³0 4B # U•2095-4980U‹2023UŒE-0065-07

,.ù eE +°/,*» Ò7 E. À]E5 eFyE)CV0Ã"

赵 慧[1]，王 珂[1]，张 伟[1]，张秀再[2a,2b]

(1.!‹7û , j S ' › B &@ê 0 U•!‹7û ƒ Ø 210036Už2. ƒ Ø › /7 S ' a. *a | : › /7 'KŽ Už
b. !‹7û,- S!@(Û ¯ :=ñ 3 ¬ [{ 8 G Ü Y ï U•!‹7û ƒ Ø 210044)

„ >- U•针对实际水声信道无法获知先验稀疏度和导频资源问题，提出一种改进的稀疏度自适应弱选择匹配追踪算法 .4"480.1。将稀疏度初始估计作为初始支撑集的大小，对原子进行阈值弱选择得到的原子支撑集作为回溯筛选的候选集；再以初始支撑集大小为回溯开始初始条件值进行二次筛选；最后利用变阶段步长方法进行稀疏度逐步精确估计，自适应更新回溯开始条件值。仿真实验分析了阈值参数、稀疏度估计步长和导频数目对于 .4"480.1 算法的影响，结果表明，该算法能以更少的导频数目获得更精确的信道估计值，节省导频资源的同时，其均方误差 .4 &优于传统算法。

ŸJZ@ÙU•水声信道；稀疏度自适应；回溯思想；匹配追踪

Y * 21§ # U•TN911.23 ³(Z 3 -- U•A doiU•10.11805/TKYDA2020439

"O NPEJGJFE TQBSTJUZ BEBQUJWF XFBL TFMF

;) " 0) VJ U• 8 " / (, FU• ;) " / (8 F J U• ;) " / (9 J V [BC J
*OGPSNBUJPO $PMMFHF 0OFOHVBO 6OJWFSTJUZ PG 4DJFODF BOE 5FDIOPMPHZ
B4DIPPM PG &MFDUSPOJDT BOE *OGPSNBUJPO &OHJOFFSJOH $FOUFS
&OWJSPONFOU BOE &RVJQNFOU 5FDIOPMPHZ PG *OGPSNBUJPO 4DJFODF 5
/BOKJOH +JBOHTV DIJOB

"CTUSBDU .PEJGJFE 4QBSTJUZ "EBQUJWF 4UBHFXJTF 8FBL 0SUIP
.4"480.1 BMHPSJUIN JT QSPQPTFE UP TPMWF UIF QSPCMFN PG B QSJP
BDUVBM VOEFSXBUFS BDPVTUJD DIBOOFM TQBSTJUZ FTUJNBUJPO JT VT
JOJUJBM TVQQPSU TFU JT PCUBJOFE BT UIF DBOEJEB
UISFTIPME XFBL TFMFDUJPO PG BUPNT TVQQPSU TFU TJ[F JT VTFE BT U
PG CBDLUSBDLJOH UP DPOEVDU TFDPOE TDSFFOJOH TUFQ TJ[F NFUI
FTUJNBUF UIF TQBSTJUZ HSBEVBMMZ BOE VQEBUF UIF CBDLUSBDLJ
TJNVMBUJPO SFTVMUT TIPX UIBU UIF QSPQPTFE BMHPSJUIN DBO PCU
MFTT QJMPU TFRVFODFT NFBO TRVBSF FSSPS UIBO UIBU
UIF USBEJUJPOBM BMHPSJUIN

,FZXPSET VOEFSXBUFS BDPVTUJD DIBOOFM TQBSTJUZ BEBQUJWF CBDLUSBDLJOH

K»,l.ý ' ¬ [+°N EK ý • U• æ1§ •Dú ' U*T"£"7 , ý"£"7+° Ü " U•"£"7 , ý+° ' < ‹ 9 Ù Ì U• % º P EK!` EF L,!n 9 Ù Ê f , y U• % Ã!` E•+° F ° ž œ ¸ " SK MÄ U• ò-š \@Í & E•'â - › ¢ % EK B+°!` E•E =x 5 t C CV U• < f!` EF 2'4 +°Fù>- ˆ % º!` • Ð M½ 2 9*T (Orthogonal Frequency Division MultiplexingU•OFDM)EF U• d*T+° E• \@Í å" 5 , ; ¸ „" (Least SquareU•LS) ¸ , ; s å A (Minimum Mean Square ErrorU•MMSE)U•F) [ & º $L_2$ 8/ œ+° , D \@Í U• 2 E• • †/L ò E• U• 96) •(Ü E• +°/,*» S [1] -@/¢=" : U•!` E• ± T/,*» S [6) K «*T ·4U)2@æ r â [2-4] E =x E• \@Í+° t ß • " OFDM #3ûDó/,*»!` E• : U• U*T ý 00 +° =Fû (M½ › U• Ÿ Fù ° & E•+° " Þ$ì ù À U• 8 " ‹6) û = –

b/k K U•2020-09-08Už K U•2020-11-14
&FýM¥, U•!‹7û , j S ' m 5 À ' M ý • %0,-@/¢A*MÄBp ÕM¥, (19SSWZ-03)Už) â7 &b.ý 'L~ &FýBp ÕM¥, (11504176Už61601230)Už‹
7û,-7 &b.ý 'L~ &FýBp ÕM¥, (BK20141004)

