDTH EFFICIENCY

The bandwidth required to transmit the signal from the relays to the CBS could be reduced with the new proposed methods.

In the conventional TDOA estimation, the relay is required to transmit the whole received signal from the MS. To compare the different methods there are considered the same parameters as the simulations. The MS sends a 64 subcarriers OFDM signal of 50 symbols which is received by the relays of the system and the CBS.

Conventional method requires the relay to forward the whole received signal to the CBS. In this situation it must amplify and forward or decode and forward the whole OFDM signal.

In the feature method the relay extracts one feature per symbol received and joins together all these values to create the feature signal and send it. Working with the commented simulation parameters, the relay only needs to send a signal with 50 samples. If the system works with 64 subcarriers, the amount of data that the relay needs to send is less than one OFDM symbol.

In the trigger relay with pilot signal method, the relay sends a pilot signal at the moment when it receives the signal sent by the MS. It is independent of the length of the original signal, it only depends on the number of subcarriers fixed on the OFDM communication.

The following figure shows an example of the signals that are sent by a relay in three different methods, trigger relay with pilot signal method, feature method and conventional AF:

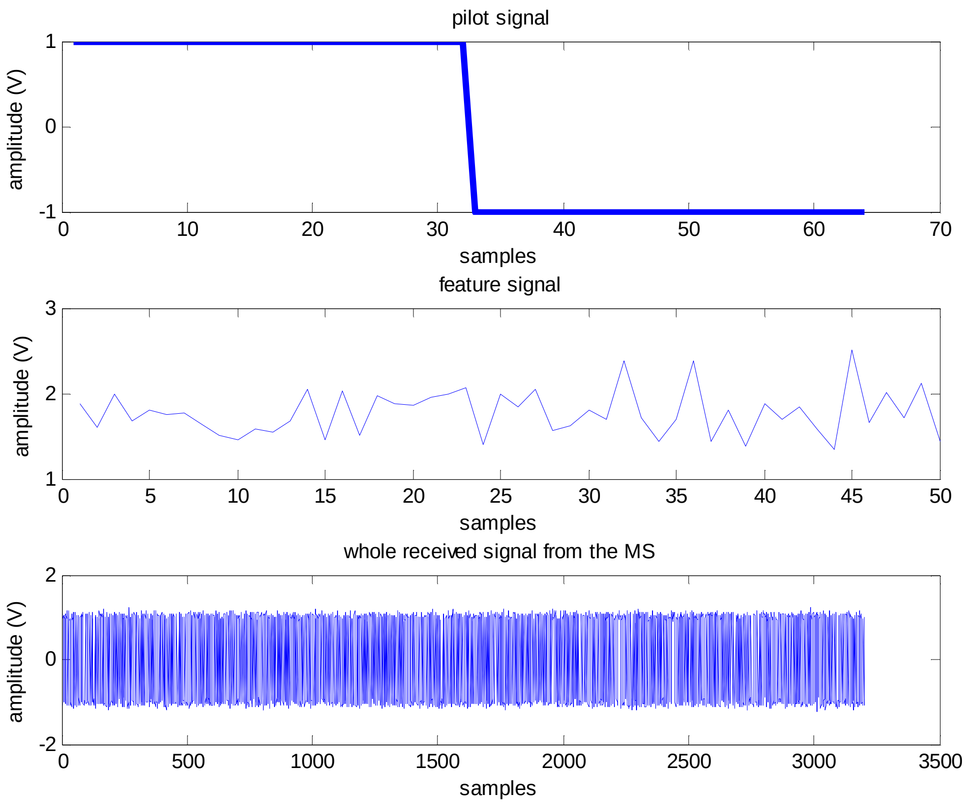


*Figure 5.1 Signals sent by the relay in different methods.*

The first plot of the figure 5.1 shows the pilot signal, with the same length as an OFDM symbol, in this situation it has 64 samples as a consequence of the 64 subcarriers employed on the system. The second plot is the feature signal, which has one sample per symbol received, in this example it has 50 samples because the MS sent a signal of 50 OFDM symbols. The third plot shows the whole signal received on the relay, which is needed to forward to the CBS, it has 3200 samples, result of being 50 OFDM symbols of 64 samples per symbol.

### 5.2.2. SYSTEM COMPLEXITY

The relays of the TDOA estimation system have an important role transmitting a signal to the CBS in order to compute the cross correlation to estimate the TDOA.

Depending on the method employed by the system, the relays need to be more or less complex, because the tasks required for them are different.

AF relay for the conventional method requires a power amplifier to compensate the signal attenuation suffered in the MS-relay link.

A relay of the feature method is a DF relay, which decodes the signal, and also needs an extra software/hardware to compute the feature. Comparing the three methods, this relay is the most complex.

Trigger relay has the lowest system complexity, because it does not need to process the received signal, neither decoding nor amplifying, only needs to detect the incoming signal, and to transmit the simple pilot signal.

### 5.2.3. COMPUTATIONAL EFFICIENCY

In this section they are compared the computational operations required for the relays on the TDOA estimation process.

In the conventional way the relay needs to process the full signal, and depending on the relay employed, it needs to decode all bits and forward them, or amplify and forward the whole data.

The relays of the feature method need to process every received symbol and extract a statistical feature for each one. The process requires more signal processing operations than the conventional method, but the relays of the feature method save the transmitting power respect the other methods in the transmission of the signal, because they only need to transmit a small signal saving power consumption.

The trigger relay with pilot signal method is the most computational efficient scheme for the relays. They only need to generate and transmit the pilot signal, which is one OFDM symbol, and don't need to do other kind of signal processing.

## 5.3. TDOA ESTIMATION COMPARISON

### 5.3.1. SIMULATION PARAMETERS

In this section it is compared the TDOA estimation quality of four different schemes:

- Trigger relay with pilot signal method
- Feature method, being PAPR the selected feature
- Conventional AF method forwarding the raw data
- Trigger relay with pilot signal method, with a pilot signal with doble amplitude

The simulation parameters and the criteria employed to compare the results are the same as used in the previous sections.

### 5.3.2. SIMULATION RESULTS

The following figure shows the average of the TDOA error for the four different methods:

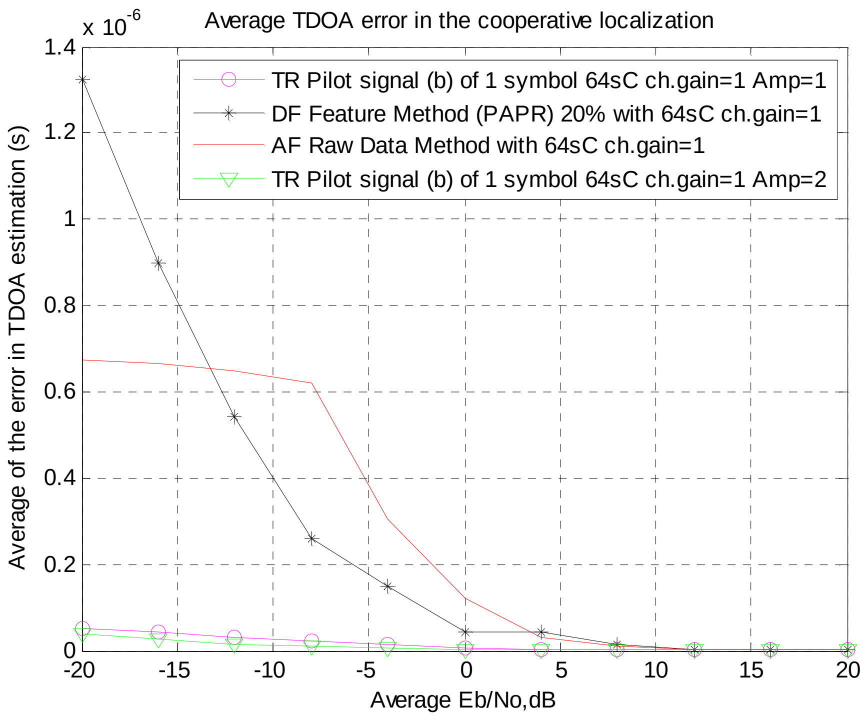


*Figure 5.2 Average of the TDOA error of the different methods*

Figure 5.2 shows the big difference between the trigger relay method and the rest. The average of the TDOA error is huge in low SNR conditions for both AF and feature method.

The following plot compares the probability of error of the different methods:

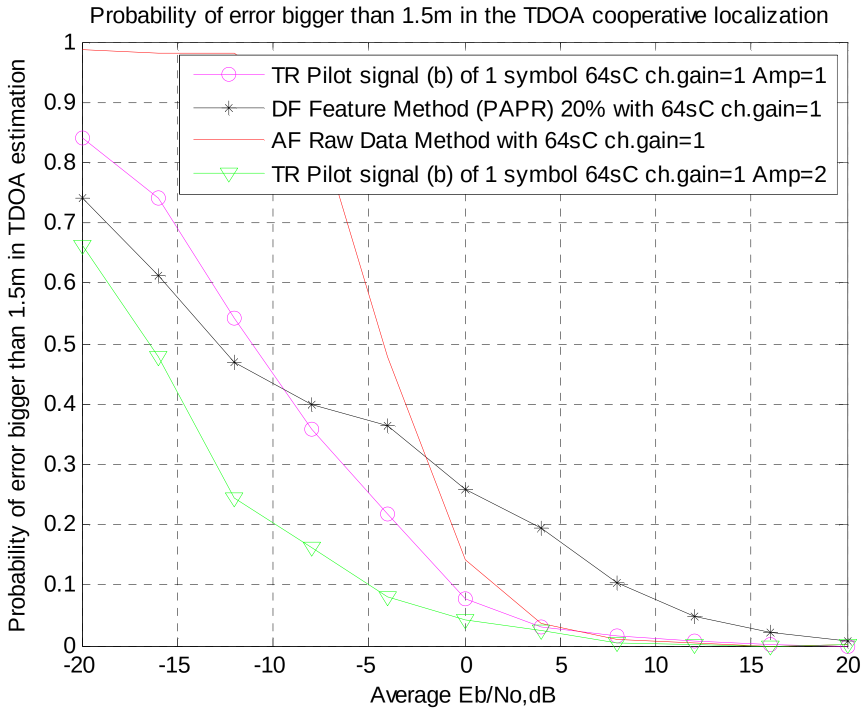


*Figure 5.3 Probability of error for the different methods*

In figure 5.3 there is depicted the probability of having an error bigger than 5ns. and it is clear the comparison between the different methods. Feature method improves the performance in low SNR conditions respect the AF method. It could be though that the feature method achieves only the symbol level resolution, because it is extracted one feature value per symbol received, but as the feature signal is composed by one sample per symbol received, and it is sent independently, when the cross correlation is done, the time resolution is the same as the system time resolution, delimited by the bandwidth of the transmission.

Trigger relay method has the best performance on the TDOA estimation. Increasing the amplitude of the pilot signal improves the performance in low SNR conditions, allowing reasonable errors even in harsh conditions.

The next plot shows the variance of the TDOA error for the different methods:

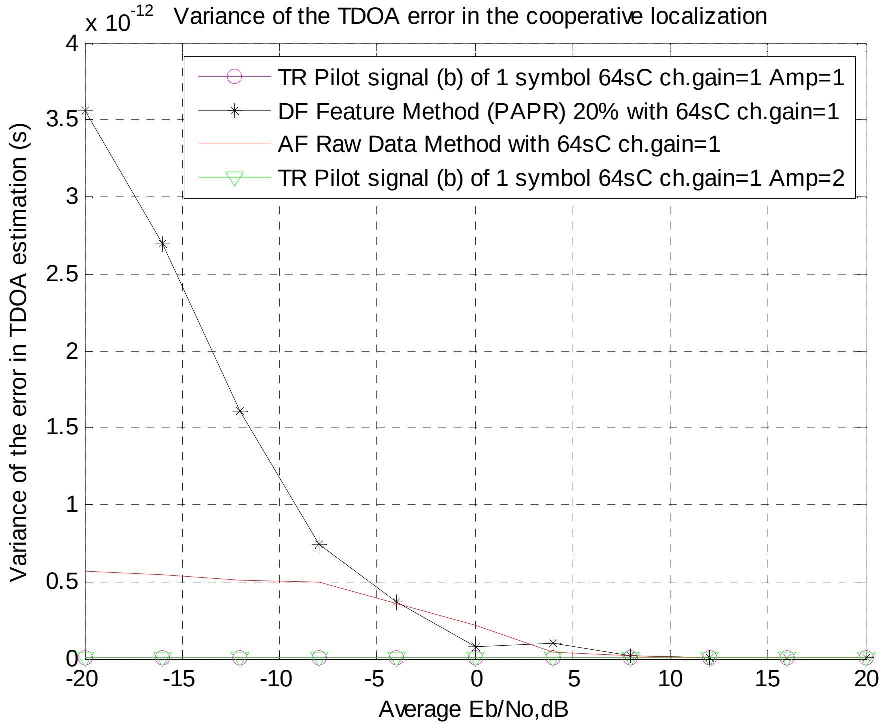


*Figure 5.4 Variance of the TDOA error for the different methods*

This figure shows the big variance that the feature method has. That fact demonstrates the behavior of the feature method, why it has a big average TDOA error, but good probability of error. It's because feature method estimates the TDOA without error in a big percentage of the times, but when is in error, the errors are extremely big.

That behavior could be seen clearly with a histogram of the TDOA error for the feature method, in which there is depicted where are located the errors during the simulation. There are plotted 1000 values, one per simulation iteration, and with resolution of ns. they are located in its region:

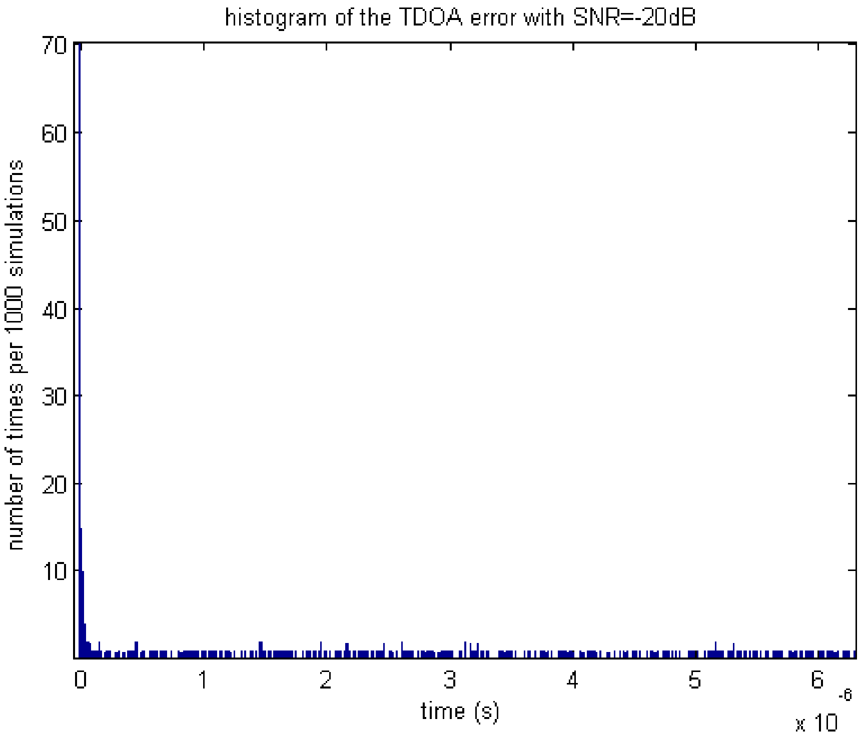


*Figure 5.5 Histogram of the TDOA error of the feature method in SNR=-20dB*

It is depicted how the majority of the simulation results are focused on the small values, but there are also discrete values which have a big error, even in the order of microseconds. For that reason the variance and the average of the TDOA error of the feature method is so big.

The following graph shows the zoom of the tens of nanoseconds ($10^{-8}s$) region of the histogram:

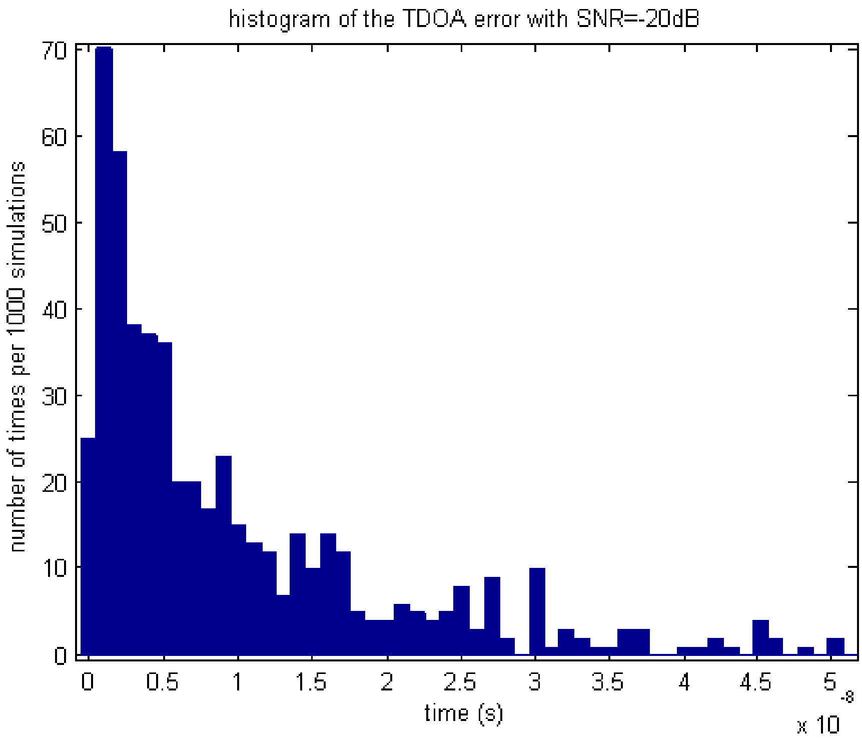


*Figure 5.6 Zoom of the histogram of the TDOA error of the feature method in SNR=-20dB*

In this simulation of 1000 iterations, 431 times the relative error was less than the 25%, and 453 times was bigger than the 100%. Those results contribute to the commented behavior of having a good probability of error but a big variance and average error.

The following graphs show the CDF of the TDOA error of the different methods:

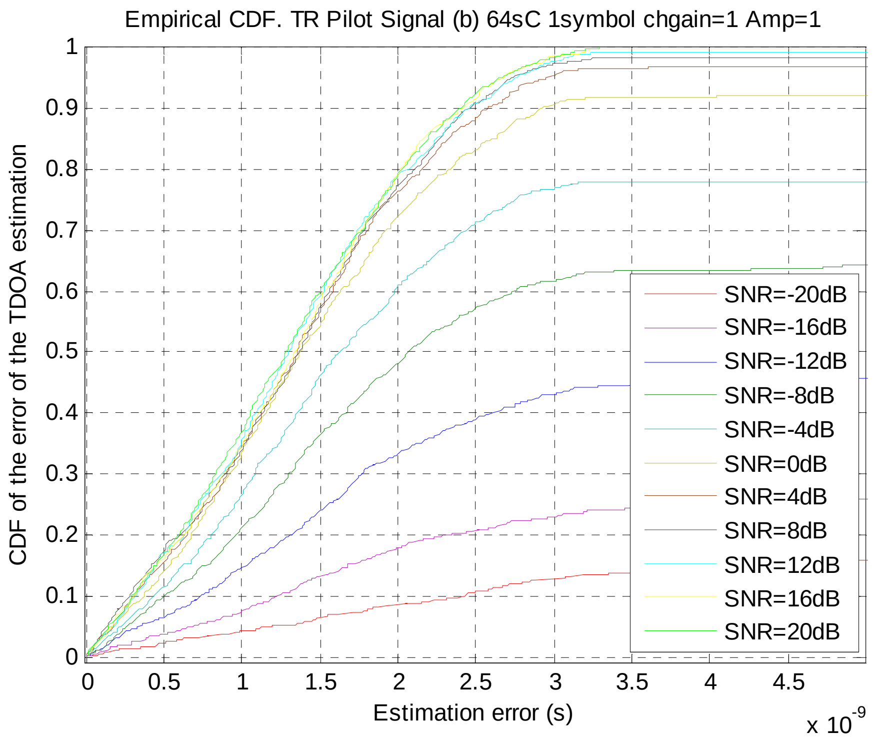


*Figure 5.7 CDF of the TDOA error of the Trigger relay with pilot signal (Amp=1) method*

Trigger relay method increases its performance progressively, and since SNR=0dB it has a great performance.

