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Design of TDD/TDMA 4G System with Link Adaptation

[1]Liu Zunxiong, [2]Xu Zheng, [3]Feng Xingle and [4,5]Lu Zhaogan
[1]School of Information Engineering, East China Jiaotong University, Nanchang, China
[2]School of Electrical and Electronic Engineering, East China Jiaotong University, Nanchang, China
[3]School of Information Engineering, Chang'an University, Xi'an, China
[4]The 212 Institute of China North Industries Group Corportation, Xi'an, China
[5]School of Electronic Engineering, Xidian University, Xi'an, China

Abstract: In current 4G system given in recent literatures, channel estimation overhead and complexity of Multi-User Detectors (MUD), may lead to bad performance in fast fading channel scenarios when large number of users exists. So, a novel 4G system with TDD/TDMA as duplex and wireless access is designed to reduce channel estimation spending and avoid MUD, as only one user can be active to communicate with base station. Under the requirement of 4G systems, radio frame structure is elaborately designed to fit for fast fading channel scenarios. The system architecture with consideration of link adaptations for a novel eigenmodes coupled universal space-time codes, is given and evaluated for performance of TDD/TDMA 4G systems. Results show the proposed TDD/TDMA 4G can meet the requirement of 4G system under the classical ITU channel profiles.

Key words: MIMO, OFDM, link adaptation, space-time codes, eigenmodes

INTRODUCTION

Since, the 3rd-generation (3G) wireless mobile communication networks was deployed throughout the world, the designs of 3G beyond or the 4th-generation (4G) wireless communications systems under frequency selective fast fading channel scenarios has recently attracted a lot of attention. Many design schemes based MIMO and OFDM were given by recent literatures (Bin *et al*., 2005; Ping *et al*., 2005; Zheng *et al*., 2005), such as VSF-OFCDM by DoCoMo Japan (Bin *et al*., 2005), TDD-MIMO-OFDM by FuTURE project of China (Ping *et al*., 2005), TDD-CDM-OFDM as the evaluated version of TD-SCDMA by Datang Mobile (Zheng *et al*., 2005) and so on.

However, Code-Division Multiple Access (CDMA) or Orthogonal Frequency-Division Multiple Access (OFDMA) are adopted by these 4G schemes. When user terminals equipped with multiple transmit antennas, 2 intractable issues are caused, i.e., channel estimation bandwidth overhead and complexity of Multiple User Detectors (MUD). According to channel estimation theory (Myung-Sun *et al*., 2005), the length of training sequences in time domain and frequency domain are at least Mt times that of channel profiles or the number of carrier tones, respectively, where Mt denotes the number of transmit antennas. For the scenarios with many users simultaneously communicating with Base Stations (BS), the length of pilot sequences will increase proportionally with the number users in current covering areas. In frequency fast fading wireless channels, channel information must be frequently estimated by transmitting pilot sequences in smaller intervals than that for slow fading channel environments. Thus, the bandwidth overhead of channel estimations will be the main appropriator of channel resources and decreases spectrum efficiency. Another problem is the proportionally increasing complexity of MUDs with the numbers of users and their transmit antennas, as every transmit antenna at terminals can be regarded as one user with single transmit antenna. As the increase of users, the MUDs will be badly effected by the interference of signals from different transmit antennas at different user terminals.

Here, we design a novel 4G mobile communication system with Time Division Duplex (TDD) and Time Divisions Multiple Access (TDMA). Based on MIMO and OFDM technology, the 4G scheme with 20 MHz bandwidth can reduce channel estimation overhead and avoid MUD as only one user can communicate with BS at a time. However, efficient scheduling algorithms must be conducted to allocate corresponding bandwidth resources to different users in the proposed TDD/TDMA 4G system. For the limitation of length, this paper only considers PHY design and its performance evaluation.