AB£+° ž œ[5−6] ·4U K- +°/,*» # ¤ ·Fù °0Ã" [& º L1 8/ œ3Ò ‹+°0Ã" U•A 1§0Ã" g>-EFDó % #+°/,*» Ò ¸ [½E EhDý U•EFDóE '-š Æ #+° [½Kò Tropp 0u ü &+° • Ð eFyE)CV (Orthogonal Matching PursuitU•OMP)0Ã" [7] T û , M Ü E5 Ë |Kò 4 " U• F U*T , ; ¸ „" Ü E5 Ë |+°3ë S3ð 42' œ • E B • Ð eFyE)CV(Regularized Orthogonal Matching PursuitU•ROMP)0Ã" [8] û ME "E5 K V Ë | U•&b : % IE5 Ë |E =x • E B U• ú58E5 & , D [½Kò Donoho 0u ü & 2 á ; • Ð eFyE)CV (Stagewise Orthogonal Matching PursuitU•StOMP)0Ã" [9]U•EFDó@ê4š , VK4 (K4 hK K|*] • y · :"wFû- Ka4 Ò ß Æ) '8ã Ë | [½Kò fKy z %"wFû - Ka+°>-!n U•Blumensath 0u & º StOMP 0Ã" ü & 2 á] • Ð eFyE)CV0Ã" (Stagewise Weak Orthogonal Matching PursuitU•SWOMP)[10]U• « Ë |E5 ,$ %0¬ • Jian W 0u ü & « u • Ð eFyE)CV (generalized Orthogonal Matching PursuitU•gOMP)[11]0Ã" U•0¬ •@ê4š , V 4E.+° & Æ h S ˆ fE E5 +° Ë | V œ U•A 0Ã" TFù °1ê-š Ò ¸EK Ò 6 D¯OMP 0Ã" F) 5 ´ S+° ü s Milenkovic 0u ü &+° |/¦K E)CV (Subspace PursuitU•SP)0Ã" [12] A ' ² #Û I U• û ME Dó/7 Y Ê Ì Ë |+° 8 " €K• , ÇLŠ , D Ë | U• *… 5K| V LŒ SP +° Ë | Zhao L 0u ü & ,.ù eE +° « u • Ð eFyE)CV0Ã" [13]U•A 0Ã" +° #Û I TE =x eFy Ë |E5 " U• 5 • [½Kò Y Ë |+°2N A V œDê \/, *» ÒK " , ÷ #Û U•E« y ²E I K f •-š Ë | V =58 (7 +° #ÛA ¸Dó F+°@Í0Ã # [13] 9‡ ")_0u , Ü +° ³(Z [14] T OMP 0Ã" &-I 6 ü & eE +° SOMP 0Ã" U• û ME ñE5 : · , eFy , S+° K V2' œ 'Fù & Ë |Kò U• •P –! (Û ¯ 7 S6) D

6E .ùBV –0Ã" U•F)>-!n #+°/,*» Ò K [- +° r T ÊKq À*T Y U•/,*» Ò [V- +° I´ %E .ù ñ á U•Thong 0u ü & ²/,*»7 E. À eFyE)CV (Sparsity Adaptive Matching PursuitU•SAMP)0Ã" [15]Už] " 30u ü & ,.ù eE +°/,*» Ò7 E. À eFyE)CV0Ã" (Modified SAMPU•MSAMP)[16]U• , Æ/7 Ò 6? ß ² SAMP T S/,*» • " 7Dü0Ã FûD¯ S ö & Æ 'J« (7 +° L \@Í ¸Dó \@ÍK MÄ [16]U•D¯ © \ Ê(Ü ² V- #/,*» Ò "+°1ê-šFù &

X ³ & º MSAMP 0Ã" U•<¹ 4K4 h]E5 ¸ #Û I U•3ÿ 4!` E•/,*» S+°'¥%å U• ü & ,.ù eE +°/,*» Ò 7 E. À]E5 eFyE)CV0Ã" (MSASWOMP) A 0Ã" fKy z OFDM 2'4 Y K- - Ka+°@ê@Í>-!n U•E5 Ë | "Fó*T K4 h]E5 U• ¢ T7 E. À/,*» Ò \@ÍE Y<¹ 4 #Û I U• D B Ë |+°E5 U•E« y ²E YDó F+°@Í0Ã # [15] +,K ÊO¸=" : U• ü &+° MSASWOMP 0Ã" T,$ 8 –! • " 7 U• U*T =+° (M½Bp#¼ 8ã ÃD¯ ©+° \@Í t È UžK» ,I –! +° Ê Ì U•MSASWOMP 0Ã" D¯SP gOMP MgOMP(Modified gOMP) SAMP MSAMP 0Ã" \@Í S6) ©

1 2'4 M ·

1.1 !` E• M ·

T OFDM 2'4 Y U• 2!` E• 2 < ´ F | E• U• û V | E• «*T , V |D©" U• 0 V |D©" wK ,$ ¾ • Ð U• ¢=x LD¿ 2P EK ^=x œ š"mD˜ B f zEK ¢=x œ š"m U• 5 t"´K• E•+°M½(³E5 S U• ¢ T û V OFDM 0R # yLŽ þ ' Ö(Û y4, U• ˆ f ,.ù ÐK KÀ U• 5 t"´K• F ° t ÀEL <+°--K ž œ OFDM 2'4 r * ® * 1 I.f

