The Next Generation CDMA Technology - its Opportunities and Challenges

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Outline

- *Introduction*
- *Why we need NG-CDMA?*
- *What is NG-CDMA?*
- *Innovation in spreading code design*
- *Chip-level ST coding for MIMO-CDMA*
- *Doppler-resilient wireless systems*
- *Opportunities and Challenges*
- *References*

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Introduction (1/4)

Multiple access (MA) technology is the core of a communication system. We see the major MA technologies as follows:

- Frequency division multiple access (FDMA)
- Time division multiple access (TDMA)
- Code division multiple access (CDMA)
- Orthogonal frequency division multiple access (OFDMA)
- Spatial division multiple access (SDMA, and MU-MIMO)
- Interleaving division multiple access (IDMA)
- Opportunity division multiple access (ODMA, cognitive radio)

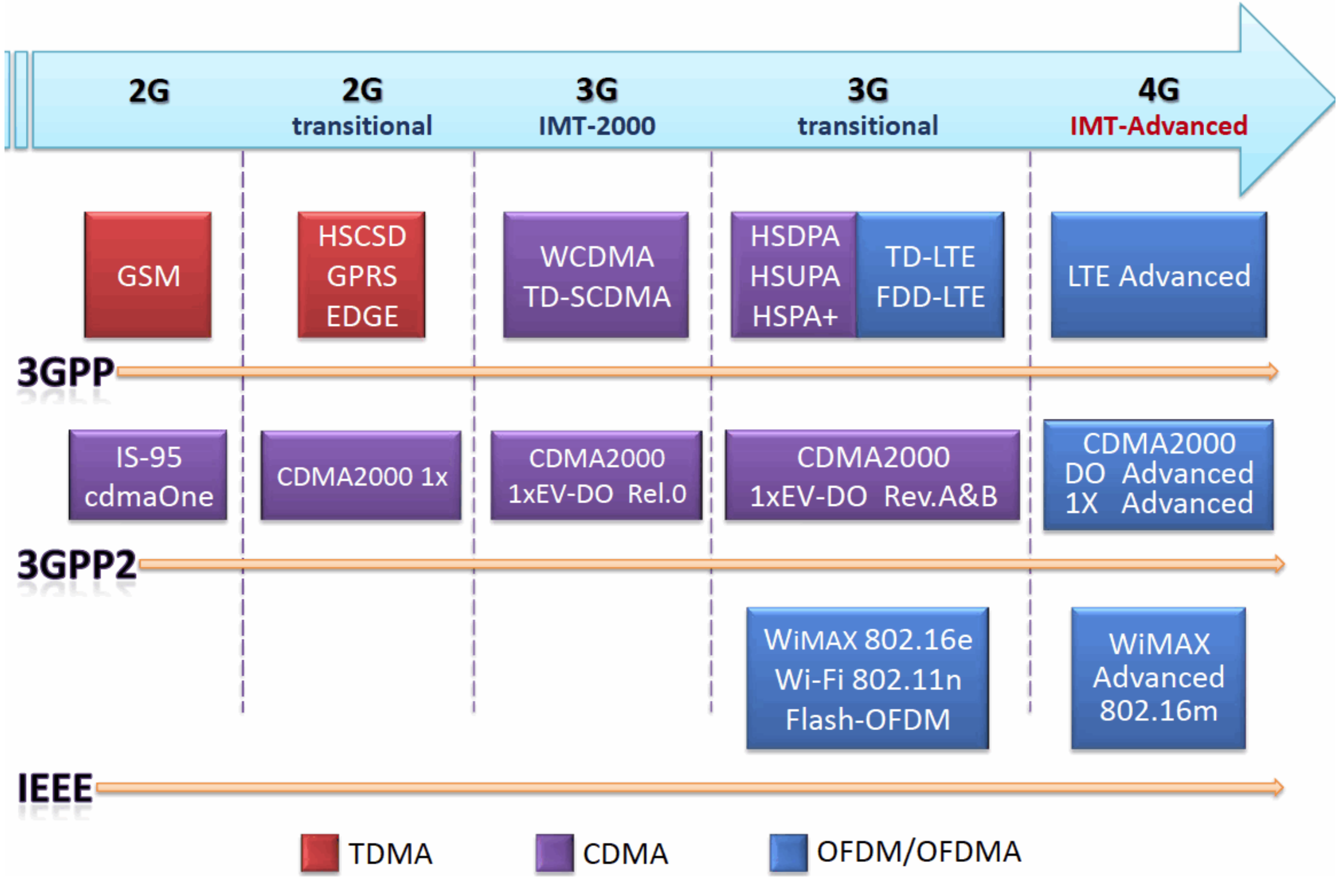
Introduction (2/4)

Any more MA technologies will come?

- May not say no, but doubt many will come. Why?
- The reason is there are only VERY limited ways to separate signals in some proper orthogonal spaces, by frequency (or tone), time (or interleaving), code, space, etc.
- That is why we need cognitive radio (also called “opportunity division multiple access”)!
- IPR issue has a huge impact on the evolution of MA technologies (either positively or negatively).

Introduction (3/4)

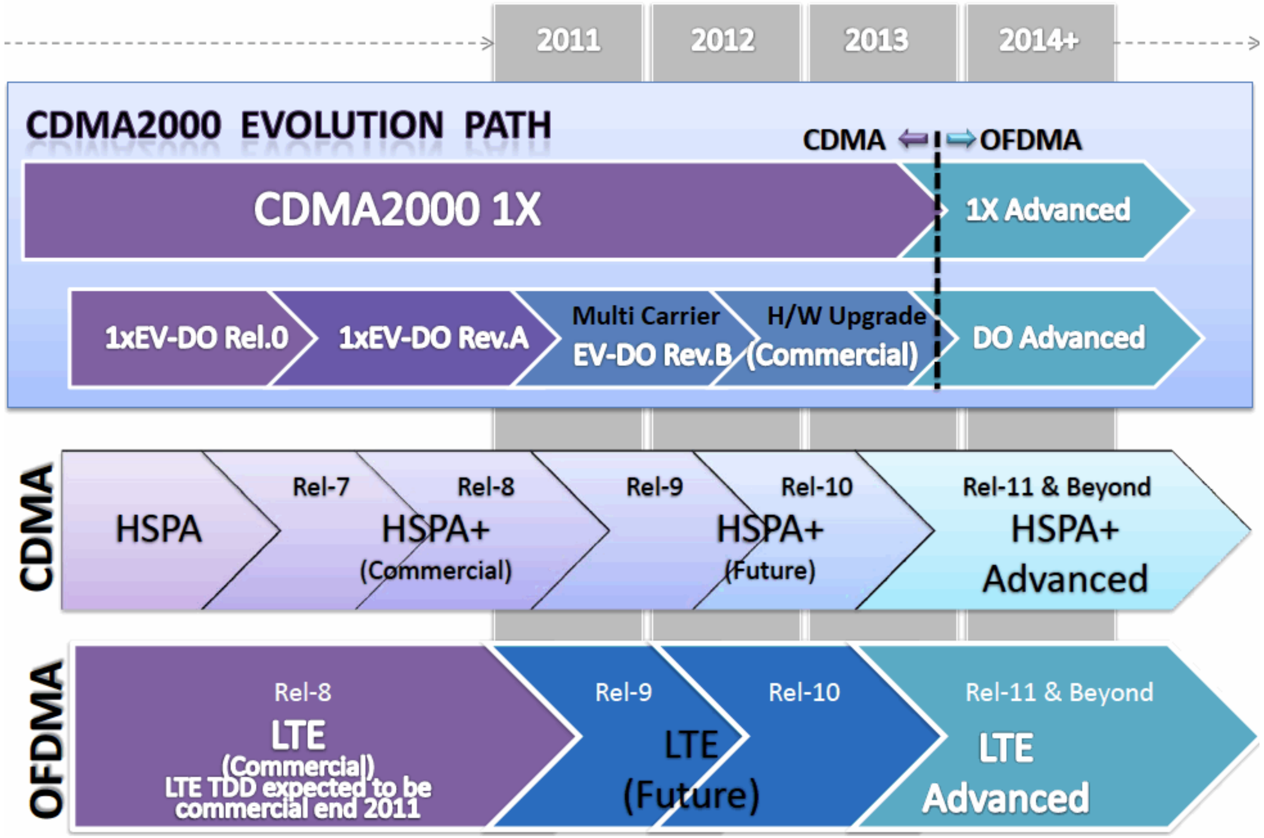
Roadmaps towards ITU IMT-Advanced
(No more CDMA after 3G transitional?)



Source: http://zh.wikipedia.org/

Introduction (4/4)

Qualcomm's roadmaps towards 4G



Source: http://www.qualcomm.cn/

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What's wrong with CDMA? (1/3)

- **Developed for voice-centric applications**
  - It needs long frame for signal detection.
  - It suits for low-speed continuous-time transmission.
  - It simply was not designed for high-speed burst-data!
- **Poor orthogonality of spreading codes**
  - Only periodic correlation functions were considered in code design process.
  - Codes are not orthogonal at all in uplink transmissions.
  - Bad aperiodic correlations
  - Bad partial correlations
  - Only unitary codes are used, i.e., Gold, Walsh, Kasami, etc.

What's wrong with CDMA? (2/3)

- **Low spreading efficiency (SE) in DS spreading**
  - SE is defined as bits deliverable per chip
  - The SE for DS spreading is only 1/*N* bit per chip (if PG=*N*)
  - A big room left to improve SE, which is the same as bandwidth efficiency
- **Unsuitable to support QoS sensitive multimedia traffic**
  - Difficult to adjust data rate on-a-fly
  - Data rate change always comes with the change in PG
  - Data rate change always needs Tx power adjustment
  - Data rate change in ONE user affects cell-wise code-assignment plan (e.g., OVSF code used in WCDMA)
  - Data rate change requires huge traffic overhead

What's wrong with CDMA? (3/3)

- **Implementation complexity**
  - Precision power control to overcome near-far effect.
  - Multi-user detection to decorrelate user signals.
  - RAKE for multipath signal separation and detection.
  - Sectorized antennas to reduce co-channel interference.
- **Interference-limited performance**
  - Multi-user interference (MUI) is a serious problem.
  - RAKE receiver may not work well under mutipath interference (MI).
  - Capacity is far less than processing gain (PG).
- **Almost all problems come from the SAME root: Bad Codes …**
  - "Unitary codes" work on an one-code-per-user basis.
  - All current CDMA systems use "unitary codes".