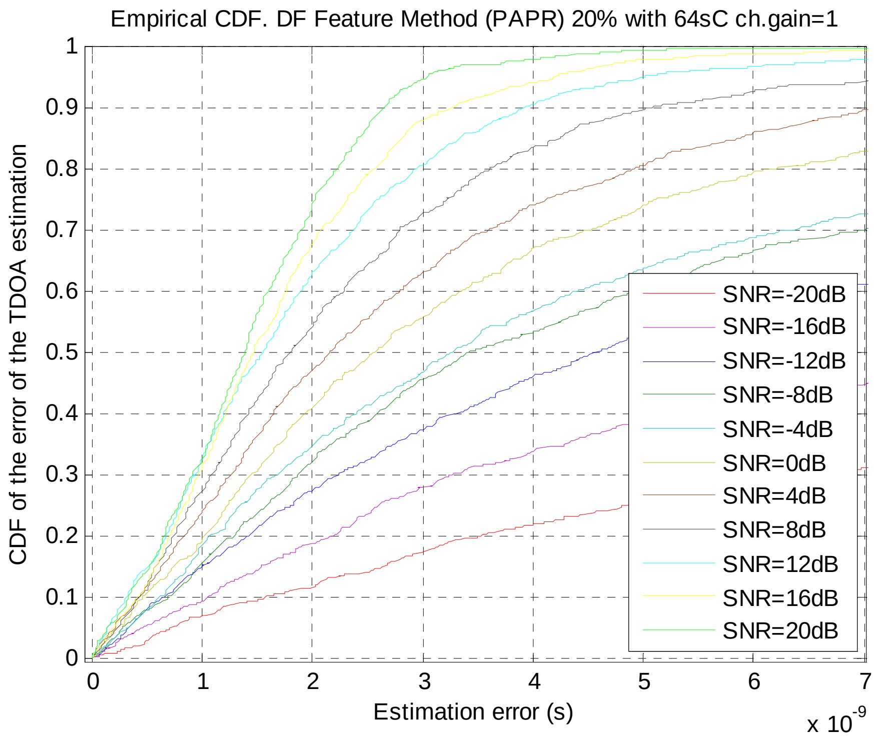


*Figure 5.8 CDF of the TDOA error for the feature method*

Feature method improves its performance as the SNR increases, but in large SNR its TDOA error is not good enough respect the other methods.

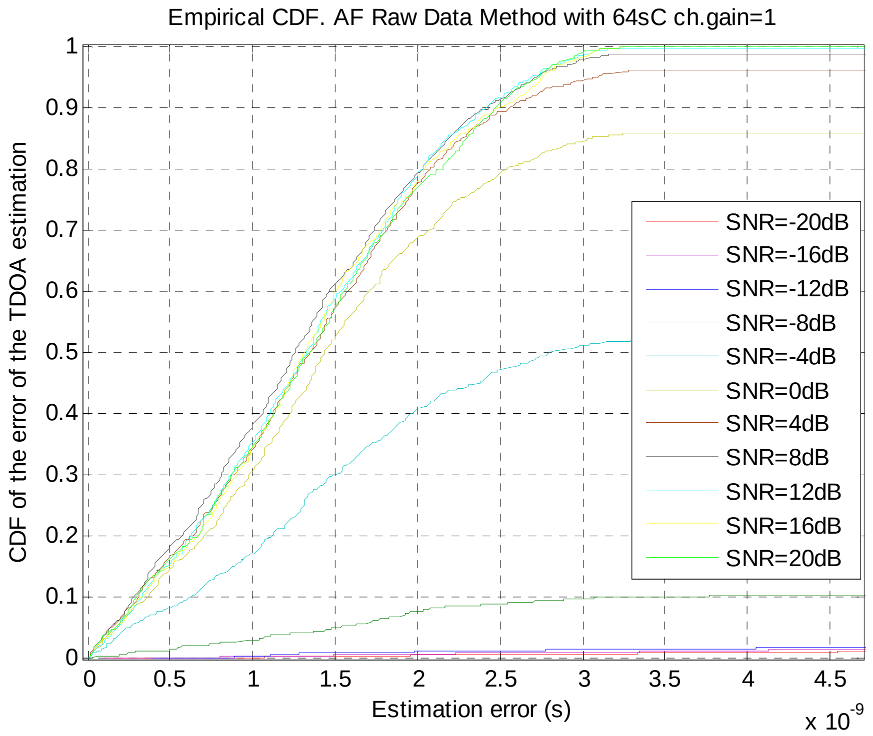


*Figure 5.9 CDF of the TDOA error for the AF conventional method*

AF method has bad performance in low SNR conditions, but its TDOA estimation improves and has low error with a SNR bigger than 0dB.

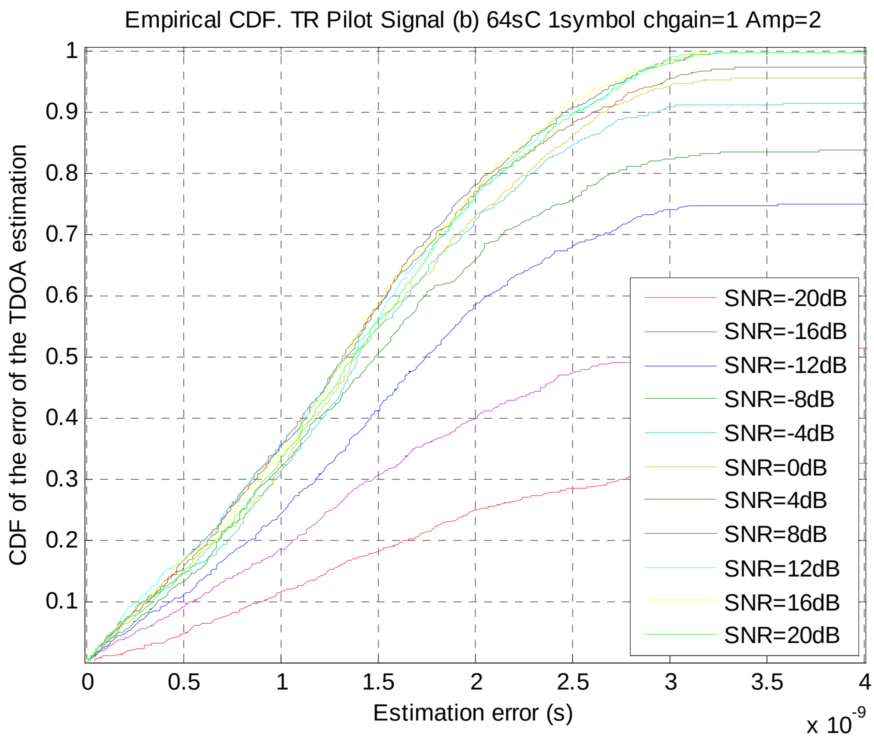


*Figure 5.10 CDF of the TDOA error of the Trigger relay with pilot signal (Amp=2) method*

If the amplitude of the pilot signal increases, the performance improves. Even in SNR=-12dB the error is reasonable. Trigger relay with pilot signal method has the best performance, and has the chance of improve the low SNR situations increasing the amplitude of the pilot signal.

The following figures compare the performances of the different methods in situations of -20dB, 0dB and 20dB SNR:

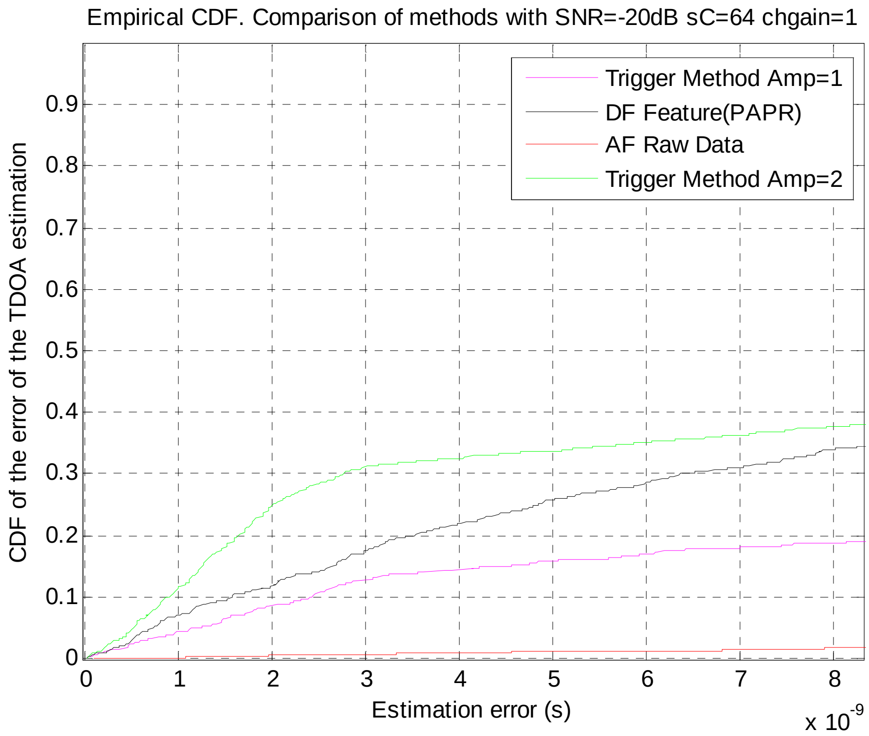


*Figure 5.11 Comparison in SNR=-20dB of the TDOA error for the different methods*

In low SNR feature method provides better results than the conventional method. It is shown also the improvement on the performance increasing the amplitude of the pilot signal.

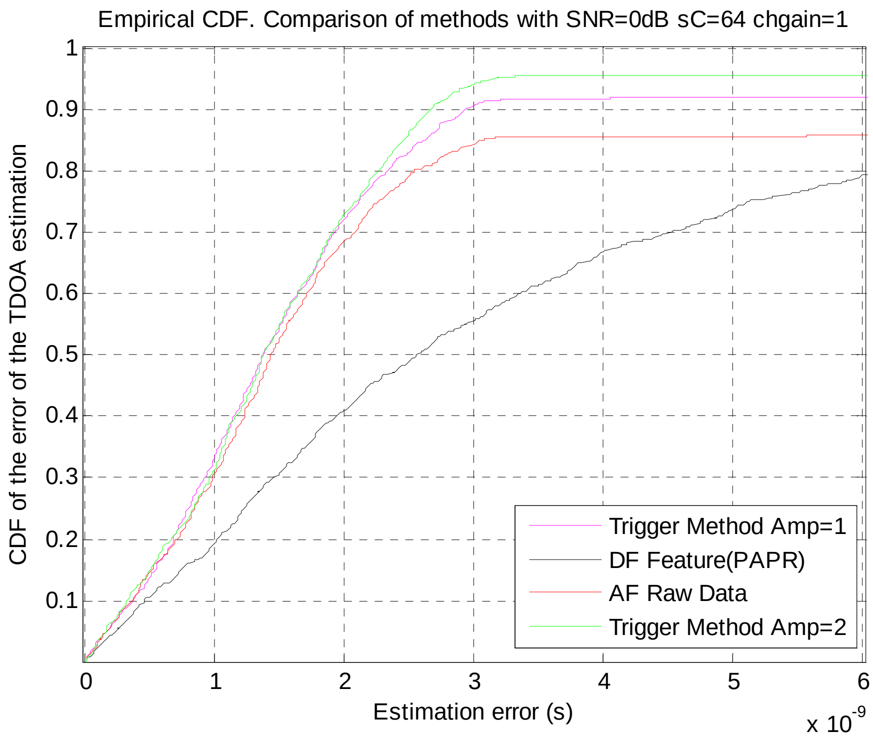


*Figure 5.12 Comparison in SNR=0dB of the TDOA error for the different methods*

In 0dB SNR both trigger relay and AF conventional method have good performance, but the feature method hasn't got a good enough TDOA estimation.

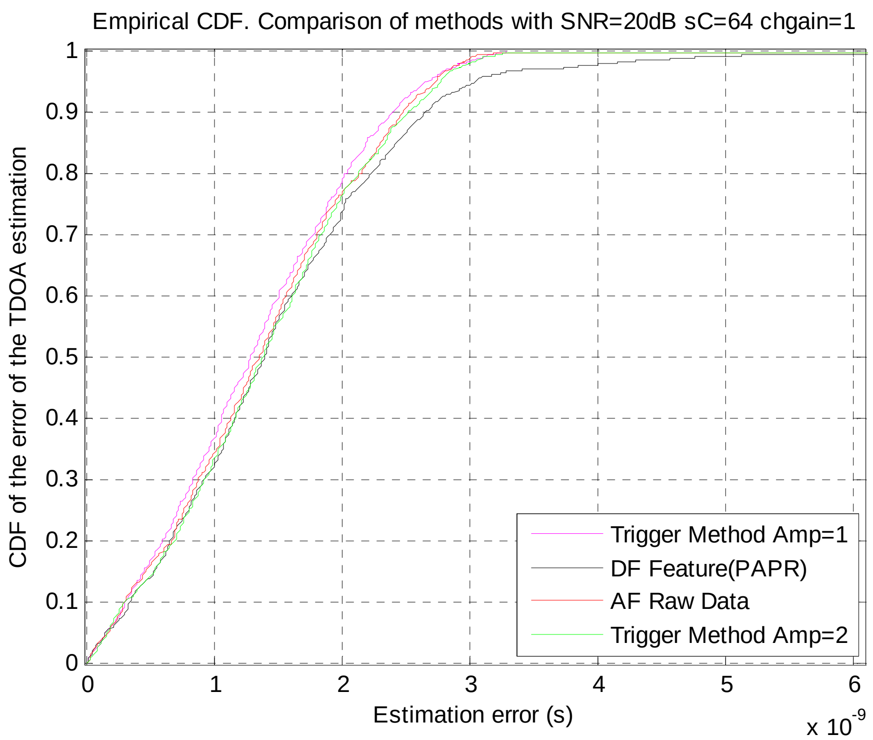


*Figure 5.13 Comparison in SNR=20dB of the TDOA error for the different methods*

In large SNR conditions, every method has a good performance.

## 5.4.CONCLUSIONS

The new proposed methods improve the efficiency compared with the conventional TDOA estimation method. They require less computational operations and less bandwidth to do the TDOA estimation.

The quality of the TDOA estimation is improved as well, especially with the trigger relay method, in which modifying some parameters provides a good performance even in low SNR conditions.

The following chart shows the comparison of the performance of the different methods:

| | BW Efficiency | System Complexity | Computational Efficiency | TDOA Estimation |
|---|---|---|---|---|
| AF relay | No | Medium | No | Reasonable |
| DF feature | High | High | Medium | Reasonable |
| Trigger relay | High | Low | High | Very good |

# 6. Conclusions and Recommendations

## 6.1. CONCLUSIONS

Indoor localization is an interesting topic with lot of potential applications. In this thesis it is wanted to provide an accurate localization method based on ZP-OFDM technology and helped by the cooperative communications. The aim is to estimate the position of an unknown device that joins a wireless network in an accurate and efficient way. The error must be small because in indoor scenarios an error of tens of meters means a useless localization system.

Mobile devices with known locations that are connected to the wireless network act as cooperative relays, helping with the localization process. For that reason, the proposed methods must be efficient in order to save battery and to use the less power consumption as possible, because the battery life of the mobile devices is the most critical resource they have.

TDOA estimation focused on indoor localization was performed by the conventional method, which requires the relays to process and forward the whole signal received from the emitter to the CBS that computes the TDOA estimation.

This method is inefficient because it requires a large bandwidth to transmit the raw data received, and also consumes too much power, which is a critical resource for the mobile devices that act as relays.

Two new methods are proposed in order to estimate the TDOA in an efficient and accurate way.

### 6.1.1.FEATURE METHOD

Feature method requires the relays to extract one statistic feature from each OFDM symbol received. They need to forward the feature signal, which contains one sample per feature extracted, to the CBS that computes the cross correlation with its own feature signal in order to estimate the TDOA between the relay and the CBS.

This new process to estimate the TDOA is bandwidth efficient respect the conventional method because the relays only need to transmit a short signal to the CBS compared with the raw data that send the relay in the conventional method. That fact also has an impact on the battery consumption, saving energy, because the relays retransmit a small quantity of bits.

On the other hand, the complexity of the relays increases in this new method, because the relays are required to extract a statistic feature, and that signal processing is more complicated than the conventional AF or DF scheme.

There were tested different statistic features (mean, variance, skewness, kurtosis, symbol phase, PAPR) and compared their performance. The signal sent by the MS processed to extract the feature is randomly generated, and Gaussian distributed with zero mean and variance equal to one. Depending on the behavior of the different statistical process, the features could be divided into two different types. The zero convergence type features, which have values closer to zero for their feature signal; those are the mean, skewness, kurtosis and symbol phase. And the power related features, which are the variance and the PAPR, and have higher values for their feature signal. After the comparison of the performance of all the features, it is concluded that the best TDOA estimation results are provided by the PAPR feature, as a consequence of having it feature signal values with the highest amplitude values, being more robust against the detrimental effects of the channel.

With the feature method employing PAPR it is improved the performance on the TDOA estimation in low SNR conditions compared with the conventional method.

It is possible to adjust different parameters in order to improve the performance of the TDOA estimation, but usually implies a tradeoff with the power consumption, which is a limited resource for the mobile devices.

To extract the features it is taken a percentage of the OFDM symbol. Working with PAPR, which has the best performance, in general increasing the percentage taken implies a better TDOA estimation, but also requires the relay to do more operations, that means more power consumption. This parameter only has sense to be increased when the SNR conditions aren't good enough, having a tradeoff between computational efficiency and TDOA estimation quality.

Comparing the feature method with the conventional method it is concluded that the feature method improves the performance of the TDOA in low SNR situations, and it is also more bandwidth efficient. But on the other hand, feature method requires more complexity for the relays to be able to extract the statistic feature and its TDOA estimation in large SNR is not as good as the conventional method.

### 6.1.2. TRIGGER RELAY WITH PILOT SIGNAL METHOD

The second new method proposes a new kind of relay, called trigger relay, which is less complex than the other relays employed in the conventional method (AF or DF) and the feature method.

When the trigger relay receives a signal from an emitter, instantaneously it retransmits a pilot signal, which is a known shape OFDM signal that is employed in the system for every device in order to do the cross correlation to estimate the TDOA.

This new proposed method is bandwidth efficient because it only needs to transmit (usually) one OFDM symbol, instead of the raw received data transmitted on the conventional method.

It is also computational efficient because it only needs to generate and transmit one OFDM symbol, which requires low power consumption, saving battery for the mobile cooperative devices involved on the TDOA estimation process.

The pilot signal has an important role in this new proposed method. It has been studied the TDOA estimation performance changing different parameters of the pilot signal:

The shape of the pilot signal is not a critical issue and doesn't have a big impact on the TDOA estimation. Four different shapes were compared on the simulations obtaining similar results for all of them. The criterion to choose the shape of the pilot signal for this method was to select one which has a good performance and could be easy to generate it.

The length of the pilot signal has a tradeoff between loosing efficiency and improving the TDOA estimation. If the pilot signal increases, the TDOA estimation gets better, but the relay needs to transmit more data, decreasing the computational and bandwidth efficiency and increasing the power consumption. For that reason it is only recommended to increase the length of the pilot signal in low SNR conditions.

The amplitude of the pilot signal probably is the most important parameter. It has a tradeoff between power consumption and the improvement on the TDOA estimation. But this tradeoff deserves it because if in low SNR conditions the amplitude of the pilot signal is increased, it provides an acceptable TDOA estimation even in harsh environments, where other methods have almost always a big error on the estimation.