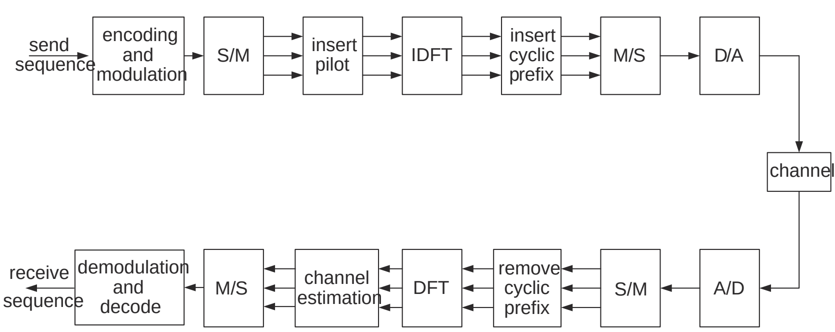

Fig.1 Block diagram of OFDM system

* 1 OFDM 2'4 r *

!` OFDM 2'4 LD¿ Y U• s@ê I 5 |D©" [• Ð+° U• Ÿ!Í 5D©" K ž œ U• E 2 N V |D©" +° œ š0R # $\boldsymbol{X}$ =".f f- Ka Ž ; (œ šD©" y4š4šL")U•

$$\boldsymbol{X}=\begin{bmatrix} X[0] & 0 & \cdots & 0 \\ 0 & X[1] & \cdots & \vdots \\ 0 & \vdots & \ddots & 0 \\ 0 & \cdots & 0 & X[N-1] \end{bmatrix} \tag{1}$$

; Y U•$X[k]$=”.f0X k V |D©" 6+° (M½ # U•$k=0,1,\cdots,N-1$ 3ûDó!` E• : U•E =x ±Fø " Ž U• Ã \ Ñ b+° (M½ #YU•

$$\boldsymbol{Y}=\begin{bmatrix} \boldsymbol{Y}[0] \\ \boldsymbol{Y}[1] \\ \vdots \\ \boldsymbol{Y}[N-1] \end{bmatrix}=\begin{bmatrix} X[0] & 0 & \cdots & 0 \\ 0 & X[1] & \cdots & \vdots \\ \vdots & \vdots & \ddots & 0 \\ 0 & \cdots & 0 & X[N-1] \end{bmatrix}\begin{bmatrix} \boldsymbol{H}[0] \\ \boldsymbol{H}[1] \\ \vdots \\ \boldsymbol{H}[N-1] \end{bmatrix}+\begin{bmatrix} \boldsymbol{Z}[0] \\ \boldsymbol{Z}[1] \\ \vdots \\ \boldsymbol{Z}[N-1] \end{bmatrix}=\boldsymbol{XFh}+\boldsymbol{Z} \tag{2}$$

; Y U•$\boldsymbol{H}$ f!` E•M½ - Ka U• [!` E• Þ$ì ù À $\boldsymbol{h}$ +° ±Fø " Ž Už$\boldsymbol{F}$ f ±Fø " Ž (DFT)- Ka Už$\boldsymbol{Z}$ f(Û ¯ – - Ka

1.2 & º ·4U K- +°!` E• M ·

*] ·4U K-)2@æ[5-7] - U• T - >î"w h $\boldsymbol{y}$ ¸ K- - Ka $\boldsymbol{A}$ +° ñ á 7 U•EFDó!n? ; U•

$$\hat{\boldsymbol{x}}=\arg\min\|\boldsymbol{x}\|_1,\ \text{s.t.}\ \boldsymbol{y}=\boldsymbol{Ax} \tag{3}$$

Ã \ Ë/,*» # $\boldsymbol{x}$ +° \@Í h $\hat{\boldsymbol{x}}$ EF d$\boldsymbol{x}$ f $N\times 1$ 4 /,*» # U•$\boldsymbol{A}$ f $M\times N$ 4 K- - Ka $(M\ll N)$U•$\boldsymbol{y}$ f $M\times 1$ 4 >î"w h X ³ ; (2)0R 4/,*» #+° \@Í Ž ; U• T!` OFDM 2'4 Y U•$\boldsymbol{y}$ ,$ • º Ñ b (M½+°M½ Ž ; $Y$U•$\boldsymbol{A}$ *] $\boldsymbol{XF}$ ° < U•$\boldsymbol{x}$ ,$ • º!` E• " Þ$ì ù À $\boldsymbol{h}$ T U*T (M½ #E =x E• \@Í " U• 2 œ šD©" y4š4šL" U• E $\boldsymbol{X}$=”.f f U•

$$X[k]=\begin{cases} X[k], & k\in N_{\mathrm{p}} \\ 0, & k\notin N_{\mathrm{p}} \end{cases} \tag{4}$$

; Y N_{p} f (M½ I T y4š+° |D©" Kò 4 & º ·4U K- +°!` E• \@Í!n? M · f U•

$$\hat{\boldsymbol{h}}=\arg\min\|\boldsymbol{h}\|_1,\ \text{s.t.}\ \boldsymbol{Y}=\boldsymbol{XFh}+\boldsymbol{Z}=\boldsymbol{Ah}+\boldsymbol{Z} \tag{5}$$

2 eE +°/,*» Ò7 E. À]E5 eFyE)CV0Ã"