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What is Next Generation CDMA? (1/3)

- Technological innovation from its 1G version
  - Current CDMA technology is very much unitary code centric.
  - Almost all existing CDMA technologies are based on one-dimensional DS spreading.
- Offer interference-resistant performance
  - Current CDMA systems are strictly interference-limited.
  - Orthogonality among codes should be ensured in both synchronous and asynchronous transmissions.
  - Code design approach should take into account real operational conditions.

What is Next Generation CDMA? (2/3)

- Support high-speed burst-traffic
  - Long-frame transmissions no long exists in B3G wireless.
  - Gigabit all-IP wireless needs to support high-speed packet data.
  - To detect a short packet (with only a few bits) is challenging.
  - Spreading codes should maintain a good partial correlation functions.
- Enable MIMO applications
  - MIMO improves performance without consuming bandwidth resource.
  - Integration of ST coding and CDMA coding.
  - Applications of 3-dimensional (STF) spreading codes.
  - Chip-level ST coding is more powerful than bit-level ST coding.

What is Next Generation CDMA? (3/3)

- Support rate-on-demand high-speed data access
  - "Unitary codes" with DS spreading are not agile to support multi-media applications.
  - Rate-on-demand capability should be enabled.
  - Rate changes should not generate too much traffic overhead.
- Support Doppler-resistant wireless communications
  - High-speed railway (HSR) communications (a mass HSR project in China).
  - IEEE 802.11p standard for V2V and V2R communications is based on IEEE 802.11a, not designed for fast-fading channels.
  - Military applications: missile control, air-force inter-jetfighter data links...
  - A completely new CDMA code design paradigm is needed.
- Technically feasible to implement
  - Precision power control should not be a necessity.
  - Inter-code correlation should be removed at transmitter, instead of receiver, and thus MUD is not needed.
  - RAKE receiver is not a must to achieve multipath diversity.
  - Cell sectorization is not necessary to ease cell planning.

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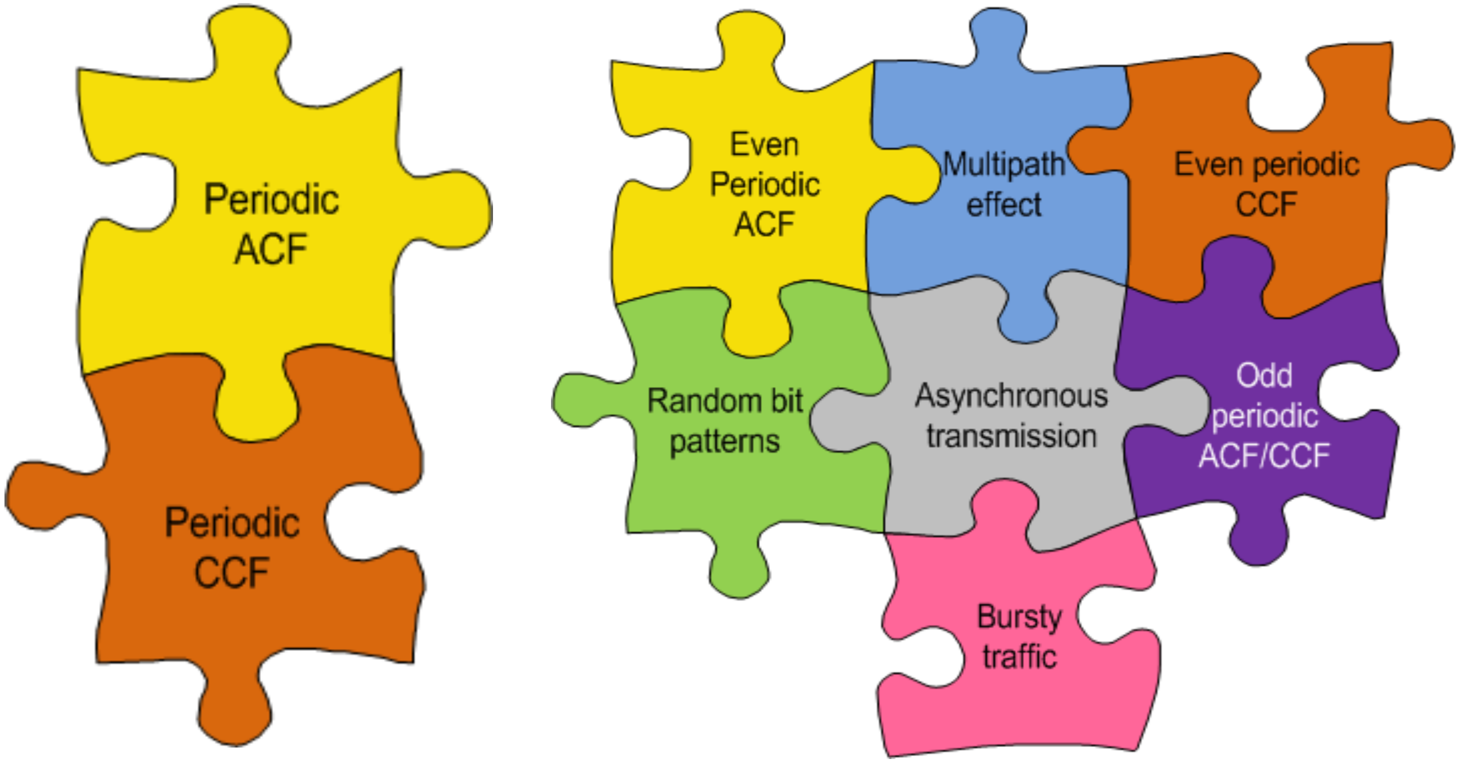
Multi-dimensional spreading code design (1/8)

- Innovation in spreading code design plays an important role in development of NG-CDMA technology.
- "Real Environment Adaptation Linearization" (REAL) approach was proposed for this purpose, and it takes into account:
  - asynchronous transmissions
  - multipath interference
  - random data signs in two consecutive bits
  - Partial correlation functions
- THREE key parameters used in the REAL approach:
  - K: number of users supported in a cell;
  - M: number of element codes used by each user or flock size;
  - N: length of an element code in chips;
  - Thus, the processing gain of the system is defined by $M \times N$.

Multi-dimensional spreading code design (2/8)

