Research on Channel Estimation Algorithm in 60GHz System Based on 802.15.3c Standard

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Abstract**—** 60GHz communication occupies huge transmission bandwidth and presents a diffuse multipath transmission characteristic, so there is a certain complexity in channel estimation. This paper using actual 60GHz-HSI-OFDM system model and realistic 60GHz channel model, presents the estimation scheme based on training sequence and pilot signal respectively. 60GHz channel usually belongs to time-invariant channel, while in reality, each frame may last several hundred milliseconds. So channel status may change during this time. The OFDM data symbols in each frame using the channel estimated value by the training sequence may appear deviation, which led to a decline in system performance. This moment the pilot subcarriers are designed to estimate channel. But because the number of pilot subcarriers is only 16, the estimation precision may be inadequate. To solve this problem, this paper proposes pilot subcarriers jointing null subcarriers, guard subcarriers to estimate the channel information and improves the estimated precision. Meanwhile, in order to improve the poor estimation performance when using pilot subcarriers, compressed sensing (CS) technology is introduced to 60GHz channel estimation. The simulation results show that CS algorithm could get better performance than LS and DFT algorithm when using OFDM subcarriers to estimate channel information. Finally the best subcarriers estimated solution is proposed for 60GHz LOS and NLOS channels respectively by analysis.

Index Terms**—**60GHz, channel estimate, compressed sensing, pilot subcarriers, training sequence

I. Introduction

Due to the ever increasing market demands for Gbps data rate indoor wireless applications, such as wireless personal area networks (WPAN), wireless local area networks (WLAN), and uncompressed high definition media interface (HDMI) transmission system, 60GHz centered millimeter-wave (MMW) communication has become the preferred technology for Gbps near field communication because of several GHz wide spectrums, low-cost CMOS devices implements, 10W maximum transmit power and other advantages[1]-[3].

802.15.3c standard is specifically developed by IEEE for 60 GHz wireless communication transmission, which earned a lot of support by WirelessHD alliance and vendors. The high transmission rate is supported by its physical layer standard. Two key technologies are adopted in the physical layer [4], [5]. One is Orthogonal Frequency Division Multiplexing (OFDM), the other is signal carrier frequency domain equalization (SC-FDE). 802.15.3c working group proposed three different physical schemes: signal-carrier physical layer (SC PHY), high-speed interface physical layer (HSI PHY), Audio and video physical layer (AV PHY). Except SC PHY, HSI PHY and AV PHY are both based on OFDM technology. OFDM technology is adopted in a large number of wireless standards as a mature technology.

The 60 GHz channel propagation environment model is also built by TG3c, which is called 802.15.3c channel model. 60GHz wireless channel model is divided into two cases: line-of-sight (LOS) channel model and Non line-of-sight (NLOS) channel model. TG3c considering the multi-path phenomenon caused by reflection, scattering and diffraction of radio waves during the transmission, introduces the idea of cluster and gives the measurement parameters of 9 kinds of channel based on TSV model and SV model respectively. In this paper, the application and simulation to 60 GHz channel model are all based on this channel model. 60GHz communication system occupies huge transmission bandwidth and presents a diffuse multipath transmission characteristic, so there is a certain complexity in channel estimation. Beam forming technology [6] and related receiving technology are usually adopted in 60GHz system, and the applications of the two technologies for 60GHz are under the premise of acquiring the channel state information. So channel estimation technology should be often applied by 60 GHz communication systems. In the 60 GHz system, the accuracy of channel estimation will affect the system's performance to a large extent. So the research to

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channel estimation technology which suited for the 60GHz standard will become important. So far, the channel estimation for 60GHz system is mainly depend on classical channel estimation methods, rarely used the channel characteristics of 60GHz. Reference [7] gives the improved pilot design for 60GHz OFDM system under 802.11ad. In this paper the channel estimation methods consistent with 60GHz channel characteristics are design under the 802.15.3c standard.

The rest of this paper is organized as follows. Section II describes the 60GHz OFDM system, and presents the 60GHz HSI OFDM PHY and 60GHz OFDM transmission expressions. 802.15.3c channel model for 60GHz is presented in Section III and the 60GHz channel characteristic is analyzed in this Section. The 60GHz channel estimate based on training sequence and the subcarriers in OFDM data symbol are discussed respectively in Section IV, some methods are proposed in this section in order to solve the bad channel estimate performance when using the pilot subcarriers to estimate the channel state. Finally, Section V concludes this paper.

II. 60GHZ OFDM SYSTEM MODEL

Table I is the timing-related parameters of 802.15.3c standard HSI OFDM scheme. As shown in Table I, each OFDM symbols contains N=512 subcarriers. The input data after QPSK modulation convert to transmitted data. Then the transmitted data symbols in the N subcarriers with serial-to-parallel could be expressed as $X(k)$ (k= 0,1,2,…, N-1). $X(k)$ could be transformed into time-domain signal $x(n)$(n=0,1,2…N-1) after IFFT;

$$x(n) = IFFT\{X(k)\} = \frac{1}{N}\sum_{k=0}^{N-1} X(k)\exp(j2\pi kn/N) \qquad (1)$$

The cyclic prefix (CP) is added into the front of $x(n)$, which could eliminate inter-symbol interference (ISI) and suppress inter-carrier interference(ICI), meanwhile translates linear convolution into circular convolution between the signal and channel impulse response. Because the length of CP is N_{GI}, then the signal sequence could be expressed as $x_f(n)$ after the CP is added.

$$x_f(n) = \begin{cases} x(N+n) & n = -N_{GI}, -N_{GI}+1, \cdots -1 \\ x(n) & n = 0,1,\cdots,N-1 \end{cases} \qquad (2)$$

For the receiving end, make the following assumptions firstly.

- CP should not less than the length of channel maximum multipath delay;
- Channel status remains constant within one OFDM symbol;
- Received signals keep fully synchronous.

The sending signal $x_f(n)$, through the frequency selective fading channel, could be expressed as $y_f(n)$. $y_f(n)$ is the linear convolution between $x_f(n)$ and channel impulse response $h(n)$.

$$y_f(n) = x_f(n) * h(n) + w(n) \qquad (3)$$

where $w(n)$ is zero-mean additive white gaussian noise sampling sequence, $h(n)$ is the sampling sequence of channel impulse response, the sampling rate of $h(n)$ is same as input data $X(k)$.The receiving signal $y(n)$ removed CP is expressed as

$$y(n) = y_f(n) \quad n = 0,1,\cdots,N-1 \qquad (4)$$

Make FFT transformation to $y(n)$,

$$\begin{aligned} Y(k) &= \mathrm{FFT}\{y(n)\} \\ &= \sum_{n=0}^{N-1} y(n)\exp\left(-\frac{j2\pi kn}{N}\right),\ k = 0,1,\cdots N-1 \end{aligned} \qquad (5)$$