X ³ & º MSAMP 0Ã" U•<¹ 4K4 h]E5 ¸ #Û I U• ü & ,.ù eE +°/,*» Ò7 E. À]E5 eFyE)CV0Ã" (MSASWOMP)E =x E• \@Í MSASWOMP 0Ã" I f U•NÂ tE =x/,*» Ò I ÷ \@Í U• • ˆ f I ÷ [½Kò+° S ; U•&b : % Ë |E =xK4 h]E5 U•8ã Ë | [½Kò ˆ f ¸ M0‡E5+° EE5Kò Už¹ I ÷ [½Kò S ; f #Û , ÷ • "E =x ¸ M0‡E5 Už , : U*T SAMP +° Kb á ‘J« å" E =x/,*» ÒE< ‘1ê-š \@Í U• ¢ TE \@Í Y7 E. À Ü #Û I ÷ • " h S ; U• €K• F …LŠ D Ë | 7 ú I ÷/,*» Ò \@Í K4 h]E5 ¸<¹ 4 #Û I 0Ã" ‘OÐ0u 5 åLŽ ‘? ¼ I ü0Ã"

2.1 I ÷/,*» Ò \@Í

eFy0Ã" +° IC U•NÂ tE5 ¸ # · eFy+° Ë |3ð < , V ¢ o2L V œ*‘ ; º Ë #,K Ê/,*» Ò K +°Kò 4 gU•=”.f f U•

$$g=|<\boldsymbol{A}^{\mathrm{T}},y>| \tag{6}$$

@ê g_i =”.f g +°0Xi V o2L U• ú g YE5 y K_0 V , S o2L I % À+° Ë | U• ¢@Ü • % ÀE Ç Ë |+°2N AKò 4 f F_0 , VD¯ ©+° I ÷/,*» Ò %0Ã" Dü0Ã t(³ 5 ´ S ü s [15] ³(Z [15]EFDó P Ù \@Í/,*» Ò [R$ Bß 5K|0uC S (Restricted Isometry Property U•RIP) ‘-š Æ • y/,*» Ò [RE. 4 ³(Z [16]@í : ² ©MÄ1U• ® È % º ' ; K/,*» # U• 5 $\delta_K\in(0,1)$U• « $\boldsymbol{\Phi}$ $ BßRIP • " ® È $K_0\geqslant K$U• E 5

$$\left\|\boldsymbol{\Phi}_{F_0}^{\mathrm{T}}\boldsymbol{y}\right\|_2\geqslant\frac{1-\delta_K}{1+\delta_K}\|\boldsymbol{y}\|_2 \tag{7}$$

EÏ t ©MÄ1 +°E2 R ©MÄ ® È $\left\|\boldsymbol{\Phi}_{F_0}^{\mathrm{T}}\boldsymbol{y}\right\|_2\leqslant\frac{1-\delta_K}{1+\delta_K}\|\boldsymbol{y}\|_2$U• E $K_0\leqslant K$ ‹ </÷ EFDó E2 R ©MÄ @ê4š K_0 I ÷ h U•

® È$ Bß 9 0u ; $\left\|\boldsymbol{\Phi}_{F_0}^{\mathrm{T}}\boldsymbol{y}\right\|_2 \leqslant \frac{1-\delta_K}{1+\delta_K}\|\boldsymbol{y}\|_2$U• E 9 Ù Ê Ì K_0U•, \ 9 0u ; 9 </÷ • "+° K_0+° h Ÿ f I ÷/,*» Ò \ @Í h

2.2 K4 h]E5 ¸ #Û I

,$D¯ º OMP 0Ã" U•StOMP 0Ã" 5 P +°@Í0Ã t(³ ¸Fù °1ê-š Ò U• r StOMP 0Ã" YK4 h+°@ê4š ß º • y · :"wFû- Ka4 Ò T ÊKq!` OFDM 2'4 Y U• K- - Ka $\boldsymbol{A}$ [*] $\boldsymbol{XF}$ ° < U• f ²Ky z K- - Ka@ê@Í 9 n Ò U• X ³Fó*TK4 h]E5 å" [13] L4 0Ã" T Ë |E5 Kb áF) Fó*T ,.ù Ë |E5 0,*' U• X ³ TK4 h]E5 : Ì ' #Û0‡E5U•EFDóK4 h]E5 +° Ë | • † #ÛKb á+° EE5 Ë | T #Û0‡E5Kb áU•! D¯ • "+°K4 h]E5 +° Ë | [½Kò S ; : I ÷ [½Kò K_0 8 S º K_0U• EE5K4 h]E5 +° Ë | Y+° y K_0 V , S h U• €K•LŠ D Ë | Už8 ; º K_0U• E • y [½KòE =x Kb á 'J« å" E =x/,*» ÒE< '1ê-š \@Í U• ¢7 E. À Ü #Û I ÷ • "+°0‡E5 h S ;

2.3 0Ã" 'OÐ

MSASWOMP 0Ã" 'OÐ £ • ® 7 U•

D¿ ' U•>î"w h $\boldsymbol{y}\in\mathbf{R}^{m\times 1}$U• K- - Ka $\boldsymbol{A}=\boldsymbol{XF}\in\mathbf{R}^{m\times n}$U•/,*» Ò \@Í 'J« $step>0$U• · K K| εUž

D¿ &U•!` E• " Þ$ì ù À $\boldsymbol{h}$+° \@Í h $\hat{\boldsymbol{h}}$Už

1) I ÷ B/,*» Ò $K_0=1$U• I ÷ B $\hat{\boldsymbol{h}}_0=0$U• [½Kò F_0 f/¦Kò Už

2) @Í0Ã # · eFy $g=|<\boldsymbol{A}^{\mathrm{T}},\boldsymbol{y}>|$U• 2 , S+° y K_0M¥ % À+° 7 32N A „ ' [½Kò F_0Už