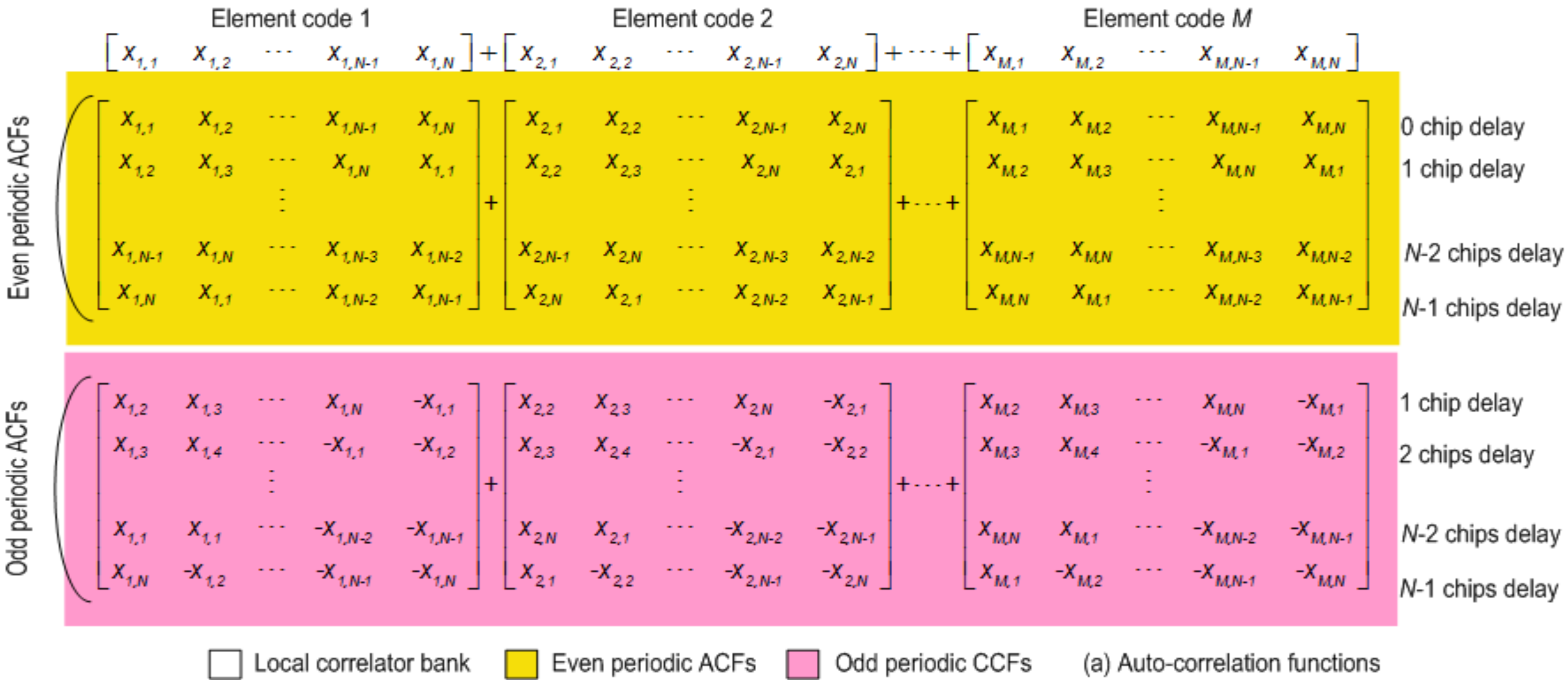


(a) Design scenario in traditional approach

(b) Design scenario in REAL approach

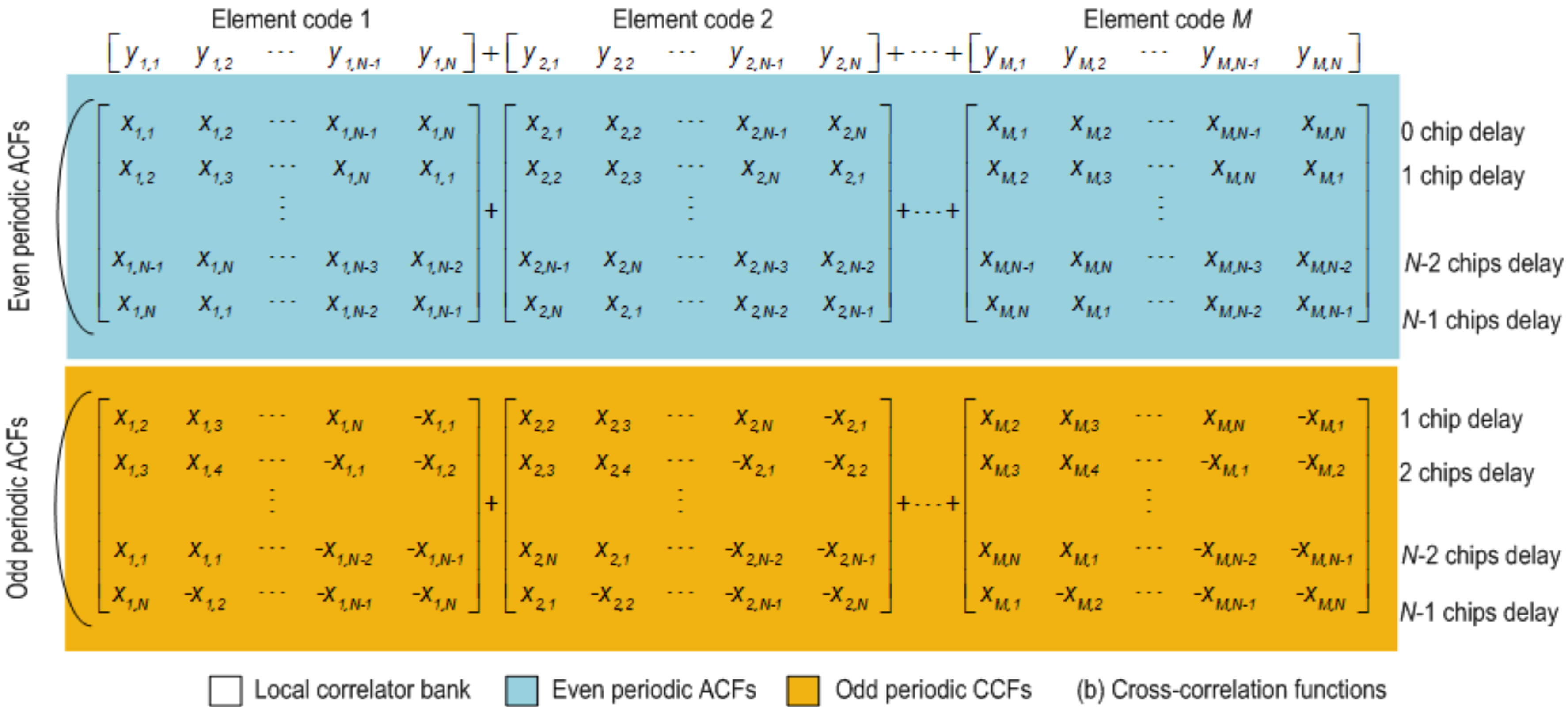
Comparison between (a) traditional CDMA code design and (b) the REAL Approach.

Multi-dimensional spreading code design (3/8)



The REAL Approach for DS-spreading. All possible patterns of EPACFs and OPACFs of a generic complementary code. The set size, flock size and element code length are K, M and N, respectively. (Reference: Hsiao-Hwa Chen, Hsin-Wei Chiu and Mohsen Guizani, Orthogonal complementary codes for interference-free CDMA technologies, IEEE Wireless Communications, pp. 68-79, February, 2006.)

Multi-dimensional spreading code design (4/8)



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Multi-dimensional spreading code design (5/8)

TABLE I

TWO EXAMPLE OC CODE SETS GENERATED BY REAL APPROACH WITH THEIR PARAMETERS BEING $K = 4$, $M = 4$, $N = 4$ AND $K = 4$, $M = 4$, $N = 8$, RESPECTIVELY. (NOTE: k IS THE FLOCK INDEX AND m IS THE ELEMENT INDEX.)

(a) K=4, M=4, N=4:				
Flock 1:	$(+++-)$	$(++-+)$	$(+++-)$	$(--+-)$
Flock 2:	$(+-++)$	$(+---)$	$(+-++)$	$(-+++)$
Flock 3:	$(+++-)$	$(++-+)$	$(---+)$	$(++-+)$
Flock 4:	$(+-++)$	$(+---)$	$(-+--)$	$(+---)$
(b) K=4, M=4, N=8:				
Flock 1:	$(+++-++-+)$	$(+++---+-)$	$(+++-++-+)$	$(---+++-+)$
Flock 2:	$(+-+++---)$	$(+-++-+++)$	$(+-+++---)$	$(-+--+---)$
Flock 3:	$(+++-++-+)$	$(+++---+-)$	$(---+--+-)$	$(+++---+-)$
Flock 4:	$(+-+++---)$	$(+-++-+++)$	$(-+---+++)$	$(+-++-+++)$

[2] Hsiao-Hwa Chen, The Next Generation CDMA Technologies, 1st Edition, July 2007, 468 Pages, Hardcover, John Wiley & Sons.

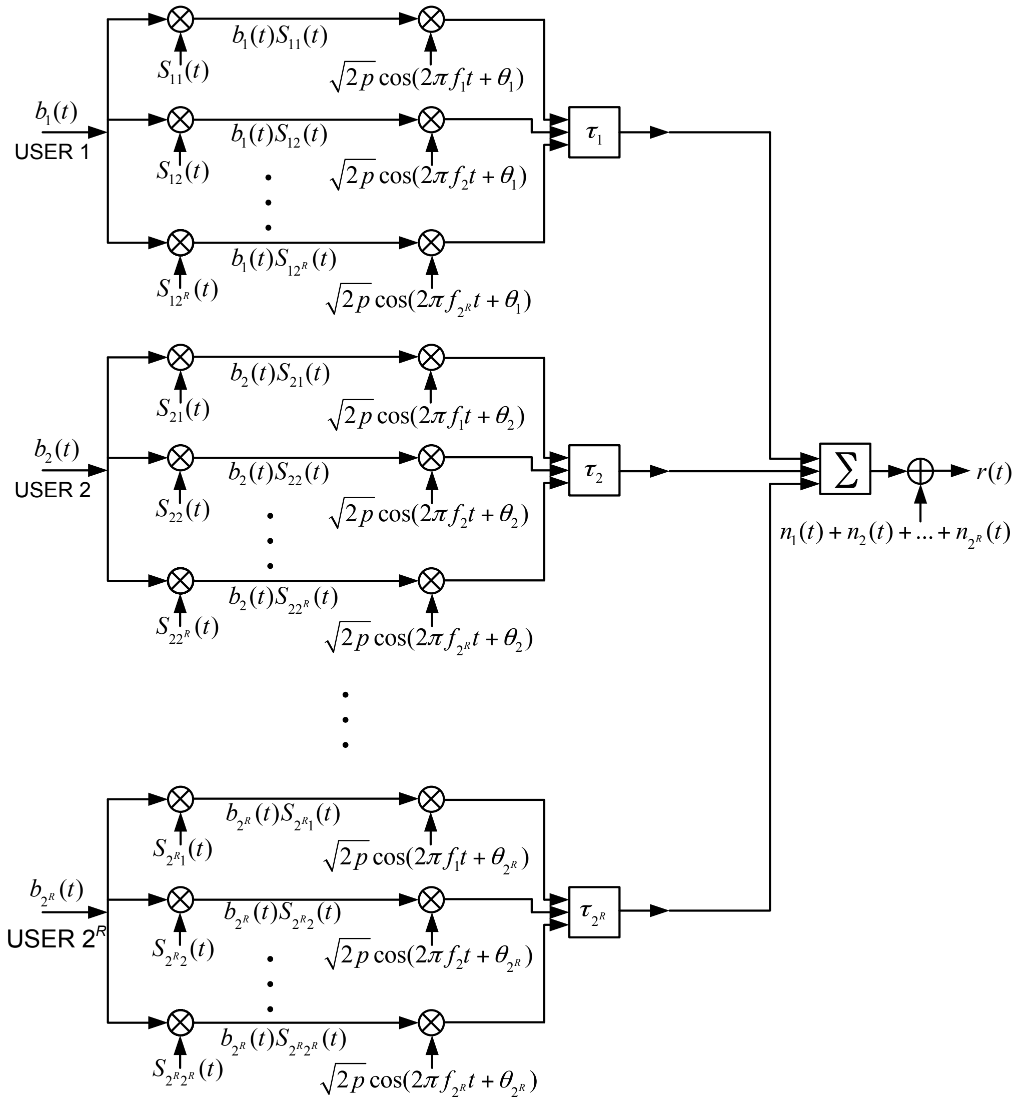
Multi-dimensional spreading code design (6/8)