Other external parameters were tested in order to show how this new method with them copes:

The channel gain affects directly to the performance of the system. If it increases, the TDOA estimation improves, and if the channel gain decreases, the estimation gets worse.

The number of subcarriers of the OFDM system has a tradeoff between the efficiency and the quality of the TDOA estimation. If the number of subcarriers increases, the TDOA estimation improves. Those results are visible in low and middle SNR conditions. Increasing the number of subcarriers implies more data for each OFDM symbol. The relay needs to transmit and generate a bigger pilot signal, which decreases the efficiency and increases the power consumption, but on the other hand there are more useful samples to compute the cross correlation for the TDOA estimation, obtaining a better result.

Taking advantage of the multipath diversity and with a proper design of the receiver, it is possible to take advantage of the multipath effect and improve the performance of the system.

It is needed to remark that the big differences changing the parameters are shown in low and middle SNR conditions (from SNR=-20dB until SNR=4dB) because this new proposed method has a good performance in large SNR conditions with every configuration of the parameters. For that reason, when there is a tradeoff between efficiency and improvement on the performance, in large enough SNR conditions it should be the best choice to work with the most efficient configuration.

The following chart compares briefly the two proposed methods with the conventional way to estimate the TDOA for localization.

| | BW Efficiency | System Complexity | Computational Efficiency | TDOA Estimation |
|---|---|---|---|---|
| AF relay | No | Medium | No | Reasonable |
| DF feature | High | High | Medium | Reasonable |
| Trigger relay | High | Low | High | Very good |

The new proposed "trigger relay with pilot signal method" for localization has a great TDOA estimation and also is the most bandwidth and computational efficient method to estimate the TDOA.

It is attached a scientific publication accepted on the PIMRC '11 conference, made by us:

H. Lu, P. Martínez and H. Nikookar "*Cooperative TDOA Estimation with Trigger Relay*", Proc. IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC 2011), Toronto, Canada, Sep. 2011, pp. 1-5.

## 6.2. RECOMMENDATIONS

This thesis is focused on the TDOA estimation in an accurate and efficient way to provide a precise localization. It is needed to use the TDOA estimations provided with this method in a localization algorithm to estimate the position of an unknown device.

The number of cooperative relays could be a good parameter to study. Simulations needs to be done to show how could be improved the performance of the system if there are used more number of relays, or which is the optimal number of cooperative relays to have the most quality position estimation.

NLOS situations need to be studied. How could affect on the performance, and how to prevent this problem.

An analysis of the energy consumption could be done. Comparing the power required to do the extraction of the feature plus the transmission of the feature signal for the different percentages taken, taking into account also the quality of the TDOA estimation, and compare it with the process of doing the AF/DF of the raw data and the transmission of the full signal in order to compare how much power could be saved employing the new proposed method.

Synchronization error in ZP-OFDM could be another detrimental effect to take into account. It could be a good test to check how robust the methods against this error are. In the feature method it means to do the feature extraction of different bits, obtaining different values for each feature signal which will be cross correlated. In the trigger relay method it could affect at the time in which is generated the pilot signal, and could have an inaccurate estimation of the TDOA obtaining an error directly related with the synchronization error.

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# 8. PIMRC 2011 Publication

H. Lu, P. Martínez and H. Nikookar "*Cooperative TDOA Estimation with Trigger Relay*", Proc. IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC 2011), Toronto, Canada, Sep. 2011, pp. 1-5.

# Cooperative TDOA Estimation with Trigger Relay

H. Lu, P. Martinez and H. Nikookar
IRCTR, Faculty of EEMCS
Delft University of Technology
Mekelweg 4, 2628 CD Delft, The Netherlands
l.hao@tudelft.nl and h.nikookar@tudelft.nl

*Abstract*—**In this paper, we investigate the relaying issue of Zero-Padding (ZP) Orthogonal Frequency Division Multiplexing (OFDM) technique to estimate Time Difference of Arrival (TDOA) for locationing applications. In order to benefit from the easy processing of Amplify-and-Forward (AF) relay as well as the noise and interference cancellation of Decode-and-Forward (DF) relay schemes, we introduce the trigger relay technique for TDOA estimation. The trigger relay possesses the merit of bandwidth efficiency, since only a short pilot or preamble needs to be sent. Compared to its counterparts AF and DF relays, trigger relay achieves a better performance in terms of system complexity and TDOA accuracy. Gaining from multipath diversity, the trigger relay TDOA resolution can be improved further.**

***Keywords-Trigger relay; cooperative TDOA; OFDM; multipath diversity; block features***

## I. INTRODUCTION

Wireless location information and wireless location-based services have been receiving a growing attention over the past decades. Although the Global Positioning System (GPS) usually provides worldwide high-accuracy position measurements, it requires Line of Sight (LOS) to multiple satellites. For the GPS-denied scenarios [1], such as indoor, in urban canyons, and under tree canopies, GPS is known to be ineffective due to the inability of obstacle penetration. Thus, alternative methods of positioning and navigation are of interest, either as a backup or for use in areas unreachable by satellites. Beacon localization, on the other hand, relies on terrestrial anchors, such as WiFi access points or GSM base stations. However, in areas where network coverage is sparse, localization errors can be unacceptably large [2].

Generally, in the LOS scenario, high-accuracy localization can only be achieved using high-power anchors or a high-density anchor deployment. A practical way to address this need is through a combination of cooperative localization and wideband transmission, which is investigated in this paper.

Cooperative localization is an emerging paradigm that offers additional localization accuracy by enabling the agents to help each other in estimating their positions [3]. There are mainly two relaying protocols in classical cooperative networks: AF and DF. In AF, the received signal is amplified and retransmitted to the destination. The advantage of this protocol is its simplicity and low-cost implementation. However, the noise is also amplified at the relay. In DF, the relay attempts to decode the received signals. If successful, it re-encodes the information and retransmits it. If some relays cannot fully decode the signal, they should be discarded. In this paper, we propose a new relaying technique for cooperative localization, called trigger relay, which combines the advantages of AF relay and DF relay, i.e., less complexity because of no decoding, while removing the noise and interference effect at relay.

The fine delay resolution and robustness of wide bandwidth or Ultra-Wide Bandwidth (UWB) transmission enable accurate and reliable range measurements in harsh environments. Adopting UWB signal, the cooperative network enables the high speed communication and refines the position estimation [4]. In the modern wideband wireless communication system, OFDM technology has been widely used. ZP-OFDM, with the advantages of low transmission power and low spikes in the Power Spectrum Density (PSD), has been proposed in [5] for the IEEE Standard to design UWB transceivers. In Dec. 2008, the European Computer Manufacturers Association (ECMA) adopted ZP-OFDM for the latest version of High rate UWB Standard as well [6].

In this paper, we focus on TDOA-based methods with the ZP-OFDM wideband signals. TDOA always means the time difference of signal propagation between the two transmission links received at one common receiver or two synchronized receivers. TDOA estimation is often determined from the cross correlation of the two received signals [7]. ZP-OFDM is a multicarrier block transmission scheme, and with a highly block-structured transmission format. This block structure enables us to calculate some statistical features (e.g., mean, variance, skewness, kurtosis, etc.) of each block. Then, we can only transmit or forward the block features values to calculate the TDOA of two transmission links, rather than transmitting the entire signal. This feature-based TDOA needs less transmission bandwidth and is so called bandwidth efficient localization [8].

In this paper, we propose trigger relay for TDOA estimation. Only a short pilot or preamble signal is sent to the primary receiver, which can achieve bandwidth efficient localization as well. Compared to the AF relay and DF relay with block feature, the trigger relay reduces the system complexity and enhances the TDOA estimation accuracy.

The rest of paper is organized as follows. In section II, the cooperative ZP-OFDM TDOA based on AF relay and DF relay with block feature are reviewed. The trigger relay TDOA estimation is proposed in Section III. In section IV, the TDOA estimation performances of different relaying schemes are shown and analyzed. Results illustrate that the trigger relay TDOA has advantages in bandwidth efficiency, system complexity and resolution. Simulation results are provided in Section V to verify the theoretical analysis. Finally, Section VI concludes the paper.

## II. REVIEW OF AF AND DF RELAY FOR TDOA

### A. Conventional TDOA with AF or DF relay

In this paper, we consider the cooperative localization for the wideband communication system in LOS scenario. We assume the locations of the base station and relays are known by the primary receiver. Scatterers locate between the base station (anchor), relays (agents) and primary receiver (agent), causing multipath channels. The ZP-OFDM is adopted as the modulation scheme. In general, by using the ( $q-1$ ) TDOA estimates together with the classical hyperbolic intersection searching, the primary receiver can localize its position in $q$ dimensions.

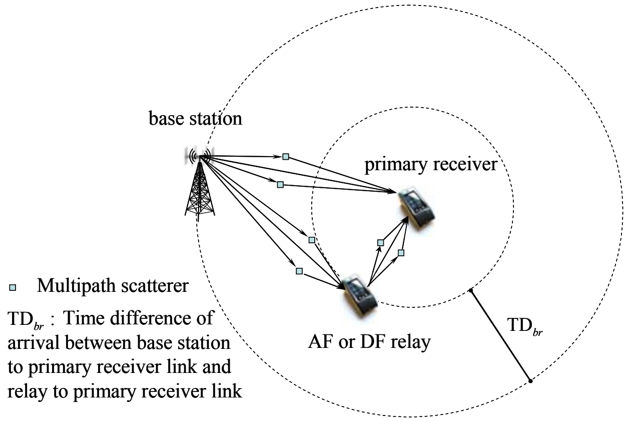


Fig.1. Cooperative TDOA system model with classical AF relay or DF relay.

In this section, we briefly review the conventional TDOA estimation based on AF relay or DF relay. As depicted in Fig. 1, the base station first broadcasts the signal. The relay receives the signal, and then amplify-and-forwards or decode-and-forwards the signal to the primary receiver. In this figure the two circles are concentric, with primary receiver as the centre of the circles. The radius of the inner circle represents the signal propagation time from relay to primary receiver, and the radius of the outer circle illustrates the signal propagation time from base station to primary receiver.

In this paper, we assume that the primary receiver can distinguish the signals from base station and relay. In order to obtain TDOA estimation, the primary receiver performs a correlation:

$$C_y\left(d_s\right)=\sum_{s=1}^{S} y_{ba}^{*}\left(s\right) y_{re}\left(s+d_s\right), \tag{1}$$

where $y_{ba}\left(s\right)$ and $y_{re}\left(s\right)$ denote the $s$-th sample of the received signals at the primary receiver from base station and relay, respectively. $(\cdot)^{*}$ denotes the conjugate operation. The primary receiver need to compute Eq. (1) for all anticipated ranges of the arrival time difference in sample, i.e., $-D_s \le d_s \le D_s$, and $D_s$ stands for the maximum anticipated arrival time difference in time sample. $S$ refers to the number of received signal samples used for TDOA estimation. Then, the TDOA between the link from base station to relay to primary receiver and the link from base station directly to primary receiver $\mathrm{TD}_{brp}$ can be computed as

$$\mathrm{TD}_{brp}=\delta T_s, \tag{2}$$

where
$$\delta=\arg\max_{-D_s \le d_s \le D_s}\left|C_y\left(d_s\right)\right|, \tag{3}$$

$|\cdot|$ denotes the modulus, and $T_s$ denotes the sampling period. Because the distance between base station and relay $L_{br}$ is known, the transmission time from base station to relay can be calculated as $T_{br}=L_{br}/c$, where $c$ is the speed of light. We assume the total data processing time at relay is $T_r$, the TDOA between the link from base station to primary receiver and the link from relay to primary receiver $\mathrm{TD}_{br}$ can be expressed as

$$\mathrm{TD}_{br}=T_{br}+T_r-\mathrm{TD}_{brp}. \tag{4}$$

### *B. Feature-based TDOA with DF realy*

For the DF relay, the boundary of the OFDM block can be determined. Therefore, block features of OFDM system can be exploited to achieve the bandwidth efficient TDOA [8]. The block features include the normalized central moments (mean, variance, skewness, and kurtosis) of the first $Q$ samples of the $k$-th block effective OFDM symbol, i.e., the part of OFDM symbol that includes only the transmitted information and without the redundancy introduced by Guard Interval (GI):

the mean
$$\mu_{rx}\left(k\right)=\frac{1}{Q}\sum_{i=1}^{Q} y_{rx}\left(k\right)_i, \tag{5}$$

the variance
$$\sigma_{rx}^2\left(k\right)=\frac{1}{Q}\sum_{i=1}^{Q}\left(y_{rx}\left(k\right)_i-\mu_{rx}\left(k\right)\right)^2, \tag{6}$$

the skewness
$$\lambda_{rx}\left(k\right)=\frac{1}{Q}\sum_{i=1}^{Q}\left(\frac{y_{rx}\left(k\right)_i-\mu_{rx}\left(k\right)}{\sigma_{rx}\left(k\right)}\right)^3, \tag{7}$$

the kurtosis
$$\varepsilon_{rx}\left(k\right)=\frac{1}{Q}\sum_{i=1}^{Q}\left(\frac{y_{rx}\left(k\right)_i-\mu_{rx}\left(k\right)}{\sigma_{rx}\left(k\right)}\right)^4, \tag{8}$$

where the subscript "rx" denotes received signal either from the base station or relay. $y_{rx}(k)_i$ refers to the $i$-th sample of the $k$-th block effective OFDM symbol. In this paper, we consider signals from base station and relay are transmitted on different subcarriers as a frequency division system. Therefore, the primary receiver can distinguish between the features of base station and relay.

Other features, such as the average symbol's phase

$$\Phi_{rx}\left(k\right)=\frac{1}{Q}\sum_{i=1}^{Q}\arctan\left(\frac{\mathrm{Im}\left(y_{rx}\left(k\right)_i\right)}{\mathrm{Re}\left(y_{rx}\left(k\right)_i\right)}\right), \tag{9}$$

the Peak Power (PP)

$$\mathrm{PP}_{rx}=\mathrm{Max}\left(\left|y_{rx}\left(k\right)_1\right|^2,\cdots,\left|y_{rx}\left(k\right)_Q\right|^2\right), \tag{10}$$

and the Peak to Average Power Ratio (PAPR)

$$\mathrm{PAPR}_{rx}=\frac{\mathrm{Max}\left(\left|y_{rx}\left(k\right)_1\right|^2,\cdots,\left|y_{rx}\left(k\right)_Q\right|^2\right)}{\frac{1}{Q}\sum_{i=1}^{Q}\left|y_{rx}\left(k\right)_i\right|^2}, \tag{11}$$

are considered as block features as well, where $\mathrm{Im}(\cdot)$ and $\mathrm{Re}(\cdot)$ stand for the imaginary and real part of the complex value, respectively. $\mathrm{Max}(\cdot)$ denotes the maximum of a vector $(\cdot)$.

After receiving and decoding the signal from base station, the DF relay calculates the above mentioned features for each OFDM block. Then, block features are forwarded to the primary receiver. Meanwhile, primary receiver calculates the features based on the signals transmitted from the base station. Subsequently, primary receiver computes the cross correlation of the features from base station and relay to obtain the TDOA estimation. Generally, these features can be classified into 2 types. The first one is the zero convergence type, which includes the mean, skewness, kurtosis and average symbol's phase, because for the random zero mean signals, their values converge to zero as $Q$ increases. The second one is the power type, which includes the variance, PP and PAPR, since they relate to the power of the signals.

The zero convergence type features always have values closer to zero. Thus, the noise can easily pollute these block features, which implies a bigger error of the TDOA estimation. On the other hand, since the power features have larger values than zero convergence type features, they are more robust against the noise. For the constant modulus signals, such as Binary Phase Shift Keying (BPSK), Quadrature Phase Shift Keying (QPSK), 2-Quadrature Amplitude Modulation (QAM), 4-QAM, etc., after linear equalization, variance of the one block equalized signal always has a value between 0 and 1, and PAPR has the largest value among all the above mentioned features, and is the best feature for TDOA estimation. For the non-constant modulus signal, such as 16-QAM, 64-QAM, etc., PP has the largest value among all the above mentioned features, and is the best feature.

Given the features from the base station and relay, the primary receiver can compute the cross correlation of the features. Let us denote the $k$-th block feature values of base station and relay as $f_{\mathrm{ba}}(k)$ and $f_{\mathrm{re}}(k)$, respectively. The primary receiver computes the cross correlation of the features as

$$C_f(d)=\sum_{k=1}^{K} f_{\mathrm{ba}}(k)\left(f_{\mathrm{re}}(k+d)\right)^*, \qquad (12)$$

where $K$ stands for the number of the OFDM blocks used for calculating the feature cross correlation. The primary receiver must compute Eq. (12) for all anticipated valid ranges of the block arrival time difference, say $-D \le d \le D$, where $D$ stands for the maximum anticipated arrival time difference in block. Thus, the TDOA between the link from base station to relay to primary receiver and the link from base station directly to primary receiver $\mathrm{TD}_{brpf}$ can be computed as

$$\mathrm{TD}_{brpf}=T_s M\Delta, \qquad (13)$$

where

$$\Delta=\arg\max_{-D\le d\le D}\left|C_f(d)\right|, \qquad (14)$$

$M$ stands for the number of the samples within each OFDM block, i.e., FFT size. Then, similar to the conventional TDOA procedure, $\mathrm{TD}_{br}$ can be calculated.

Then, $\mathrm{TD}_{br}$ can be translated into the distance difference between base station to primary receiver link and relay to primary receiver link by multiplying it with $c$. According to the hyperbolic theorem, the primary receiver should appear at the hyperbola with the locations of base station and relay as the foci. Together with another two hyperbolas calculated from another base station and relay pairs, primary receiver can locate its position in 2-dimensional plane. Many location estimation algorithms were proposed to deal with the localization procedure, which have been reviewed in [9] and [10]. In this paper, for the sake of simplicity, we only pay attention to the TDOA estimation and not localization.

## III. Trigger Relay for TDOA Estimation

The advantage of AF is that it doesn't need the complicated signal decoding, while the strong point of DF relay relies on that it can get rid of the noise effect and channel interferences. Therefore, we propose a trigger relay technique to take advantage of these two merits. This scheme is shown in Fig. 2. Three circles are concentric circles, with primary receiver as the centre of the circle. Three radii, from short to long, are the signal propagation times from relay 1, relay 2 and base station to primary receiver, respectively.

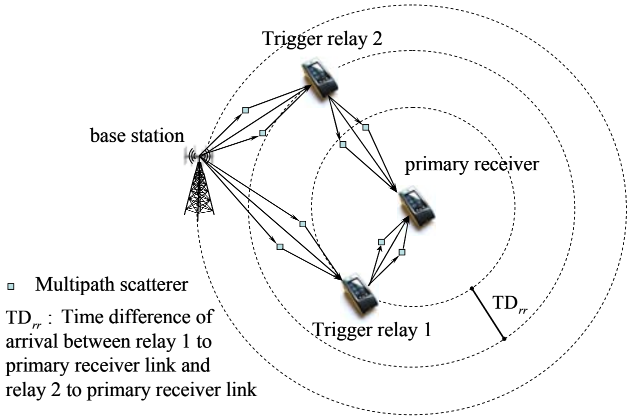

Fig.2. Cooperative TDOA system model with trigger relays.

The diagram of signal transmissions in the trigger relay TDOA estimation is shown in Fig. 3. Immediately after relay 1 and relay 2 receiving the base station signals at $t_1$ and $t_2$, they transmit a predetermined signal to the primary receiver at known $t_1'$ and $t_2'$, respectively. This predetermined signal can be a short pilot or preamble. We assume that the processing intervals at two relays are the same, i.e., $t_1'-t_1=t_2'-t_2$. Then, primary receiver receives the signals from relay 1 and relay 2 at $t_{r1}$ and $t_{r2}$, respectively. All $t_1$, $t_2$, $t_{r1}$ and $t_{r2}$ are determined from the leading edges of the received signals.