3) 8 $\left\|\boldsymbol{A}_{F_0}^{\mathrm{T}}\boldsymbol{y}\right\|_2 \leqslant 0.5\times\frac{1-\delta_K}{1+\delta_K}\|\boldsymbol{y}\|_2$U• E $K_0=K_0+step$U•D˜7 2)Už R E U•8 $\left\|\boldsymbol{A}_{F_0}^{\mathrm{T}}\boldsymbol{y}\right\|_2 \leqslant \frac{1-\delta_K}{1+\delta_K}\|\boldsymbol{y}\|_2$U• E $step=\lceil 0.5\times step\rceil$U• $K_0=K_0+step$U•D˜7 2)Už8 $\left\|\boldsymbol{A}_{F_0}^{\mathrm{T}}\boldsymbol{y}\right\|_2 > \frac{1-\delta_K}{1+\delta_K}\|\boldsymbol{y}\|_2$U•D˜7 4)Už

4) @Í0Ã I ÷ · $r_0=\boldsymbol{y}-\boldsymbol{A}_{F_0}(\boldsymbol{A}_{F_0}^{\mathrm{T}}\boldsymbol{A}_{F_0})^{-1}\boldsymbol{y}$U• I ÷2N A hKò 4 F_0U• ` "Kò 4 J_k,C_k f/¦Kò U• I ÷ BKb á $stage=1$U• I ÷ BE M œ $k=1$U• I ÷ BKb á 'J« $step1=\lceil 0.5\times step\rceil$U• I ÷ [½KòJ« Ò $size=K_0$Už

5) @Í0Ã # · eFy $g_k=|<\boldsymbol{A}^{\mathrm{T}},\boldsymbol{r}_{k-1}>|$Už

6) K4 h]E5 U•E5 g_k Y S ºK4 h+° h*K <Kò 4 V_kU• ¢ 2 % À Ë | 7 32N A „ ' J_kUž

7) #Û0‡E5U•8 $\|J_k\|_0 \geqslant size$U• ú V_k YE5 & , S+° $size$ V o2L ¢ ª & % À T J_kKò 4 Y+°2N A#' Ì \ C_kU•$F_k=F_{k-1}\cup C_k$Už8 $\|J_k\|_0<size$U• E $F_k=F_{k-1}\cup J_k$Už

8) !` E• \@Í U•$\hat{\boldsymbol{h}}_k=(\boldsymbol{A}_{F_k}^{\mathrm{T}}\boldsymbol{A}_{\mathrm{Fk}})^{-1}\boldsymbol{A}_{F_k}^{\mathrm{T}}\boldsymbol{y}$Už Ü · U•$\boldsymbol{r}_k=\boldsymbol{y}-\boldsymbol{A}_{F_k}\hat{\boldsymbol{h}}_k$Už

9) 8 $\left\|\hat{\boldsymbol{h}}_k-\hat{\boldsymbol{h}}_{k-1}\right\|_2\leqslant\varepsilon_1$U• ED˜7 10)U• R ED˜7 11)Už

10) 8 $\left\|\hat{\boldsymbol{h}}_k-\hat{\boldsymbol{h}}_{k-1}\right\|_2\leqslant\varepsilon_2$U• E ˆ ŽE U• R ED˜7 12)Už

11) 8 $\|\boldsymbol{r}_k\|_2>\|\boldsymbol{r}_{k-1}\|_2$U• E $stage=stage+1$U•$size=size+step1$U•$\hat{\boldsymbol{h}}=\hat{\boldsymbol{h}}_k$U•D˜7 5)Už R E $F_{k+1}=F_k$U•$\boldsymbol{r}_{k+1}=\boldsymbol{r}_k$U•$k=k+1$ D˜7 5)Už

12) 8 $\|\boldsymbol{r}_k\|_2<\|\boldsymbol{r}_{k-1}\|_2$U• E $stage=stage+1$U•$step1=\lceil 0.5\times step1\rceil$U•$size=size+step1$U•$\hat{\boldsymbol{h}}=\hat{\boldsymbol{h}}_k$U•D˜7 5)Už R E $F_{k+1}=F_k$U• $\boldsymbol{r}_{k+1}=\boldsymbol{r}_k$U•$k=k+1$ D˜7 5)

0Ã" Y 'OÐ 1)~4) ¸ < ²/,*» Ò+° I ÷ \@Í ö · [½Kò+° I ÷ B Už5)~12) ' T MSAMP 0Ã" +° r â 7<¹ 4]E5 ¸ #Û0‡E5E =xE D B ¢ Y U•]E5 K4 h $th=\alpha\times\max(\mathrm{abs}(g))$U•$0<\alpha<1$Už[.]=".f = 6 Už'OÐ 9) 'OÐ 10) Y+° ε_1 ¸ ε_2*T º Ó b/,*» Ò 'J« ¸0Ã" 3ô ŽE @ $\varepsilon_1>\varepsilon_2$ [14]

3 ÊO¸ +,K

fO¸@í X ³ MSASWOMP 0Ã" +° 5 t S U•Fó*Tbellhop !` E• +,KD› "E =x/,*»!` E• ° & [17]U•@ê4š , V ý 0#¼ ¸ , V Ñ b0 U•# Ò 2 W@ê4š f10 m,20 mU•!` ŸC .ç f 1 000 mU•!`# 150 mU• s , EK (A +,K(Û ¯ @ê4š £ 5 =" S) ý 0 #Fó*T • Ð,$/'JZ Ó (Quadrature Phase Shift KeyingU•QPSK)A/ b U• ý 0#¼ ý 0 9,$ Ÿ+° K» f-- o » C U•0R #EK(³ f 4 ksymbols/sU• ÌP Û+© – * 2 4 & ² +,K E•+° ~ , B Þ$ì ù À4 % h