$H(k)$=FFT{$h(n)$}, $H(k)$ is the frequency domain description of $h(n)$, $W(k)$ =FFT{$w(n)$}, $W(k)$ is the frequency domain description of $w(n)$, then $Y(k)$ also could be expressed as:

$$Y(k) = X(k)H(k) + W(k) \quad k = 0,1,\cdots N-1 \qquad (6)$$

TABLE I . TIMING-RELATED PARAMETERS

Parameters	Description	Value	Formula
f_s	Reference sampling rate/chip rate	2640MHz	
T_C	Sample/chip duration	～0.38ns	1/fs
N_{sc}	Number of subcarriers/FFT size	512	
N_{dsc}	Number of data subcarriers	336	
N_P	Number of pilot subcarriers	16	
N_G	Number of guard subcarriers	141	
N_{DC}	Number of DC subcarriers	3	
N_R	Number of reserved subcarriers	16	
N_U	Number of used subcarriers	352	$N_{dsc}+N_P$
N_{GI}	Guard interval length in samples	64	
Δf_{sc}	Subcarrier frequency spacing	5.15625MHz	fs/N_{sc}
BW	Nominal used bandwidth	1815MHz	$N_U \times \triangle f_{sc}$
T_{FFT}	IFFT and FFT period	～193.94ns	$1/\triangle f_{sc}$
T_{GI}	Guard interval duration	～24.24ns	$N_{GI} \times T_C$
T_S	OFDM Symbol duration	～218.18ns	$T_{FFT}+T_{GI}$
F_S	OFDM Symbol rate	～4.583MHz	1/Ts
N_{CPS}	Number of samples per OFDM symbol	576	$N_{sc}+N_{GI}$

III. 60GHZ 802.15.3C CHANNEL MODEL

Generally, the channel model depends on the carrier frequency, bandwidth, environment type and application system. 60 GHz system usually is broadband system and works in indoor environment. The channel model needs to consider the influence of antennas because the two-way property of 60GHz communication system. At present, IEEE has designed two channel models for

60GHz, that is 802.15.3c and 802.11ad, and the two models descript the signal propagation characteristics for 60GHz communication system. In 2009, the IEEE TG3c working group released MAC layer and physical layer standard for high speed wireless networks (WPANs) and gave the channel model of 60 GHz wireless communication system. This model is based on a lot of measured data and statistical analysis [8]-[13], which suitably described the large-scale fading and small-scale fading characteristics for 60GHz wireless channel. In this paper, the channel estimation design scheme is based on 802.15.3c standard. And the application environment is based on 802.15.3c 60GHz channel model.

TABLE II . CM1 AND CM2 CHANNEL PARAMETER

Residential	LOS(CM1)		NLOS(CM2)	
	TX360° RX 15° (CM1.1)	TX30° RX 15° (CM1.3)	TX360° RX 15° (CM2.1)	TX30° RX 15° (CM2.3)
Λ/(1/ns)	0.191	0.144	0.191	0.144
λ/(1/ns)	1.22	1.17	1.22	1.17
Γ/ns	4.26	21.50	4.26	21.50
γ/ns	6.25	4.35	6.25	4.35
σ_c/dB	6.28	3.71	6.28	3.71
σ_γ/dB	13.00	7.31	13.00	7.31
σ_ϕ/(°)	49.8	46.2	49.8	46.2
$\overline{L}$	9	8	9	8
Δk/dB	18.8	11.9	18.8	11.9
$\Omega(d)$/dB	-88.7	-111.0	-88.7	-111.0
n_d	2	2	2	2
A_{NLOS}	0	0	0	0

In order to present the 60 GHz channel characteristics accurately, this paper further employs two kinds of indoor living environment channels model recommended by TG3c and carries out the channel characteristics simulation. That are indoor LOS channel (CM1) and indoor NLOS channel (CM2) respectively. Table II is the CM1 and CM2 channel parameter list.

Excess delay spread indicates the effective duration of channel impulse response. It is the essential parameter which judges the existence of ISI in OFDM system. If it is shorter than the duration of protection interval, it will not generate ISI in the demodulation process, otherwise, it will generate ISI. The cyclic prefix length(which equal to the length of protection interval) is set as 24.24ns for 60GHz OFDM system by 802.15.3c standard. If excess delay is larger than this length, it is easier to generate ISI. Fig. 1 is the 60GHz LOS and NLOS channel excess delay spread simulation represented by CM1.1, CM1.3, CM2.1 and CM2.3 respectively, where the red dotted line shows the 100 times average excess delay. The excess delay of LOS channel is smaller than NLOS channel from the simulation results. The 100 times average excess delay simulation is about 0.01ns in CM1.1 channel, 0.08ns in CM1.3 channel, 21.55ns in CM2.1 channel, 28.4ns in CM2.3 channel. The differences of excess delay between CM1.1 and CM1.3, CM2.1 and CM2.3 are caused by the different half power beam width (HPBW) of transmission signal.

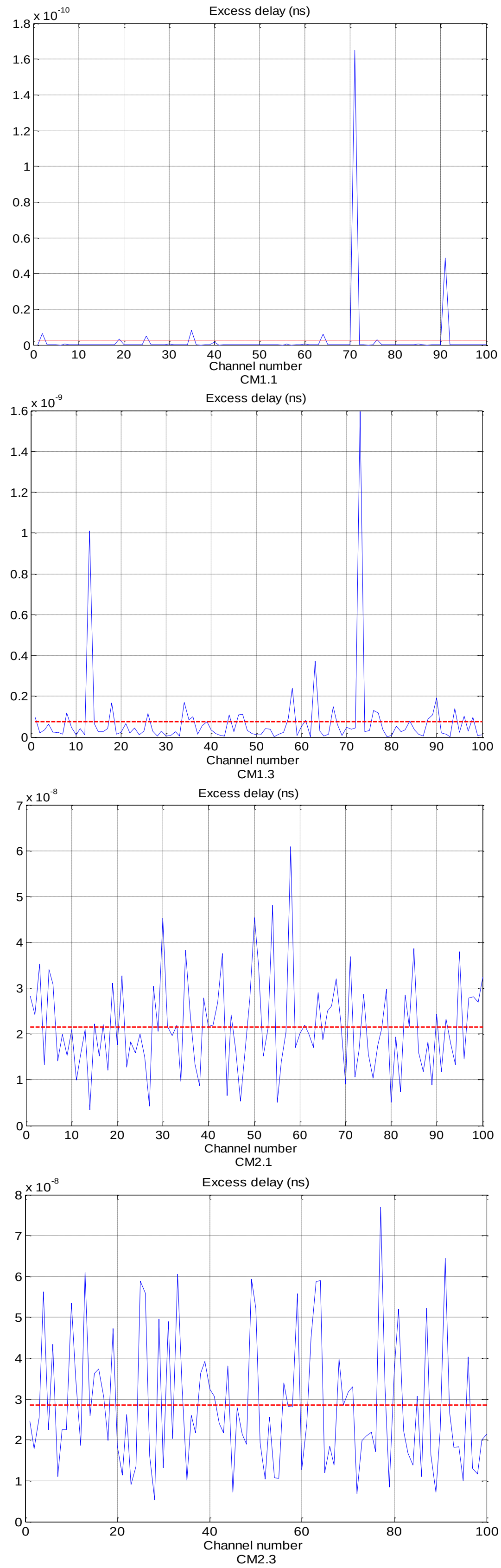

Fig. 1. 100 times excess delay spread simulation of 802.15.3c residential LOS and NLOS channel(CM1.1,CM1.3,CM2.1,CM2.3 respectively)

The discrete channel impulse response could reflect the channel characteristics more clearly. Fig. 2 shows that the power of LOS channel (represented by CM1.3) is concentrated in the first arriving path. The multipath phenomenon of NLOS channel (represented by CM2.3) is more obvious, and energy is relatively dispersed. The strongest energy path is not the first arriving path.

