Next Generation CDMA Technologies for Futuristic Wireless Communications

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ICETE 2008

Outline

- Introduction
- What's wrong with CDMA?
- What is next generation CDMA?
- Multi-dimensional spreading code design
- MIMO-enabled next generation CDMA
- Applications of next generation CDMA
- Summary
- References

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Introduction (1/16)

- Today's communication problems are always related to multi-user communications, where many users share a common media for information exchange.
- Multiple access technology is the key to enable multi-user communications.
- Now, the question is:

  How many different ways can be used to separate users/channels effectively?

Introduction (2/16)

Major multiple access technologies are:

- Frequency division multiple access (FDMA)
- Time division multiple access (TDMA)
- Code division multiple access (CDMA)
- Spatial division multiple access (SDMA)
- Interleaving division multiple access (IDMA)
- Orthogonal frequency division multiple access (OFDMA)

Introduction (3/16)

Frequency division multiple access (FDMA)

- FDMA is the first multiple access scheme ever successfully used in practical systems, such as 1G cellular mobile systems.
- It is simple to implement: no synchronization among terminals.
- Its bandwidth efficiency is low, due to guide-bands needed to separate different channels.
- The use of FDMA is free (no IPR problem).

Introduction (4/16)

Time division multiple access (TDMA)

- TDMA offers a better bandwidth-efficiency than FDMA, and has been widely used in 2G mobile cellular systems, such as GSM, etc..
- Its operation is based on time synchronization among peer terminals and thus is more costly to implement than FDMA.
- Guide-intervals are needed to separate different time slots.
- The use of TDMA is also free (no IPR problem).

Introduction (5/16)

Code division multiple access (CDMA)

- CDMA offers an even better bandwidth-efficiency than TDMA and FDMA, and has been widely used in 3G mobile cellular systems, such as CDMA2000, WCDMA, TD-SCDMA, etc.
- Transmissions from different users proceed in both time and frequency domains.
- Its successful operation is based on many complex sub-systems, such as power-control, multi-user detection, etc., and therefore it is very costly to implement if compared with FDMA and TDMA.
- It is very robust due to its unique processing gain.
- The use of CDMA is NOT free (the IPR problem).

Introduction (6/16)

Spatial division multiple access (SDMA)

- Operation of SDMA is based on antenna-array technology with its beam-forming capability.
- User separation will only be possible if DOAs of different signals are sufficiently larger than angular resolution of the antenna-array.
- SDMA has never been widely used, due to its inefficiency in user-separation mechanism.
- Its operation is based on complex and large-sized antenna arrays, which are impossible to implement in portable terminals.
- The use of SDMA is free (no serious IPR problem).

Introduction (7/16)

Interleaving division multiple access (IDMA)

- Operation of IDMA is based on turbo signal processing techniques, which works quite similarly to successive cancelation techniques.
- IDMA is a kind of extension of CDMA cum MUD signal processing.
- IDMA separates users based on offset times (instead of codes) difference among users. In this sense, IDMA can be viewed as an extension of TDMA.
- Implementation complexity of IDMA is relatively high, still beyond today's micro-electronics capability.
- IDMA has not been used in any practical systems so far.
- Its operation is relatively sensitive to multipath, if compared to CDMA.
- The core of IDMA was patented (the IPR problem).*

* Li Ping, Interleave-division multiple access and chip-by-chip iterative multi-user detection, IEEE Communications Magazine, vol. 43, No. 6, pp. 19-23, June 2005.

Introduction (8/16)

Orthogonal frequency division multiple access (OFDMA)

- OFDMA works like an enhanced FDMA scheme, based on IFFT and FFT digital signal processing techniques.
- It offers a very good bandwidth-efficiency, and will probably be used in many 4G wireless systems, such as E-UTRA (LTE), Qualcomm's UMB, and ITU's IMT-Advanced, etc.
- It mitigates multipath-induced ISI using cyclic prefix (CP).
- It does NOT offer processing gain.
- Its operation is VERY PAPR sensitive due to AM used in its RF loop.
- The use of OFDMA is definitely NOT free (QUALCOMM acquired Flarion).

Introduction (9/16)

Any more multiple access technologies?

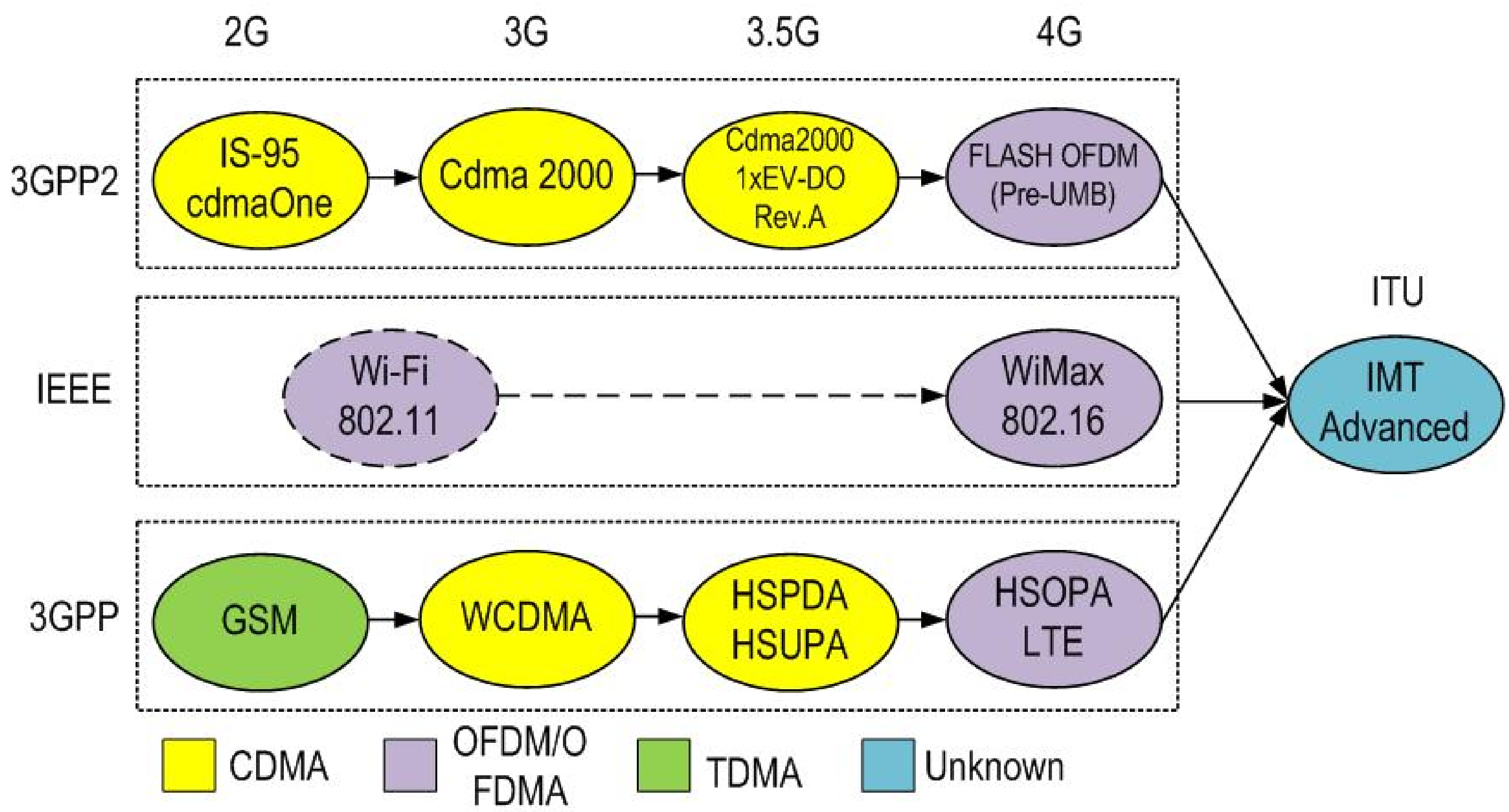
- I would not say no, but I doubt many will come. Why?
- The reason is simple: there are only limited ways to separate signals in some proper orthogonal spaces: by frequency (or tone), time (or interleaving), code, space, etc.
- That is why we need cognitive radio (also called “opportunity division multiple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

Introduction (10/16)

- Milestones in cellular technologies
  - The first cellular network (AMPS) was put into service in early 1980s
  - The first IS-95 cellular network was launched in 1995
  - The first cdma2000 network was in service in the end of 2000
  - The first 3G WCDMA network started service in 2001
  - The first 3.5G cdma2000 1xEV-DO network was launched in 2002
  - The first 3.5G HSDPA network operated in May 2006
  - The first 3.5G cdma2000 1xEV-DV network will be launched in 2007?
- In 20 years cellular systems have evolved from 1G to 3.5G (about 7 years per generation).
- However, we have not seen any major breakthrough in CDMA core technology since IS-95 was launched in 1995.