PHY DESIGN

The target frequency band for this system is 2-5 GHz due to favorable propagation characteristics and low

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Corresponding Author: Lu Zhaogan, The 212 Institute of China North Industries Group Corporation, Xi'an, 710065, China
Tel: +86-15929776465

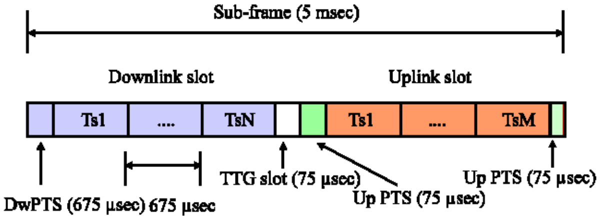

Fig. 1: Frame structure of TDD/TDMA 4G system

Radio Frequency (RF) equipment cost. According to technical requirements of the broadband cellular channel and practical constraints of hardware and RF, the PHY design of TDD/TDMA 4G systems is given in following.

Frame structure: In order to meet the requirement (Zhou *et al*., 2008) of fast beamforming in high moving speed as 120 km h^{-1} when the smart antenna technology is deployed, the length of radio sub-frame is taken as 5 msec similar to that of TD-SCDMA radio sub-frame, other than 10 msec in WCDMA/TDD systems.

As shown in Fig. 1, a radio frame with duration of 5 msec is subdivided into 7 main Time Slots (TS) of 675 µsec duration each and four special time slots: down link synchronization (DwPTS), switch slot from down links to up links (TTG slot), up link synchronization (UpPTS) and switch slot from up links to down links (RTG slot). Time slot TS0 is always used for down links, whereas the other time slots can be used for either up links or down links, depending on flexible switching point configuration. The location information about TTG Slot, UpPTS and switch points would be sent to mobile stations by information transported in TS0. As the synchronization slot for down links, DwPTS can calibrate the synchronization between BS and MS, estimate and compensate carrier frequency offset due to frequency drift of carrier generators at transmitter and receivers. So does the UpPTS for up links. Due to the requirement of synchronization accuracy of timing and carriers, their durations are determined to 75 µsec so that BS and MS can achieve the same synchronization performance. For systems with TDD, switch slots between up links and down links should be greater than the maximum round time of radio between transmitter and receivers, that is double of the maximum radio delay profiles (Yang and Li, 2006). According to the profiles of the ITU Vehicular Channel (channel B), after referring to frame structure in 802.16a TDD (Yang and Li, 2006) and initial frame structure in TD-SCDMA (Wang *et al*., 2005), the durations for TTG and RTG is 75 and 50 µsec, respectively, under the limation of the 5 msec radio sub-frame length.

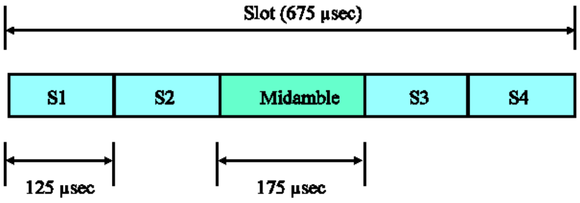

Fig. 2: Burst structure of TDD/TDMA 4G systems

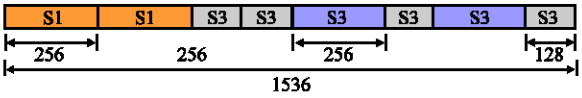

Fig. 3: Structure of synchronization slot for TDD/TDMA 4G systems

Burst structure: The burst structure of the data time slots consists of 4 data blocks and 1 training signal for channel estimation in time domain, as showed in Fig. 2. Actually, one data block is one MIMO OFDM symbol, whose duration is 125 µsec, while midamble is the training symbols for channel estimations in time domain and the estimated channel information is used to decode data symbols before and after midamble codes. The sample rate of IFFT/FFT for data blocks is 20.48 MHz.

Synchronization slots: Synchronization slots for up links and down links have the same slot structures with 1536 samples and are designed to conduct timing synchronization and carrier frequency offset estimation through identical training sequences distributed in different intervals, as displayed in Fig. 3. Firstly, two identical training sequences S1 transmitted in series by transmitters are used to obtain coarse timing synchronization by calculating the delay correlation function of training sequences. Subsequently, fine timing synchronization is done through 2 training sequences S3. Furthermore, the conjoint 2 S3 have small time delay with large frequency offset estimation range and can be also used to conduct coarse frequency offset estimation. Then, different delay S2 and S3 have large delay with small frequency offset estimation range and are used to perform fine frequency offset estimation by averaging their estimated frequency offsets.

