An Adaptive Space-time DFE Combined with Successive Interference Cancellation

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Abstract - **We investigate the use of a multi-element antenna array (MEA) at the base station (BS) in a time division multiple access (TDMA) broadband fixed wireless access (BFWA) system. At high data rates the intersymbol interference (ISI) induced by dispersive channels becomes a technological bottleneck. Space-time processing at the BS offers a solution to improve the wireless link quality in the uplink. First, we investigate the performance of a space-time decision feedback equalizer (DFE) trained with the LMS algorithm for a single user BFWA system (i.e. one user per frequency channel and per time slot). Then we propose an algorithm for space division multiple access (SDMA) in the uplink based on a combination of adaptive space-time equalization and successive interference cancellation (SIC). It is shown via simulations that this combined approach offers an improvement in the probability of symbol error (P_S) for a two-user system (i.e. two users per frequency channel and per time slot) compared to a space-time DFE without SIC. The RLS algorithm is used for the two-user system to ensure fast convergence. The proposed iterative approach offers a low complexity solution compared to minimum mean square error solutions based on direct matrix inversion, which would be costly for the expected delay spreads associated with BFWA systems.**

I. INTRODUCTION

The use of a multi-element antenna array (MEA) at the base station (BS) of a single carrier time division multiple access (TDMA) broadband fixed wireless access (BFWA) system is considered in this paper. Space-time processing at the BS offers an interesting solution to combat the detrimental effects induced by the BFWA channel. Installing a MEA at the BS will be the first step to achieve higher capacity and give resilience to fading in future BFWA systems. A MEA at the BS improves the wireless link quality through receive diversity and antenna gain and further enables space division multiple access (SDMA) in the uplink. Multi-user communication on the same frequency channel and at the same time slot in the uplink (i.e. SDMA) is the key to improve the throughput of future BFWA systems.

Successive interference cancellation (SIC) has been extensively investigated in the context of code division multiple access (CDMA) systems [1, 2, 3, 4]. However the application of SIC in TDMA systems has received relatively little attention. Early work on SIC for TDMA has concentrated on single antenna systems [5, 6]. However the performance improvement obtained through SIC is poor in this case. Hence, the main theme of this paper is the combination of SIC with multiple BS antennas in the context of SDMA/TDMA systems, where more substantial performance improvement is envisioned.

SDMA has been investigated for single carrier wireless communication systems [7, 8, 9]. However, in these studies SDMA was not combined with SIC. It should be noted that V-BLAST uses a similar approach to the one proposed here, however it is computationally expensive owing to the use of signal ordering based upon the pseudoinverse of the vector channel transfer function [10, 11]. In order to lower complexity the user signals in the proposed system are ordered based upon the magnitude of the channel estimates. Further, SDMA combined with SIC has been investigated for multi-carrier OFDM systems [12]. The optimum minimum mean square error (MMSE) solution for the space-time DFE can be obtained by direct matrix inversion, which is however very costly for the expected delay spread associated with BFWA systems. To overcome this problem, we train our space-time DFEs with the LMS or RLS algorithms and use low complexity correlation-based channel estimation as well as correlation-based user power estimation in our proposed adaptive SDMA/TDMA detection algorithm.

II. SPACE-TIME CHANNEL MODEL

The performance of space-time algorithms strongly depends on the spatial properties of the 3D channel. Nevertheless, many of the performance studies conducted to date, assume that the elements of the channel matrix are independently distributed.