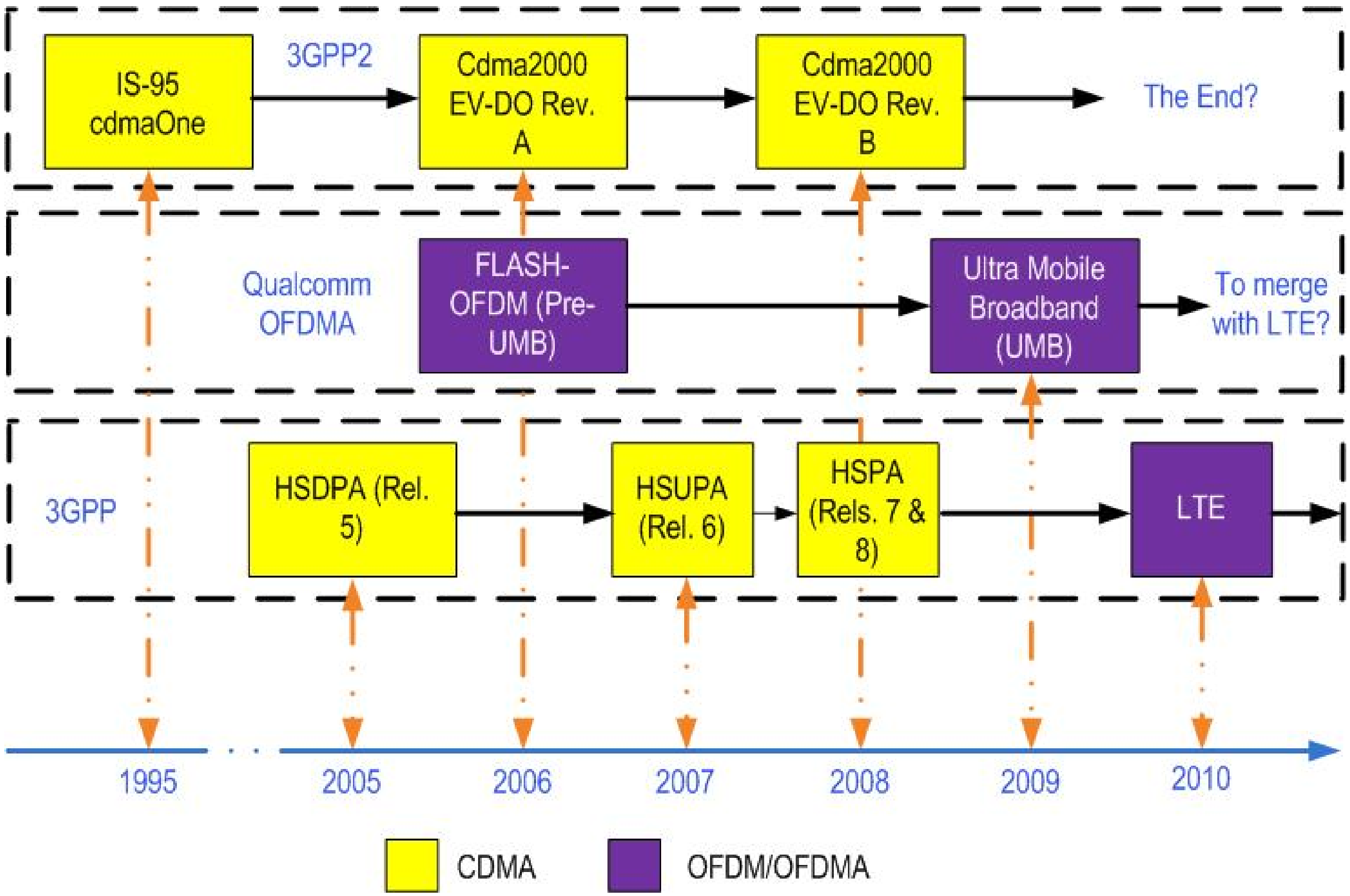
Introduction (11/16)

The roadmap towards ITU IMT-Advanced



Introduction (12/16)

Qualcomm's Roadmap



Introduction (13/16)

- Qualcomm has 5700 US patents and patent applications of CDMA and related technologies, including WCDMA.
- In 2006 Qualcomm's revenue was $7.53 billion* (vs. 200 billion for the whole wireless industry), and a very big portion came from IPR licensing and royalty payments.
- Qualcomm has enjoyed growing worldwide CDMA license and royalty revenues since 1995.

* $8.87 billion for the fiscal 2008.

Introduction (16/16)

- CDMA related IPR royalty has become a thorny issue in the whole wireless industry.
  - European Commission Complaints (Broadcom, Ericsson, NEC, Nokia, Panasonic Mobile Communications and Texas Instruments, October 28, 2005)
  - Qualcomm/Broadcom Litigation (September 1, 2006)
  - Qualcomm/Nokia License Negotiations and Litigation (November 4, 2005-April 3, 2007)
  - Korean Fair Trade Commission Complaints (April 4, 2005)
- QUALCOMM acquired Flarion Technologies in 2006.
  - It is expected the similar IPR conflict will happen after OFDMA techniques will be widely used in wireless/mobile applications.
- QUALCOMM is interested in both CDMA and OFDMA.

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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 direct-sequence (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 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
  - Multiple access interference (MAI) is a serious problem.
  - RAKE receiver may not work well to deal with mutipath interference (MI).
  - Capacity is far less than the processing gain (PG).
- 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)

- Technologically different from its 1G version
  - 1G CDMA technology is very much unitary code centric.
  - Almost all existing CDMA technologies are based on one dimensional DS spreading.
- To offer at least interference-resistant performance
  - All 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.
  - 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.
- Facilitate MIMO applications
  - MIMO improves performance without consuming bandwidth resource.
  - Joint design of S-T coding and CDMA coding.
  - Applications of 3-dimensional spreading codes.

What is Next Generation CDMA? (3/3)

- Support rate-on-demand high-speed data
  - “Unitary codes” with DS spreading are not agile to support multi-media applications.
  - Rate-on-demand capability should be enabled.
  - Rate changes should not produce too much traffic overhead.
- Support fast fading channel applications
  - High-speed railway communications.
  - IEEE 802.11p standard for V2V and V2R communications is based on IEEE 802.11a , which was not designed for fast-fading channels.
  - A completely new CDMA code design methodology is needed.
- Easy 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 offer multipath diversity.
  - Cell sectorization is not necessary to ease cell planning.