Important conclusions made from the REAL approach:

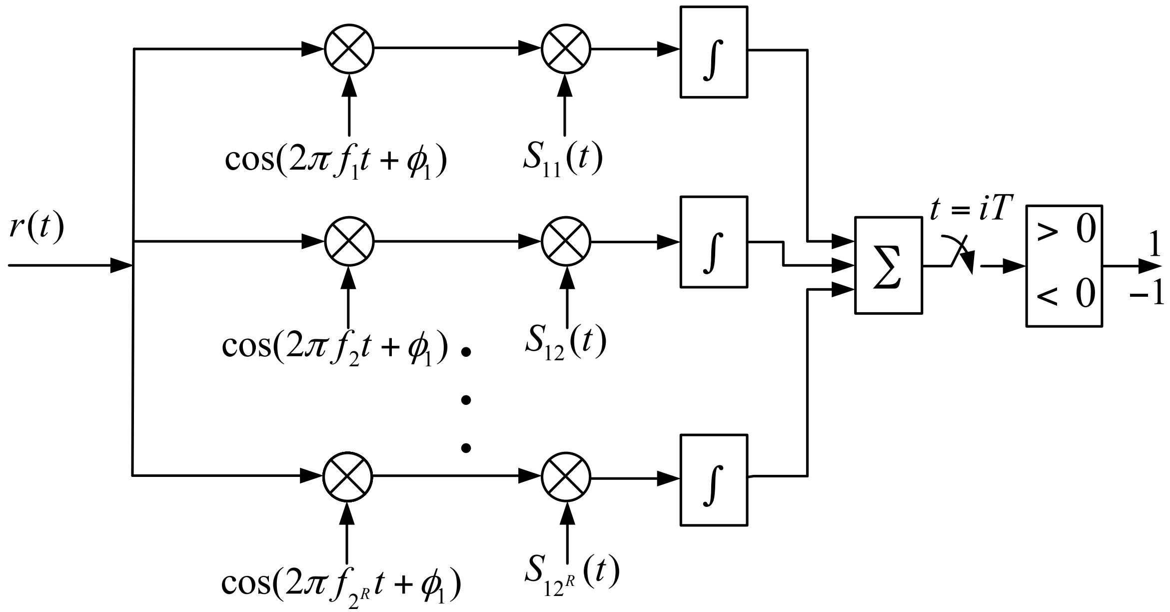
- The REAL approach offers a unique framework, which has showed that CDMA can be made interference-free, the most important feature for the NG-CDMA technology.
- Such an interference-free CDMA must be implemented by orthogonal complementary codes.
  - The solutions to the REAL approach exist if and only if $M>1$.
- The number of channels accommodated in one cell is equal to the flock size of the complementary code.
  - The solutions to the REAL approach exist ONLY if $K=M$.
  - Each user employs one flock of M element codes for CDMA.

Multi-dimensional spreading code design (7/8)

Transmitter for a complementary coded CDMA system, where the multi-carrier modulator can be implemented by OFDM (IFFT).



Multi-dimensional spreading code design (8/8)



Receiver block diagram for a complementary coded CDMA system, where the multi-carrier demodulator can be implemented by OFDM (FFT).

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Chip-level ST coding for MIMO-CDMA (1/13)

- MIMO is one of the most important technological breakthroughs for wireless communications in recent 20 years.
- MIMO provides three powerful capabilities: diversity, multiplex, and user-division, without consuming the precious bandwidth.
- All futuristic wireless systems will not be made possible without MIMO.

Chip-level ST coding for MIMO-CDMA (2/13)

The first milestone publication was published by Siavash M. Alamouti, who proposed a simple transmitter diversity scheme[1], which laid a foundation for the development of later numerous MIMO applications. This scheme works based on Space-Time Block Coding, as shown in the following table:

TABLE I
THE ENCODING AND TRANSMISSION SEQUENCE FOR THE TWO-BRANCH TRANSMIT DIVERSITY SCHEME

	antenna 0	antenna 1
time t	s_0	s_1
time $t+T$	$-s_1^*$	s_0^*

IEEE JOURNAL ON SELECT AREAS IN COMMUNICATIONS, VOL. 16, NO. 8, OCTOBER 1998 1451

A Simple Transmit Diversity Technique for Wireless Communications

Siavash M. Alamouti

Abstract—**This paper presents a simple two-branch transmit diversity scheme. Using two transmit antennas and one receive antenna the scheme provides the same diversity order as maximal-ratio receiver combining (MRRC) with one transmit antenna, and two receive antennas. It is also shown that the scheme may easily be generalized to two transmit antennas and M receive antennas to provide a diversity order of $2M$. The new scheme does not require any bandwidth expansion any feedback from the receiver to the transmitter and its computation complexity is similar to MRRC.**

Index Terms—**Antenna array processing, baseband processing, diversity, estimation and detection, fade mitigation, maximal-ratio combining, Rayleigh fading, smart antennas, space block coding, space–time coding, transmit diversity, wireless communications.**

I. INTRODUCTION

THE NEXT-generation wireless systems are required to have high voice quality as compared to current cellular mobile radio standards and provide high bit rate data services (up to 2 Mbits/s). At the same time, the remote units are supposed to be small lightweight pocket communicators. Furthermore, they are to operate reliably in different types of environments: macro, micro, and picocellular; urban, suburban, and rural; indoor and outdoor. In other words, the next generation systems are supposed to have better quality and coverage, be more power and bandwidth efficient, and be deployed in diverse environments. Yet the services must remain affordable for widespread market acceptance. Inevitably, the new pocket communicators must remain relatively simple. Fortunately, however, the economy of scale may allow more complex base stations. In fact, it appears that base station complexity may be the only plausible trade space for achieving the requirements of next generation wireless systems.

The fundamental phenomenon which makes reliable wireless transmission difficult is time-varying multipath fading [1]. It is this phenomenon which makes tetherless transmission a challenge when compared to fiber, coaxial cable, line-of-sight microwave or even satellite transmissions.

Increasing the quality or reducing the effective error rate in a multipath fading channel is extremely difficult. In additive white Gaussian noise (AWGN), using typical modulation and coding schemes, reducing the effective bit error rate (BER) from 10^{-2} to 10^{-3} may require only 1- or 2-dB higher signal-to-noise ratio (SNR). Achieving the same in a multipath fading environment, however, may require up to 10 dB improvement in SNR. The improvement in SNR may not be achieved by higher transmit power or additional bandwidth, as it is contrary to the requirements of next generation systems. It is therefore crucial to effectively combat or reduce the effect of fading at both the remote units and the base stations, without additional power or any sacrifice in bandwidth.

Theoretically, the most effective technique to mitigate multipath fading in a wireless channel is transmitter power control. If channel conditions as experienced by the receiver on one side of the link are known at the transmitter on the other side, the transmitter can predistort the signal in order to overcome the effect of the channel at the receiver. There are two fundamental problems with this approach. The major problem is the required transmitter dynamic range. For the transmitter to overcome a certain level of fading, it must increase its power by that same level, which in most cases is not practical because of radiation power limitations and the size and cost of the amplifiers. The second problem is that the transmitter does not have any knowledge of the channel experienced by the receiver except in systems where the uplink (remote to base) and downlink (base to remote) transmissions are carried over the same frequency. Hence, the channel information has to be fed back from the receiver to the transmitter, which results in throughput degradation and considerable added complexity to both the transmitter and the receiver. Moreover, in some applications there may not be a link to feed back the channel information.

Other effective techniques are time and frequency diversity. Time interleaving, together with error correction coding, can provide diversity improvement. The same holds for spread spectrum. However, time interleaving results in large delays when the channel is slowly varying. Equivalently, spread spectrum techniques are ineffective when the coherence bandwidth of the channel is larger than the spreading bandwidth or, equivalently, where there is relatively small delay spread in the channel.

In most scattering environments, antenna diversity is a practical, effective and, hence, a widely applied technique for reducing the effect of multipath fading [1]. The classical approach is to use multiple antennas at the receiver and perform combining or selection and switching in order to improve the quality of the received signal. The major problem with using the receive diversity approach is the cost, size, and power of the remote units. The use of multiple antennas and radio frequency (RF) chains (or selection and switching circuits) makes the remote units larger and more expensive. As a result, diversity techniques have almost exclusively been

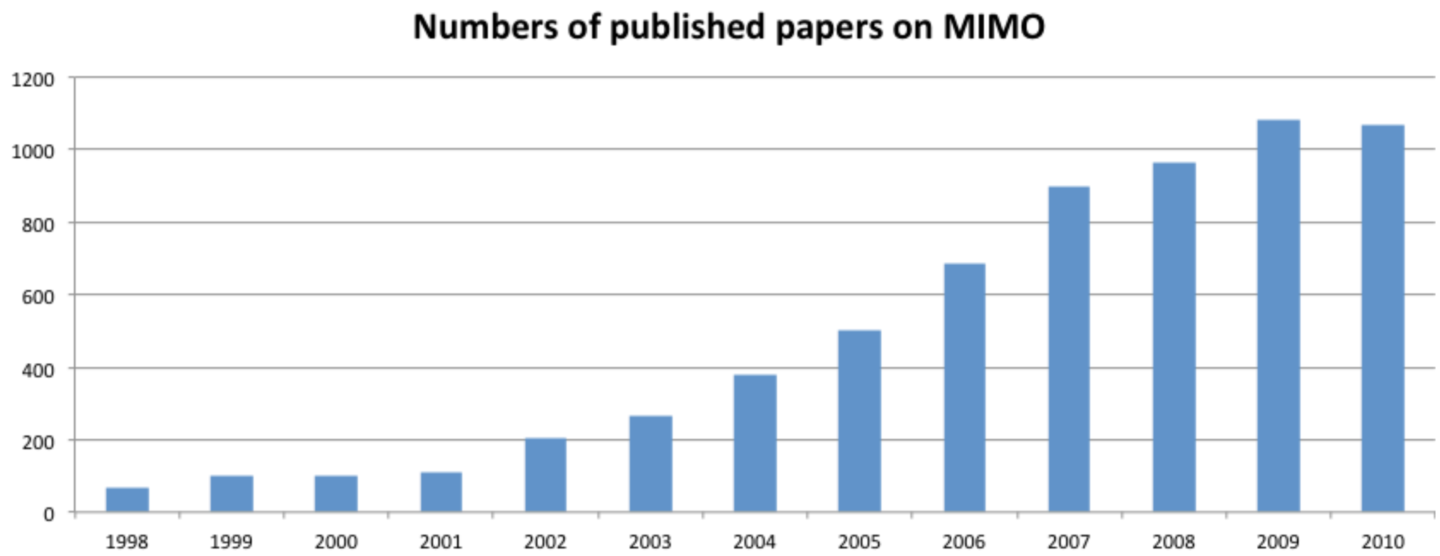
Manuscript received September 1, 1997; revised February 1, 1998.
The author was with AT&T Wireless Services, Redmond, WA, USA. He is currently with Cadence Design Systems, Alta Business Unit, Bellevue, WA 98005-3016 USA (e-mail: siavash@cadence.com).
Publisher Item Identifier S 0733-8716(98)07885-8.