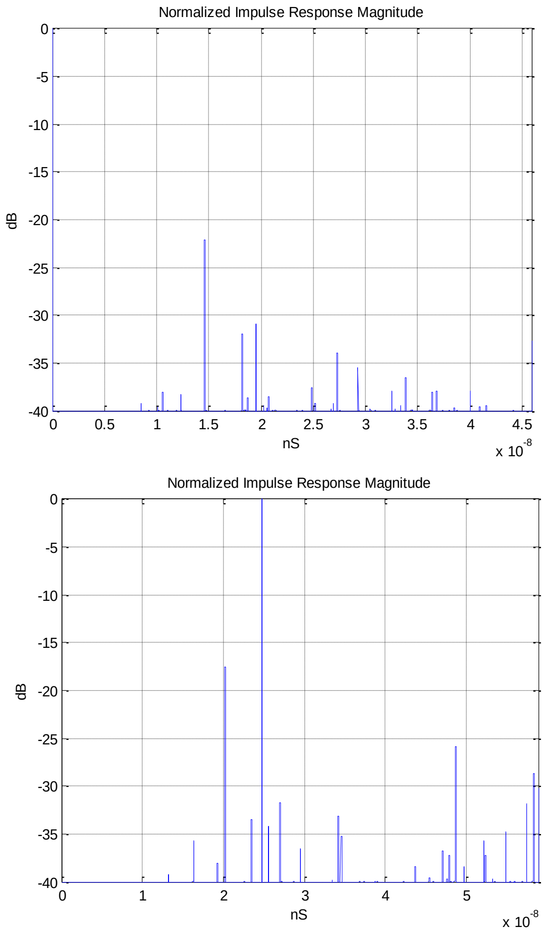

Fig. 2. The discrete channel impulse response of 802.15.3c channel(CM1.3 and CM2.3 respectively)

The discrete channel impulse response could reflect the channel characteristics more clearly. Fig. 2 shows that the power of LOS channel (represented by CM1.3) is concentrated in the first arriving path. The multipath phenomenon of NLOS channel (represented by CM2.3) is more obvious, and energy is relatively dispersed. The strongest energy path is not the first arriving path.

802.15.3c channel could use the cluster arriving model recommended by TG3c and could be expressed as:

$$h(t,\theta)=\sum_{k=1}^{K}\sum_{l=1}^{L_k}\alpha_{kl}\delta\left(t-T_k-\tau_{kl}\right)\delta\left(\theta-\theta_k-\omega_{kl}\right) \quad (7)$$

where δ(·) expresses impulse function, K expresses the number of cluster arriving the receiver, L_k expresses the number of multipath in the kth cluster. α_{kl} , τ_{kl} and ω_{kl} express the plural amplitude value, delay and arrival angle in the kth cluster, lth path respectively. T_k and θ_k express the delay and arrival angle in the kth cluster.

This model is the traditional S-V model which extends to angle domain. Expression is complex, so it is inconvenient to analyze and simulate. In this paper, the model is simplified, unify the meaning of clusters and multipath. All the signals at the receiver are identified as multipath component which through the different time delay and attenuation. In addition, the multipath gain caused by azimuth angle is incorporated into the variable α_{kl} . The model is simplified and expressed as

$$h(t)=\sum_{l=1}^{L}\alpha_l\left(t\right)\delta\left(t-\tau_l\left(t\right)\right) \quad (8)$$

where $\alpha_l\left(t\right)$ is a plural which reflect the gain causing by multipath, arrival angle, and antenna configuration, it's modulo indicates the amplitude attenuation of lth path, and it's phase indicates the phase information of lth path. $\tau_l(t)$ indicates the additional delay of the lth path. L indicates the total number of multipath reaching the receiver. Each path has own delay, phase shift and gain. The linear superposition of all paths constitutes the channel impulse response. 60GHz wireless communication system receiver has excellent multipath resolution, if the system bandwidth is 5GHz, the multipath resolution of the receiver will be 0.2ns. According to the parameters given by TG3c, the multipath average interval of 60GHz channel is greater than 0.2ns. Take CM2 NLOS indoor channel for example, the average interval of clusters is 5.24 ns, the average interval of multipath in clusters is 0.82 ns [14]. Obviously, each multipath can be distinguished on the receiver basically.

The formula (8) could be expressed as after sampling:

$$h(l)=\sum_{n=1}^{N}\alpha\left(n\right)\delta\left(l-n\right) \quad (9)$$

where N is the total sampling points, which is the total number of sampling tap delay line in discrete-time channel.

IV. 60GHz Channel Estimation Technique

There are two basic channel estimation[15] methods in OFDM systems which are illustrated in Fig. 3. The first one, block-type pilot channel estimation, is developed under the assumption of slow fading channel. The multiple continuous OFDM symbols are divided into groups (frames). One or several OFDM symbols in the front of each group transmits pilot signal and all the subcarriers of these OFDM symbols are used for channel estimation. The remaining OFDM symbols in one frame transmit data information. The second one, comb-type pilot channel estimation, is introduced to satisfy the need for equalizing when the channel status changed. A few of pilot signals are inserted into each OFDM symbol and partial subcarriers are used for channel estimation. The channel estimation characteristics of non pilot subcarriers depend on the channel characteristics of pilot subcarriers through interpolation in comb-type pilot channel estimation. These two basic types are adopted in the 802.15.3c OFDM scheme. Training sequence is inserted into the beginning of each frame for channel estimation (block-type pilot channel estimation), and the channel estimation result is used in the following data symbols for the whole frame. At the same time 16 pilot signals is inserted in each OFDM data symbol of this frame (comb-type pilot channel estimation) [4]. If the channel status changes in the duration of one frame, comb-type pilot channel estimation will be employed. In the following research and simulation, we will use these two estimation methods for 60 GHz channel estimation.

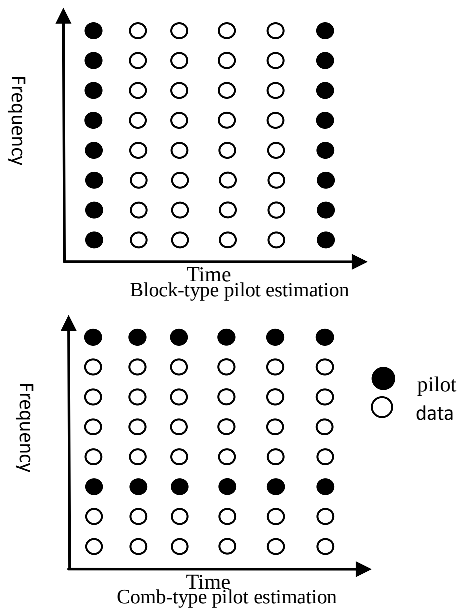

Fig. 3. Two basic types OFDM channel estimations

A. Channel Estimation based on Training Sequence

In the 802.15.3c standard, the training sequence belongs to the PHY preamble. PHY Preamble locates in the front of frame header, whose tasks are the frame detection, frequency recurrence, frame synchronization and channel estimation and so on [4], the structure of HSI physical frame is demonstrated in Table III. The length of preamble symbol equals to the length of FFT (512) in OFDM system.