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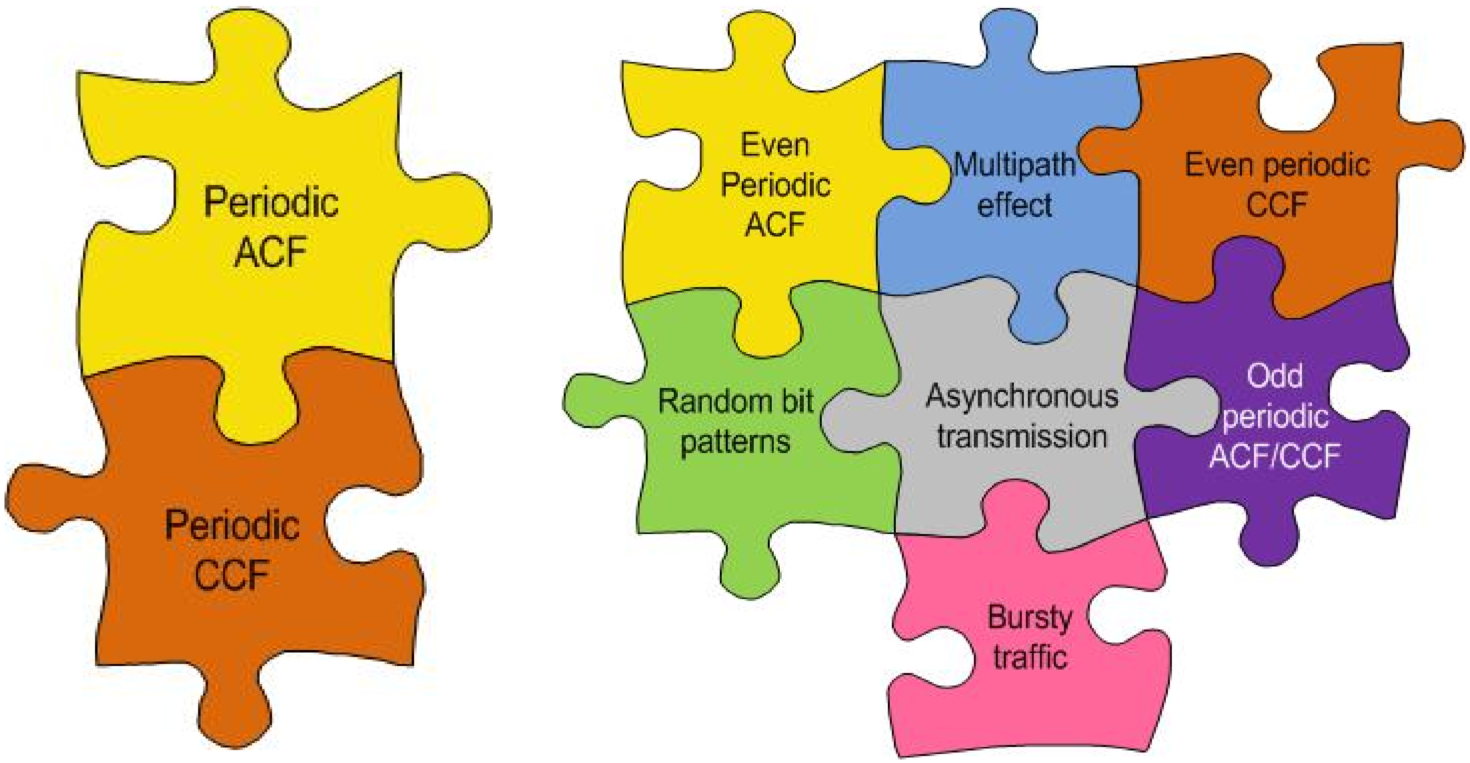
Multi-dimensional spreading code design (1/11)

- "Real Environment Adaptation Linearization" (REAL) approach takes into account:
  - Asynchronous transmission
  - Multipath interference
  - Random data signs in two consecutive bits
  - Partial auto-correlation and partial cross-correlation functions
- Parameters used in design of the next generation CDMA system:
  - 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
  - MN: processing gain of the system

Multi-dimensional spreading code design (2/11)

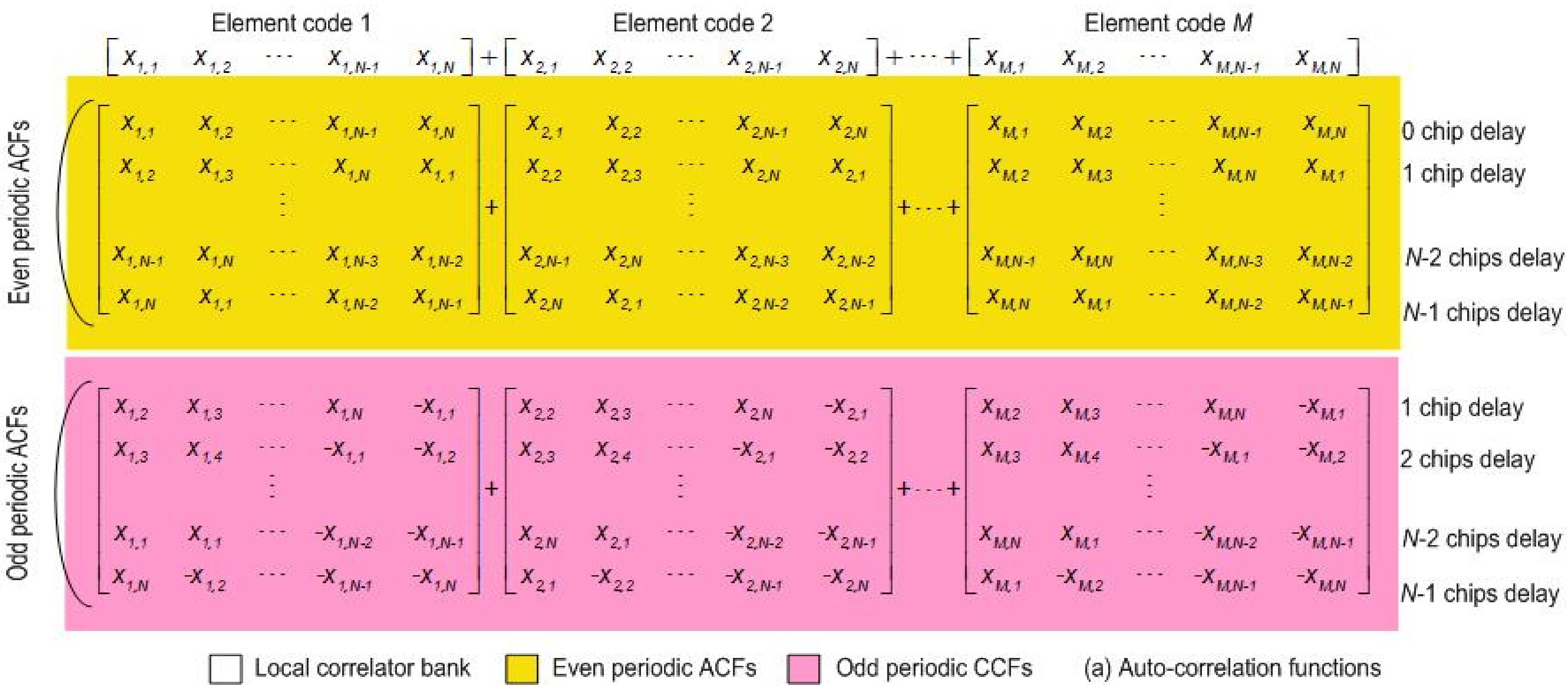


(a) Design scenario in Traditional approach

(b) Design scenario in REAL approach

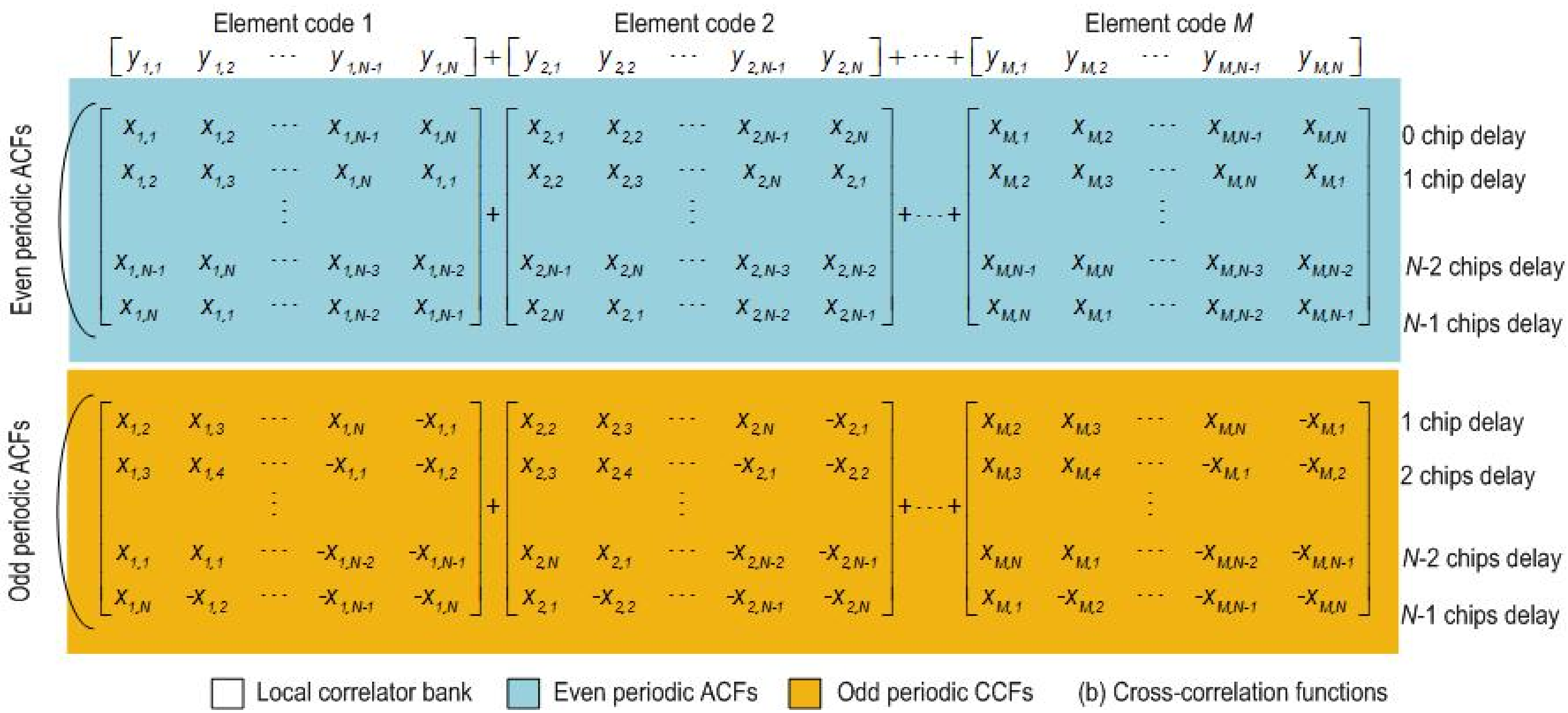
Comparison between (a) traditional code design approaches and (b) the REAL Approach.