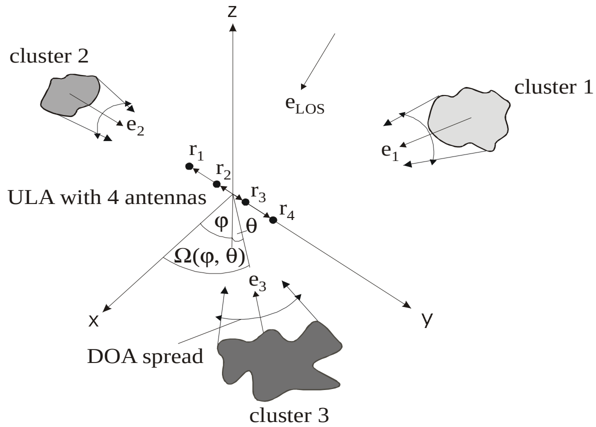

Fig. 1: GWSSUS channel model

This is difficult to justify from a physical standpoint and so in our study, we employ the Gaussian wide sense stationary uncorrelated scattering (GWSSUS) channel model [13, 14]. In doing so antenna geometry, spacing and correlation coefficient are all taken into account. A detailed description of the GWSSUS channel model shown in Fig. 1 is beyond the scope of this paper, but can be found in the cited literature.

It has been observed via propagation measurements [15] that for macroscopic environments, the direction of arrival (DOA) follows a Gaussian distribution. To model the power delay profile we use characteristic SUI-2 from [16], which represents a strongly Ricean propagation environment for BFWA systems operating in the multi-channel multipoint distribution services (MMDS) band.

Each cluster c is modelled with the following equation, which gives the channel taps $\boldsymbol{h}_{u,c}=(h_{u,1,c}\ h_{u,m,c},\ \ldots,\ h_{u,M,c})^T$ for user u and cluster c, for antennas m=1…M (here: u=1…U and c=1…C):

$$\boldsymbol{a}_{l,m}(\Omega_l)=e^{-j\frac{2\cdot\pi}{\lambda}\cdot\boldsymbol{e}(\Omega_l)\bullet\boldsymbol{r}_m},\quad \boldsymbol{a}_{LOS,m}(\Omega_{LOS})=e^{-j\frac{2\cdot\pi}{\lambda}\cdot\boldsymbol{e}(\Omega_{LOS})\bullet\boldsymbol{r}_m}$$

$$\boldsymbol{h}_{u,c}=A_{LOS}\cdot e^{j\phi_{LOS}}\cdot\boldsymbol{a}_{LOS}+\frac{1}{\sqrt{N_{scat}}}\sum_{l=1}^{N_{scat}}A_{Ray}\cdot e^{j\phi_l}\cdot\boldsymbol{a}_l \quad (1)$$

where: $\boldsymbol{a}$ is the spatial signature or steering vector
$\boldsymbol{e}\bullet\boldsymbol{r}$ is the vector dot product
l is the scatterer index (l=1…N_{scat})
Ω is the 3D DOA $\Omega(\varphi, \theta)$
λ is the wavelength
ϕ_l is the phase component of the individual scatterer
ϕ_{LOS} is the phase component of the line-of-sight (LOS) component
A_{LOS} is the path amplitude of the LOS component
A_{Ray} specifies the amplitude of the Rayleigh component generated via the summation

Note that small bold face letters are vectors and that capital bold face letters are matrices.

$$A_{LOS}=\sqrt{\frac{1}{1+\frac{1}{K}}\cdot P_{tap}},\quad A_{Ray}=\sqrt{\frac{1}{1+K}\cdot P_{tap}} \quad (2)$$

where: P_{tap} is the channel tap power specified by the SUI-2 channel model and K is the K-factor, i.e. $K=\frac{A_{LOS}^2}{A_{Ray}^2}$

The position of the antenna elements is modelled with the '$\boldsymbol{r}$' vector. The '$\boldsymbol{e}$' vectors are unit vectors pointing towards the uniform linear array (ULA) corresponding to their DOA. The phase components of the LOS and of the Rayleigh component are uniformly distributed from 0 to 2π. We assume a Gaussian distributed DOA spread of 3° for the Rayleigh components. For K=0 and A_{LOS}=0 one gets a Rayleigh distribution and hence the LOS terms in (1) can be neglected. Each cluster corresponds to one SUI-2 channel tap. Further horizontal wave propagation is assumed, and hence we do not model the elevation θ. Therefore the 3D DOA Ω reduces to a 2D DOA, which is equal to the azimuth φ in our model (Fig. 1). The number of scatterers N_{scat} for each cluster is 50. Further, we assume burst mode digital communication in which the channel is static during one burst. Table 1 gives the mean DOA and DOA spread used:

	e_{LOS}	e_0	e_1	e_2
mean DOA	60°	30°	80°	40°
DOA spread	0°	3°	3°	3°

Table 1: GWSSUS model parameters

DOA spread	3°		
spacing	0.5·λ	5·λ	10·λ
ρ	0.95	0.84	0.87
DOA spread	10°		
spacing	0.5·λ	5·λ	10·λ
ρ	0.95	0.83	0.87
DOA spread	40°		
spacing	0.5·λ	5·λ	10·λ
ρ	0.92	0.84	0.84