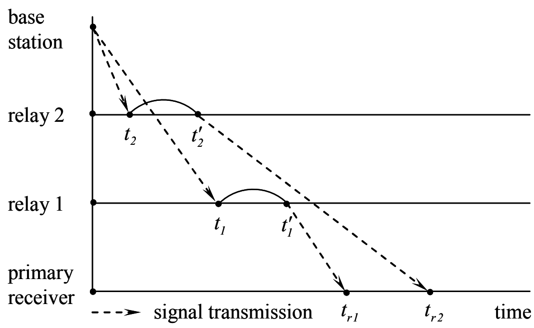

Fig.3. Signal transmissions in trigger relay TDOA estimation scheme.

Subsequently, The TDOA between the relay 1 to primary receiver link and the relay 2 to primary receiver link $\mathrm{TD}_{rr}$ can be calculated by primary receiver as

$$\mathrm{TD}_{rr}=\left(t_{r2}-t_{r1}\right)+\left(t_1-t_2\right) \qquad (15)$$

where $\left(t_{r2}-t_{r1}\right)$ can be achieved by correlation of signals from two relays, similar to the AF and DF relay case, and $\left(t_1-t_2\right)$ can be calculated from the known positions of base station and relays, which are already known by the primary receiver.

## IV. Comparison of Different Relaying Schemes

In this section, we compare the AF relay, DF relay with block feature (DF feature) and trigger relay in the context of cooperative ZP-OFDM TDOA, and illustrate their performances in Table 1.

TABLE I. COMPARISON OF TDOA PERFORMANCE FOR DIFFERENT RELAYING SCHEMES

| | bandwidth efficiency | system complexity | TDOA estimation error |
|---|---|---|---|
| **AF relay** | **no** | **medium** | **reasonable** |
| **DF feature** | **yes** | **high** | **large** |
| **Trigger relay** | **yes** | **low** | **good** |

DF relay with block feature reduces the data required compared to the conventional TDOA based on cross correlation of the whole received signal, and achieves a bandwidth efficient transmission. Trigger relay can send short pilot or preamble for TDOA estimation, and reduces the amount of data transmission compared to the conventional AF and DF relays. Thus, trigger relay possesses the merit of bandwidth efficiency similar to DF relay with block feature.

As the name suggests, AF relay requires a proper power amplifier to compensate the signal attenuation in the base station to relay link, while DF relay with block feature not only decodes the signal, but also computes the features. Compared to AF relay and DF relay with block feature, trigger relay TDOA estimation has the lowest system complexity, as no amplification or feature detection is required.

For the TDOA estimation accuracy, generally, DF relay with block feature can only reach the block level resolution, not sample level as the conventional TDOA does. For the Multi-band (MB)-OFDM adopted in the UWB standards [5], [6], the sample period $T_s$ is 1.894 ns, the FFT size is 128, ZP accounts for 32 samples, the block interval is 312.5 ns, which includes 9.47 ns Guard Interval. The 312.5 ns is the lower bound of the feature-based TDOA resolution. If the smaller FFT size is adopted, the block interval can be reduced and accordingly can improve the lower bound of feature-based TDOA resolution. If more accurate localization is required, we need to compute TDOA involving a correlation of the signals at the sample level, i.e. 1.894 ns in MB-OFDM system. Sample signal correlation with AF relay and trigger relay can achieve the resolution up to sample level. It is worth mentioning that, AF relay TDOA estimation is more suffered from the noise effect and multipath interference in base station to relay link than the trigger relay TDOA estimation. Thus, trigger relay obtains the highest TDOA resolution among the above mentioned three relaying schemes.

Furthermore, in the ZP-OFDM transmission with multipath channel, trigger relay TDOA estimation can further gain from the multipath diversity, and improve the TDOA accuracy. When adopting the linear transceiver proposed in [11], ZP-OFDM channel holds the linear structure or tall Toeplitz structure, where its full column rank property always guarantees the matrix invertibility and signal detection. Meanwhile, the tall Toeplitz ZP-OFDM channel matrix ensures the full multipath diversity gain for the signal detection, only with the linear equalizers, such as Zero-Forcing (ZF) and Minimum Mean Square Error (MMSE) equalizers [12], [13].

Therefore, in the trigger relay TDOA estimation, the above mentioned linear transceiver can be used to achieve the full multipath diversity gain in the relay to primary receiver link, to combat the noise effect, and to improve the signal detection. Utilizing the well detected signal to process the TDOA estimation, it will consequently enhance the TDOA estimation accuracy. Meanwhile, this linear transceiver possesses a lower system complexity, compared to those systems with non-linear maximum-likelihood equalizers.

## V. SIMULATION RESULTS

In this section, we present the simulation results to show the performance of trigger relay in TDOA estimation, and verify the above analysis. BPSK is adopted as the modulation scheme. We consider the $N = 8$ subcarriers ZP-OFDM system with ZP accounts for 25% of the effective OFDM symbol duration, and with sample period $T_s = 1.894$ ns. The channels: from base station to relay, from base station to primary receiver and from relay to primary receiver are considered to be independent to each other and Rayleigh distributed. Since the MMSE equalizer can be transformed into the ZF equalizer, we adopt MMSE equalizer here to show the performance of the linear equalizer. In these simulations, absolute error of TDOA estimation is shown to compare the performances of different schemes. The absolute error is defined as the absolute difference between the estimated TDOA and the true TDOA in ns.

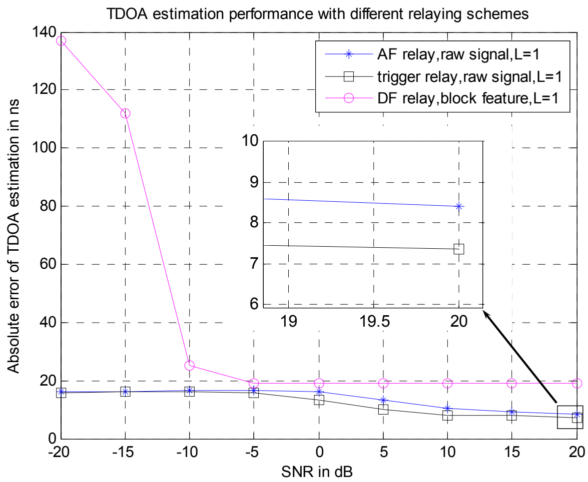


Fig. 4. Different relaying schemes for TDOA estimation in flat fading channel

*Test Case 1 (Different relaying schemes):* In this example, we compare different relaying schemes for TDOA estimation. For the DF relay with block feature, we adopt the first $Q = 7$ samples of OFDM symbol for PAPR feature calculation. For AF relay and trigger relay cases, the primary receiver correlates the raw received signals, i.e., no channel equalization or decoding at primary receiver is assumed.

As shown in the Fig. 4, a flat fading channel is considered, i.e., $L = 1$. The DF relay with block feature can only reach the block level resolution, i.e., 18.94 ns. Since AF relay amplifies the noise before relaying, while trigger relay not, we can see from the figure that, the trigger relay slightly outperforms the AF relay, and enjoys a better TDOA estimation error. The error gap between AF relay and trigger relay decreases as the Single to Noise Ratio (SNR) increases.

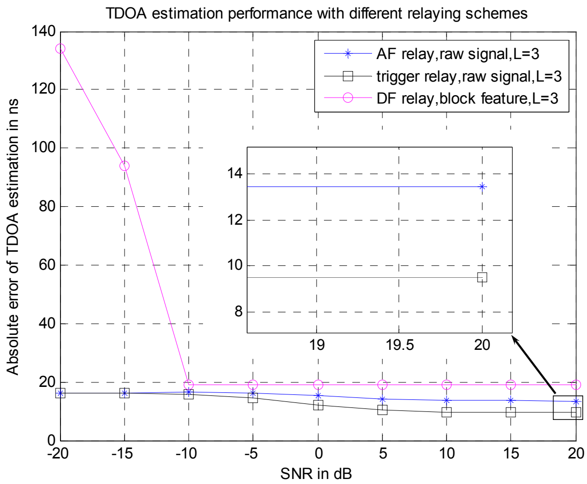


Fig. 5. Different relaying schemes for TDOA estimation in multipath channel

In the Fig. 5, we consider a 3-path channel scenario, i.e., $L = 3$ . Compared to Fig. 4, due to multipath channel equalization, DF relay with block feature gains from multipath diversity, and the TDOA resolution in low SNR region is improved accordingly. However, for the AF relay and trigger relay cases, as they do not use channel equalization, they cannot gain from multipath diversity. In the high SNR region, multipath interference becomes the dominant effect on TDOA estimation, which degrades the TDOA resolution for both AF relay and trigger relay cases. The error gap between AF relay and trigger relay in Fig. 5 is larger than the gap in Fig. 4, which comes from the multipath interference in base station to relay link of AF case.

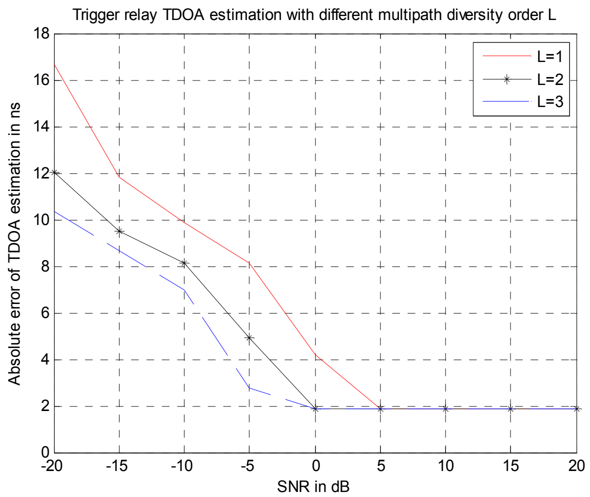


Fig. 6. Multipath diversity for TDOA estimation with trigger relay.

*Test Case 2 (Multipath diversity for trigger relay):* In this example, we show how the trigger relay TDOA estimation benefits from multipath diversity. Multipath diversity order $L = 1$, 2, and 3 are considered. In order to achieve the multipath diversity, primary receiver should equalize the channel, detect the frequency domain signal, and then transfer it into the time domain by FFT, pad zeros again to restore the original time domain transmitted signal. Fig. 6 shows that, the signal detection improves the TDOA estimation error performance, and the absolute error of TDOA estimation reaches its lower bound 1.894 ns. We can see from the figure that, in the low SNR region, multipath diversity helps reducing the absolute TDOA estimation error, and the more multipath diversity orders, the smaller the TDOA estimation error.

## VI. CONCLUSIONS

In this paper, we investigated different relaying schemes for cooperative ZP-OFDM TDOA estimation, and proposed a trigger relay technique to gain from the easy processing together with noise and interference immunity of the base station to relay link. Compared to AF relay and DF relay TDOA estimation cases, the trigger relay reduces the system complexity. Meanwhile, trigger relay enables the bandwidth efficient TDOA, since it significantly reduces the amount of data for transmission. In terms of TDOA estimation error, among AF relay, trigger relay and DF relay with block feature, the trigger relay achieves the best accuracy. Furthermore, by exploiting multipath diversity, the improved signal detection at primary receiver further contributes to trigger relay a better TDOA estimation error.

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# Efficient Cooperative OFDM Localization

## Thesis presentation

P. Martinez Grande, MSc Student TU Delft

Mentor: Hao Lu

Supervisor: H. Nikookar

26-10-2011

# Content

- Purpose description
- Background Information
    - OFDM
    - Cooperative communications
    - Localization
- System model
- Existing methods
- Bandwidth and computational efficient OFDM localization method
    - Feature method
    - Trigger Relay with pilot signal method
- Comparison of methods
- Conclusions
- Recommendations

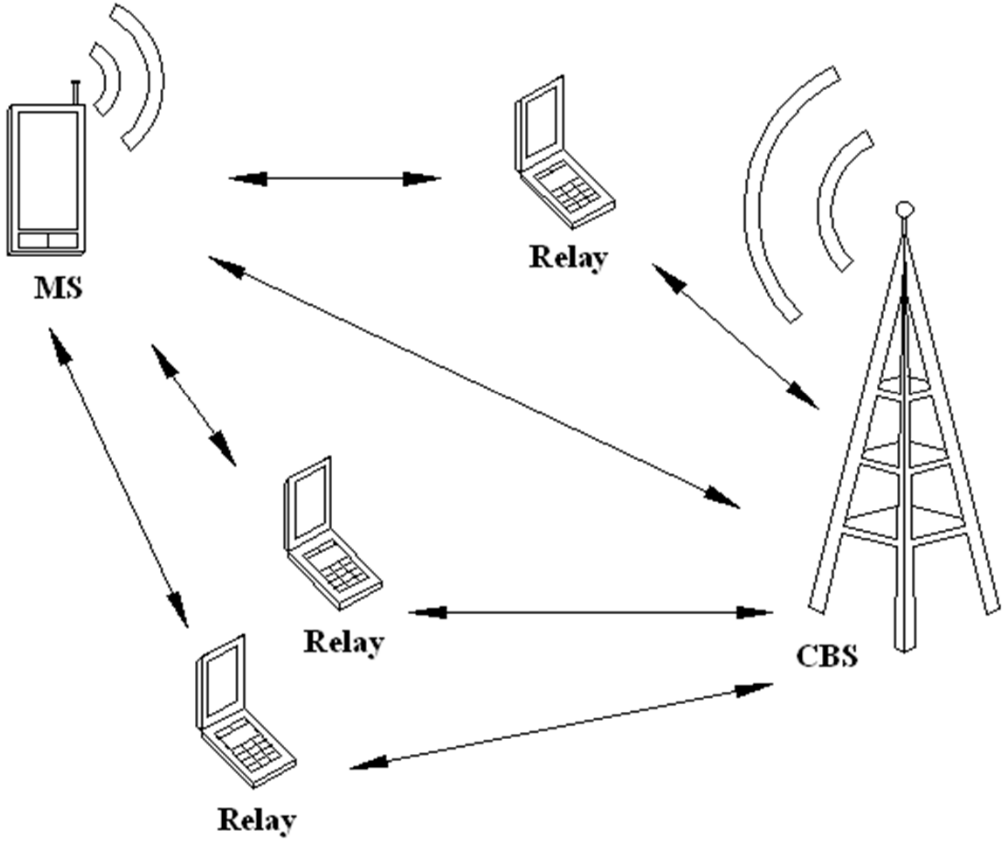
# Purpose description [1]

- Conventional methods of Localization/Navigation couldn't provide an accurate estimation in harsh scenarios.

- The scope of the thesis is to propose a new method which provides an accurate localization being the most efficient possible.

# Purpose description [2]

- We want to create a localization (or navigation) method for a device while it is having a wireless communication, in an efficient and accurate way.



# Purpose description [3]

- Those pillars are joined together to provide a method and accomplish the scope:
  - Orthogonal frequency division multiplexing (OFDM)
  - Cooperative communications
  - Localization

# Background Info – OFDM [1]

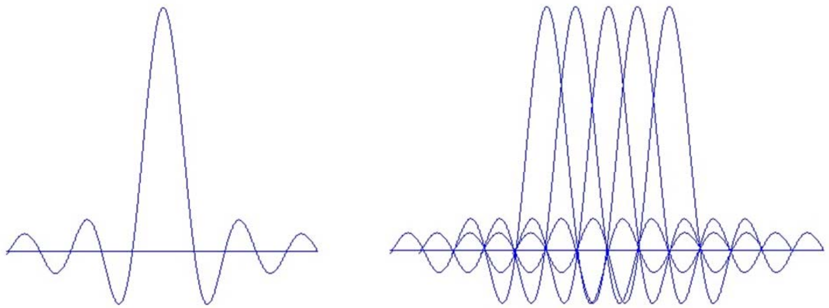
- Orthogonal frequency division multiplexing

- Multicarrier technique

- Orthogonal subcarriers implies spectral efficiency

- Block structure

- Guard time in symbols to avoid the inter symbol interference (ISI)

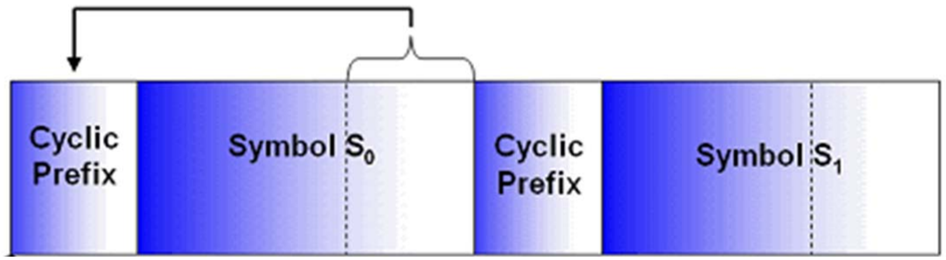


*Single carrier and multiple orthogonal subcarriers*

# Background Info – OFDM [2]

- Depending on the filling of the guard time:

- Cyclic prefix OFDM (CP-OFDM)
  - The guard time is filled by a periodic extension of the last part of an OFDM symbol




- Zero padding OFDM (ZP-OFDM)
  - The guard time is filled by zeros

# Key Concepts – OFDM [3]

- We focus on ZP-OFDM
- It has lower power to transmit
- Less interference between symbols
- Good time resolution due to wideband transmission
- But, it has synchronization error problems

# Background Info – Coop. Comm.[1]

- Cooperative communications
- While the MS has a communication with CBS, the cooperative communications can improve the performance
- Spatial diversity
- Help non line of sight (NLOS) situations
- Collaboration for localization

# Background Info – Coop. Comm.[2]

- Relays on the scenario collaborate with CBS to improve the communication and to locate the MS.

- Relays could be other users (with known location) that are connected in the same wireless network

- Their power consumption is a critical issue

# Background Info – Coop. Comm.[3]

- Basically there are two different relays:
  - Amplify and Forward (AF) Relay
    - The received signal is amplified and retransmitted to the destination
    - Simple, but it also amplifies the noise
  - Decode and Forward (DF) Relay
    - Try to decode the received signal, and if successful, it re-encodes the info and retransmits it.

# Background Info – Localization [1]

- Interesting topic
- Usually covered by Global Positioning System (GPS)
  - Critical areas where it doesn't work properly
- Measurements to approach the problem
  - Angle of arrival (AOA)
  - Received Signal Strength (RSS)
  - Time of arrival (TOA)
  - Time difference of arrival (TDOA)
- We focus on TDOA based methods

# Background Info – Localization [2]

- Time difference of arrival (TDOA)

- No requires synchronization between transmitter and receiver

- No requires global clock

- High time resolution working with ultra wide band (UWB), which provides an accurate measurements with errors around centimetres

- Works with differences of time; same signal received from different sources.