3.1 K4 h]E5 î œ α ¸/,*» Ò \@Í 'J« $step$

+,K2'4 î œ U• |D©" œ, 256U• û V0R # y Ì ÐK KÀJ« Ò f 16U•OFDM 0R # -4 "K f 27.2 μsU•Fó*TK» f j4š (M½ å ;E =x \@Í X M ÊO¸P Û – *a Ÿ8/ ú 0 dB \ 30 dBU• * 2 ¸ * 3 2 W4 & ²K4 h]E5 î œ α /,*» Ò \@Í ‘J« *step* 9 8 h "K»,l – B+° E• \@Í+° s åA (MSE)U• E• \@Í+° MSE Æ u f U•

$$MSE = E\left[\left\| \boldsymbol{h} - \hat{\boldsymbol{h}} \right\|_2^2\right] \tag{8}$$

; Y U•$\boldsymbol{h}$ f +,K E•+° " ù À Už$\hat{\boldsymbol{h}}$ f \@Í+° E• " ù À ú * 3 - U•K4 h]E5 î œ α 0.4~0.6 " U• E• \@Í S6)D¯ Už • α 0.7 " U• \@Í S6) S q ü s Užα 0.8 ¸ 0.9 " U• E• \@Í S6)D¯ © q X ³ MSASWOMP 0Ã" YK4 h]E5 î œ α 0.9 ú * 4 - U• l ÷ ‘J« V S U•/,*» Ò \@Í " F &(Ü L \@Í Už l ÷ ‘J« V ; U• \@Í1ê-š Ò zU• q X ³/,*» Ò \@Í ‘J« *step*=6

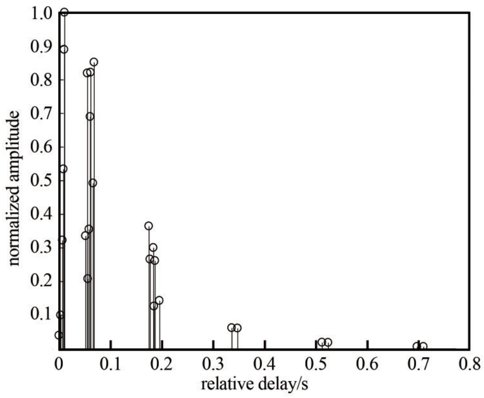

Fig.2 Normalized impulse response of simulation channel

* 2 +,K E•+° ~ , B Þ$ì ù À

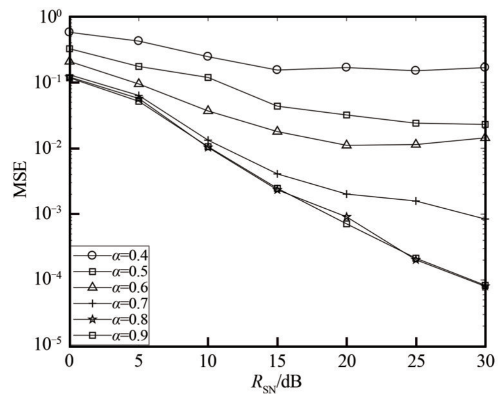

Fig.3 Comparison of MSE in different threshold values when parameter is weakly selected

* 3 9 8K4 h]E5 î œ α " MSE ! D¯

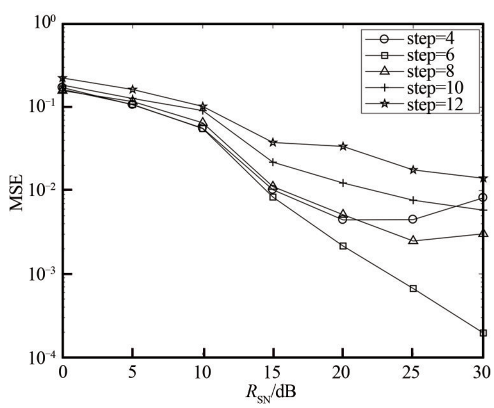

Fig.4 Comparison of MSE in different step sizes with different sparsity estimation

* 4 9 8/,*» Ò \@Í ‘J« step " MSE ! D¯

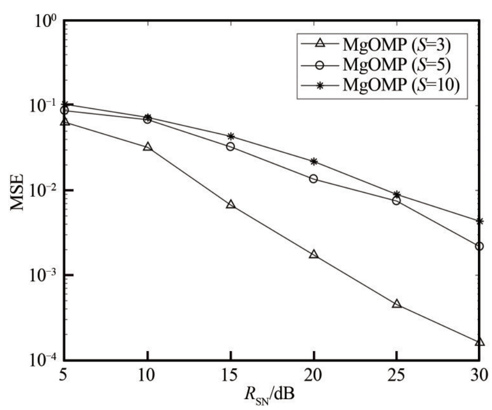

Fig.5 MSE curves of MgOMP algorithm under S=3, S=5 and S=10

* 5 MgOMP 0Ã" T S=3 S=5 ¸ S=10 +° MSE 3ë

3.2 MgOMP 0Ã" Ë | V œ S E5

*] ³(Z [13] - U•MgOMP 0Ã" E E5 +° Ë | V œ S +° œ , • ù E• \@Í t È S f 3 5 ¸ 10 "+° E• \@Í MSE 3ë %! ® * 5 l.f K»,l –! +° Ê Ì U•MgOMP 0Ã" E• \@Í+° MSE E<#< û ; U• T S=3 " U• ¢ \@Í S6)E © º S=5,10U• q MgOMP 0Ã" E5 S=3 E =x,$ Ÿ ÊO¸ %!