Table 2: Simulated cross-correlation ρ for GWSSUS SUI-2

Table 2 gives the simulation results for the cross-correlation ρ of the received symbols for various antenna spacings and DOA spreads. ρ is computed between adjacent antennas with a burst of 4000 symbols averaged over 100 channel realizations with a 4 antenna ULA at an SNR of 20dB. It is striking to realize that for the simulated scenario, ρ is always above 0.8 even for a DOA spread of 40° and an antenna spacing of 10·λ. The high cross-correlation is caused by the strong LOS component (i.e. K=10 in our simulation).

The proposed TDMA/SDMA system consists of a number of subscriber units with one antenna and a BS equipped with an M-element antenna array. The SUI-2 channel has 3 taps (corresponding to 3 clusters) and a total channel span of 1μs. This gives rise to frequency selective fading for the target QPSK symbol rate of 5MS/s. The received signal $\boldsymbol{X}$ in matrix notation is [18]:

$$\boldsymbol{X}=\boldsymbol{N}+\sum_{u=1}^{U}\boldsymbol{X}_u=\boldsymbol{N}+\boldsymbol{H}\cdot\boldsymbol{S} \quad (3)$$

where: $\boldsymbol{N}$ is a M x L AWGN matrix
$\boldsymbol{H}$ is the M x ($U\cdot C$) channel impulse matrix
$\boldsymbol{S}$ is the ($U\cdot C$) x L matrix of transmitted user symbols
$\boldsymbol{X}_u$ denotes the part of the signal caused by user u
L is the total number of transmitted symbols
C is the total number of channel taps (i.e. clusters)

$$\boldsymbol{H}=\begin{bmatrix}\boldsymbol{h}_{1,1}^T & \ldots & \boldsymbol{h}_{U,1}^T\\ \vdots & \ddots & \vdots\\ \boldsymbol{h}_{1,M}^T & \ldots & \boldsymbol{h}_{U,M}^T\end{bmatrix},\quad \boldsymbol{h}_{u,m}^T=\left(h_{u,m,1}\ldots h_{u,m,C}\right)$$

$$\boldsymbol{S}=\begin{bmatrix}\boldsymbol{S}_1\\ \vdots\\ \boldsymbol{S}_U\end{bmatrix},\quad \boldsymbol{S}_u=\begin{bmatrix}s_{u,1} & \cdots & s_{u,C} & \cdots & s_{u,L}\\ \vdots & \ddots & \vdots & & \vdots\\ 0 & \cdots & s_{u,1} & \cdots & s_{u,L-C+1}\end{bmatrix}$$

Using this notation, the channel impulse response matrix $\boldsymbol{H}$ is composed of the following individual user 2D vector channel impulse responses $\boldsymbol{H}_u$:

$$\boldsymbol{H} = \begin{bmatrix} \boldsymbol{H}_1 & \cdots & \boldsymbol{H}_U \end{bmatrix},\ \boldsymbol{H}_u = \begin{bmatrix} h_{u,1,1} & \cdots & h_{u,1,C} \\ \vdots & \ddots & \vdots \\ h_{u,M,1} & \cdots & h_{u,M,C} \end{bmatrix} \qquad (4)$$

Additionally at each antenna processing branch RRC filtering is performed with a roll-off factor of 0.35 and 20 samples per symbol.

III. SPACE-TIME ADAPTIVE DFE COMBINDED WITH SUCCESSIVE INTERFERNCE CANCELLING

To detect individual users, we use a space-time decision feedback equalizer (DFE) [19] at the BS using the well known RLS adaptation algorithm.