- It is calculated by the cross correlation of two signals

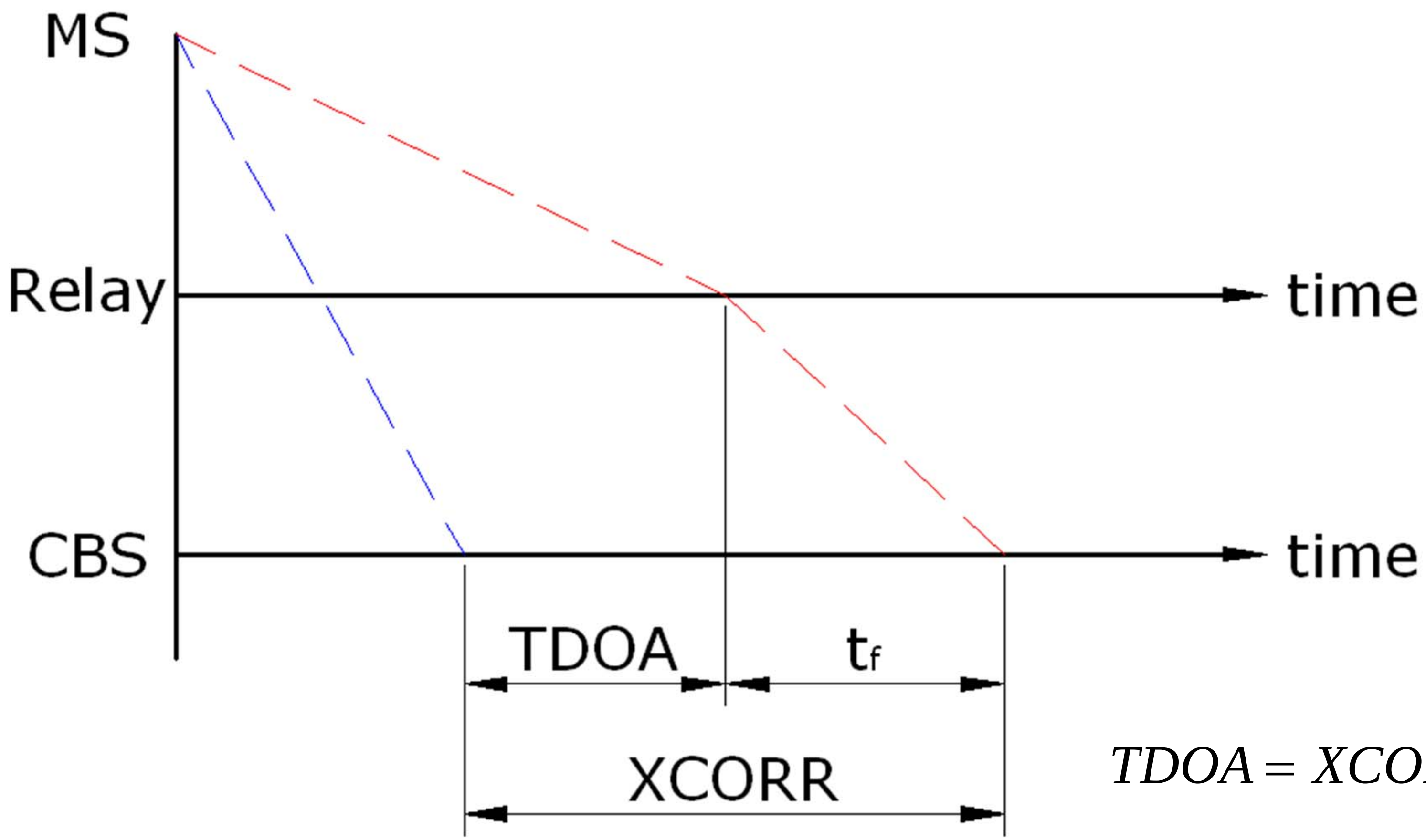
# Background Info – Localization [3]

- MS broadcasts a signal, which is received by the relay(s) and CBS
- CBS computes the TDOA estimation
- Conventional way
  - Relay sends the whole received signal from MS, to the CBS
  - CBS makes the cross correlation of the raw data

$$R_y(d) = \sum_{i=1}^{K} y_R(i) y_{CBS}^*(i+d)$$

- Where $y_R(i)$ is the signal sent by the relay, $y_{CBS}(i)$ is the signal received on the CBS from the MS, $K$ is the length of the signal and $d$ is the range of values of the time arrival of the signal.

# Background Info – Localization [4]




$$TDOA = XCORR - t_f$$

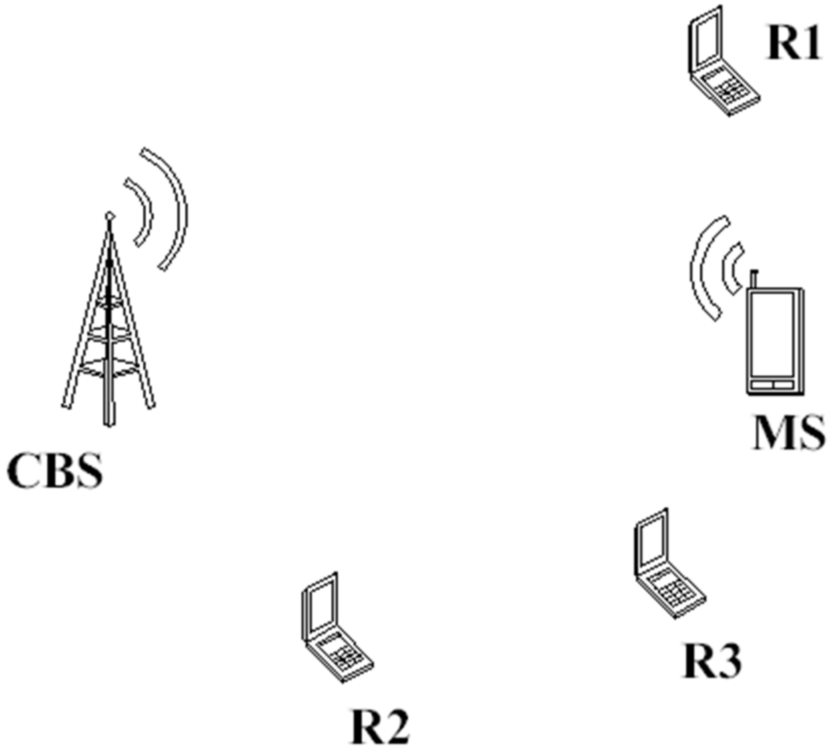
# Background Info – Localization [5]

- It is needed at least three TDOA measurements for the localization estimation in 2 dimensions.

- With those TDOA values and with a method based on hyperbolic equations it could be estimated the position of the MS.

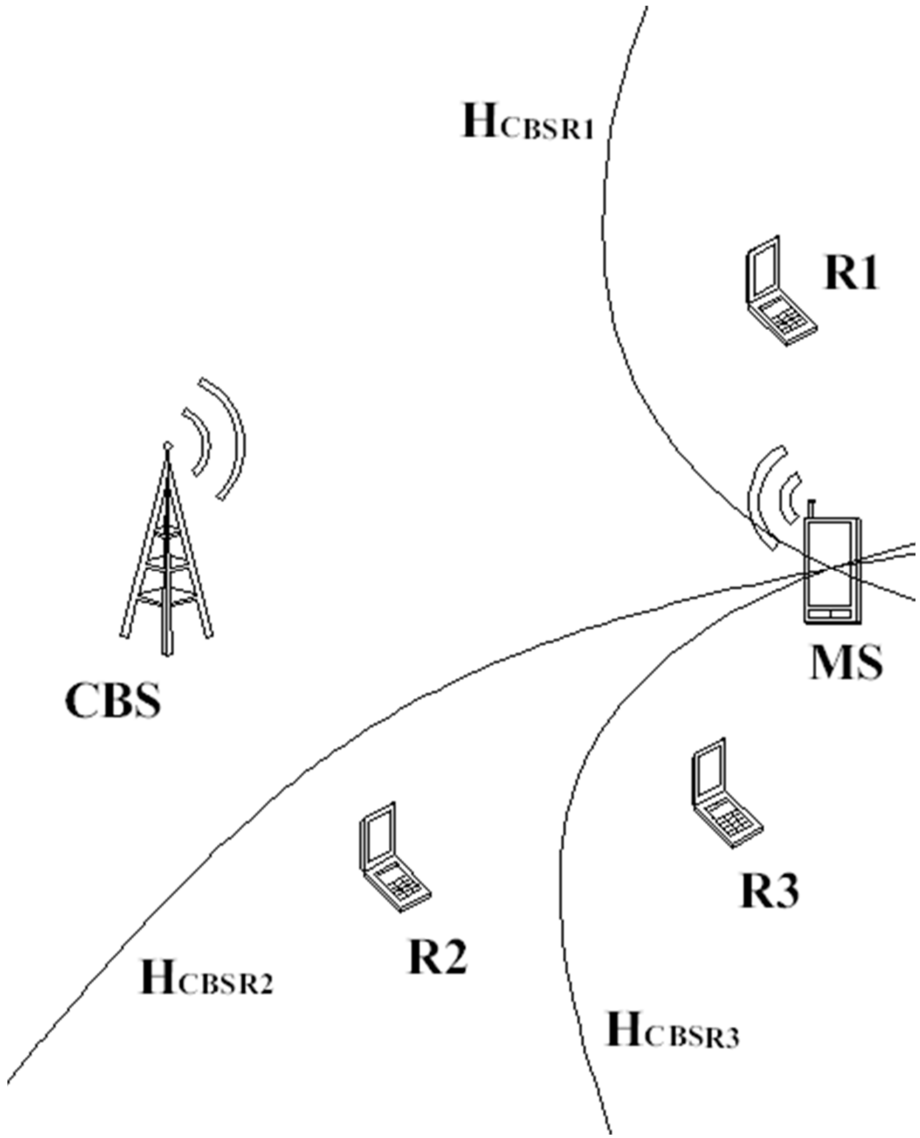
# System Model [1]

- In the scenario there is a MS having a communication with CBS
- Relays collaborate with CBS to locate MS
- CBS computes TDOA measurements to estimate the MS position
- Position of relays and CBS are perfectly known



# System Model [2]

- With three TDOA measurements together with the hyperbolic localization algorithm it is possible to estimate the position of the unknown mobile device



# Existing Methods [1]

- Conventional Method
  - AF or DF relay forwards the whole received signal
  - Cross correlation of the raw data to estimate the TDOA
    - ☹ too much BW used
    - ☹ too much power consumption for the relays to retransmit
    - ☹ bad performance in low SNR conditions

# Existing Methods [2]

- BW efficient cooperative CP-OFDM TDOA computation
  - Method provided by this publication:

  R. K. Martin, J.S. Velotta, and J. F. Raquet, "*Bandwidth Efficient Cooperative TDOA Computation for Multicarrier Signals of Opportunity*", IEEE Transactions on signal processing, vol. 57, No 6, June 2009.

# BW and computational efficient OFDM localization methods

- We propose two bandwidth and computational efficient cooperative ZP-OFDM localization methods:
  - Feature Method
  - Trigger Relay with Pilot Signal Method

# Feature Method [1]

- Based on the idea of the CP-OFDM "*Bandwidth Efficient Cooperative TDOA Computation for Multicarrier Signals of Opportunity*"

- OFDM has a block structure

- The method consists on the extraction of a statistic feature for each OFDM symbol and transmit the feature signal instead of the whole data.

# Feature Method [2]

- Process
  - MS broadcast a signal
  - Relay receives the signal, extracts a statistical feature for each symbol, and sends the feature signal to CBS
  - CBS also receives the signal and extracts a feature per symbol, obtaining its feature signal
  - The CBS receives the feature signal from the relay and cross correlates it with its own CBS feature signal to obtain the TDOA

# Feature Method [3]

- Bandwidth and computational efficient method because:
  - Instead of sending the whole signal, it is only needed to send one feature signal
  - Instead of compute the cross correlation of two long signals, in this situation both signals are shorter
- This method was developed for CP-OFDM using the mean of the CP as a feature
- No sense for ZP-OFDM (mean of zero padding)

# Feature Method [4]

- Different features had been tested
  - Mean
  - Variance
  - Skewness
  - Kurtosis
  - Symbol Phase
  - Peak to average ratio (PAPR)

- The features have been calculated with different percentages of the symbol, varying them since 1% until 100%

- We want to obtain a good performance with the less amount of computational operations possible

# Feature M. - Simulation Results [1]

- For the simulations the MS sends a signal of 50 symbols, generated by a random Gaussian distribution with mean=0 and variance=1,  with a BPSK modulation

- In this system we assume AWGN and flat fading Rayleigh channel but no multipath

- For simplicity in the system there is only one relay, the CBS and the unknown MS.

- It has been calculated the TDOA values for 1000 simulations per each different percentage of the symbol.

# Feature M. - Simulation Results [2]

- To compare the quality of the results it is used different criteria:
- Average of the time error:

$$\mu_e = \frac{1}{N}\sum_{i=1}^{N} e_i \quad \text{where} \quad e = \left| TDOA_{true} - TDOA_{estimation} \right|$$

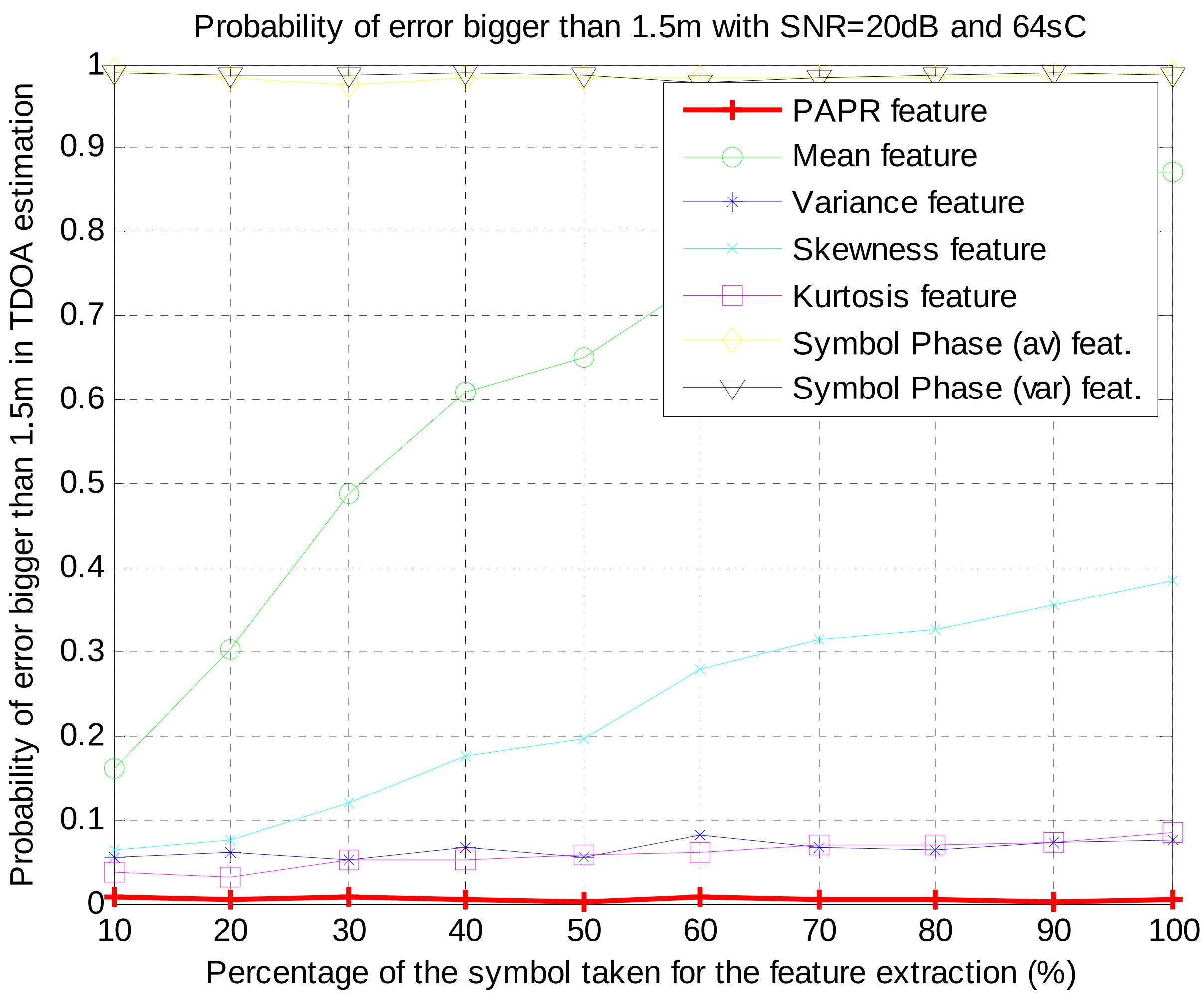
- Probability of having an error bigger than 1.5 meters (5ns.)

$$p_e = P\left(e > 5\times 10^{-9}\right)$$

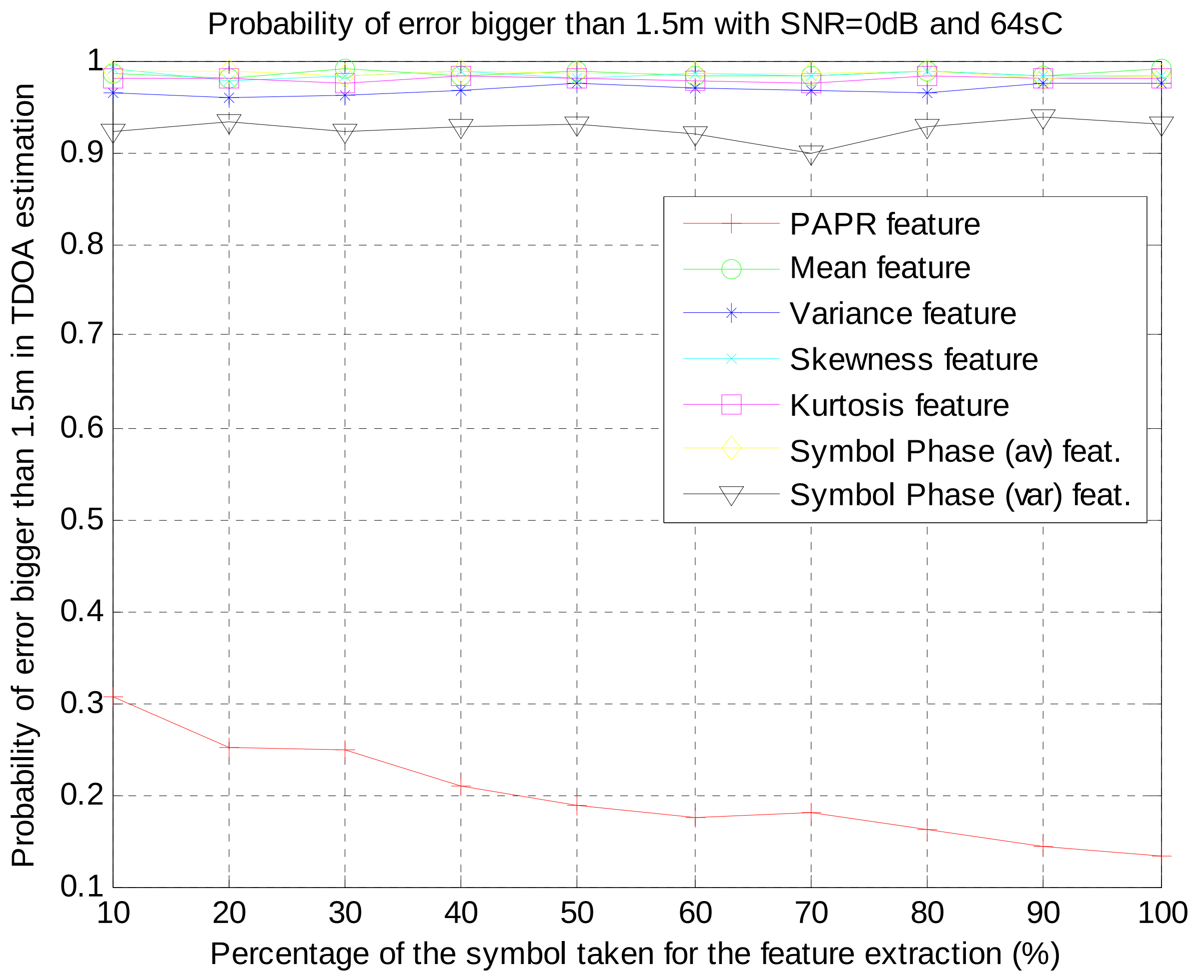
- Cumulative distribution function (CDF) of the error