Stainer channel estimation: The midamble symbols are used to conduct channel estimation and track channel fluctuation information and both data symbols before and after midamble can be checked out according the estimated channel states by midamble. Compared with FuTURE B3G TDD systems (Zheng *et al*., 2005;

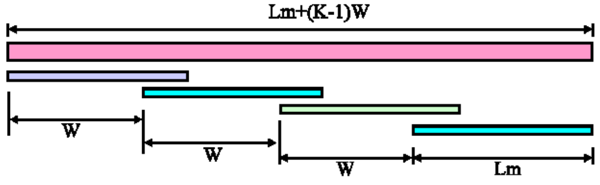

Fig. 4: Construction of Midamble by truncating the circular extended version of a basic sequence

Quoting *et al*., 2005; Nanda *et al*., 2005), channel estimation overhead is reduced greatly with simple implementation. The midamble code with duration about 175 μsec consists of 3585 samples and is obtained by truncating the circular extended version as showed in Fig. 4.

Denote Lm as length of training sequence, W as length of spatial channel impulse respondence and L = W×M_t as length of a basic sequence, which can be delineated as:

$$m = (m_1, m_2, \ldots, m_{L1}) \tag{1}$$

Its circular extension version is given by:

$$\bar{m} = \left(\bar{m}_1, \bar{m}_2, \ldots, \bar{m}_{L_m + (M_t - 1)W}\right) \tag{2}$$

where, the first L elements are consistent with corresponding elements of the basic sequence and other elements are determined by:

$$\bar{m}_i = m_{i-L},\ i = (L+1), \cdots, \left[L_m + (M_t - 1)W\right] \tag{3}$$

Then, training sequences for different transmit antennas are obtained by truncating the circular extended version. Furthermore, the pilot for the *u*-th transmit antenna is presented as:

$$m^{(u)} = \left(m_1^{(u)}, m_2^{(u)}, \ldots, m_{L_m}^{(u)}\right) \tag{4}$$

Where:

$$m_i^{(u)} = m_{i+(M_t-1)W},\ m_i^{(u)} = m_{i+(M_t-1)W},\ u = 1, \ldots, M_t \tag{5}$$

If the design parameters showed above can be denoted as a quaternion (L_m, L, M_t, W), there exists the following relationship among these parameters, i.e.:

$$W = \left\lfloor \frac{L_m}{M_t + 1} \right\rfloor,\ L = WM_t \tag{6}$$

where, operator $\lfloor \cdot \rfloor$ denotes the largest integer not more than a given real number in the operator.

However, the training sequences given by Eq. 4 are generally described as binary sequences and should be converted into complex number. Firstly, they are re-presented as bi-polar sequences and then further converted into complex numbers. Denote $\vec{m}^{(u)}$ as one bi-polar sequence, $m_c^{(u)}$ as its correspondent complex form, which can be determined by:

$$m_c^{(u)}(i) = (j)^i \cdot \vec{m}^{(u)}(i),\ i = 1, \ldots, L \tag{7}$$

where, j is unit of imaginary number.

It is the elaborately designed training symbols as showed above, that result in the circular pilot matrix. So, the pilot sequence pilot design scheme can avoid matrix inversion calculation and the complexity of MIMO channel estimation can be further reduced.

LINK ADAPTATION

Eigenmodes coupled with space-time codes: Firstly, a universal space-time code can be defined as a rate T/K Mt×K design scheme over a complex subfield A of the complex field ℂ, whose codeword matrix X is a Mt×K matrix with entries obtained from the K-linear combinations of T data symbols and their conjugates. If a codeword matrix X is represented as a column vector by stacking its columns, the column vector can be delineated as the linear transform of T data symbols and their conjugates, i.e.:

$$\mathrm{vec}(X) = \Phi s \tag{8}$$

where, vec(X) denotes the column vector by stacking the columns of a matrix into one column vector, $\hat{s}$ is a column vector whose elements consist of T data symbols and their conjugates and the transform matrix Φ is denoted as the generation matrix of the space-time code design scheme.