Multi-dimensional spreading code design (3/11)



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 (4/11)



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Multi-dimensional spreading code design (5/11)

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:	(+ − + + + − − −)	(+ − + + − + + +)	(− + − − − + + +)	(+ − + + − + + +)

Multi-dimensional spreading code design (6/11)

The REAL approach tells us:

- It is possible to design an interference-free CDMA, which is the most important characteristic feature for the next generation CDMA technology.
- The interference-free CDMA must be implemented by complementary codes.
  - The solutions to the REAL approach exist if and only if $M>1$.
- The number of channels accommodated in one cell of the interference-free CDMA system is equal to the flock size of the complementary code.
  - The solutions to the REAL approach exist when $K=M$.

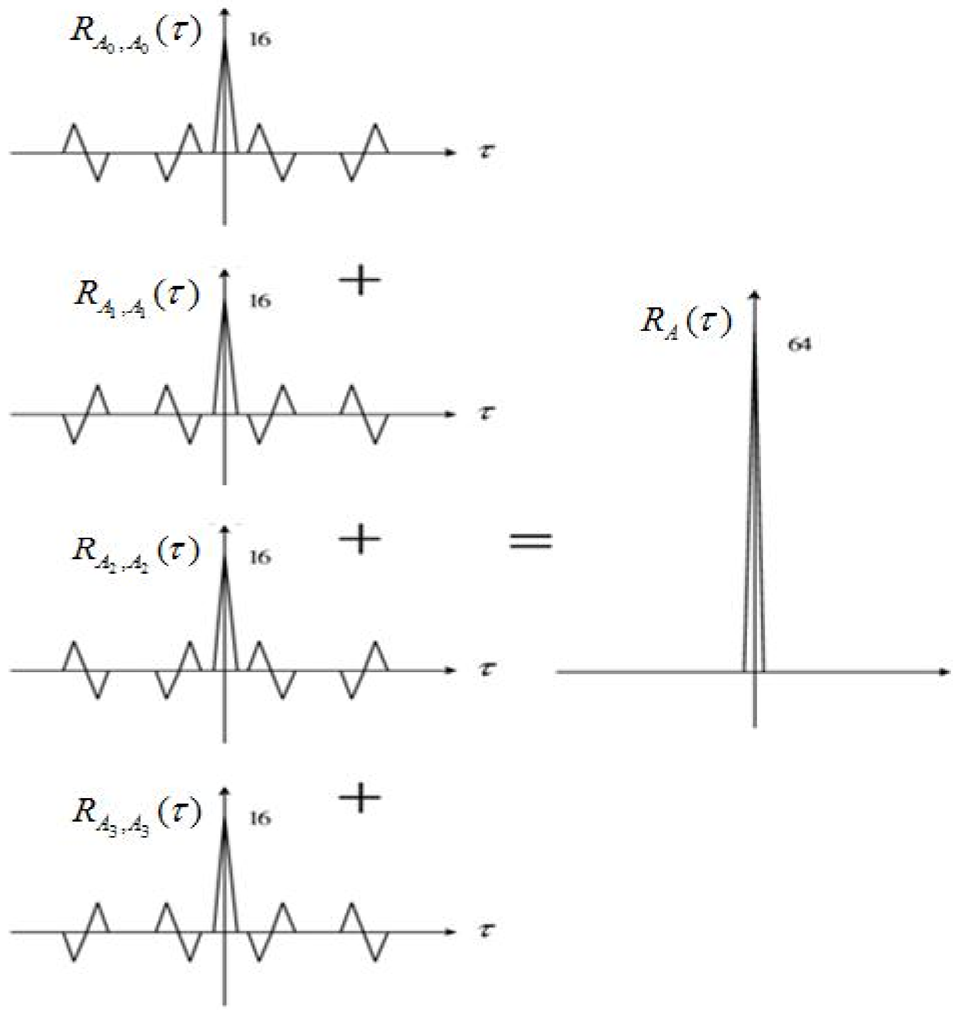
Multi-dimensional spreading code design (7/11)

Why complementary code makes a difference?

- Correlation function is based on a flock of element codes, instead of only ONE code.
- Each element code may have non-zero correlation levels, which will be cancelled in the summation process before detection.
- Relaxation on the non-zero correlation functions of individual element codes is the key to make a perfect flock-wise correlation function.

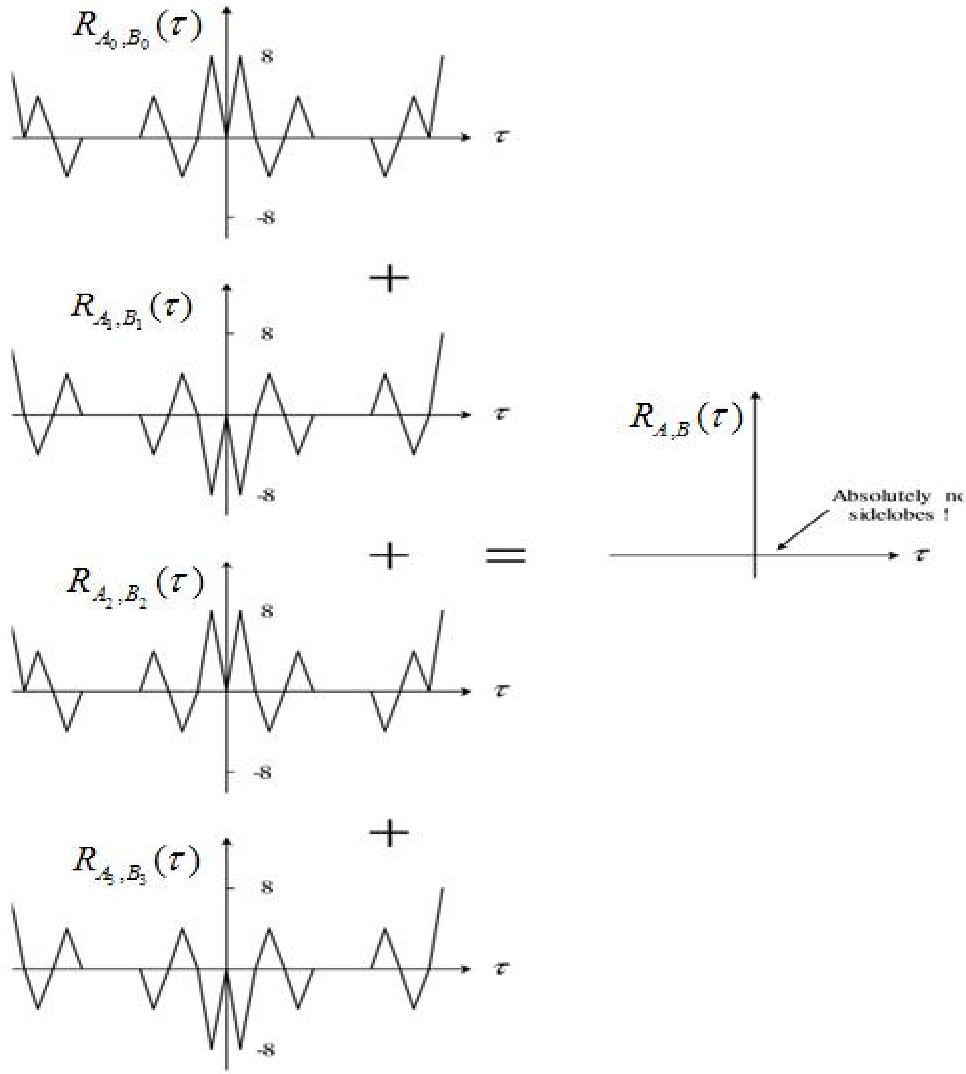
Multi-dimensional spreading code design (8/11)