0733–8716/98$10.00 © 199 IEEE

[1]Siavash M. Alamouti, A Simple Transmit Diversity Technique for Wireless Communications, IEEE JOURNAL ON SELECT AREAS IN COMMUNICATIONS, VOL. 16, NO. 8, OCTOBER 1998.

Chip-level ST coding for MIMO-CDMA (3/13)

- MIMO has become one of the most important research topics in wireless communications since Siavash M. Alamouti's first publication on transmitter diversity appeared in 1998, as shown in this plot.



Source: http://apps.webofknowledge.com

Chip-level ST coding for MIMO-CDMA (4/13)

- Numerous space-time coding schemes were proposed for MIMO applications, including space-time block coding (STBC), space-time trellis coding (STTC), space-time differential coding (STDC), etc.
- Traditional ST coding schemes offer orthogonal signal transmissions through different antennas, to achieve diversity combining or multiplex capabilities at receivers.
- However, all well-known ST coding schemes used bit-level ST codes, whose orthogonality is extremely sensitive to multipath propagation and multi-user interference.
- Thus, naturally a chip-level space-time coding will be more robust against multipath and multi-user interferences.

Chip-level ST coding for MIMO-CDMA (5/13)

- A few works [1][2] on spreading assisted space-time coding schemes appeared in the literature, called "space-time spreading" to separate transmissions from different antennas. However, they used traditional spreading codes which are still vulnerable to asynchronous transmissions and multipath.

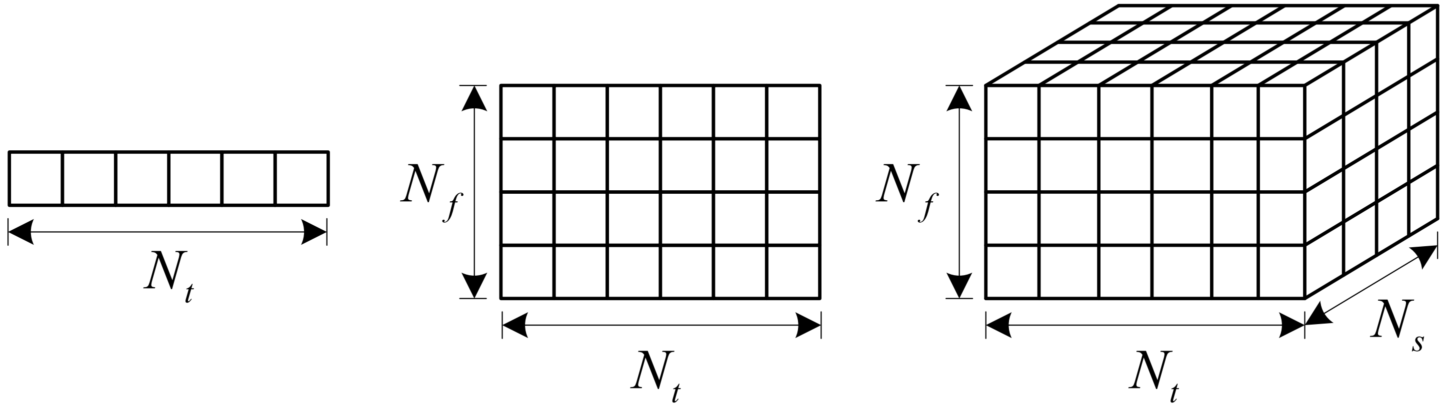
- Therefore, we are motivated to find some innovative ways to design chip-level ST codes in particular for MIMO applications.

[1] Bertrand Hochwald, Thomas L. Marzetta, and Constantinos B. Papadias, A Transmitter Diversity Scheme for Wideband CDMA Systems Based on Space–Time Spreading, IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS, VOL. 19, NO. 1, JANUARY 2001

[2] Lie-Liang Yang, and Lajos Hanzo, Performance of Broadband Multicarrier DS-CDMA Using Space–Time Spreading-Assisted Transmit Diversity, IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS, VOL. 4, NO. 3, MAY 2005

Chip-level ST coding for MIMO-CDMA (6/13)

- Our approach is to generalize 1D and 2D spreading codes to 3D codes based on the REAL approach we proposed for NG-CDMA systems.



(a) One dimensional spreading

(b) Two dimensional spreading

(c) Three dimensional spreading

Evolution from 1D spreading (traditional CDMA), 2D spreading to 3D spreading (N_t: number of chips; N_f : number of sub-carriers; N_s : number of antennas)

Chip-level ST coding for MIMO-CDMA (7/13)

- There are two approaches to implement orthogonal complementary coded chip-level ST coding:
  - Directly use 2D orthogonal complementary codes for different antennas, namely 2D complementary coded MIMO.

    Disadvantage: the number of users will be limited by the number of antennas used by each user.
  - Design new 3D orthogonal complementary codes for different users, each of which will use N_T antennas to form an MIMO system, namely 3D complementary coded MIMO.

    Advantage: the number of users is not limited by the number of antennas used by each user.

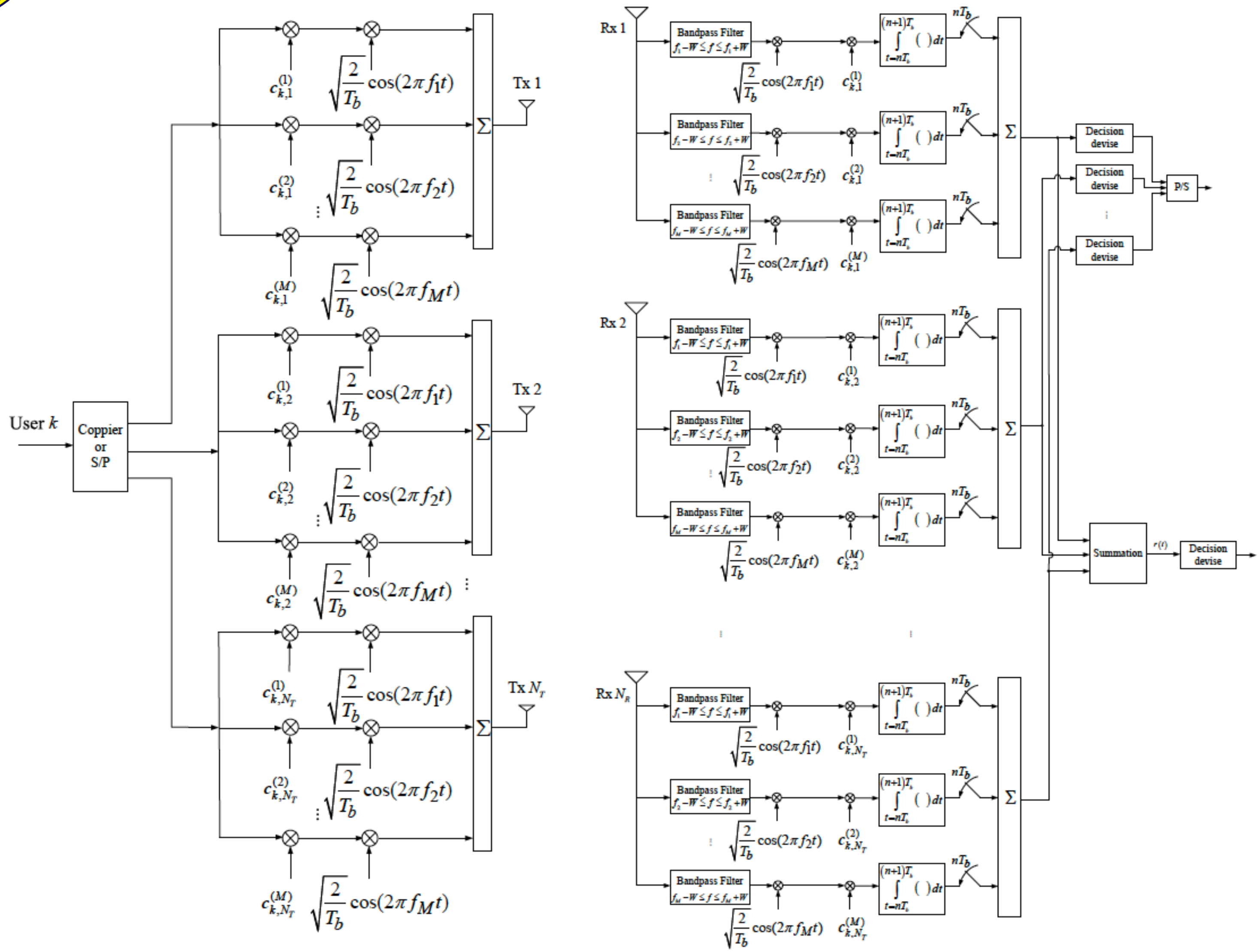
Chip-level ST coding for MIMO-CDMA (8/13)

- The 2D orthogonal complementary codes can be applied to different antennas to to implement orthogonal complementary coded chip-level ST coding, namely 2D complementary coded MIMO.