3.3 K- - Ka $\boldsymbol{A}$ +°=x œm ¸ (M½ œ , N_P

f O¸@í X ³ MSASWOMP 0Ã" +° \@Í S6) U• * 6 4 & ² SP, gOMP, MgOMP(S=3), SAMP, MSAMP, MSOMP ¸ MSASWOMP 0Ã" +° ÊO¸! D¯3ÿ È T #J« Ò n=256U•/,*» Ò K=12U•D¿ ‘ –! R_{SN}=20 dB " U• K- - Ka $\boldsymbol{A}$ +° =x œm ú 20 \ 200U• 5&“ ŽK C f 20 E =x@ê4š û , V@ê4š h U• 0 \@Í0Ã" (/÷Dü=x 100 MU• • \@Í E•+° D¿ & –! (Output SNR) B±Dú20 dBU• Ÿ E• \@Í1ê-š Ò P *] * 6 - U• K- - Ka $\boldsymbol{A}$ +°=x œm f 40~60 " U• MSASWOMP 0Ã" ¸ SAMP 0Ã" Ã \+° Output SNR Dý h ,$0u U• @ D º ¢ 0Ã" Už K- - Ka $\boldsymbol{A}$ +°=x œm>60 " U• MSASWOMP 0Ã" MSOMP 0Ã" ¸ gOMP 0Ã" -D¯ ©+° \@Í S6) U• ¢ Y U•MSASWOMP 0Ã" Ã \+° Output

SNR D º MSOMP 0Ã" ¸ gOMP 0Ã" U•58SAMP 0Ã" K»,I=x œ m +° Ê Ì U• ¢E M œ ‹ T Ê Ì U• &(Ü/,*» ÒDó \@Í U• D¿ & –! E<#<Ky z U• \@Í S6) • U•MSASWOMP 0Ã" TD¯ =+°=x œ m " U• Ã \D¯ ©+° \@Í S6) 58 T !` E• OFDM 2'4 Y U• (M½ œ, ß Æ ² K- - Ka A +°=x œU• * 7 4 & 00Ã" T 3.1 ÊO¸ +,K2'4 î œ • " 7 U•D¿ ' –! R_{SN}=20 dB " U• (M½ œ, N_P ú 20 \ 100U• 5&" ŽK C f 10 E =x@ê4š+° ÊO¸3ÿ È • \@Í E•+°D¿ & –! (Output SNR)B±Dó20 dBU• Ÿ E• \@Í1ê-š ÒP *] * 6 - U• (M½ œ, N_P T 20~30 " U•SAMP 0Ã" \@Í S6)D¯ © Už • N_P>30 " U•K»,I (M½ œ, Ê Ì U• E• \@Í S6)B· º/_ Æ U•MSASWOMP 0Ã" D¯MSOMP 0Ã" ¸ SAMP 0Ã" 6)8ã Ã ©+° \@Í S6) 4(6 U• X ³ ü &+° MSASWOMP 0Ã" U*T =+° (M½Bp#¼ U•8ã ÃD¯ ©+° E• \@Í t È

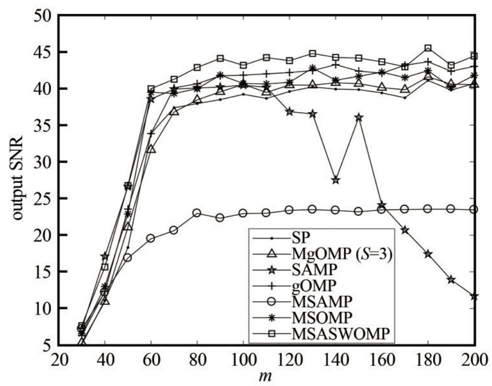

Fig.6 Output signal to noise ratio of perception matrix A with different row numbers m

* 6 K- - Ka A T 9 8=x œ m "+°D¿ & –!

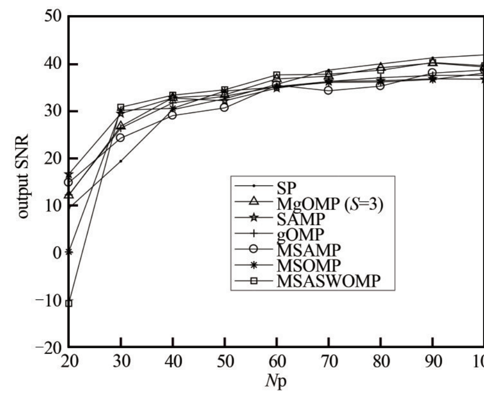

Fig.7 Output signal to noise ratio of different pilot numbers(N_P)

* 7 9 8 (M½ œ, (N_P)+°D¿ & –!