Relaxation on the non-zero auto-correlation side-lobes of an individual element code is the key to make a perfect flock-wise auto-correlation function.



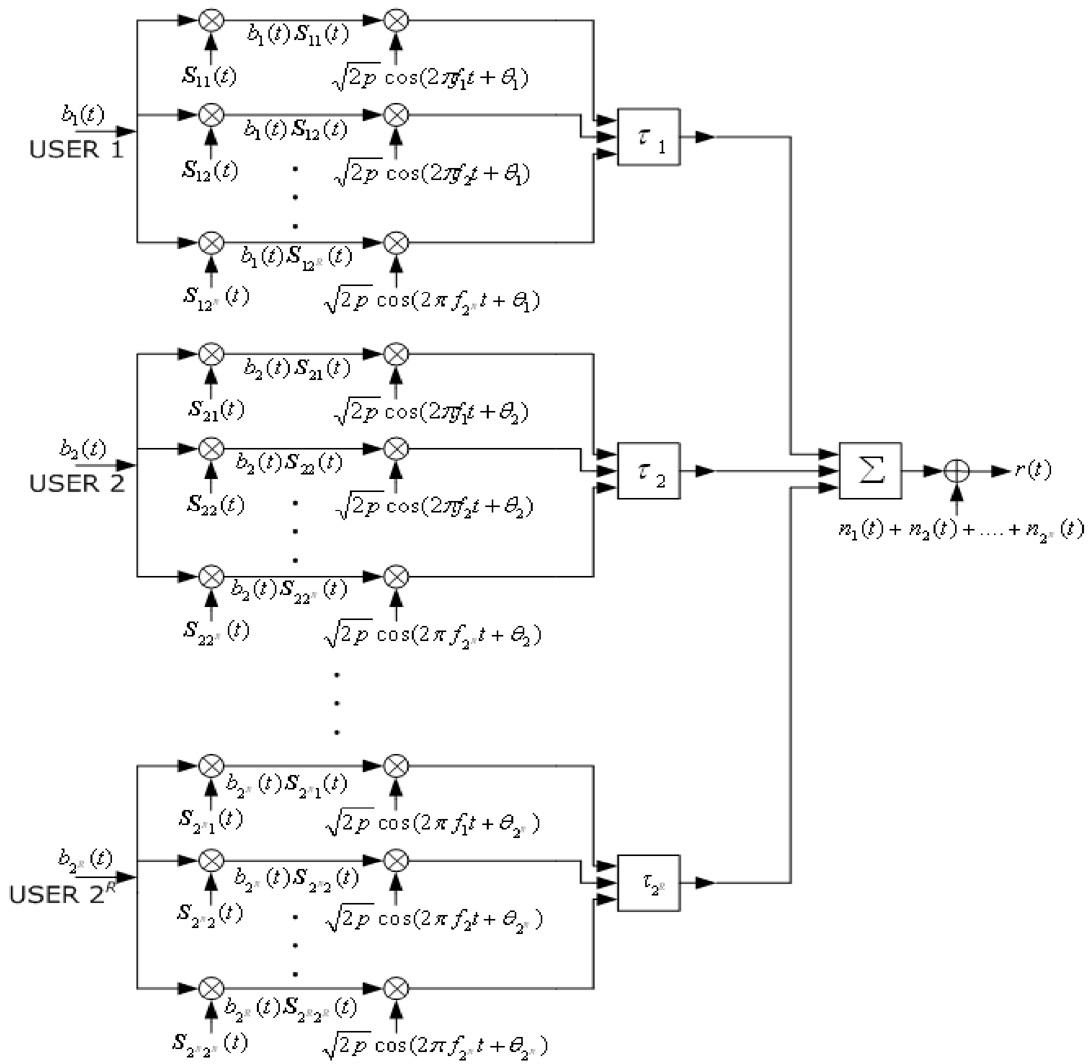
Multi-dimensional spreading code design (9/11)

Relaxation on the non-zero cross-correlation functions of individual element codes is the key to make a perfect flock-wise cross-correlation function.

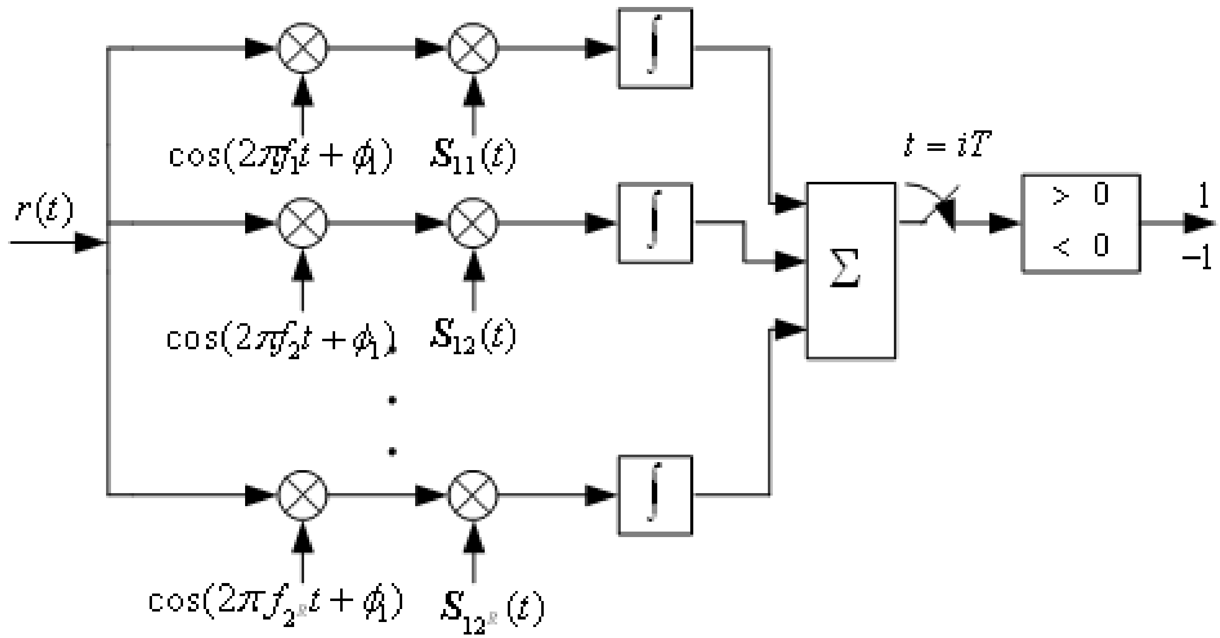


Multi-dimensional spreading code design (10/11)

Transmitter block diagram for a CDMA system based on complementary codes, where the multi-carrier modulator can be implemented using an OFDM (IFFT) block



Multi-dimensional spreading code design (11/11)



Receiver block diagram for a CDMA system based on complementary codes, where the multi-carrier demodulator can be implemented by an OFDM (FFT) block