First we use a correlator-based channel estimation method to obtain synchronization, user channel estimates $\tilde{\boldsymbol{H}}_u$ and user signal power. A detailed description of the correlation-based channel estimation method is beyond the scope of this paper but is available in [20]. Our SIC is based on an estimate of the user signal power obtained via the correlator. Based on the user signal power and without loss of generality, the users in our SDMA system are ordered from user 1 to user U in such a way that the strongest is labelled user 1 and the weakest is labelled user U. The detection process starts first by detecting the strongest signal (i.e. user 1). Then the effect of the strongest user $\boldsymbol{X}_1$ on the antenna array input $\boldsymbol{X}$ is estimated via the following operation:

$$\tilde{\boldsymbol{X}}_1 = \tilde{\boldsymbol{H}}_1 \cdot \boldsymbol{Y}_1,\ \boldsymbol{Y}_1 = \begin{bmatrix} y_{1,1} & \cdots & y_{1,C} & \cdots & y_{1,L} \\ \vdots & \ddots & \vdots & & \vdots \\ 0 & \cdots & y_{1,1} & \cdots & y_{1,L-C+1} \end{bmatrix} \qquad (5)$$

where: $\tilde{\boldsymbol{H}}_1$ is the 2D vector channel estimate of user 1 obtained from the correlator and $\boldsymbol{y}_1 = (y_{1,1} \cdots y_{1,L})$ are the symbol decisions for user 1.

$\tilde{\boldsymbol{X}}_1$ is then subtracted from $\boldsymbol{X}$ to form the input to the second stage, where user 2 is detected. This process is repeated until the weakest user is detected. In this way the interference contributions of all the stronger users are cancelled before the weaker user is detected.

IV. NUMERICAL SIMULATION RESULTS

A. Single user diversity system

This subsection of our simulation study shows the performance of the space-time DFE receiver trained with the LMS algorithm for one user per frequency channel and per time slot. We assume a ULA with an antenna spacing of $0.5 \cdot \lambda$. The DOA spread is set to 3°, and the other settings for the GWSSUS model are as in Table 1.

Fig. 2 gives the convergence rate for this system for different numbers of antennas. It is interesting to see that as the number of antennas increases the convergence rate is improved, though at the cost of increased complexity. The minimum mean square error (MSE) is greatly improved when employing more antennas. The SNR at the input to the antenna array is set to 20dB. The feedforward filter (FF) of the space-time DFE has 8 symbol spaced taps and the feedback filter (FB) has 7 symbol spaced taps. The maintap is set to FF tap 6.

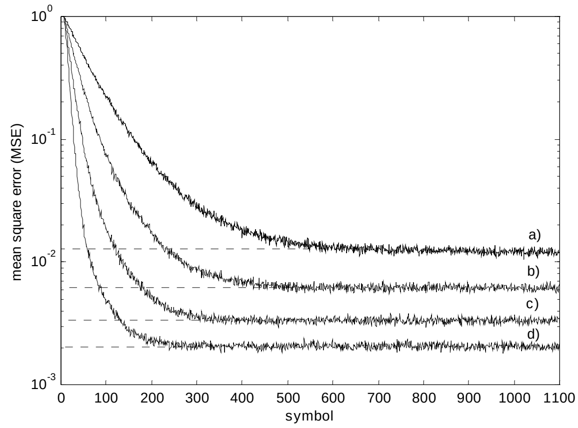

Fig. 2: convergence rate for SUI-2, ULA(0.5 λ spacing), DOA spread 3°: a) 1 antenna, b) 2 antennas, c) 4 antennas and d) 8 antennas

Fig. 3 shows the probability of symbol error (Ps) as a function of SNR for different numbers of antennas. The following parameters are chosen to compute the Ps for the four different systems:

a) 1 antenna: training sequence length = 1000 symbols
b) 2 antenna: training sequence length = 800 symbols
c) 4 antenna: training sequence length = 400 symbols
d) 8 antenna: training sequence length = 300 symbols

The payload of each burst is set to 4000 data symbols and in addition 200 symbols are reserved for synchronization and correlation operations. It can be seen that Ps can be greatly improved for a single user system by the use of a MEA at the BS.