- Disadvantage: The number of users will be limited to M/N_T, where M is the set size of the orthogonal complementary codes, and N_T is the number of antennas used by each user.

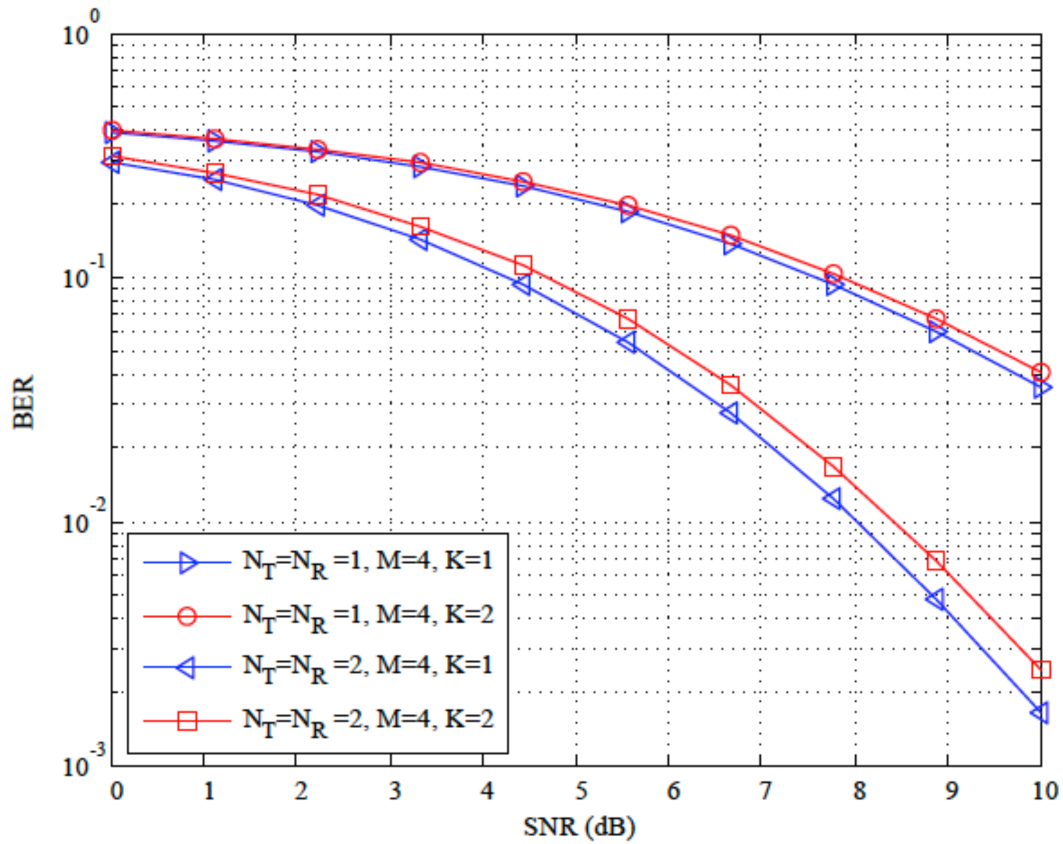
- Advantage: Great flexibility to achieve both diversity gain and multiplex transmission simultaneously. For instance, if there are N_T antennas in each user, you can group them into P groups, each of which has N_T/P antennas for diversity combining, to support P independent transmissions at the same time.

Chip-level ST coding for MIMO-CDMA (9/13)



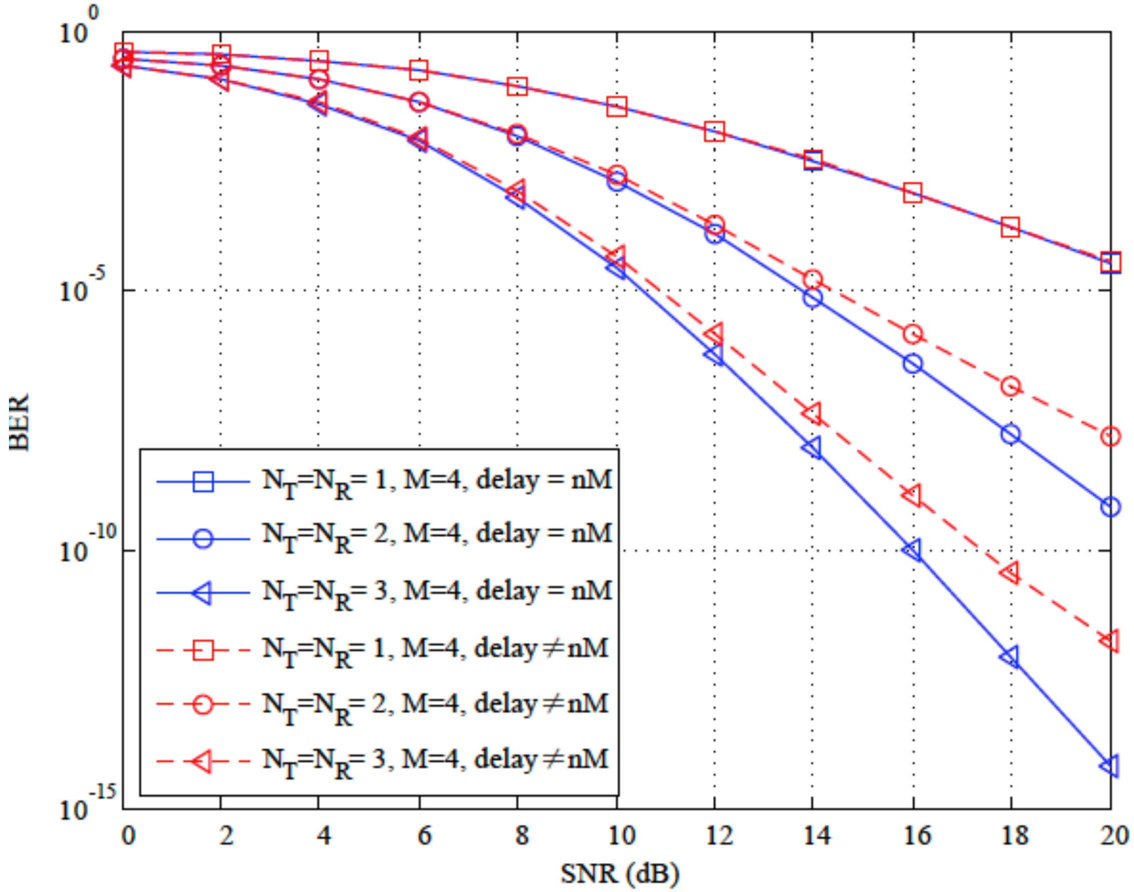
Chip-level ST coding for MIMO-CDMA (10/13)

- Multipath Rayleigh fading channel;
- N_T, N_R: numbers of transmit and receive antennas;
- M: number of sub-carriers;
- K: number of users.



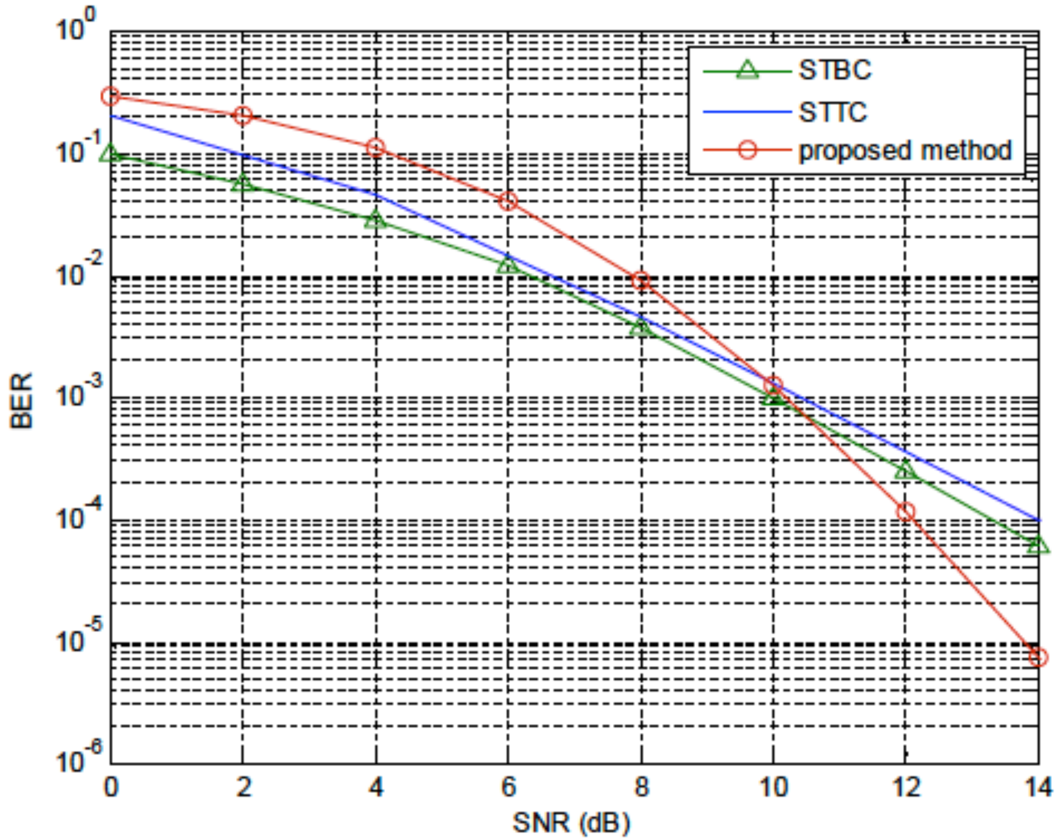
Chip-level ST coding for MIMO-CDMA (11/13)

- Multipath Rayleigh fading channel;
- N_T, N_R: numbers of transmit and receive antennas;
- M: number of sub-carriers;
- When delay is equal to nM chips, the scheme offers a better multipath resistance.