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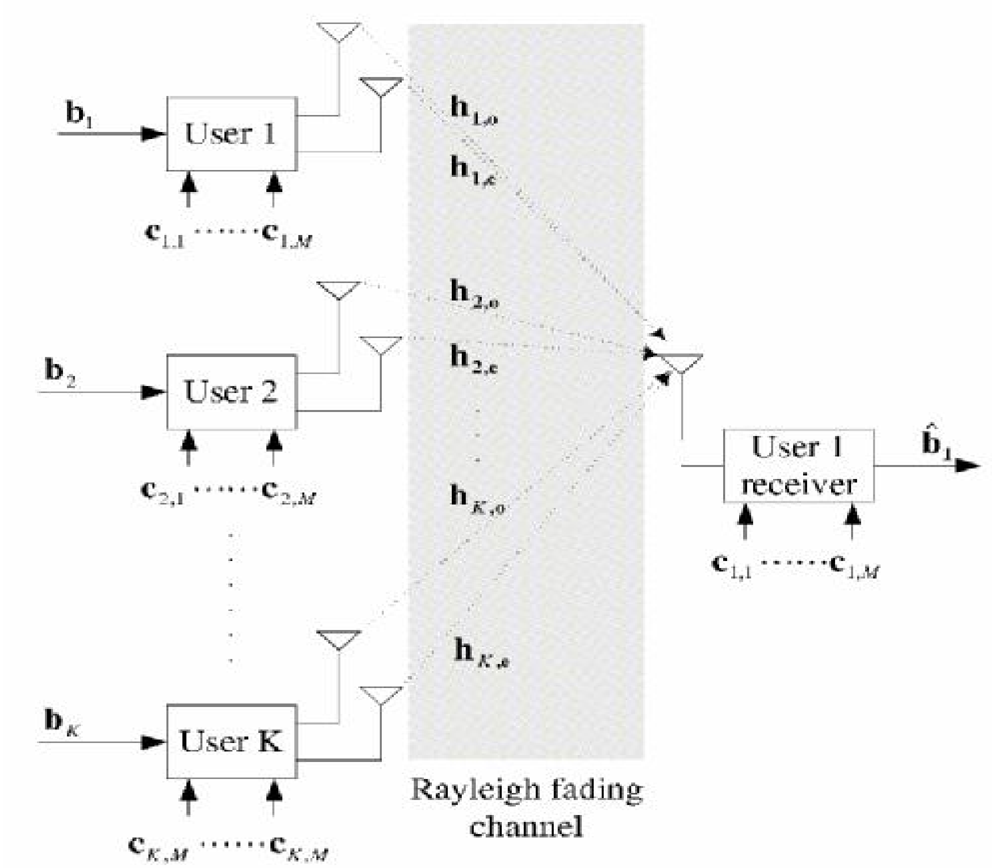
MIMO-enabled next generation CDMA (1/10)

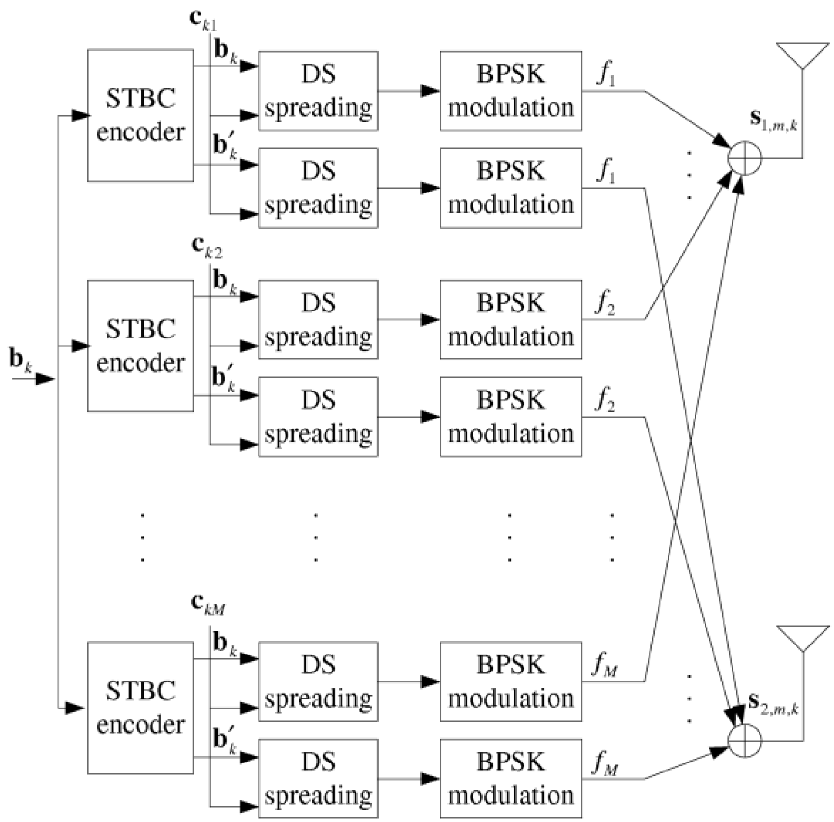
Bit-level space-time-frequency complementary coding (BL-STFCC)



NG CDMA works jointly with STBC system model with *K* users

MIMO-enabled next generation CDMA (2/10)

Tx of bit-level space-time-frequency complementary coding (BL-STFCC)



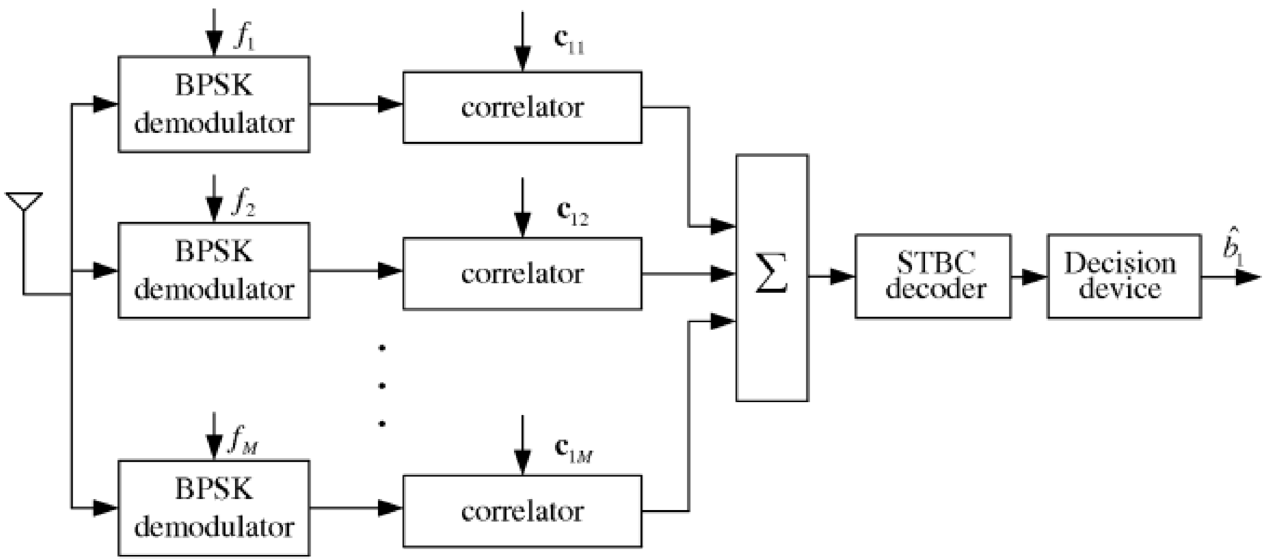
$$\mathbf{b}_k = b_{k,1}, b_{k,2}, b_{k,3}, b_{k,4}, b_{k,5}, b_{k,6}, \cdots\cdots$$

$$\mathbf{b}'_k = b_{k,2}, -b_{k,1}, b_{k,4}, -b_{k,3}, b_{k,6}, -b_{k,5}, \cdots\cdots$$

The *k*th transmitter of NG CDMA working jointly with STBC

MIMO-enabled next generation CDMA (3/10)