TABLE III .THE FRAME STRUCTURE OF HSI PHYSICAL

PHY Preamble	Frame header			Payload
	PHY header	MAC header	HCS	

The channel estimation method based on training sequence employs all the 512 subcarriers of PHY Preamble for channel estimation and the acquired channel estimation result is used in the following data symbols for the whole frame. Two kinds of channel estimation algorithms based on training sequence are introduced in the next section. The two algorithms are suitable for 60GHz channel characteristics.

1) 60GHz OFDM channel estimation algorithm based on least square method (LS)

60GHz OFDM system uses N = 512 points FFT, $X(k)$ indicates the data within the OFDM symbol, which contains the data signals and pilot signals. The received signal $\mathbf{Y}$ at the receiver is a $N\times1$ vector:

$$\mathbf{Y} = \mathbf{XH} + \mathbf{N_0} \tag{10}$$

where $N\times N$ matrix $\mathbf{X} = diag(X(1), X(2), \cdots, X(N))$, $N\times1$ vector $\mathbf{H}$ is the sampling values of frequency domain channel response impulse. $N\times1$ vector $\mathbf{N_0}$ is noise vector.

LS algorithm [16] is the most common algorithm of channel estimation. When using the training sequences of each frame to estimate channel, the LS estimation is expressed as:

$$H_{LS}(k) = Y(k)/X(k) = H(k) + \overline{W(k)} \tag{11}$$

where $\overline{W(k)} = W(k)/X(k)$. Make IDFT to $H_{LS}(k)$ and get the time domain channel response impulse representation $h_{LS}(n) = IFFT\{H_{LS}(k)\}$. The length of $h_{LS}(n)$ is equal to the length of $H_{LS}(k)$, so it is 512. Without using any priori information of the channels, the LS estimators are calculated with very low complexity. But it ignores the additive noise in the estimation process, so LS algorithm is sensitive for the influence of noise disturbance.

There is another basic channel estimation method, minimum mean square error (MMSE) algorithm[17]. The estimation precision is higher than LS algorithm. But this algorithm needs to obtain the autocorrelation function of current frequency domain channel impulse response and needs to take matrix inversion. 60GHz OFDM system needs 512×512 matrix inversions. The complexity is too high, and obtaining the autocorrelation function of frequency domain channel impulse response is not very easy, so this kind of estimation algorithm is not very suitable for 60GHz channel estimation.

2) 60GHz OFDM channel estimation algorithm based on DFT

As shown in Table I, the sampling interval of HSI OFDM system is about 0.38ns, so the total sampling duration of 512 points is about 218.18 ns. As shown in figure 2, channel impulse response is basically concentrated in the first 20ns in 60GHz LOS channel, multipath energy has become very weak after 20ns (CM1.1 channel impulse response is more concentrated, focuses on the first few sampling points). Meanwhile NLOS channel is basically concentrated in the first 60ns(about first 160 sampling points). The LS channel estimation is continuous throughout the 512 sampling points, so the length of estimated time has greatly surpassed the duration of 60GHz channel impulse response. The estimated value which exceed the duration of 60GHz channel impulse response could be considered as noise, could be expressed as

$$h_{LS}(n)=\begin{cases} h_{LS}(n) & n=0,1,\cdots,L-1 \\ w(n) & n=L,L+1,\cdots,N-1 \end{cases} \quad (12)$$

where L is effective sampling value of time-domain channel. Thus only the first L points contained useful estimated channel information, the rest of the N-L points only contain noise information. The DFT channel estimation algorithm uses this characteristic. First using LS estimation algorithm and get the channel transfer function $H_{LS}(k)$, then $H_{LS}(k)$ is processed by IDFT and get $h_{LS}(n)$. The value of sampling point which greater than L in the channel impulse response is set to 0. And it is equivalent to using a simple L length window. We could select Hamming window, Kaiser window and Rectangular window, etc. This algorithm compensates the effects of channel noise to some extent, especially in the condition of low SNR, DFT channel estimation algorithm have more obvious effect. In this paper we select the rectangular window in the simulation and could be expressed:

$$h_{LS}(n)=\begin{cases} h_{LS}(n) & n=0,1,\cdots,L-1 \\ 0 & n=L,L+1,\cdots,N-1 \end{cases} \quad (13)$$

Finally, transform $h_{LS}(n)$ to frequency domain with N points DFT, expressed as

$$H_{DFT}(k)=DFT\{h_{LS}(n)\}. \quad (14)$$

Assume $\mathbf{W}$ as N dimension DFT transformation matrix

$$W=\frac{1}{\sqrt{N}}\begin{bmatrix} \omega^{00} & \cdots & \omega^{(N-1)0} \\ \vdots & & \vdots \\ \omega^{0(N-1)} & \cdots & \omega^{(N-1)(N-1)} \end{bmatrix} \quad (15)$$

where $\omega^{(n)(k)}=e^{-j2\pi nk/N}$ .set $\mathbf{I}_{\mathbf{L}\times\mathbf{L}}$ as $L\times L$ unit matrix, $\mathbf{Q}=\begin{bmatrix} \mathbf{I}_{\mathbf{L}\times\mathbf{L}} & 0 \\ 0 & 0 \end{bmatrix}$, $\mathbf{Q}$ is 512×512 matrix, so the DFT channel estimation algorithm in frequency domain also could be written as

$$H_{DFT}=WQW^{H}H_{LS} \quad (16)$$

Transforming H_{DFT} to time domain and getting the time domain channel estimation h_{DFT}.

Because there are 9 kinds of different channel models in 802.15.3c channel model, the size L of rectangular window should be selected according to the different channel environments. Generally, the performance of channel estimation algorithm is measured through symbol error rate (SER) and mean square error (MSE). where $MSE=trace\{E[(\hat{H}-H)\cdot(\hat{H}-H)^{H}]\}$, $\hat{H}$ is the estimated frequency domain channel impulse response, and H is the actual frequency domain channel impulse response, $trace(\bullet)$ indicates matrix trace. The duration of channel impulse response is generally less than the duration of cyclic prefix (CP) in LOS channel(the duration of CP is 24.24ns). The orthogonality has been kept between subcarriers when the duration of channel impulse response is smaller than the duration of CP, and the MSE of channel estimation will not increase obviously. So the value of L could be considered as the length of CP (64) for LOS channel. While the duration of channel impulse response is far less than the duration of CP(24.24ns) in CM1.1 channel. In order to get a better channel estimation, L could be defined smaller than 64. In this paper we set L = 64 and L = 10 respectively in the LOS channel simulation. The duration of channel impulse response is larger than 24.24ns in NLOS channel in most cases. If set L=64 or L<64, it is likely to cause the energy loss of partial multipath in the estimation process and led to the poor performance in channel estimation.

As shown in Fig. 4 whether the SER or MSE performance of DFT algorithm (L=64) are both better than LS algorithm, DFT (L=10) is better than DFT(L=64) in CM1.1 channel. This is because the multipath phenomenon is not obvious in CM1.1 channel. Most of the energy is concentrated in the first few sampling points. So the value of L is smaller, the possibility of filtering out the noise is bigger.