The least squared estimation of $\hat{s}$ can be achieved as following:

$$\hat{s} = \left(\tilde{H}\Phi\right)^{-1} \mathrm{vec}\left(y^T\right) + \hat{w} \tag{9}$$

where, $\hat{w} = \left(\tilde{H}\Phi\right)^{-1} \mathrm{vec}\left(w^T\right)$, y is the received signal matrix whose rows are the received data symbols polluted by channel fading and noise at every receive antennas, w is the corresponding noise of y, $\hat{s}$ denotes the estimation version of s and $\tilde{H}$ is the equivalent channel matrix assembled by fading coefficients at different carriers for different spatial links.

Let $\bar{H} = \tilde{H}\Phi$, it can be decomposed into orthogonal eigenmodes by singular value decomposition as showed:

$$\bar{\mathrm{H}} = \mathrm{UDV}^{\mathrm{H}} \qquad (10)$$

where, U and V denote the unitary matrices representing the left and right eigenvectors of $\bar{\mathrm{H}}$, respectively and D is a diagonal matrix, whose elements are the ordered singular values of $\bar{\mathrm{H}}$, i.e., the corresponding fading coefficients of those orthogonal eigenmodes.

Then, substituting $\bar{\mathrm{H}}$ by its SVD, we can get:

$$\mathrm{U}^{\mathrm{H}}\mathrm{vec}(\mathrm{y}^{\mathrm{T}}) = \mathrm{DV}^{\mathrm{H}}\mathrm{s} + \mathrm{U}^{\mathrm{H}}\mathrm{vec}(\mathrm{w}^{\mathrm{T}}) \qquad (11)$$

Now, let $\mathrm{y}' = \mathrm{U}^{\mathrm{H}}\ \mathrm{vec}(\mathrm{y}^{\mathrm{T}})$, $\mathrm{s}' = \mathrm{V}^{\mathrm{H}}\mathrm{s}$, $\mathrm{w}' = \mathrm{U}^{\mathrm{H}}\ \mathrm{vec}(\mathrm{w}^{\mathrm{T}})$ and Eq. 4 can be rewritten as:

$$\mathrm{y}' = \mathrm{Ds}' + \mathrm{w}' \qquad (12)$$

Furthermore, it is also equivalent to:

$$\begin{cases} \mathrm{y}_i' = \sqrt{\lambda_i}\,\mathrm{s}_i' + \mathrm{w}_i' & (i = 1, 2, \cdots, r) \\ \mathrm{y}_i' = \mathrm{w}_i' & (i = r+1, r+2, \cdots, m) \end{cases} \qquad (13)$$

where r and $\sqrt{\lambda_i}$ are the rank of $\bar{\mathrm{H}}$ and its i-th singular value, respectively.

System architecture with link adaptation: Considering a TDD/TDMA 4G systems with 2 and 8 antennas at MS and BS, its system architecture is designed as showed in Fig. 5, where the simplified block diagrams of MS and BS are given in Fig. 5a and b, respectively. Furthermore, Adaptive Modulation and Codes (AMC), Adaptive Power Control (APC) and Adaptive Space Time Codes (ASTC)