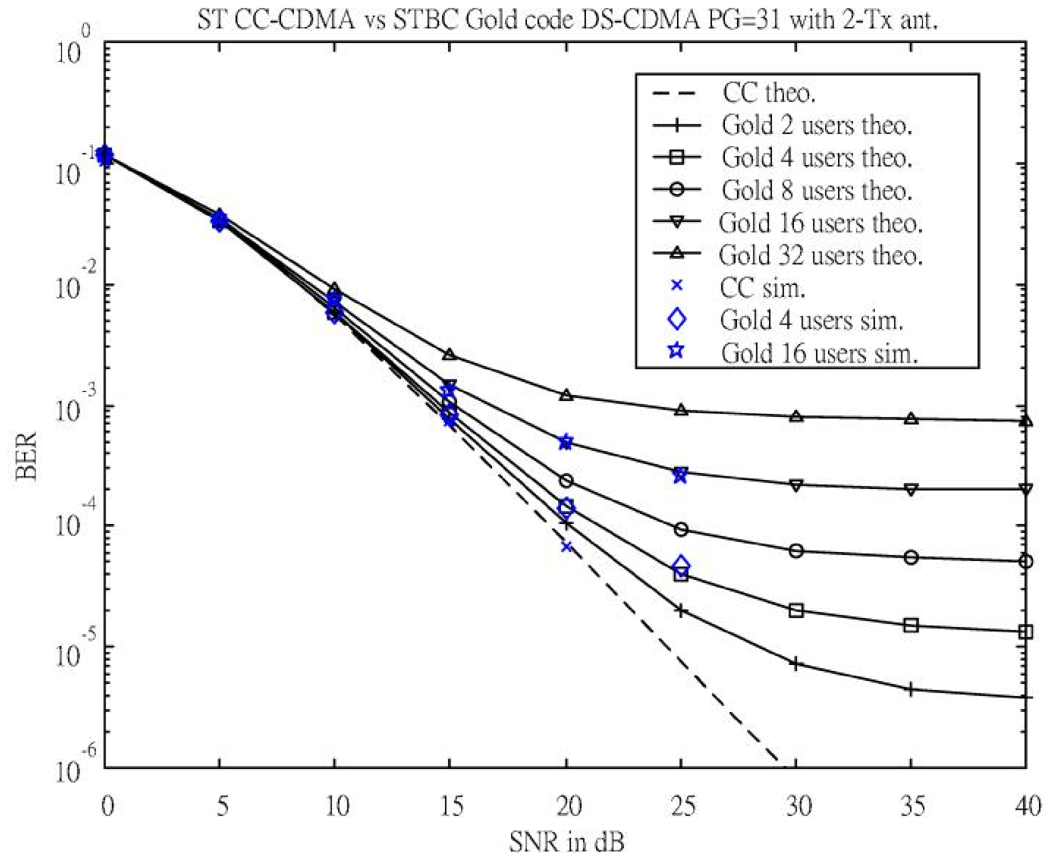
Rx of bit-level space-time-frequency complementary coding (BL-STFCC)



The *k*th receiver of NG CDMA working jointly with STBC

MIMO-enabled next generation CDMA (4/10)

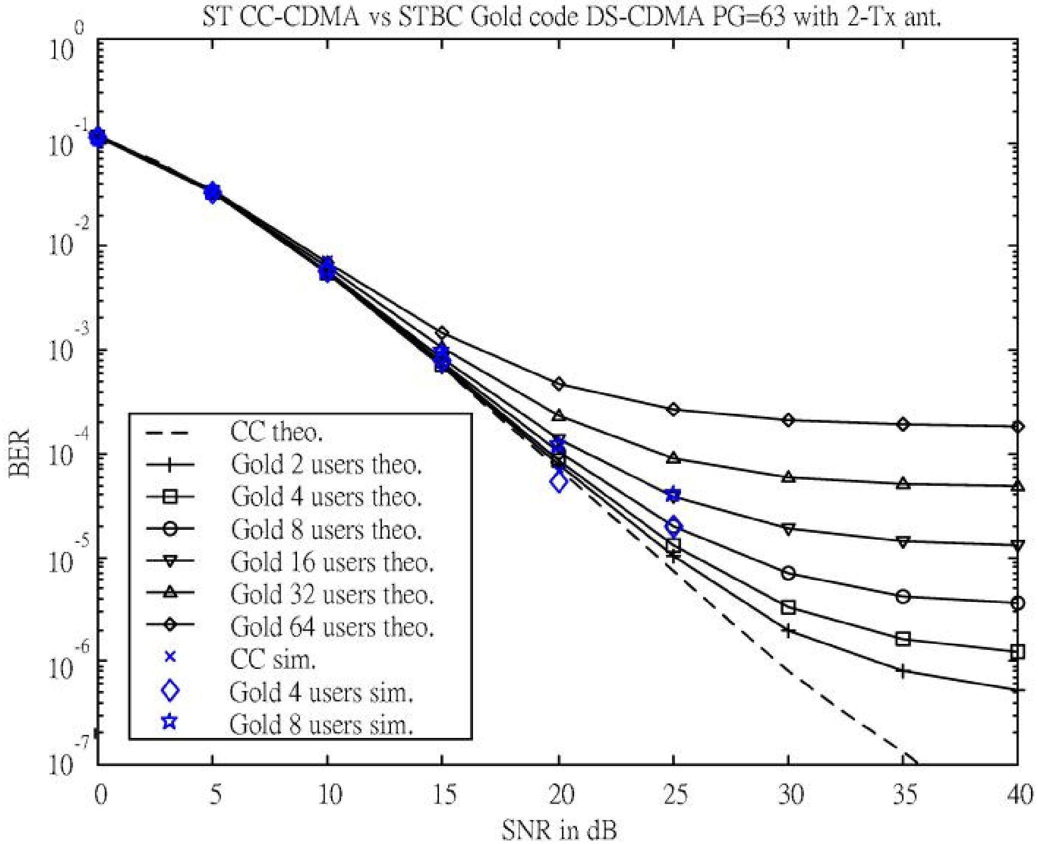
Bit-level space-time-frequency complementary coding (BL-STFCC)



BER performance for 2-Tx antenna NG CDMA working jointly with STBC in Rayleigh fading channel with PG=32

MIMO-enabled next generation CDMA (5/10)

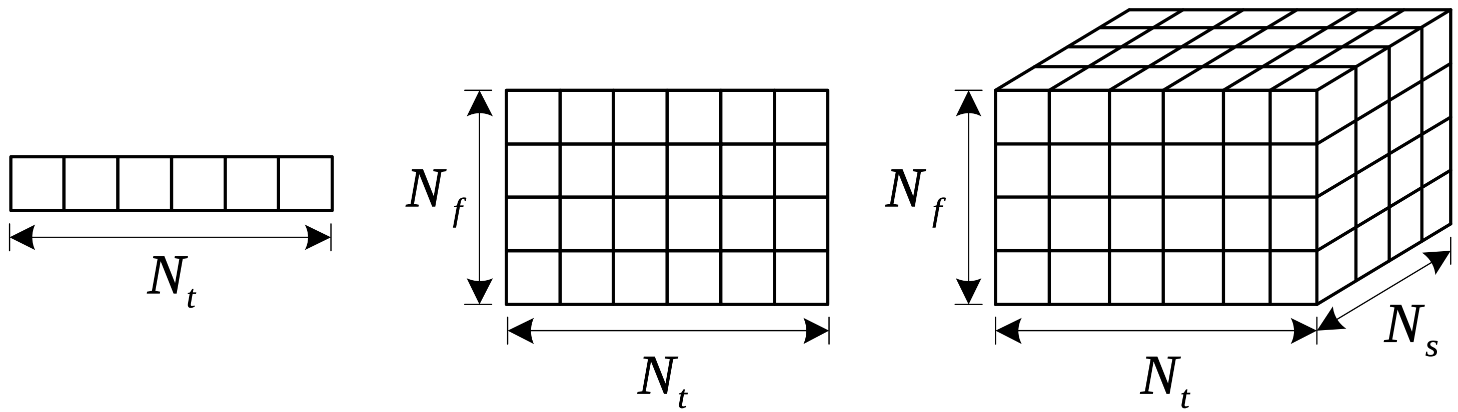
Bit-level space-time-frequency complementary coding (BL-STFCC)



BER performance for 2-Tx antenna NG CDMA working jointly with STBC in Rayleigh fading channel with PG=64

MIMO-enabled next generation CDMA (6/10)