Chip-level ST coding for MIMO-CDMA (12/13)

- Rayleigh fading channel;
- $N_T=N_R=2$: numbers of transmit and receive antennas;
- Performance curves for STBC and STTC schemes were taken from the following references.



Claude Oestges, and Bruno Clerckx, "MIMO Wireless Communications: From Real-World Propagation to Space-Time Code Design," ISBN: 0123725356, Elsevier Science, 2007. (Page 24)

Volker Kuhn, "Wireless Communications Over MIMO Channels: Applications to CDMA and Multiple Antenna Systems," ISBN-13 978-0-470-02716-5, John Wiley & Sons Ltd, 2006. (Page 290 and Page 300)

Tolga M. Duman and Ali Ghrayeb, "Coding for MIMO Communication Systems," ISBN 978-0-470-02809-4, John Wiley & Sons Ltd, 2007. (Page 105)

Chip-level ST coding for MIMO-CDMA (13/13)

- CL-ST coding provides both spatial diversity and spatial multiplex at the same time, different from traditional bit-level ST coding that only supports either spatial diversity or spatial multiplex, but not both simultaneously..

- CL-ST coding offers MUI-resistant and MI-resistant operation for both up-link and down-link transmissions.

- CL-ST coding works based on an integrated design of ST coding and CDMA coding, offering a unique framework for system optimization.

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- *Opportunities and Challenges*
- *References*

Doppler-resilient wireless systems (1/4)

- The NG-CDMA systems work based on 2D spreading using *M* sub-carriers to send *M* different element codes.

- A large number of orthogonal complementary codes have been generated by REAL approach. One particular type is called column-wise complementary codes, whose orthogonality is based solely on the frequency domain and is not affected by time-varying channels.

- Therefore, a NG-CDMA system based on the column-wise complementary codes is well suited for its applications in fast-fading channels, such as high-speed railway communications, V2V communications, etc..

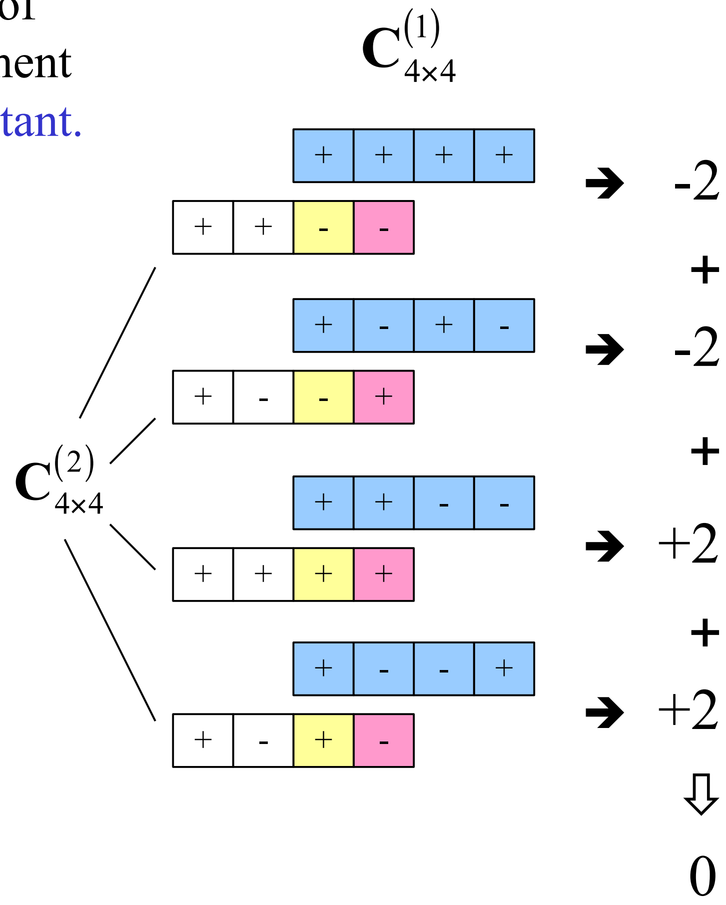
Doppler-resilient wireless systems (2/4)

The frequency-domain orthogonality:

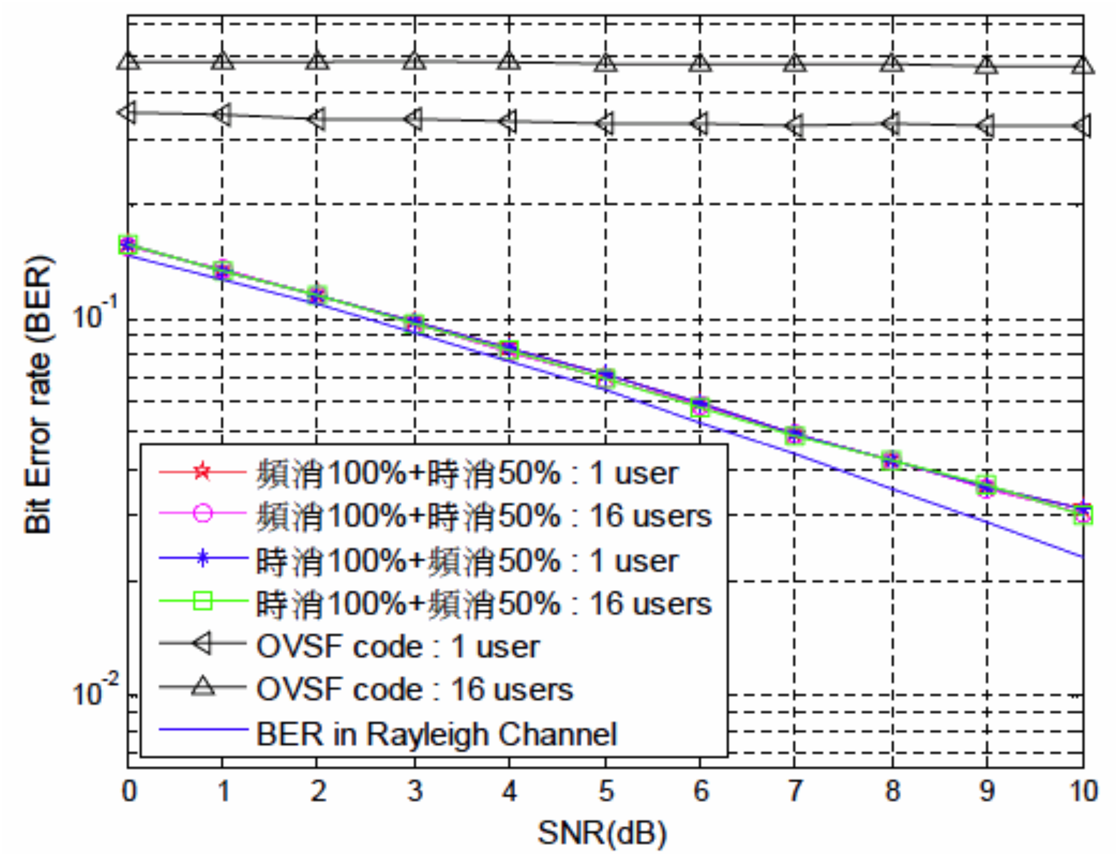
The orthogonality is based on the sum of correlation functions of individual element codes, and thus is time-selectivity resistant.

$$\mathbf{C}_{4\times4}^{(1)} = \begin{bmatrix} + & + & + & + \\ + & - & + & - \\ + & + & - & - \\ + & - & - & + \end{bmatrix}$$

$$\mathbf{C}_{4\times4}^{(2)} = \begin{bmatrix} + & + & - & - \\ + & - & - & + \\ + & + & + & + \\ + & - & + & - \end{bmatrix}$$