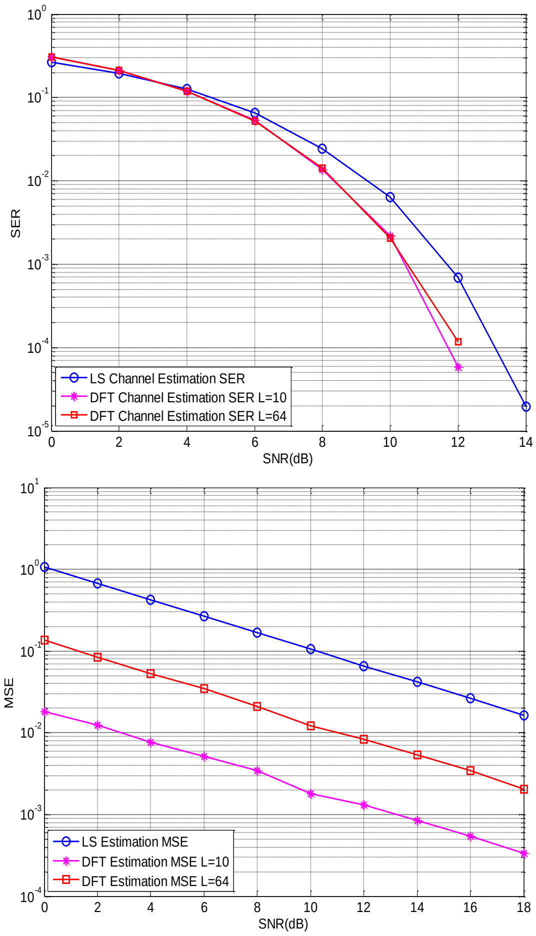

Fig. 4. SER and MSE performance comparison between LS channel estimation and DFT channel estimation in CM1.1 channel

Fig. 5 presents the simulation result in NLOS channel represented by CM2.3. The energy of multipath is average in this channel, energy is not mainly concentrated in the first arriving path. The duration of channel impulse response is generally close to or greater than the duration of CP, and it is prone to generate inter-symbol interference (ISI) at this time. The simulation result shows that the accuracy of channel estimation is very poor when L less than or equal to the length of CP in NLOS channel. That is because the channel energy is not concentrate in the duration of CP, at this moment still using L=64 DFT algorithm for channel estimation will cause high BER. The duration of channel impulse response is generally within 2 times duration of CP in NLOS channel. So the value of L could be set as 128 for NLOS channel. The simulation comparison between DFT (L=128) algorithm and DFT (L=256) algorithm tests the rationality of L. The DFT (L=256) algorithm have contained all the energy of channel impulse response, while at the same time it brings excess noise and reduces the accuracy of estimation. Under the NLOS channel, the DFT algorithm L=128 and L=256 are both superior to the LS algorithm channel estimation.

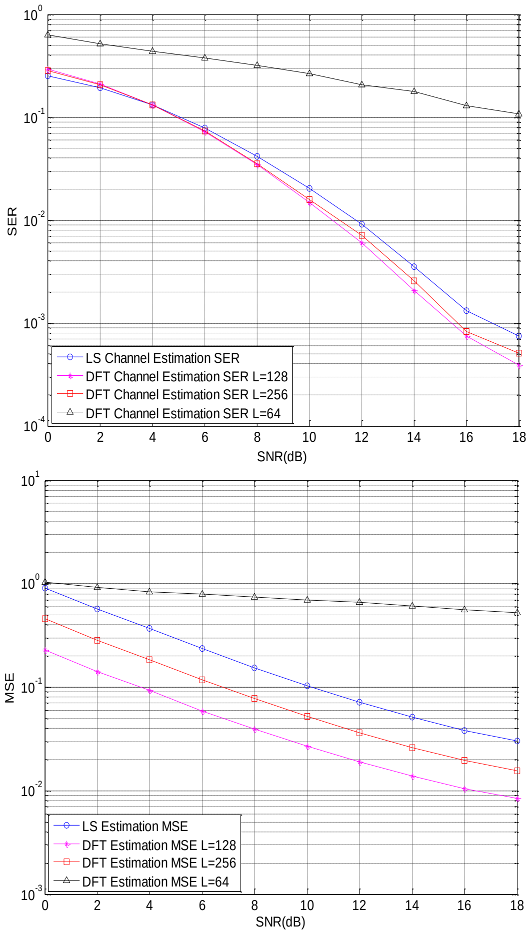

Fig. 5. SER and MSE performance comparison between LS channel estimation and DFT channel estimation in CM2.3 channel

B. Channel Estimation based on Pilot Subcarriers

If the channel is time-invariant channel during the whole period of one frame, training sequence estimation methods could be used. That is to say OFDM data symbols in each frame could use the channel estimated value by the training sequence if the channel condition have not changed. 60GHz channel usually belongs to time-invariant channel, however, each frame signal may last several hundred milliseconds in reality, so the channel status may change during this time. In 802.15.3c standard, the largest number of transmitted OFDM symbol per frame is 1024 and the duration of each OFDM symbol is 218.18ns [4]. The longest duration of data OFDM symbols after the training sequence is 218.18ns*1024=223ms in one frame. While 60GHz signal is sensitive to block and relative movement between transmitter and receiver, so it is probable that the channel condition changes in one frame. It may appear huge deviation and cause the performance decreasing if only using the training sequence channel estimation method.

The simulation results in Fig. 6 verify the validity of above consideration. When the channel status changes from LOS channel (CM1.3) to NLOS channel (CM2.3), the system SER performance comparison between using the preceding CM1.3 channel status and the correct CM2.3 channel status by training sequence is presented in this figure. The estimation result of training sequence located in the front of each frame and corresponding to LOS channel status while the OFDM data signals after the training sequence corresponding to NLOS channel. If still using the estimated channel status in LOS channel, the SER performance will be very large.

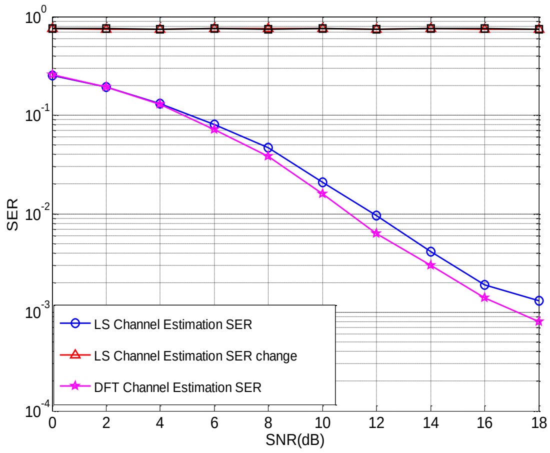

Fig. 6. SER performance simulation when the channel condition changing while the estimate method does not change timely

When the channel status suddenly changes, channel estimation can't adjust in time when using training sequence and lead to the bad performance. Regard to this problem, we could using the pilot signals to estimate the channel status in each OFDM symbol and get the channel status of current OFDM symbol. The estimation method based on pilot subcarriers has two steps: first using an algorithm, estimates the frequency channel impulse response in the position of pilot subcarriers; then using the Interpolation method to estimate the entire frequency channel function $H(k)$.