$$CDF(X) = P(x \le X) = \int_{-\infty}^{X} f(x)\,dx$$

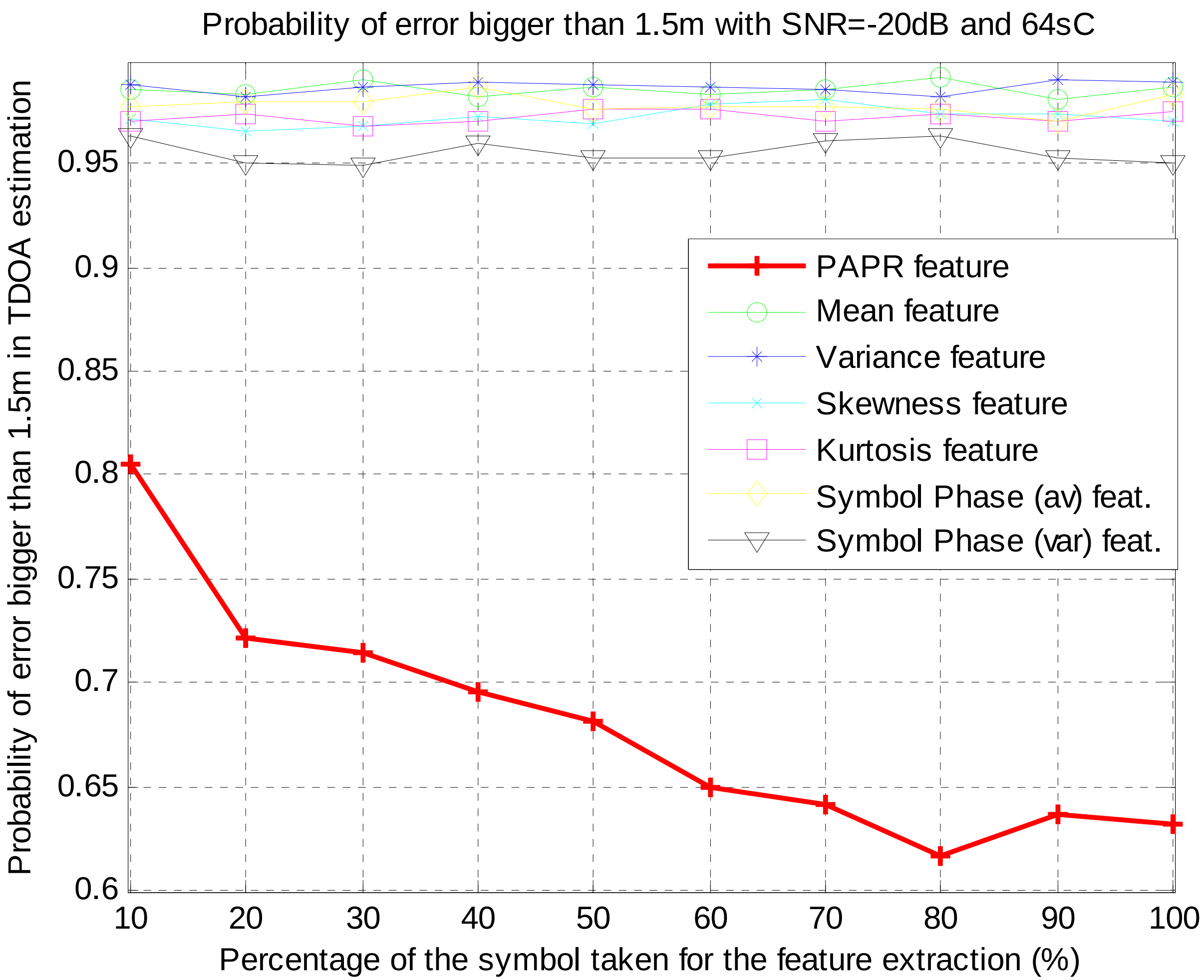
# Feature M. - Simulation Results [3]



# Feature M. - Simulation Results [4]



# Feature M. - Simulation Results [5]



# Feature Method – Conclusions

- This method is bandwidth and computational efficient because the mobile relays only need to transmit the feature signal, which is a short signal compared with the raw data sent by the MS.

- On the other hand, the relays must be more complex in order to extract the statistic feature.

- PAPR is the feature which has the best performance as a consequence of having the feature signal with more amplitude.

# Trigger Relay with Pilot Signal Method

- Trigger Relay with Pilot Signal Method (TR with PS Method) is a new efficient and accurate method to estimate the TDOA for localization

- We have published one paper with this idea:

  - H. Lu, P. Martínez and H. Nikookar "Cooperative TDOA Estimation with Trigger Relay", Proc. IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC 2011), Toronto, Canada, Sep. 2011, pp. 1-5.

# Trigger Relay

- Transmits a known signal (pilot signal) when it receives the signal sent by the MS.
- Simple
- Independent of the quality of the arriving signal
- Independent of the amount of data transmitted by the source

# Pilot Signal

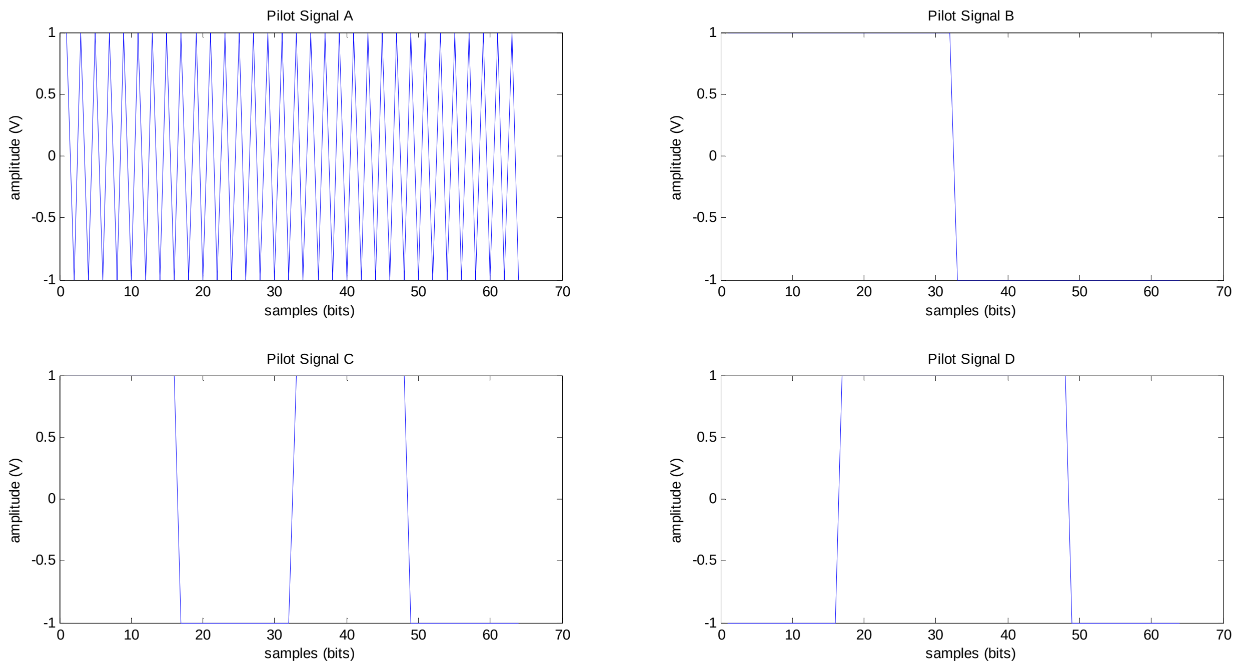
- It's a known OFDM signal which is sent by the trigger relay when it detects the arrival of the MS signal

- When the MS's signal arrives at CBS, the CBS generates its own pilot signal in order to cross correlate it with the received from the relay

- The variation of different parameters has a tradeoff between the accuracy of the TDOA estimation and the power consumption

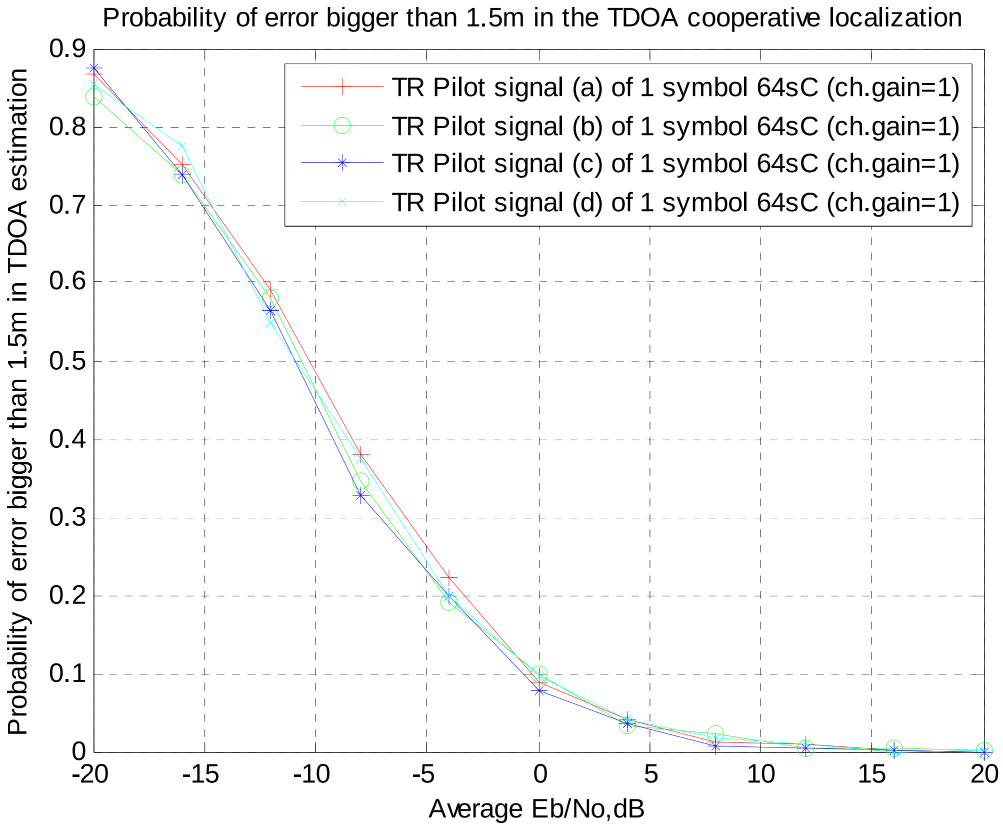
# Pilot Signal analysis [1]

- Shape



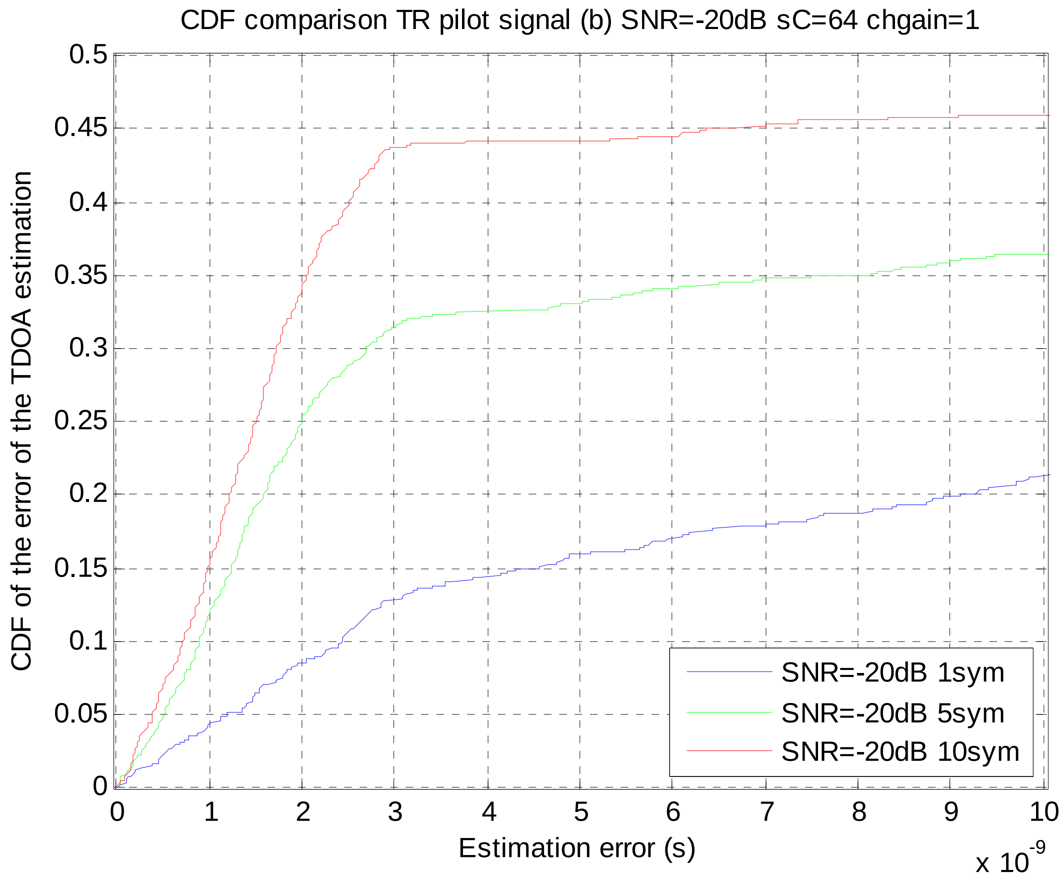
# Pilot Signal analysis [2]

- Shape
  - Hasn't got a big impact



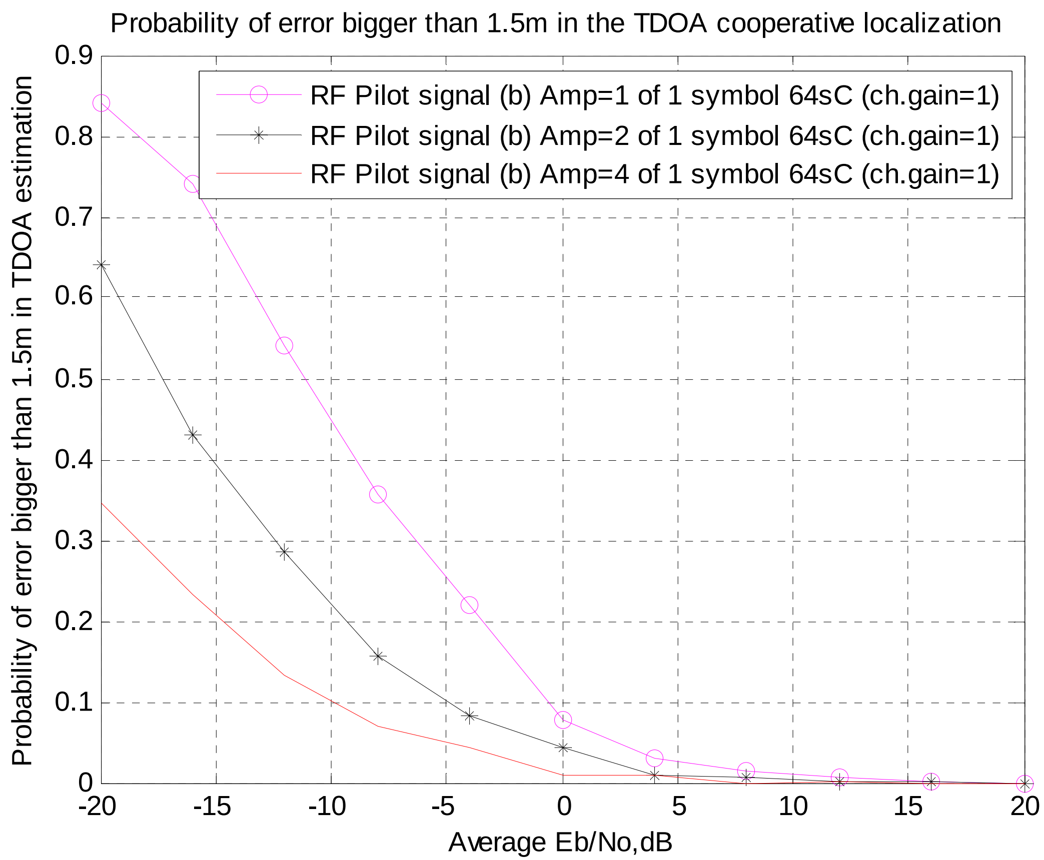
# Pilot Signal analysis [3]

- Length
  - Increasing the length improves the TDOA estimation but implies to transmit more data, decreasing the efficiency.



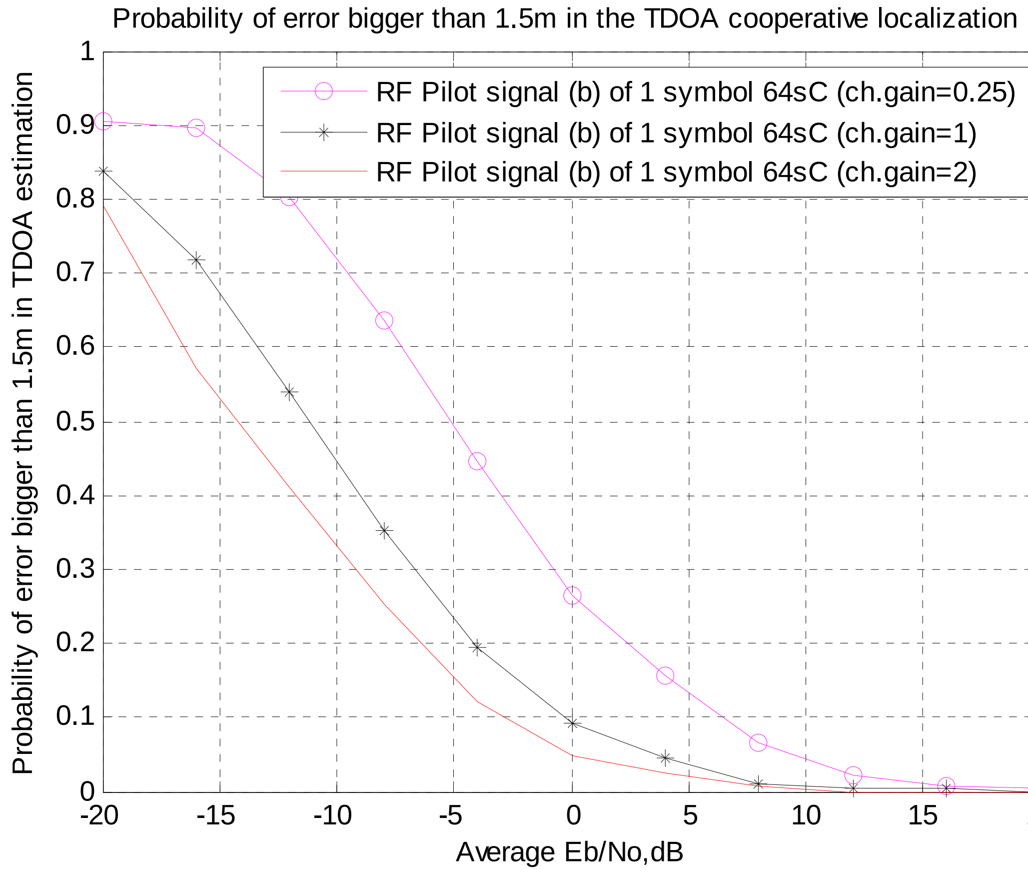
# Pilot Signal analysis [4]

- Amplitude
  - It is possible to provide a good TDOA estimation even with low SNR, with the trade-off of the power consumption



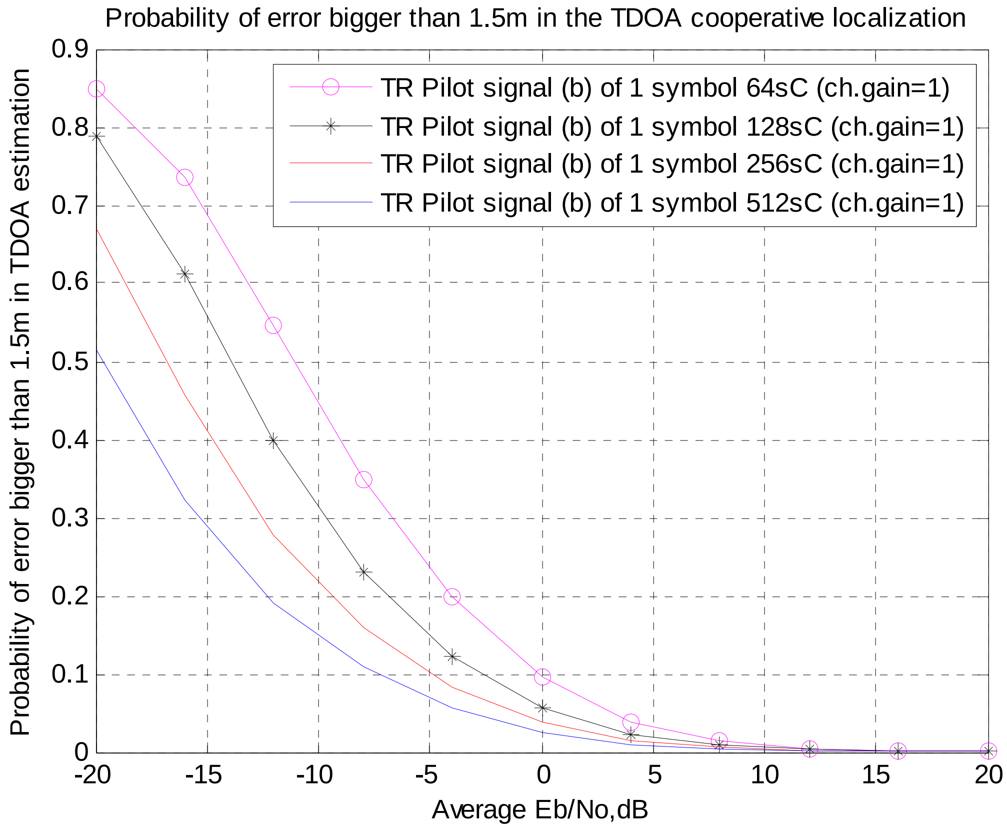
# Trigger Relay with Pilot Signal Method – Other Parameters [1]

- Channel Gain
  - If the channel gain increases, the performance improves.