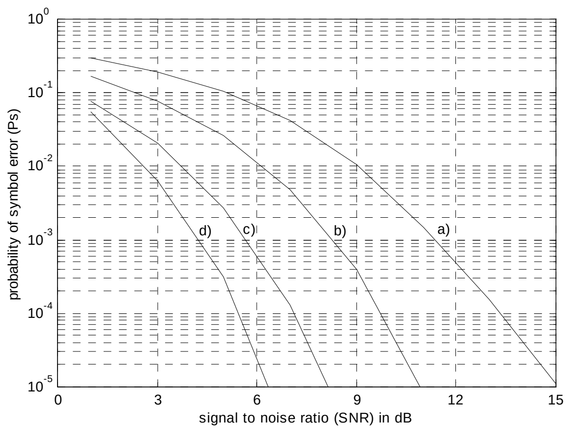

Fig. 3: Ps for one user system: a) 1 antenna, b) 2 antennas, c) 4 antennas and d) 8 antennas

B. Multi-user communication without SIC

Secondly we investigate the performance of a multi-user SDMA/TDMA system without SIC. We assume 2 users per channel and a 2 element MEA at the BS. We use the RLS algorithm to train our space-time DFEs for this case, since the LMS converges very slowly for a 2 user system. A ULA with an antenna spacing of $10 \cdot \lambda$ is employed. The FF of the space-time DFE now has 15 symbol spaced taps and FB now has 10 symbol spaced taps. The maintap is set to FF tap 10. These filter lengths were selected after performing a number of simulations with different DFE architectures and establishing the minimum MSE. Table 1 gives the mean DOA setting for user 1 and Table 3 gives the mean DOA setting for user 2.

	e_{LOS}	e_0	e_1	e_2
mean DOA	40°	80°	20°	80°
DOA spread	0°	3°	3°	3°

Table 3: GWSSUS model parameters for user 2

In Fig. 4 the $\mathrm{SNR} = \frac{\mathrm{Power}_{\mathrm{user1}}}{\mathrm{Power}_{\mathrm{noise}}}$ is 20dB and further the $\mathrm{SIR} = \frac{\mathrm{Power}_{\mathrm{user1}}}{\mathrm{Power}_{\mathrm{user2}}}$ is set to 5dB. It is seen, that full convergence is achieved at 400 symbols. The minimum MSE of the weaker user 2 without SIC (Fig. 4: d) noSIC u2) is worse than the minimum MSE of the stronger user 1 (Fig. 4: a) noSIC u1). This is simply because the effective SNR for user 2 is only 15dB. The computed Ps via Monte Carlo simulations for this system is plotted together with the Ps of the system employing SIC in Fig. 5 and Fig. 6. The training sequence length is set to 400 symbols and the payload is 4000 data symbols.

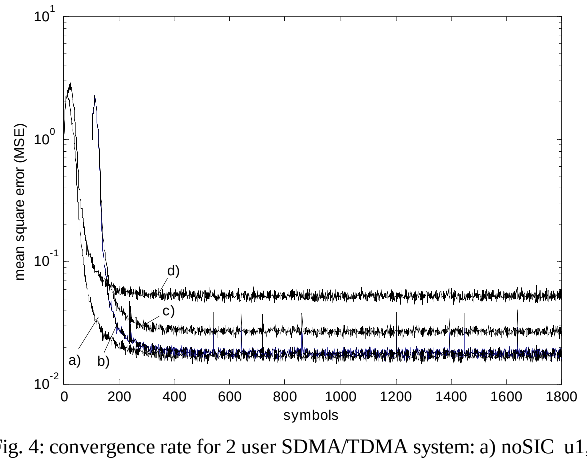

Fig. 4: convergence rate for 2 user SDMA/TDMA system: a) noSIC u1, b) idealSIC u2, c) corSIC u2 and d) noSIC u2