Each OFDM symbol contains 512 subcarriers, and is numbered as -256：255. The subcarriers contain guard subcarriers, null subcarriers, data subcarriers and pilot subcarriers, etc. Table IV is the allocation plan of subcarriers under 802.15.3c HSI scheme.

Formula (10) could be expressed as formula (17) when using N_p =16 pilot subcarriers for channel estimation

TABLE IV . SUBCARRIER FREQUENCY ALLOCATION

Subcarriers type	Number of subcarriers	Logical subcarriers indexes
Null subcarriers	141	[-256:-186]∪[186:255]
DC subcarriers	3	-1,0,1
Pilot subcarriers	16	[-166:22:-12] ∪[12:22:166]
Guard subcarriers	16	[-185:-178] ∪[178:185]
Data subcarriers	336	All others

$$\mathbf{Y_p} = \mathbf{X_p H_p} + \mathbf{N_p} = \mathbf{X_p W_p h} + \mathbf{N_p} \tag{17}$$

where p is the number of pilot subcarriers, the number is -166，-144，-122，100，-78，-56，-34，-12，12，34，56，78，100，122，144，166 respectively. $\mathbf{X_p}$ is the signal value of pilot subcarriers; $\mathbf{H_p}$ is the frequency channel impulse response of pilot subcarriers; $\mathbf{Y_p}$ is the receiving signal value of pilot subcarriers.

$$X_p = diag\left\{X_p(1), X_p(2), \cdots, X_p(N_P)\right\}^T \tag{18}$$

$$\mathbf{H_p} = \{H_p(1) H_p(2) \cdots H_p(N_p)\}^T \tag{19}$$

$$\mathbf{Y_p} = \{Y_p(1) Y_P(1) \cdots Y_p(N_p)\}^T \tag{20}$$

Referring the parameters definition of formula (10), **S** is $P \times N$ selection matrix which is used to select P pilot position from N dimensional vector. $P \times 1$ vector $\mathbf{Y_p} = \mathbf{SY}$, $P \times P$ vector $\mathbf{X_p} = \mathbf{SXS}^{-1}$, $P \times L$ vector $\mathbf{W_p} = \mathbf{SW}$ (the definition of W reference formula (15) , $P \times 1$ vector $\mathbf{N_p} = \mathbf{SN_0}$. $\mathbf{X_p}$, $\mathbf{Y_p}$ are known signals to the receiver. We could through a certain algorithm estimating the vector **h**.

According to 802.15.3c standard, the mth pilot subcarrier signal in the OFDM data symbols can be expressed as：

$$X_p(m) = \begin{cases} (1+j)/\sqrt{2} & \text{m=0,3,5,7,9,13,15} \\ (1-j)/\sqrt{2} & \text{m=1,2,4,6,8,10,11,12,14} \end{cases} \tag{21}$$

From formula (11), the frequency channel impulse response estimation by the pilot subcarriers using LS algorithm can be expressed as

$$\begin{aligned} H_{LS-pilot} &= \{H_p(1) H_p(2) \cdots H_p(N_p)\}^T \\ &= \{\frac{Y_p(1)}{X_p(1)} \frac{Y_p(2)}{X_p(2)} \cdots \frac{Y_p(N_p)}{X_p(N_p)}\}^T \end{aligned} \tag{22}$$

Make the frequency channel estimation $H_{LS-pilot}$ through interpolation calculation and could get the frequency channel estimation in other subcarriers locations. The frequency channel estimation in pilot subcarriers locations and other subcarriers locations together constitute the entire frequency channel estimation H_{LS} which containing 512 subcarriers estimation value. Transform H_{LS} to time domain and get 60GHz time-domain channel estimation $h_{LS-piolt}$. Linear interpolation method is used for simulation in this paper.

In the same way the pilot subcarriers channel estimation $h_{DFT-pilot}$ could also be obtained using DFT algorithm.

Because the number of pilot subcarriers is only 16, the estimation precision only using 16 pilot subcarriers may be insufficient. The simulation results in Fig. 7 and Fig. 8 also demonstrate this consideration. In order to solve this problem, we consider utilizing the 141 null subcarriers and 16 guard subcarriers in each OFDM symbol to estimate the channel status. As shown in Table IV, the subcarriers allocation in 802.15.3c standard, we could see that each OFDM data symbol contains 141 null subcarriers. The 141 subcarriers don't send any data, that is to say the data are 0 in these subcarriers. So the difference between pilot subcarriers and null subcarriers is the different transmitted data. The data for channel estimation in pilot subcarriers are $X_p(m)$ and in null subcarriers are data 0. Furthermore, 16 guard subcarriers are defined in 802.15.3c standard. The transmitted data are not be set in these subcarriers and these subcarriers could be used for various purposes including channel estimation. Because using more estimated data may be getting better estimation performance. So we could use 16 pilot subcarriers, 141 null subcarriers and 16 guard subcarriers, together 173 subcarriers for channel estimation. In this paper, we call that jointing subcarriers estimation method. According to 802.15.3c standard, the remaining 339 subcarriers include data subcarriers and DC subcarriers could not be used for channel estimation. The simulation result of this method is given below.

The simulation results in Fig. 7 and Fig. 8 show that the performance of channel estimation based on 16 pilot subcarriers are relatively poor whether in LOS or NLOS channel, while the channel estimation based on null subcarriers, guard subcarriers jointing pilot subcarriers has more excellent estimation performance than the channel estimation only based on pilot subcarriers. In CM1.3 LOS channel, when the SER is 10^{-3}, jointing subcarriers method have about 6dB gain than pilot subcarriers method whether LS or DFT algorithm. The identifying LS Channel Estimation SER and DFT Channel Estimation SER in Fig. 7 and 8 indicate the simulation result using entire 512 subcarriers (training sequence estimation) for channel estimation, In order to contrast the performance of jointing subcarriers method, we introduce the ideal entire 512 subcarriers for channel estimation method. The channel estimation performance based on jointing subcarriers is closed to the performance based on entire 512 subcarriers estimation. The reason for this result is that the multipath phenomenon is not obvious in CM1.3 channel and most of the energy is concentrated in the first few sampling points. Using only 16 pilot subcarriers data could not estimate the complete channel status at this time, while the estimation method based on jointing subcarriers estimation could satisfy the demand of channel estimation. So this method could get more excellent performance. In CM2.3 channel, the jointing subcarriers method has significant advantage than pilot subcarriers method whether using LS or DFT algorithm. But there is a large performance gap between the jointing subcarriers method and entire 512 subcarriers estimation method in NLOS channel. This is because the number of multipath is big and the channel status is more complicated in NLOS channel. More data information are needed for channel estimation. Null subcarriers, guard subcarriers jointing pilot subcarriers still could not give a complete estimation to the complex channel condition.