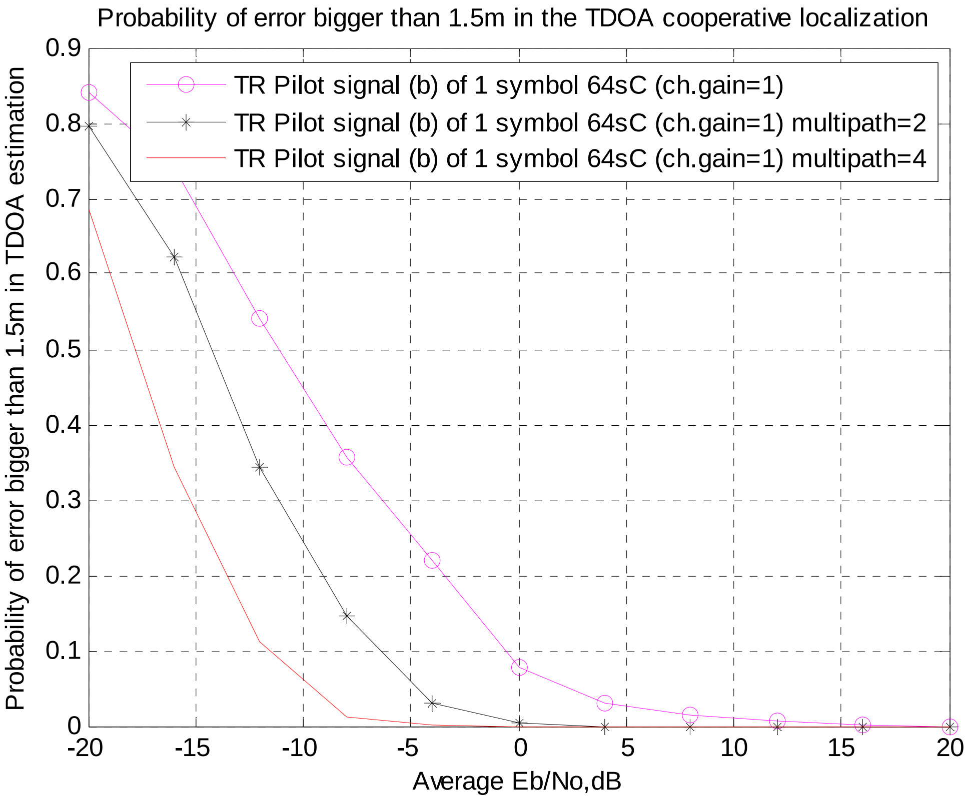
# Trigger Relay with Pilot Signal Method – Other Parameters [2]

- Number of Subcarriers
  - With more subcarriers the performance improves because there are more data to compute the cross correlation, but it implies more data to transmit for the relays, losing efficiency.



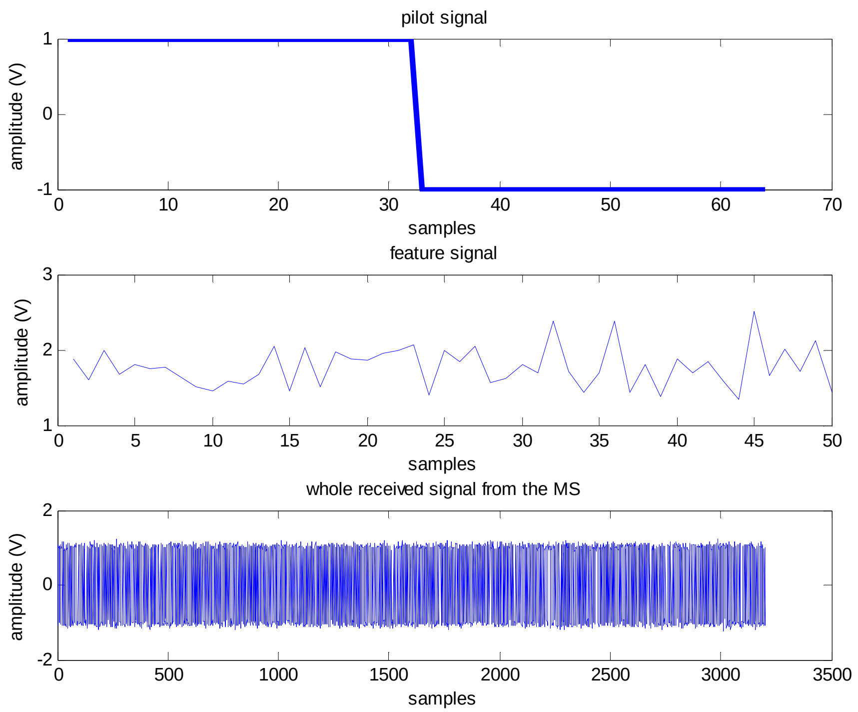
# Trigger Relay with Pilot Signal Method – Other Parameters [3]

- Multipath diversity
  - With the proper design of the receiver it is possible to take advantage of the multipath effect, improving the signal received, providing a better TDOA estimation.



# Comparison of Methods [1]

- Bandwidth Efficiency
  - Trigger Relay with Pilot Signal Method only sends a signal of one OFDM symbol length.
  - Feature Method sends a signal with the same amount of samples as OFDM symbols received from the MS.
  - Conventional Method forwards the raw received data.



# Comparison of Methods [2]

- System Complexity
  - Trigger Relay is the simplest one, does not need to do signal processing, neither decoding nor amplifying, only detect the incoming signal and transmit the pilot signal.
  - Feature Method requires the most complex relay, to extract the statistic feature signal.
  - Conventional Method with AF relay requires a power amplifier, or with DF relay requires signal processing treatment to decode.

# Comparison of Methods [3]

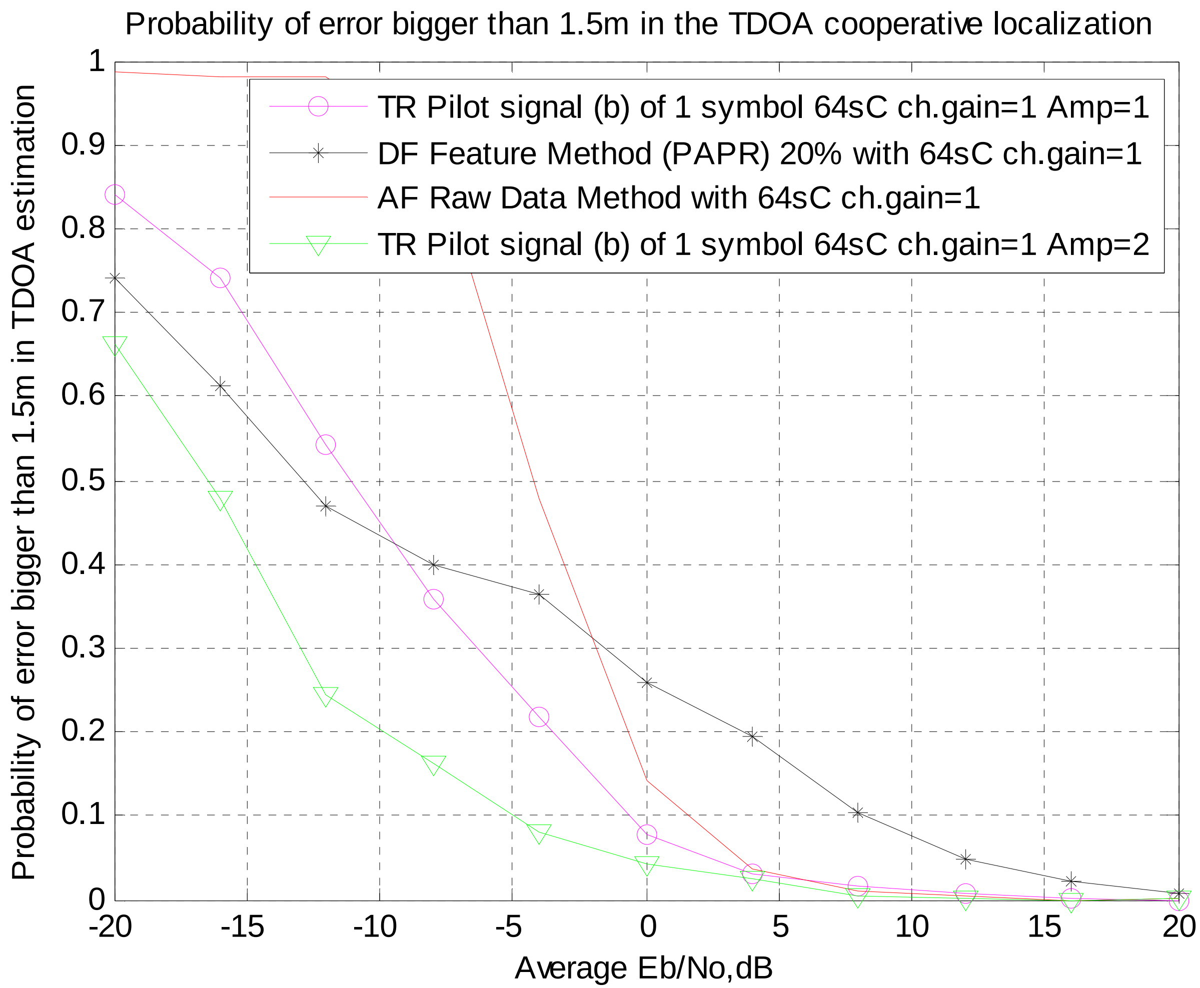
- Computational Efficiency
  - Trigger Relay is the most computational efficient, only needs to generate and transmit the pilot signal.
  - Feature Method requires the relays to process every received symbol and do the feature extraction. On the other hand, only transmits a small signal.
  - Conventional Method needs to process the whole received data.

# Comparison of Methods [4]

- Comparison Chart

| | BW Efficiency | System Complexity | Computational Efficiency | TDOA Estimation |
|---|---|---|---|---|
| AF relay | No | Medium | No | Reasonable |
| DF feature | High | High | Medium | Reasonable |
| Trigger relay | High | Low | High | Very good |

# Comparison of Methods [5]



# Conclusions

- The new proposed methods improve the TDOA estimation respect the conventional method.

- TR with PS Method provides a good TDOA estimation even with low SNR.

- TR with PS Method is the most bandwidth and computational efficient method.

- TR with PS Method requires simples relays and easy configuration.

- There is a tradeoff between the accuracy of the TDOA estimation and the power consumption, which worths it in low SNR conditions.

# Recommendations

- Study the number of cooperative relays that could improve the localization estimation.
- Non line of sight (NLOS) situations
- Analysis of the energy consumption
- Synchronization error analysis

***Thank you for your attention***

# Cooperative TDOA Estimation with Trigger Relay

H. Lu, P. Martinez and H. Nikookar
IRCTR, Faculty of EEMCS
Delft University of Technology
Mekelweg 4, 2628 CD Delft, The Netherlands
l.hao@tudelft.nl and h.nikookar@tudelft.nl

*Abstract*—**In this paper, we investigate the relaying issue of Zero-Padding (ZP) Orthogonal Frequency Division Multiplexing (OFDM) technique to estimate Time Difference of Arrival (TDOA) for locationing applications. In order to benefit from the easy processing of Amplify-and-Forward (AF) relay as well as the noise and interference cancellation of Decode-and-Forward (DF) relay schemes, we introduce the trigger relay technique for TDOA estimation. The trigger relay possesses the merit of bandwidth efficiency, since only a short pilot or preamble needs to be sent. Compared to its counterparts AF and DF relays, trigger relay achieves a better performance in terms of system complexity and TDOA accuracy. Gaining from multipath diversity, the trigger relay TDOA resolution can be improved further.**

***Keywords-Trigger relay; cooperative TDOA; OFDM; multipath diversity; block features***

## I. INTRODUCTION

Wireless location information and wireless location-based services have been receiving a growing attention over the past decades. Although the Global Positioning System (GPS) usually provides worldwide high-accuracy position measurements, it requires Line of Sight (LOS) to multiple satellites. For the GPS-denied scenarios [1], such as indoor, in urban canyons, and under tree canopies, GPS is known to be ineffective due to the inability of obstacle penetration. Thus, alternative methods of positioning and navigation are of interest, either as a backup or for use in areas unreachable by satellites. Beacon localization, on the other hand, relies on terrestrial anchors, such as WiFi access points or GSM base stations. However, in areas where network coverage is sparse, localization errors can be unacceptably large [2].

Generally, in the LOS scenario, high-accuracy localization can only be achieved using high-power anchors or a high-density anchor deployment. A practical way to address this need is through a combination of cooperative localization and wideband transmission, which is investigated in this paper.

Cooperative localization is an emerging paradigm that offers additional localization accuracy by enabling the agents to help each other in estimating their positions [3]. There are mainly two relaying protocols in classical cooperative networks: AF and DF. In AF, the received signal is amplified and retransmitted to the destination. The advantage of this protocol is its simplicity and low-cost implementation. However, the noise is also amplified at the relay. In DF, the relay attempts to decode the received signals. If successful, it re-encodes the information and retransmits it. If some relays cannot fully decode the signal, they should be discarded. In this paper, we propose a new relaying technique for cooperative localization, called trigger relay, which combines the advantages of AF relay and DF relay, i.e., less complexity because of no decoding, while removing the noise and interference effect at relay.

The fine delay resolution and robustness of wide bandwidth or Ultra-Wide Bandwidth (UWB) transmission enable accurate and reliable range measurements in harsh environments. Adopting UWB signal, the cooperative network enables the high speed communication and refines the position estimation [4]. In the modern wideband wireless communication system, OFDM technology has been widely used. ZP-OFDM, with the advantages of low transmission power and low spikes in the Power Spectrum Density (PSD), has been proposed in [5] for the IEEE Standard to design UWB transceivers. In Dec. 2008, the European Computer Manufacturers Association (ECMA) adopted ZP-OFDM for the latest version of High rate UWB Standard as well [6].

In this paper, we focus on TDOA-based methods with the ZP-OFDM wideband signals. TDOA always means the time difference of signal propagation between the two transmission links received at one common receiver or two synchronized receivers. TDOA estimation is often determined from the cross correlation of the two received signals [7]. ZP-OFDM is a multicarrier block transmission scheme, and with a highly block-structured transmission format. This block structure enables us to calculate some statistical features (e.g., mean, variance, skewness, kurtosis, etc.) of each block. Then, we can only transmit or forward the block features values to calculate the TDOA of two transmission links, rather than transmitting the entire signal. This feature-based TDOA needs less transmission bandwidth and is so called bandwidth efficient localization [8].

In this paper, we propose trigger relay for TDOA estimation. Only a short pilot or preamble signal is sent to the primary receiver, which can achieve bandwidth efficient localization as well. Compared to the AF relay and DF relay with block feature, the trigger relay reduces the system complexity and enhances the TDOA estimation accuracy.

The rest of paper is organized as follows. In section II, the cooperative ZP-OFDM TDOA based on AF relay and DF relay with block feature are reviewed. The trigger relay TDOA estimation is proposed in Section III. In section IV, the TDOA estimation performances of different relaying schemes are shown and analyzed. Results illustrate that the trigger relay TDOA has advantages in bandwidth efficiency, system complexity and resolution. Simulation results are provided in Section V to verify the theoretical analysis. Finally, Section VI concludes the paper.

## II. REVIEW OF AF AND DF RELAY FOR TDOA

### A. Conventional TDOA with AF or DF relay

In this paper, we consider the cooperative localization for the wideband communication system in LOS scenario. We assume the locations of the base station and relays are known by the primary receiver. Scatterers locate between the base station (anchor), relays (agents) and primary receiver (agent), causing multipath channels. The ZP-OFDM is adopted as the modulation scheme. In general, by using the ( $q-1$ ) TDOA estimates together with the classical hyperbolic intersection searching, the primary receiver can localize its position in $q$ dimensions.

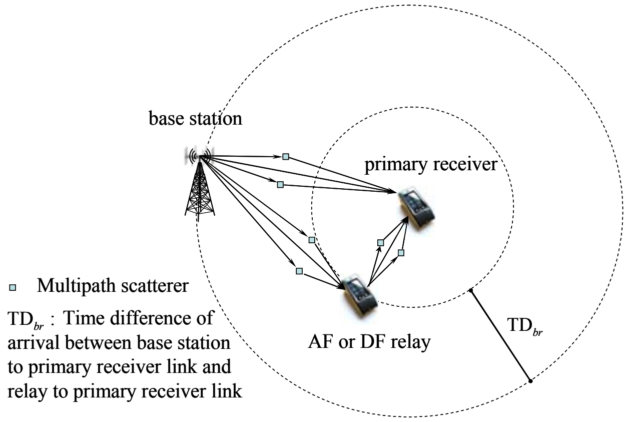



Fig.1. Cooperative TDOA system model with classical AF relay or DF relay.

In this section, we briefly review the conventional TDOA estimation based on AF relay or DF relay. As depicted in Fig. 1, the base station first broadcasts the signal. The relay receives the signal, and then amplify-and-forwards or decode-and-forwards the signal to the primary receiver. In this figure the two circles are concentric, with primary receiver as the centre of the circles. The radius of the inner circle represents the signal propagation time from relay to primary receiver, and the radius of the outer circle illustrates the signal propagation time from base station to primary receiver.