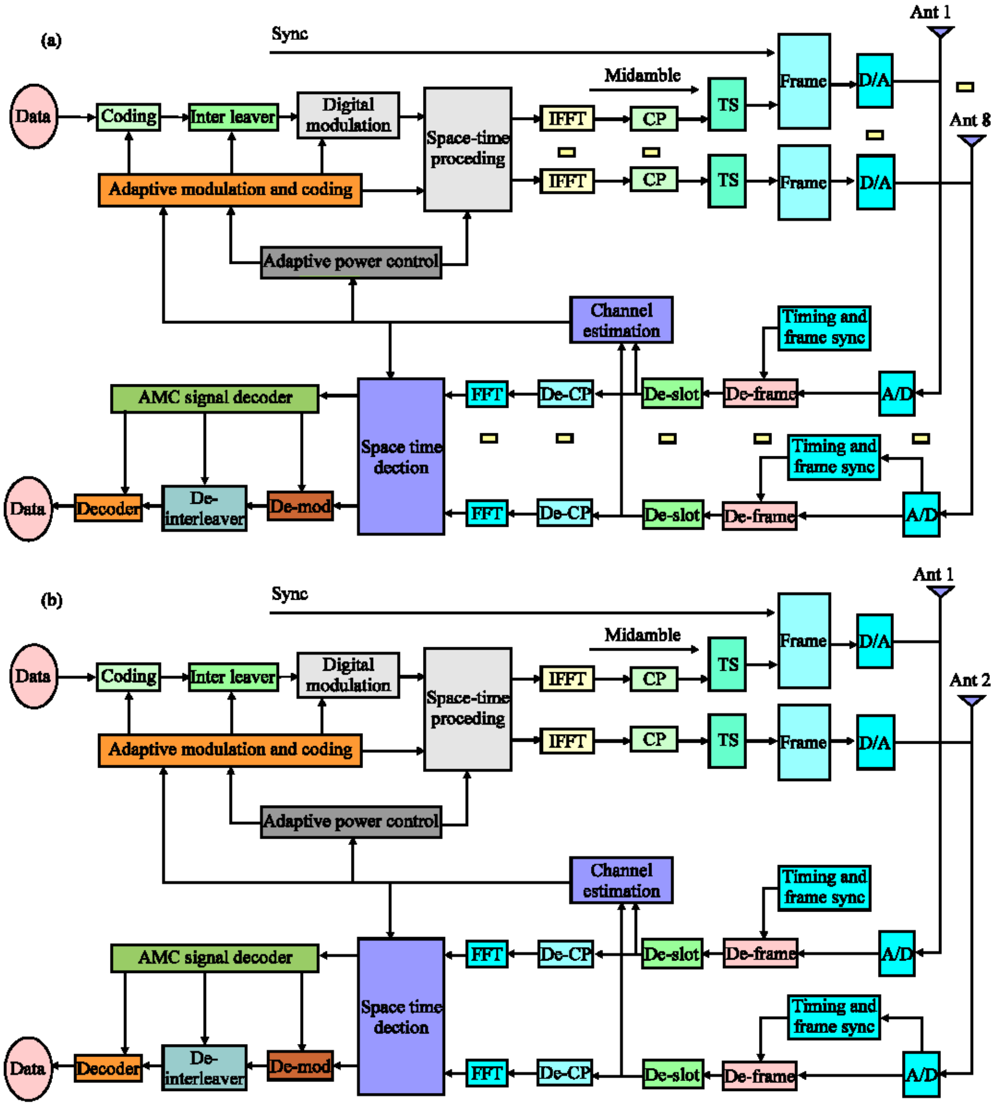

Fig. 5: System Architecture of TDD/TDMA 4G System, (a) Block diagram of BS and (b) Block diagram of MS

Table 1: System configuration of TDD/TDMA 4G, DoCoMo 4G and FuTURE TDD

		DoCoMo 4G		
System configuration	TDD/TDMA 4G	VFS-OFDM (downlink)	MC/DS-CDMA (uplink)	FuTURE TDD
FFT/IFFT sample rate	20.48 Msps	135 Msps	--	24.15 Msps
Carrier frequency	2 GHz	4.635GHz	4.9 GHz	3.5 GHz
Chip rate	--	--	16.384 Mcps	--
FFT size	2048	1024	--	1024
Carrier bandwidth	11.16 kHz	131.836 kHz	20 MHz	19.5 kHz
No. of low frequency guard sub-carrier	127	127	--	69
Number of high frequency guard sub-carrier	128	128	--	70
Number of Pilot Sub-carrier	0	0	--	52
Number of data sub-carrier	1792	768	2	832
Cyclic prefix duration (us)	25	1.674	--	10.6
Symbol duration (us)	125	9.259	--	53
Length of radio frame (ms)	5	0.481 (48 Data + 4 Pilot symbols)	0.5	5
Bandwidth	20 MHz	100 MHz	40 MHz	20 MHz
Antenna configuration	2×8	2×4	2×4	2×8
Number of sub-carrier	2048	1024	2	1024
Wireless access	TDMA	CDMA	CDMA	TDMA/OFDMA
Duplex	TDD	FDD		TDD

are used to conduct link adaptation with eigenmodes detailed in section 3.1. Compared with DoCoMo 4G (Bin *et al*., 2005) and FuTURE TDD (Ping *et al*., 2005), the proposed TDD/TDMA 4G systems have smaller carrier bandwidth and simple implementation and can fit for larger cell area with fast fading channel scenarios. What's more, the configuration with 2×8 antennas at MS and BS could also make TDD/TDMA 4G system serve as an evolution version of TDS-CDMA 3G system, proposed by Datang Mobile. Their system configuration could be shown in Table 1.