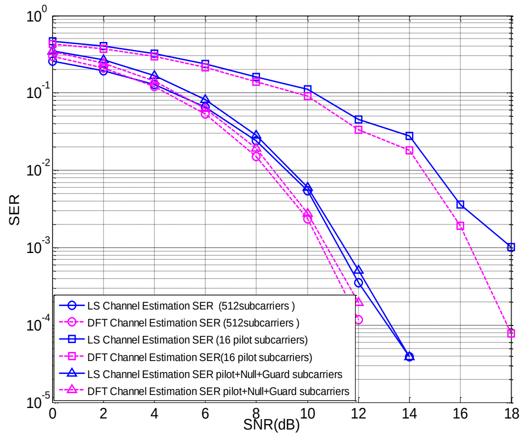

Fig. 7. The SER performance comparison between jointing estimation and 16 pilot subcarriers estimation in CM1.3 channel (DFT length L=10)

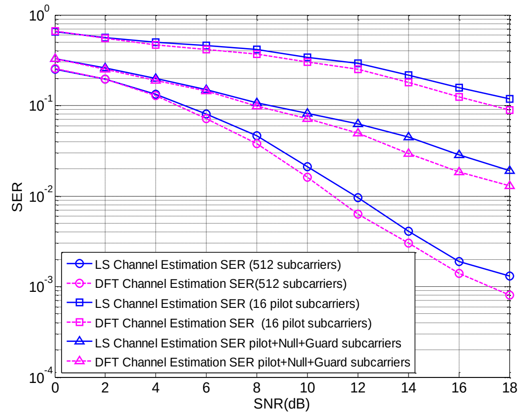

Fig. 8. The SER performance comparison between jointing estimation 16 pilot subcarriers estimation in CM2.3 channel(DFT length L=128)

C. Channel Estimation based on Compressed Sensing Orthogonal Matching Pursuit Method

As shown in Fig. 8, whether jointing pilot subcarriers estimation or only pilot subcarriers estimation both could not get good estimation performance in NLOS channel. So a better NLOS channel estimation method which could uses limited OFDM subcarriers data and gets better estimation performance should be search. As shown in Fig. 2 whether in LOS or NLOS channel, 60GHz channel impulse response show sparse characteristic in time domain. The sparse characteristic in 60GHz channel is reflected that the number of nonzero elements or greater value elements is relatively small and the number of zero elements or closing to zero elements is relatively big in $\alpha(n)$ of formula (10). In traditional signal processing methods, Nyquist sampling is an important premise for correct recovery of signal at the receiver. In order to get better channel estimation performance, only take advantage of enough subcarriers could obtain more complete estimation result for 60GHz OFDM system. While the compressed sensing (CS) theory proposed by Candes, Tao [18] and Donoho [19] demonstrate that using fewer measurements could recover the information of signals when the signals are sparse or compressible. So when the pilot signals for channel estimation are not enough, CS theory provides a new solution and makes it possible to have better channel estimation performance while using fewer estimation subcarriers.

Now, the basic principle of CS theory is illustrated firstly. Assume a discrete time signal $\mathbf{x}$ (the length is $N\times 1$) and whose transform coefficient $\boldsymbol{\alpha}$ is sparse in $\boldsymbol{\Psi}$ domain,

$$\mathbf{x} = \boldsymbol{\psi\alpha} \tag{23}$$

where $\boldsymbol{\Psi}$ is a base vector which located in same space with $\mathbf{x}$, $\boldsymbol{\alpha}$ is the projection coefficient of signal $\mathbf{x}$ in $\boldsymbol{\Psi}$ domain, that is the $\boldsymbol{\Psi}$ domain expression of $\mathbf{x}$. If could find an observation matrix $\boldsymbol{\Phi}$ which not related with base vector $\boldsymbol{\Psi}$ ($\boldsymbol{\Phi}$ is $M\times N$ matrix, $M << N$). Making the linear transformation to signal $\mathbf{x}$, we could obtain the observation vector $\mathbf{y}$($\mathbf{y}$ is $M\times 1$ matrix).

$$\mathbf{y} = \boldsymbol{\Phi}\mathbf{x} = \boldsymbol{\Phi\psi\alpha} \tag{24}$$

The original signal could be high probability of reconstruction using optimization algorithm from observation vector. Defined M/N as compression rate, which is the ratio of CS sampling rate to Nyquist sampling rate. If the signal $\mathbf{x}$ could be sparse representation or be compressed, the problem of solving formula (24) could be converted into minimum 0 norm problem. But this is a NP hard problem. Paper [20] indicated that solving a simpler minimum l_1 norm optimization problem will produce the same solution, so the problem is transformed into

$$\min\|\boldsymbol{\alpha}\|_1 \quad \text{s.t.} \quad \mathbf{y} = \boldsymbol{\Phi\psi\alpha}\,, \tag{25}$$

the reconstruction problem of signals containing noise also can be converted to the minimum l_1 norm problem,

$$\min\|\boldsymbol{\alpha}\|_1 \quad \text{s.t.} \quad \|\boldsymbol{\Phi\psi\alpha}-\mathbf{y}\| \le \varepsilon\,. \tag{26}$$

The basis pursuit (BP) algorithm[21], Matching Pursuit(MP) algorithm[20], Orthogonal Matching Pursuit

(OMP) algorithm[22] could be used to solve the problem of formula (26). This paper will use the basic principle of CS theory and the representative OMP restoration algorithm to complete 60GHz channel estimation simulation. The basic idea of OMP algorithm is that select the best match atom to approximate the observation vector from over-complete dictionary (over-complete dictionary is restore matrix $\mathbf{T}=\mathbf{\Phi\Psi}$). Working out the residual signal, then select the most matching atoms with residual signal. After a certain number of iterations, signals could be linear expression by some atoms. The selected atoms are made orthogonalization when using OMP algorithm. OMP algorithm ensures the optimality of the iteration and reduces the number of iterations.

The methods and steps of sparse channel estimation using the OMP algorithm are described below.

Supposing the observation vector $\mathbf{y}\in C^{M}$, the estimated sparse channel impulse response $\mathbf{h}\in C^{N}$, restore matrix $\mathbf{T}=\mathbf{X_p W_p}, \mathbf{T}\in C^{M\times N}$, sampling noise vector $\mathbf{z}\in C^{M}$. $\mathbf{y}$ and $\mathbf{T}$ are known vector at the receiver. According to CS theory, formula (27) could be obtained

$$\mathbf{y}=\mathbf{Th}+\mathbf{z} \tag{27}$$

Contrast formula (17) and (27), the corresponding relation is that $\mathbf{y}=\mathbf{Y_p}$, $\mathbf{T}=\mathbf{X_p W_p}$, $\mathbf{z}=\mathbf{N_p}$.

The purpose of OMP channel estimation algorithm is recovering the sparse vector **h**, which is to find the location and value of nonzero element in **h**. Since the orthogonality between subcarriers in OFDM system, the atoms in over-complete dictionary (restore matrix $\mathbf{T}=\mathbf{X_p W_p}$) are orthogonal. So to OFDM system, Gram-Schmidt orthogonalization is not needed, which reduces the computational complexity of OMP channel estimation algorithm.