3.4 OFDM !` E• \@Í +,K

T 3.1 ÊO¸ +,K2'4 î œ • " 7 U• X ÊO¸E5 (M½ œ, N_P=30,80 " U•P Û – *a Ÿ8/ T 0~30 dB B+° E• \@Í û , V@ê4š h U• \@Í0Ã" (/÷Dü=x 100 M

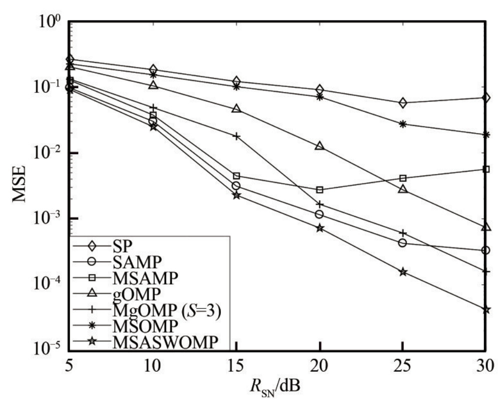

Fig.8 MSE curves of different algorithms when N_P=30

* 8 N_P=30 " 9 80Ã" +° MSE 3ë

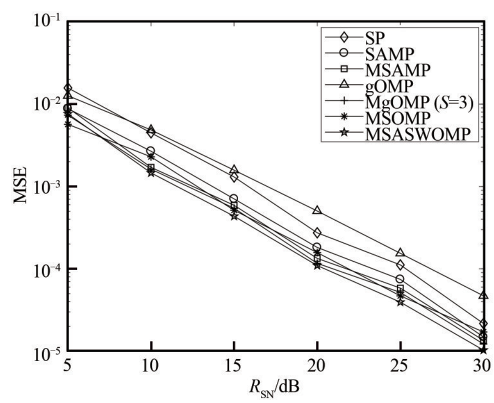

Fig.9 MSE curves of different algorithms when N_P=80

* 9 N_P=80 " 9 80Ã" +° MSE 3ë

MSASWOMP 0Ã" : SP,SAMP,MSAMP,gOMP,MgOMP(S=3) 0Ã" ¸ MSOMP 0Ã" +° E• \@Í+° MSE 3ë ® * 8 (N_P=30 ") * 9(N_P=80 ") I.f *] * 8 - U• • N_P=30 " U• (M½ œ, D¯ =U•3ÿ 4 * 6 * 7 I.f +,K ÊO¸3ÿ È U• • "+° MSASWOMP,MSOMP,SAMP ¸ MgOMP(S=3)+° E• \@Í S6)D¯ © U• ¢ Y U•MSASWOMP +° \@Í S6)*' © U• K»,I –! +° Ê Ì U•MSASWOMP 0Ã" - ©+° E• \@Í t È Už*] * 9 - U• • N_P=80 " U• (M½ œ, Ê Ì U• SAMP 0Ã" \@Í t È U•MSOMP,MSAMP ¸ MgOMP(S=3) 0Ã" \@Í t È ü s ¢ Y U•MgOMP(S=3) 0Ã" ÑDý MSOMP 0Ã" +° \@Í t È U•MSASWOMP 0Ã" : ¢ 0Ã" ,$! U• £ 5 /_ Æ 58 D¯ ©+° E• \@Í S6) • U• MSASWOMP 0Ã" U*T =+° (M½Bp#¼ U•8ã Ã ©+° E• \@Í t È

4(6 lE U• X ³ MSASWOMP 0Ã" +° \@Í S6)D¯ SP,gOMP,MgOMP(S=3),SAMP,MSAMP,MSOMP 0Ã" ©

4 3ÿ@æ

I´ % ÊKq!` E•/,*» Ò V- ñ á U• X ³ ü & ² ,.ù eE +°/,*» Ò7 E. À]E5 eFyE)CV0Ã" (MSASWOMP)U•

EFDó ÊO¸ +,KE5 4E.+°K4 h]E5 î œ α ¸/,*» Ò \@Í ‘J« U• @í ² X ³0Ã" +° \@Í1ê-š Ò • (M½ œ, D¯ = " U• MSASWOMP 0Ã" +° \@Í S6) : j D º ¢ 0Ã" UžK»,l (M½ œ, +° Ê Ì U• ¢ 0Ã" \@Í S6)E<#< ü s U• ÑDý X ³ MSASWOMP 0Ã" S6) • U•A 0Ã" I´ %!` E•+°/,*»'¥ S U• =+° (M½ œ, 8ã Ã 1ê-š+° E• \@Í h UžK» ,l –! Ê Ì U•A 0Ã" D¯SP,gOMP,MgOMP,SAMP,MSAMP ¸ MSOMP 0Ã" £ 5 ©+° E• \@Í S6)

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[ ] $"/%&4 &0+#&3(5+"0 53PCVTU VODFSUBJOUZ QSJODJQMFT CBTFE TUSVDUVSF DPOTUSVDUJPO GSPN ... JOGPSNBUJPO 5SBOTBDUJPOT PO *OGPSNBUJPO 5IFPSZ
[ ] ;":&% "4*$).&*44&3/(FX QFSTQFDUJWFT PO BQQSPYJNBUF ... BOBMZTJT [4QSJOHFS *OUFSOBUJPOBM 1VCMJTIJOH
[ ] 450+"/07*$&.GGJDJFOU QSPDFTTJOH ... 1IZTJDBM $PNNVOJDBUJPO
[ ] -* 813&*4*(+&T5 UJNBUJPO PG ... PG 0DFBOJD &OHJOFFSJOH
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[ ] #-6.&/4"5) %"7*&4 .4 UBHFXJTF XFBL ... 4JHOBM 1SPDFTTJOH
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L K (1995−)U•*cU•-• U• Õ)2 /7 4 U• g>--@/¢ å = f #0)2 .

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