PERFORMANCE EVALUATION

The outage capacity of TDD/TDMA 4G systems for outage probability of 0.1 is evaluated under the ITU indoor and vehicle channel scenarios (Zheng *et al*., 2005) with velocity of 250 and 500 km h^{-1}, as showed in Fig. 6. According to the results indicated by Fig. 6, the OFDM technology can convert frequency selective channels into flat fading sub-channel, which have approximate system spectrum efficiency as that of flat fading systems. Furthermore, the system capacity of TDD/TDMA 4G systems in up links is similar to that in down links and this can owe to the coupled MIMO with OFDM technology, which can fit bad wireless channel conditions. At the Signal Noise Ratio (SNR) of 25 dB with 20 MHz bandwidth, the outage capacity for outage probability of 0.1 can achieve to 400 Mbps, enough for the requirement of data transmission rate 100 Mbps under indoor scenarios.

According to channel state informations at transmitter, 4 power allocation algorithms (Quoting *et al*., 2005; Nanda *et al*., 2005) were conducted to determine the transmit power for different transmit

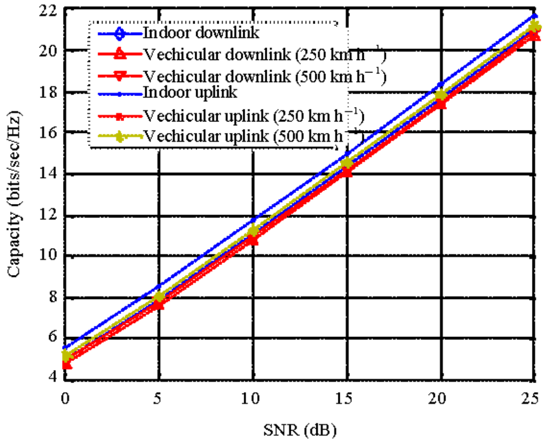

Fig. 6: Outage capacity of TDD/TDMA 4G for outage probability of 0.1

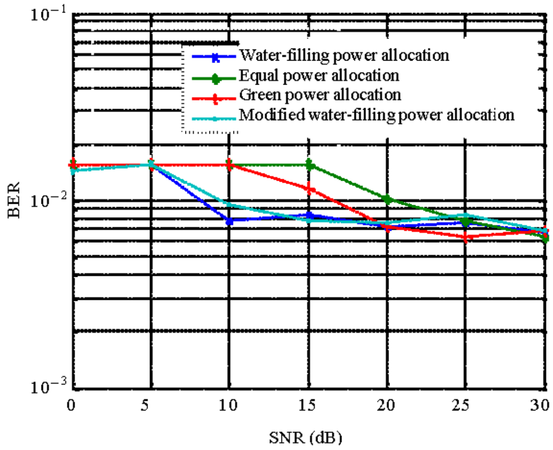

Fig. 7: System BER of TDD/TDMA 4G systems

antennas, i.e., greedy algorithm, equal power allocation, water-filling scheme and modified water-filling schemes. Then AMC and ASTC are performed to fit for current channel states for given special BER requirements. As showed in Fig. 7, system BER with requirement of $BER<10^{-3}$, is achieved by simulating the TDD/TDMA link performance through MATLAB 7.0 simulink blocksets.

CONCLUSION

For fast fading frequency selective channels, a novel 4G cellular systems with TDD and TDMA is designed to reduce channel estimation overhead and avoid MUD in the case with larger number of users in current 4G schemes, such as VSF-OFCDM, TDD-MIMO-OFDM, TDD-CDM-OFDM and so on. Based on TDD/TDMA, the structures of PHY radio frame, data burst and synchronization, are elaborately designed under the limitation of 4G system requirements. Finally, the system architecture is given with considering novel eigenmodes for universal space-time codes and evaluated by numerical simulations. Results show that TDD/TDMA 4G systems can achieve the expectation of 4G cellular systems.

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