The steps of OMP channel estimation algorithm are described as below:

- Initializing the program, iterations j =0, residual $\mathbf{r_0}$=**y**, index collection $S_0=\varnothing$.
- when $j=1,2,...$,confirm the position of index s_j , s_j should satisfy the formula $\left|<r_{j-1},\tau_{s_j}>\right|=\max\limits_{s\in\{1,\dots,N\}\backslash s_{j-1}}\left|<r_{j-1},\tau_s>\right|$, where τ_s indicates the sth column vector of matrix **T**.
- Fill s_j to index collection $S_j=S_{j-1}\cup\{s_j\}$.
- Obtain the channel estimation value $\hat{h}_{j|s_j}$ in the position of s_j using LS algorithm, $\hat{h}_{j|s_j}=\arg\min\limits_{h\in s_j}\{\left\|\mathbf{y}-\mathbf{T_{s_j}h}\right\|^2\}=\mathbf{T_{s_j}^{-1}y}$, the values outside the index collection are set as 0. Where $\mathbf{T_{s_j}}$ is $M\times j$ dimension matrix and contains all the columns which the index are S_j in restore matrix **T**.
- From formula $\mathbf{y_j}=\mathbf{T\hat{h}_j}=\mathbf{T_{s_j}\hat{h}_{j|s_j}}$, $\mathbf{r_j}=\mathbf{y}-\mathbf{y_j}$, update the observation vector and residuals. If the predetermined iterations J is smaller than j or meets the requirements of approximation error, the iteration stops. Else jump to step (2).

After J times iterations, obtain the J sparse vector $\hat{\mathbf{h}}$.

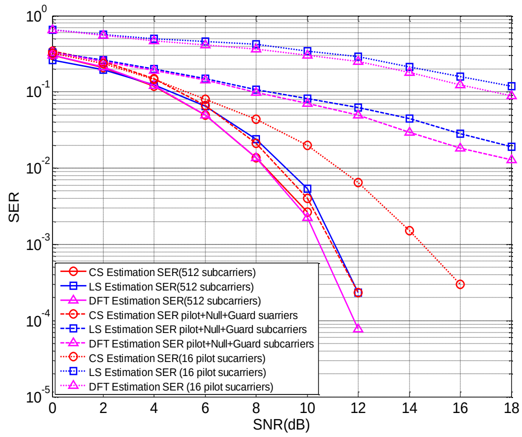

Fig. 9. The SER performance comparison among CS OMP channel estimation algorithm, LS channel estimation algorithm, DFT channel estimation algorithm in CM1.3 channel(DFT estimation length L=10)

Fig. 9 is the LOS channel (CM1.3) estimation simulation result using CS OMP algorithm, LS algorithm, DFT algorithm respectively, the simulation result shows that CS OMP algorithm has similar performance with DFT algorithm and much better than LS algorithm when using all the 512 subcarriers (equaling to training sequence)for channel estimation. When jointing subcarriers are used for channel estimation, the performance using CS OMP algorithm is closed to the performance of CS OMP and DFT algorithms using 512 subcarriers. The CS OMP algorithm based on 16 pilot subcarriers could obtain similar estimation performance to DFT or LS algorithm based on jointing 171 subcarriers. And only have 2dB lower compared to the CS OMP algorithm based on all the 512 subcarriers when the SER is 10^{-2}. This is because the number of multipath is small in LOS channel，the required number for pilot subcarriers is relatively low for CS channel estimation. To CS algorithm, 16 subcarriers have could basically meet the number requirements of sampling points in LOS channel. Simulation results proved that the advantage of CS channel estimation algorithm when the number of subcarriers for channel estimation is small. In 60GHz LOS channel, if the channel is time-variant, the CS algorithm based on jointing subcarriers channel estimation could be adopted and get good performance. When the requirement to estimated accuracy is not high, the CS channel estimation algorithm based on 16 pilot subcarriers also could be adopted. The LS and DFT channel estimation algorithms based on 16 pilot subcarriers could not obtain ideal performance in LOS channel, so these algorithms are not be recommended when using 16 pilot subcarriers.

Fig. 10 is the NLOS channel (CM2.3) estimation simulation result using CS OMP algorithm, LS algorithm, DFT algorithm respectively, the simulation result shows that CS OMP algorithm also has similar performance with DFT algorithm and these two algorithms both better than LS algorithm when using all the 512 subcarriers (equaling to training sequence)for channel estimation. When jointing subcarriers are used for channel estimation, the performance using CS OMP algorithm is closed to the performance of LS algorithm using 512 subcarriers and better than the performance of LS and DFT algorithms using jointing subcarriers. But the performance of CS OMP algorithm based on 16 pilot subcarriers is relatively bad, even worse than the performance of LS and DFT algorithms based on 16 pilot subcarriers. This is because the number of nonzero multipath is big in NLOS channel. The pilot data in 16 subcarriers lower than the number of nonzero multipath and could not meet the sampling points requirements for CS algorithm. So the estimate performance is worst. Jointing subcarriers method have could basically meet the requirements of sampling points for CS algorithm and could get relatively good performance. So in 60GHz NLOS channel when the requirement to estimated accuracy is not high, CS channel estimation algorithm based on jointing subcarriers could be adopted and get good performance. While the CS algorithm, LS algorithm and DFT algorithm based on 16 pilot subcarriers all could not obtain ideal performance and should not be recommended.

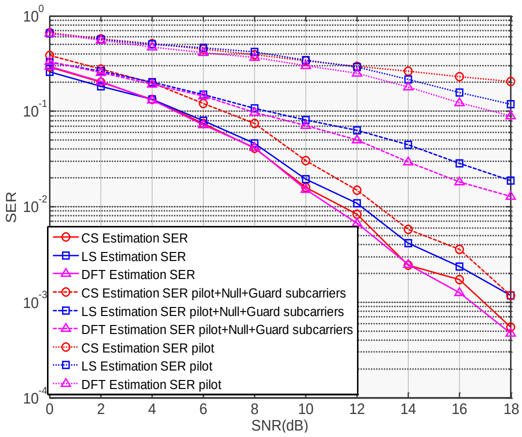

Fig. 10. The SER performance comparison among CS OMP channel estimation algorithm, LS channel estimation algorithm, DFT channel estimation algorithm in CM2.3 channel(DFT estimation length L=128)

V. Conclusion

This paper analyzes the channel characteristic of 60GHz channel. According to 802.15.3c standard, gives the channel estimation methods for 60GHz OFDM system. When channel status changing during one frame, the OFDM data symbols in each frame using the channel estimated value by the training sequence may appear deviation and led to a decline in system performance. At this moment, pilot subcarriers are used to estimate channel. While the estimation precision is relatively bad when using pilot subcarriers. In order to solve the problem of insufficient estimation precision, proposes proper solutions. At the same time presents the simulation results of various channel estimation methods in LOS and NLOS channel respectively. Integrating the simulation results, the following conclusions could be obtained: compare with 16 pilot subcarriers estimation, jointing subcarriers estimation could significantly improve the performance of channel estimation. whether in LOS channel or NLOS channel, The CS OMP algorithm using jointing subcarriers could obtain the similar performance based on 512 subcarriers. If the 60GHz channel is ascertained to be LOS channel, the CS OMP algorithm using 16 pilot subcarriers also could meet the requirement. CS algorithm has obvious advantage when the number of subcarriers for channel estimation is small. The CS OMP channel estimation algorithm using jointing subcarriers provides an efficient channel estimation solution for 60GHz system.

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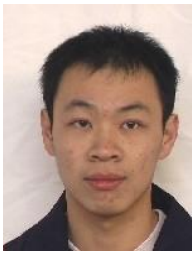

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