C. Multi-user communication with SIC

Fig. 4 shows also the convergence rate when SIC is employed. The figure shows that the RLS algorithm for user 2 is started 100 symbols after user 1. This ensures more reliable symbols for initial convergence. The glitches evident in the figure are caused by error propagation effects when SIC is used. This effect has been also investigated in [12]. Looking at each symbol decision when the glitches occur reveals that every time the user 1 detector makes a symbol error, these errors also cause symbol errors in the user 2 detector. This is, because instead of cancelling interference one adds interference if the symbol decisions $\boldsymbol{Y}_1$ used to generate $\tilde{\boldsymbol{X}}_1$ are incorrect. Note also that the error glitches in Fig. 4 appear smaller than they are in reality because the presented convergence rate curve is the average of 500 realizations. The actual squared error is around 1.5 when such a glitch occurs.

Curves CorSIC u2 and idealSIC u2 of Fig. 5 give the Ps of user 2 when SIC is employed using ideal and estimated channels, respectively at an SIR of 5dB. Similar results are presented at an SIR of 0dB in Fig. 6. With a system having an equal number of antennas and users, SIC shows a significant improvement. SIC is particularly effective if significant interference power remains after the first space-time DFE. The overall improvement is limited to that of the Ps of the strongest user (Fig. 5: noSIC u1).

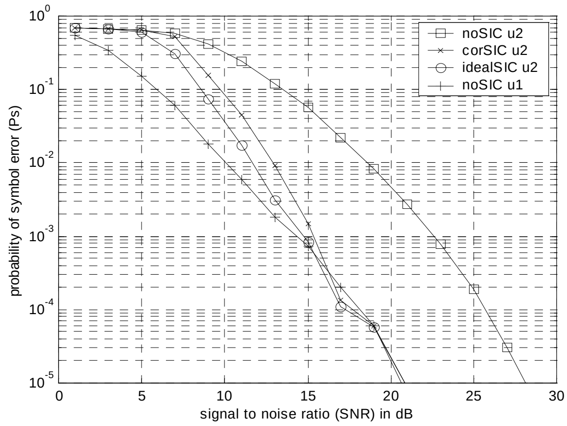

Fig. 5: probability of symbol error (Ps) for SIR=5dB

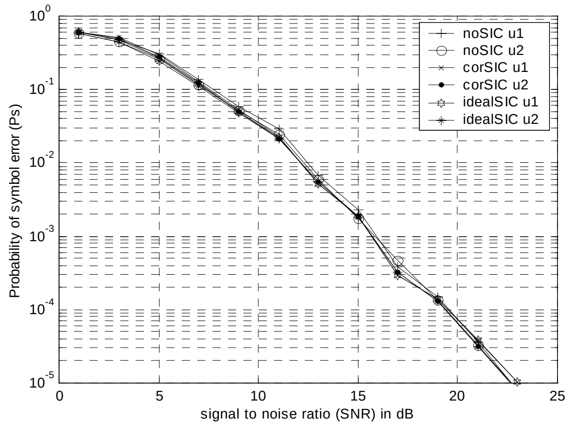

Fig. 6: probability of symbol error (Ps) for equal power users (i.e. SIR=0dB)

The reason is that symbol detection errors from the user 1 detector propagate through to the user 2 detector and cause symbol errors to occur there.

For the simulated environment in Fig. 5 where the user signal power ratio is 5dB it can be seen that SIC improves system performance for the weaker user. However, for situations, where both users have similar signal powers as in Fig. 6, SIC does not improve performance. Therefore a check on the received signal powers should be performed and only if the SIR exceeds a certain threshold then should SIC be performed.

V. CONCLUSIONS

The combination of a space-time DFE with SIC improves the Ps of a weaker user to a great extent for MMDS SDMA/TDMA BFWA systems employing 2 SDMA users and 2 antennas at the BS. Whenever the space-time DFE cannot effectively suppress the interference power of other users, the application of SIC shows an improvement. However in situations where both users signals have similar power, the additional SIC stage is not likely to provide a significant performance improvement.

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