In this paper, we assume that the primary receiver can distinguish the signals from base station and relay. In order to obtain TDOA estimation, the primary receiver performs a correlation:

$$C_y\left(d_s\right)=\sum_{s=1}^{S} y_{ba}^{*}\left(s\right) y_{re}\left(s+d_s\right), \tag{1}$$

where $y_{ba}\left(s\right)$ and $y_{re}\left(s\right)$ denote the $s$-th sample of the received signals at the primary receiver from base station and relay, respectively. $(\cdot)^{*}$ denotes the conjugate operation. The primary receiver need to compute Eq. (1) for all anticipated ranges of the arrival time difference in sample, i.e., $-D_s \le d_s \le D_s$ , and $D_s$ stands for the maximum anticipated arrival time difference in time sample. $S$ refers to the number of received signal samples used for TDOA estimation. Then, the TDOA between the link from base station to relay to primary receiver and the link from base station directly to primary receiver $\mathrm{TD}_{brp}$ can be computed as

$$\mathrm{TD}_{brp}=\delta T_s, \tag{2}$$

where $$\delta=\arg \max_{-D_s \le d_s \le D_s}\left|C_y\left(d_s\right)\right|, \tag{3}$$

$|\cdot|$ denotes the modulus, and $T_s$ denotes the sampling period. Because the distance between base station and relay $L_{br}$ is known, the transmission time from base station to relay can be calculated as $T_{br}=L_{br}/c$ , where $c$ is the speed of light. We assume the total data processing time at relay is $T_r$ , the TDOA between the link from base station to primary receiver and the link from relay to primary receiver $\mathrm{TD}_{br}$ can be expressed as

$$\mathrm{TD}_{br}=T_{br}+T_r-\mathrm{TD}_{brp}\,. \tag{4}$$

*B. Feature-based TDOA with DF realy*

For the DF relay, the boundary of the OFDM block can be determined. Therefore, block features of OFDM system can be exploited to achieve the bandwidth efficient TDOA [8]. The block features include the normalized central moments (mean, variance, skewness, and kurtosis) of the first $Q$ samples of the $k$-th block effective OFDM symbol, i.e., the part of OFDM symbol that includes only the transmitted information and without the redundancy introduced by Guard Interval (GI):

the mean $$\mu_{rx}\left(k\right)=\frac{1}{Q}\sum_{i=1}^{Q} y_{rx}\left(k\right)_i, \tag{5}$$

the variance $$\sigma_{rx}^2\left(k\right)=\frac{1}{Q}\sum_{i=1}^{Q}\left(y_{rx}\left(k\right)_i-\mu_{rx}\left(k\right)\right)^2, \tag{6}$$

the skewness $$\lambda_{rx}\left(k\right)=\frac{1}{Q}\sum_{i=1}^{Q}\left(\frac{y_{rx}\left(k\right)_i-\mu_{rx}\left(k\right)}{\sigma_{rx}\left(k\right)}\right)^3, \tag{7}$$

the kurtosis $$\varepsilon_{rx}\left(k\right)=\frac{1}{Q}\sum_{i=1}^{Q}\left(\frac{y_{rx}\left(k\right)_i-\mu_{rx}\left(k\right)}{\sigma_{rx}\left(k\right)}\right)^4, \tag{8}$$

where the subscript “rx” denotes received signal either from the base station or relay. $y_{rx}(k)_i$ refers to the $i$-th sample of the $k$-th block effective OFDM symbol. In this paper, we consider signals from base station and relay are transmitted on different subcarriers as a frequency division system. Therefore, the primary receiver can distinguish between the features of base station and relay.

Other features, such as the average symbol’s phase

$$\Phi_{rx}\left(k\right)=\frac{1}{Q}\sum_{i=1}^{Q}\arctan\left(\frac{\mathrm{Im}\left(y_{rx}\left(k\right)_i\right)}{\mathrm{Re}\left(y_{rx}\left(k\right)_i\right)}\right), \tag{9}$$

the Peak Power (PP)

$$\mathrm{PP}_{rx}=\mathrm{Max}\left(\left|y_{rx}\left(k\right)_1\right|^2,\cdots,\left|y_{rx}\left(k\right)_Q\right|^2\right), \tag{10}$$

and the Peak to Average Power Ratio (PAPR)

$$\mathrm{PAPR}_{rx}=\frac{\mathrm{Max}\left(\left|y_{rx}\left(k\right)_1\right|^2,\cdots,\left|y_{rx}\left(k\right)_Q\right|^2\right)}{\frac{1}{Q}\sum_{i=1}^{Q}\left|y_{rx}\left(k\right)_i\right|^2}, \tag{11}$$

are considered as block features as well, where $\mathrm{Im}(\cdot)$ and $\mathrm{Re}(\cdot)$ stand for the imaginary and real part of the complex value, respectively. $\mathrm{Max}(\cdot)$ denotes the maximum of a vector $(\cdot)$ .

After receiving and decoding the signal from base station, the DF relay calculates the above mentioned features for each OFDM block. Then, block features are forwarded to the primary receiver. Meanwhile, primary receiver calculates the features based on the signals transmitted from the base station. Subsequently, primary receiver computes the cross correlation of the features from base station and relay to obtain the TDOA estimation. Generally, these features can be classified into 2 types. The first one is the zero convergence type, which includes the mean, skewness, kurtosis and average symbol’s phase, because for the random zero mean signals, their values converge to zero as $Q$ increases. The second one is the power type, which includes the variance, PP and PAPR, since they relate to the power of the signals.

The zero convergence type features always have values closer to zero. Thus, the noise can easily pollute these block features, which implies a bigger error of the TDOA estimation. On the other hand, since the power features have larger values than zero convergence type features, they are more robust against the noise. For the constant modulus signals, such as Binary Phase Shift Keying (BPSK), Quadrature Phase Shift Keying (QPSK), 2-Quadrature Amplitude Modulation (QAM), 4-QAM, etc., after linear equalization, variance of the one block equalized signal always has a value between 0 and 1, and PAPR has the largest value among all the above mentioned features, and is the best feature for TDOA estimation. For the non-constant modulus signal, such as 16-QAM, 64-QAM, etc., PP has the largest value among all the above mentioned features, and is the best feature.

Given the features from the base station and relay, the primary receiver can compute the cross correlation of the features. Let us denote the $k$-th block feature values of base station and relay as $f_{\mathrm{ba}}(k)$ and $f_{\mathrm{re}}(k)$, respectively. The primary receiver computes the cross correlation of the features as

$$C_f(d) = \sum_{k=1}^{K} f_{\mathrm{ba}}(k)\left(f_{\mathrm{re}}(k+d)\right)^*, \tag{12}$$

where $K$ stands for the number of the OFDM blocks used for calculating the feature cross correlation. The primary receiver must compute Eq. (12) for all anticipated valid ranges of the block arrival time difference, say $-D \le d \le D$, where $D$ stands for the maximum anticipated arrival time difference in block. Thus, the TDOA between the link from base station to relay to primary receiver and the link from base station directly to primary receiver $\mathrm{TD}_{brpf}$ can be computed as

$$\mathrm{TD}_{brpf} = T_s M \Delta, \tag{13}$$

where

$$\Delta = \arg \max_{-D \le d \le D} \left| C_f(d) \right|, \tag{14}$$

$M$ stands for the number of the samples within each OFDM block, i.e., FFT size. Then, similar to the conventional TDOA procedure, $\mathrm{TD}_{br}$ can be calculated.

Then, $\mathrm{TD}_{br}$ can be translated into the distance difference between base station to primary receiver link and relay to primary receiver link by multiplying it with $c$. According to the hyperbolic theorem, the primary receiver should appear at the hyperbola with the locations of base station and relay as the foci. Together with another two hyperbolas calculated from another base station and relay pairs, primary receiver can locate its position in 2-dimensional plane. Many location estimation algorithms were proposed to deal with the localization procedure, which have been reviewed in [9] and [10]. In this paper, for the sake of simplicity, we only pay attention to the TDOA estimation and not localization.

## III. Trigger Relay for TDOA Estimation

The advantage of AF is that it doesn't need the complicated signal decoding, while the strong point of DF relay relies on that it can get rid of the noise effect and channel interferences. Therefore, we propose a trigger relay technique to take advantage of these two merits. This scheme is shown in Fig. 2. Three circles are concentric circles, with primary receiver as the centre of the circle. Three radii, from short to long, are the signal propagation times from relay 1, relay 2 and base station to primary receiver, respectively.

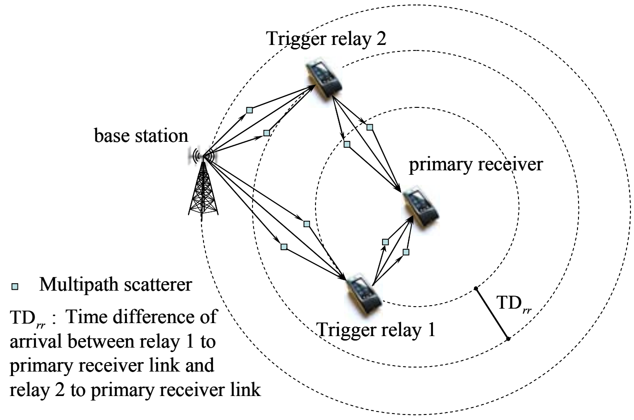



Fig.2. Cooperative TDOA system model with trigger relays.

The diagram of signal transmissions in the trigger relay TDOA estimation is shown in Fig. 3. Immediately after relay 1 and relay 2 receiving the base station signals at $t_1$ and $t_2$, they transmit a predetermined signal to the primary receiver at known $t_1'$ and $t_2'$, respectively. This predetermined signal can be a short pilot or preamble. We assume that the processing intervals at two relays are the same, i.e., $t_1' - t_1 = t_2' - t_2$. Then, primary receiver receives the signals from relay 1 and relay 2 at $t_{r1}$ and $t_{r2}$, respectively. All $t_1$, $t_2$, $t_{r1}$ and $t_{r2}$ are determined from the leading edges of the received signals.

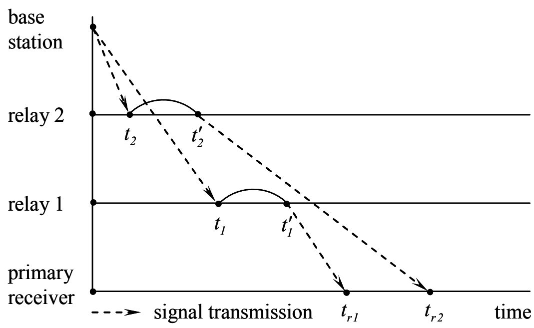



Fig.3. Signal transmissions in trigger relay TDOA estimation scheme.

Subsequently, The TDOA between the relay 1 to primary receiver link and the relay 2 to primary receiver link $\mathrm{TD}_{rr}$ can be calculated by primary receiver as

$$\mathrm{TD}_{rr} = \left(t_{r2} - t_{r1}\right) + \left(t_1 - t_2\right) \tag{15}$$

where $\left(t_{r2} - t_{r1}\right)$ can be achieved by correlation of signals from two relays, similar to the AF and DF relay case, and $\left(t_1 - t_2\right)$ can be calculated from the known positions of base station and relays, which are already known by the primary receiver.

## IV. Comparison of Different Relaying Schemes

In this section, we compare the AF relay, DF relay with block feature (DF feature) and trigger relay in the context of cooperative ZP-OFDM TDOA, and illustrate their performances in Table 1.

TABLE I. COMPARISON OF TDOA PERFORMANCE FOR DIFFERENT RELAYING SCHEMES

| | bandwidth efficiency | system complexity | TDOA estimation error |
|---|---|---|---|
| **AF relay** | **no** | **medium** | **reasonable** |
| **DF feature** | **yes** | **high** | **large** |
| **Trigger relay** | **yes** | **low** | **good** |

DF relay with block feature reduces the data required compared to the conventional TDOA based on cross correlation of the whole received signal, and achieves a bandwidth efficient transmission. Trigger relay can send short pilot or preamble for TDOA estimation, and reduces the amount of data transmission compared to the conventional AF and DF relays. Thus, trigger relay possesses the merit of bandwidth efficiency similar to DF relay with block feature.

As the name suggests, AF relay requires a proper power amplifier to compensate the signal attenuation in the base station to relay link, while DF relay with block feature not only decodes the signal, but also computes the features. Compared to AF relay and DF relay with block feature, trigger relay TDOA estimation has the lowest system complexity, as no amplification or feature detection is required.

For the TDOA estimation accuracy, generally, DF relay with block feature can only reach the block level resolution, not sample level as the conventional TDOA does. For the Multi-band (MB)-OFDM adopted in the UWB standards [5], [6], the sample period $T_s$ is 1.894 ns, the FFT size is 128, ZP accounts for 32 samples, the block interval is 312.5 ns, which includes 9.47 ns Guard Interval. The 312.5 ns is the lower bound of the feature-based TDOA resolution. If the smaller FFT size is adopted, the block interval can be reduced and accordingly can improve the lower bound of feature-based TDOA resolution. If more accurate localization is required, we need to compute TDOA involving a correlation of the signals at the sample level, i.e. 1.894 ns in MB-OFDM system. Sample signal correlation with AF relay and trigger relay can achieve the resolution up to sample level. It is worth mentioning that, AF relay TDOA estimation is more suffered from the noise effect and multipath interference in base station to relay link than the trigger relay TDOA estimation. Thus, trigger relay obtains the highest TDOA resolution among the above mentioned three relaying schemes.

Furthermore, in the ZP-OFDM transmission with multipath channel, trigger relay TDOA estimation can further gain from the multipath diversity, and improve the TDOA accuracy. When adopting the linear transceiver proposed in [11], ZP-OFDM channel holds the linear structure or tall Toeplitz structure, where its full column rank property always guarantees the matrix invertibility and signal detection. Meanwhile, the tall Toeplitz ZP-OFDM channel matrix ensures the full multipath diversity gain for the signal detection, only with the linear equalizers, such as Zero-Forcing (ZF) and Minimum Mean Square Error (MMSE) equalizers [12], [13].

Therefore, in the trigger relay TDOA estimation, the above mentioned linear transceiver can be used to achieve the full multipath diversity gain in the relay to primary receiver link, to combat the noise effect, and to improve the signal detection. Utilizing the well detected signal to process the TDOA estimation, it will consequently enhance the TDOA estimation accuracy. Meanwhile, this linear transceiver possesses a lower system complexity, compared to those systems with non-linear maximum-likelihood equalizers.

## V. SIMULATION RESULTS

In this section, we present the simulation results to show the performance of trigger relay in TDOA estimation, and verify the above analysis. BPSK is adopted as the modulation scheme. We consider the $N = 8$ subcarriers ZP-OFDM system with ZP accounts for 25% of the effective OFDM symbol duration, and with sample period $T_s = 1.894$ ns. The channels: from base station to relay, from base station to primary receiver and from relay to primary receiver are considered to be independent to each other and Rayleigh distributed. Since the MMSE equalizer can be transformed into the ZF equalizer, we adopt MMSE equalizer here to show the performance of the linear equalizer. In these simulations, absolute error of TDOA estimation is shown to compare the performances of different schemes. The absolute error is defined as the absolute difference between the estimated TDOA and the true TDOA in ns.

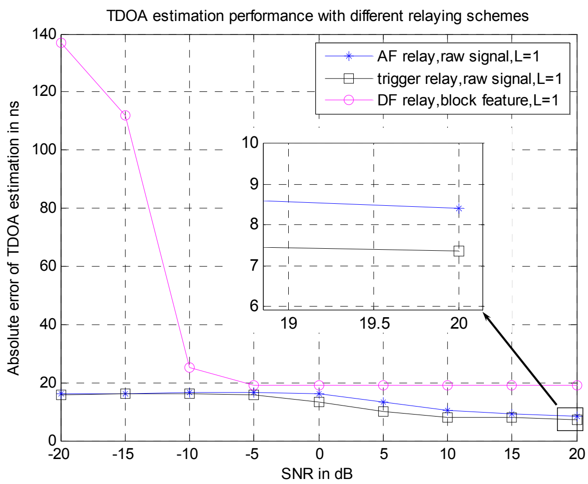



Fig. 4. Different relaying schemes for TDOA estimation in flat fading channel

*Test Case 1 (Different relaying schemes):* In this example, we compare different relaying schemes for TDOA estimation. For the DF relay with block feature, we adopt the first $Q = 7$ samples of OFDM symbol for PAPR feature calculation. For AF relay and trigger relay cases, the primary receiver correlates the raw received signals, i.e., no channel equalization or decoding at primary receiver is assumed.

As shown in the Fig. 4, a flat fading channel is considered, i.e., $L = 1$. The DF relay with block feature can only reach the block level resolution, i.e., 18.94 ns. Since AF relay amplifies the noise before relaying, while trigger relay not, we can see from the figure that, the trigger relay slightly outperforms the AF relay, and enjoys a better TDOA estimation error. The error gap between AF relay and trigger relay decreases as the Single to Noise Ratio (SNR) increases.

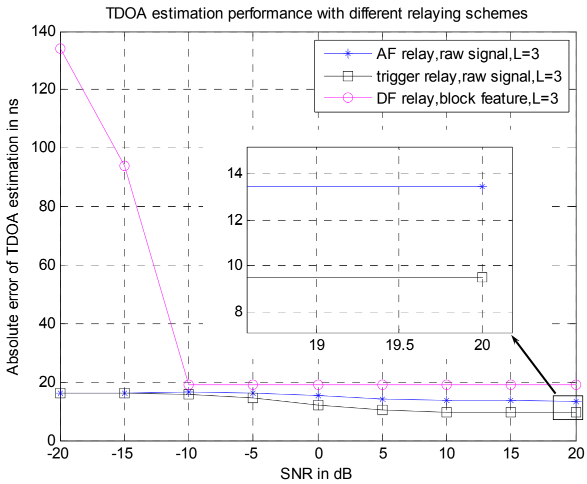



Fig. 5. Different relaying schemes for TDOA estimation in multipath channel

In the Fig. 5, we consider a 3-path channel scenario, i.e., $L=3$ . Compared to Fig. 4, due to multipath channel equalization, DF relay with block feature gains from multipath diversity, and the TDOA resolution in low SNR region is improved accordingly. However, for the AF relay and trigger relay cases, as they do not use channel equalization, they cannot gain from multipath diversity. In the high SNR region, multipath interference becomes the dominant effect on TDOA estimation, which degrades the TDOA resolution for both AF relay and trigger relay cases. The error gap between AF relay and trigger relay in Fig. 5 is larger than the gap in Fig. 4, which comes from the multipath interference in base station to relay link of AF case.

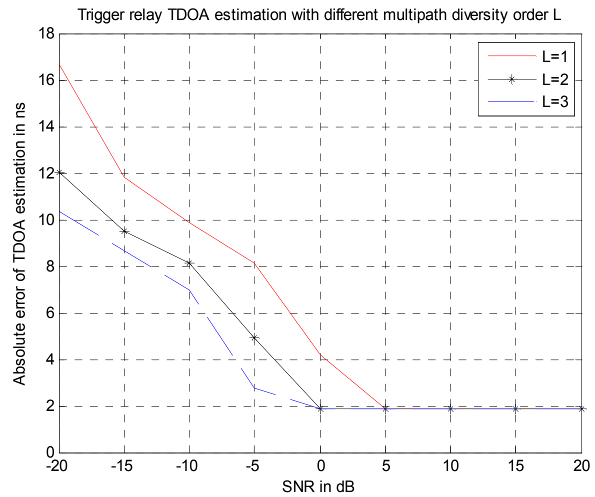



Fig. 6. Multipath diversity for TDOA estimation with trigger relay.

*Test Case 2 (Multipath diversity for trigger relay):* In this example, we show how the trigger relay TDOA estimation benefits from multipath diversity. Multipath diversity order $L=1$, 2, and 3 are considered. In order to achieve the multipath diversity, primary receiver should equalize the channel, detect the frequency domain signal, and then transfer it into the time domain by FFT, pad zeros again to restore the original time domain transmitted signal. Fig. 6 shows that, the signal detection improves the TDOA estimation error performance, and the absolute error of TDOA estimation reaches its lower bound 1.894 ns. We can see from the figure that, in the low SNR region, multipath diversity helps reducing the absolute TDOA estimation error, and the more multipath diversity orders, the smaller the TDOA estimation error.

## VI. CONCLUSIONS

In this paper, we investigated different relaying schemes for cooperative ZP-OFDM TDOA estimation, and proposed a trigger relay technique to gain from the easy processing together with noise and interference immunity of the base station to relay link. Compared to AF relay and DF relay TDOA estimation cases, the trigger relay reduces the system complexity. Meanwhile, trigger relay enables the bandwidth efficient TDOA, since it significantly reduces the amount of data for transmission. In terms of TDOA estimation error, among AF relay, trigger relay and DF relay with block feature, the trigger relay achieves the best accuracy. Furthermore, by exploiting multipath diversity, the improved signal detection at primary receiver further contributes to trigger relay a better TDOA estimation error.

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