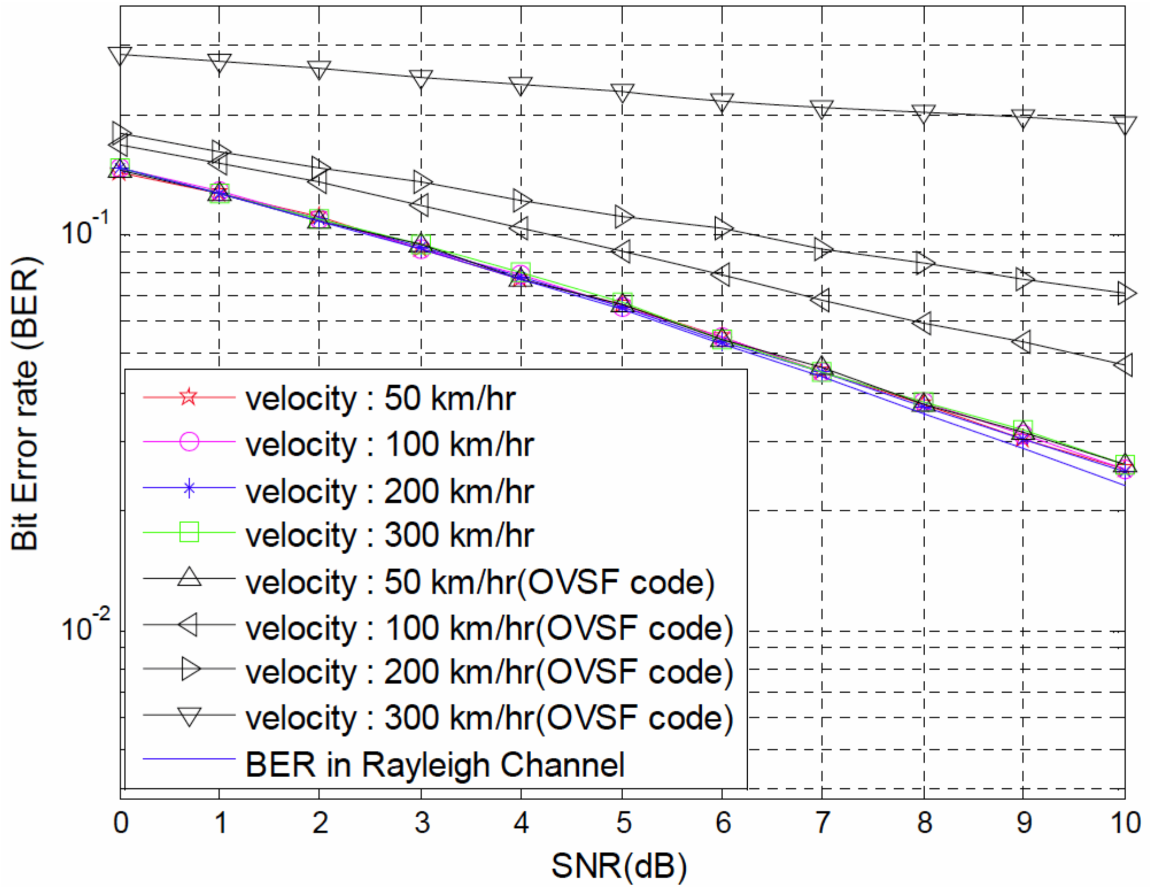


Doppler-resilient wireless systems (3/4)



Comparison of IQCCC and OVSF coded CDMA systems against time-selective and frequency-selective fading channels. We consider asynchronous multi-user transmissions with three ray multipath channel with its inter-path delay being four chips. IQCCC code set parameters: M=32, N=8, and PG=256, and OVSF code set parameters: M=1, N=256, and PG=256. The receiver uses correlator match-filter. Carrier frequency is 2 GHz, and mobility is 300 km/hr, data rate is 384 kb/s.

Doppler-resilient wireless systems (4/4)



Comparison of IQCCC and OVSF coded CDMA systems against time-selective fading channels. We consider a single-user system with flat Raileigh fading channel. IQCCC code set parameters: M=32, N=8, and PG=256, and OVSF code set parameters: M=1, N=256, and PG=256. The receiver uses correlator match-filter. Carrier frequency is 2 GHz, and mobility is 300 km/hr, data rate is 384 kb/s.

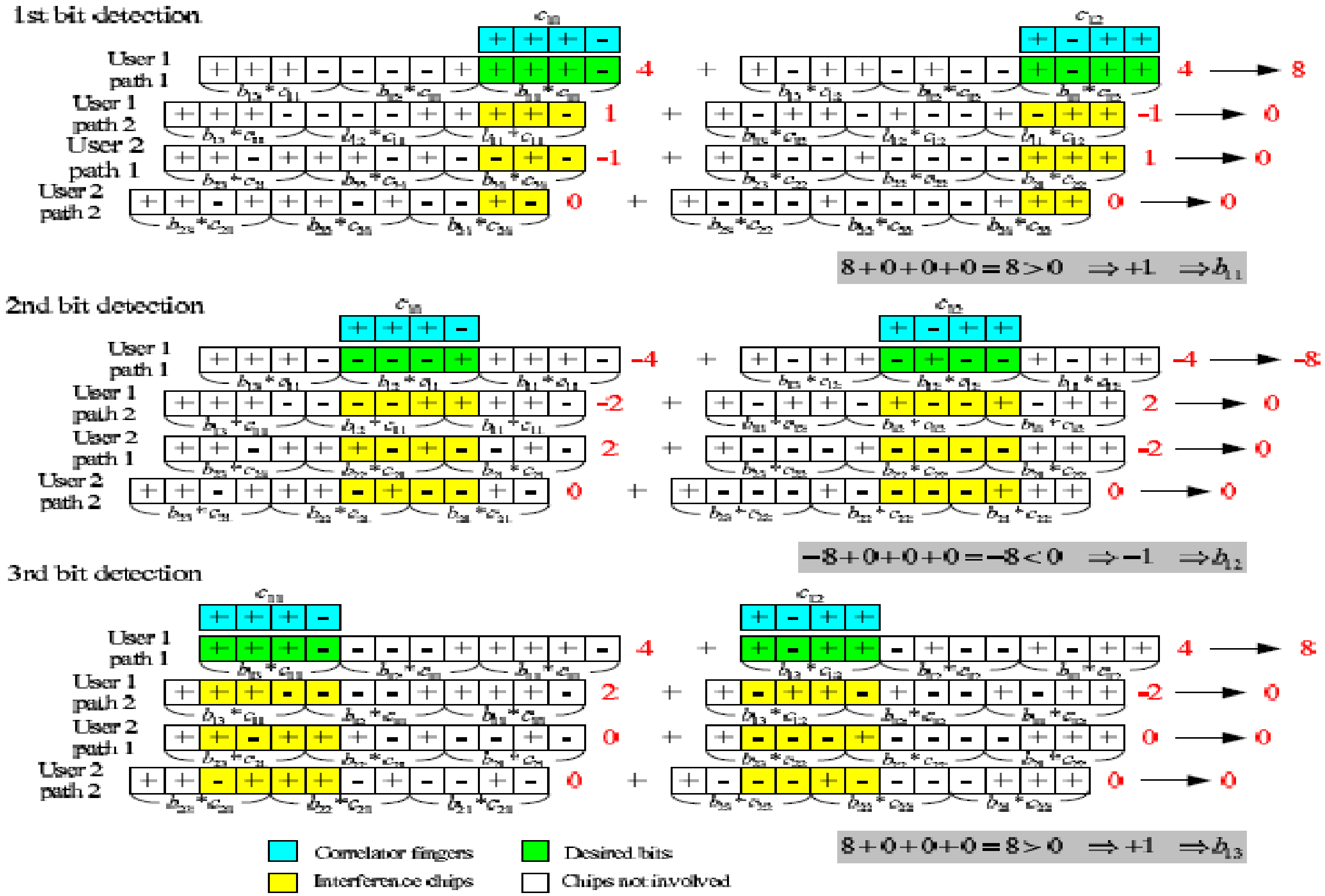
Outline

- Introduction
- Why we need NG-CDMA?
- What is NG-CDMA?
- Innovation in spreading code design
- Chip-level ST coding for MIMO-CDMA
- Doppler-resilient wireless systems
- **Opportunities and Challenges**
- References

Opportunities and Challenges (1/3)

- NG-CDMA technology was not proposed by an accident. It was developed systematically based on the optimal signature code design algorithms (i.e., REAL approach, MBGP, etc.).
- The REAL approach offers a right way to generate suitable 2D orthogonal complementary codes, making it possible to implement Doppler-resistant and/or multipath-resistant wireless systems.
- The integration of ST coding and CDMA coding leads to a powerful chip-level ST coded MIMO architecture, offering diversity, multiplex, and multi-user MIMO capabilities at the same time.
- NG-CDMA supports high-speed burst traffic required by all-IP wireless applications.

Opportunities and Challenges (2/3)



NG CDMA supports high-speed burst-traffic required by all-IP wireless applications. MI-free and MAI-free operation for a 2-user system in asynchronous up-link channels, where a two-ray multipath channel is considered with its inter-path and inter-user delays being one chip for illustration simplicity.

Opportunities and Challenges (3/3)

The challenges to implement the next generation CDMA technologies:

- The number of users K is related strictly to the number of element codes M.
- Transceiver requires an analogue multi-carrier modem with M sub-carriers, whose complexity is high. OFDM may offer a possible solution, but its use of CP will degrade the bandwidth efficiency.
- Transceiver requires wide-band RF loop and antenna due to the use of DS spreading.
- Frequency-selectivity may affect the ideal correlation reconstruction at a receiver, but it offers extra user division capability exploiting channel matrix orthogonality, for further capacity enhancement.

Outline

- *Introduction*
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- *Doppler-resilient wireless systems*
- *Opportunities and Challenges*
- ***References***

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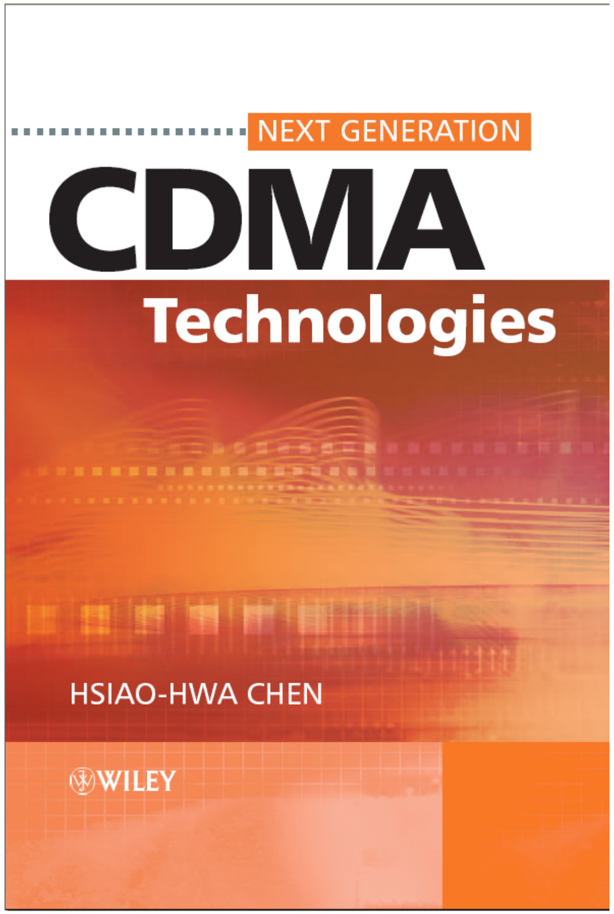

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Thank you!