Evolution of spreading modulation from 1-D to 3-D



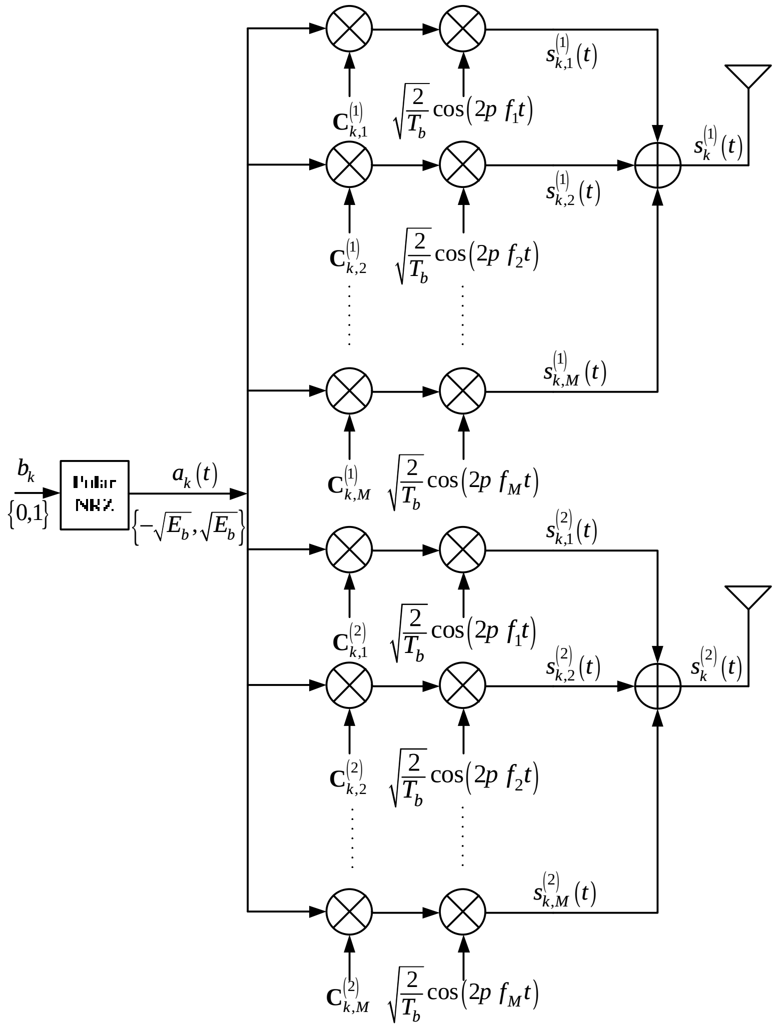
(a) One dimensional spreading

(b) Two dimensional spreading

(c) Three dimensional spreading

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

MIMO-enabled next generation CDMA (7/10)



Tx of chip-level space-time-frequency complementary coding (CL-STFCC) (only two Tx antennas are shown)

b_k : User k 's data bit

$a_k(t)$: User k 's data signal after the polar NRZ unit

$$a_k(t) = \begin{cases} -\sqrt{E_b}, & b_k = 0, nT_b < t < (n-1)T_b, \; n = 1, 2, \ldots, N \\ \sqrt{E_b}, & b_k = 1, nT_b < t < (n+1)T_b, \; n = 1, 2, \ldots, N \end{cases}$$

T_b : Bit duration

T_c : chip duration

$\mathbf{C}_{k,m}^{(n_t)}$: The mth element code used by the kth user and the n_t -th antenna

$s_k^{(n_t)}(t)$: The signal sent from the n_t -th antenna of the kth user

$s_{k,m}^{(n_t)}(t)$: The mth element code signal sent from the n_t -th antenna of the kth user

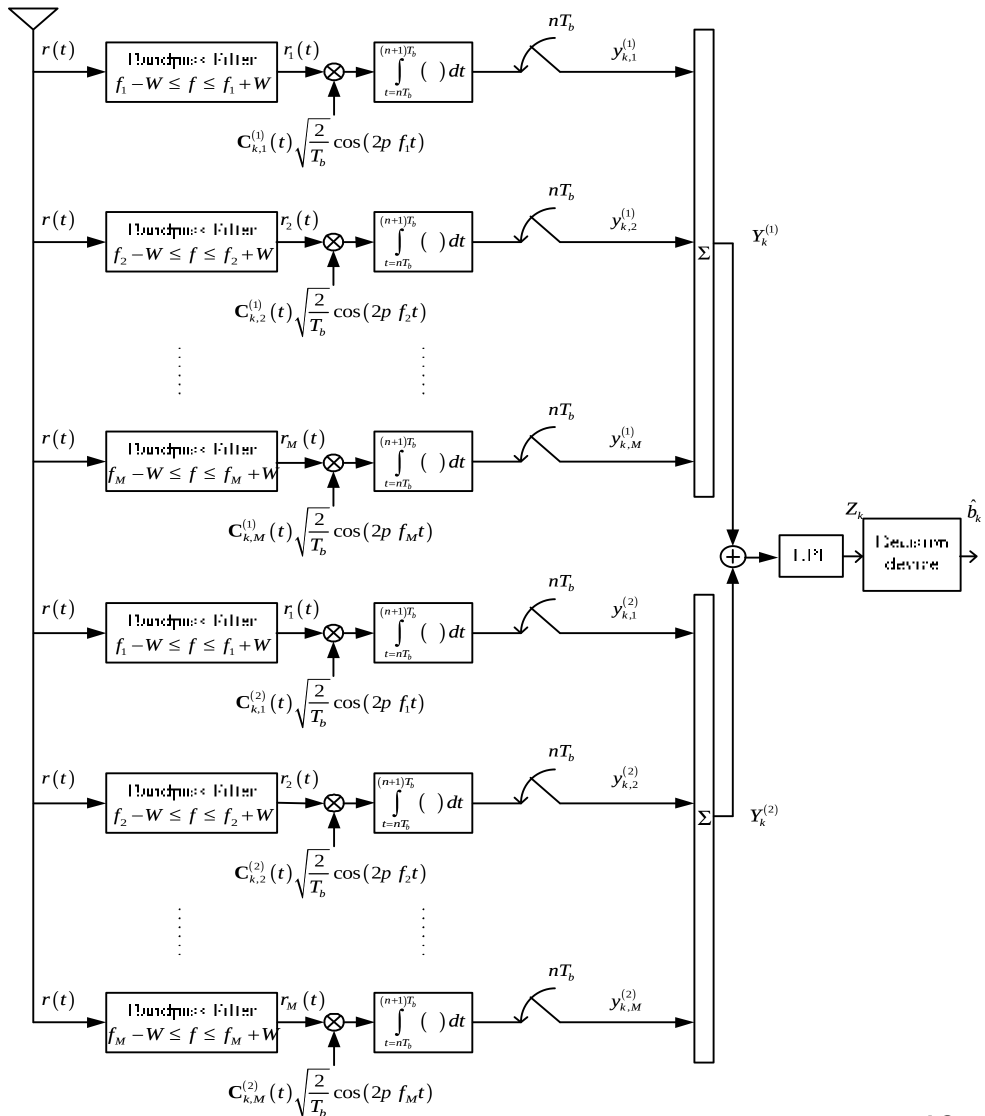
m : Subcarrier index

n : discrete time index

k : User index

MIMO-enabled next generation CDMA (8/10)

Rx of chip-level space-time-frequency complementary coding (CL-STFCC)



$C_{k,m}^{(n_t)}(t)$: The mth element code for the kth user and the n_t-th antenna

$r(t)$: The received signal by the kth user

$r_m(t)$: The received signal by the kth user after bandpass filter whose center frequency is f_m

$Y_k^{(n_t)}$: Despread signal of the kth user at the n_t-th antenna

$y_{k,m}^{(n_t)}$: Signal of the kth user at the n_t-th antenna for the mth element code after correlator

$Z_k(t)$: Combined signal for the kth user signal

MIMO-enabled next generation CDMA (9/10)

Receiver of chip-level space-time-frequency complementary coding (CL-STFCC)

- This three-dimensional spreading code set was generated using generalized REAL approach.
- A CDMA system based on this code set offers full spatial diversity gain (4X1), as well as MAI-free and MI-free operation.
- It can support 4 users, each using 4 Tx antennas, with its processing gain being 64.

Example: $K=4$, $M=4$, $N=4$, $N_f=4$

$\mathbf{x}_1^{(1)} : (++++,+-+-,++--,+--+)$
$\mathbf{x}_1^{(2)} : (--++,-++-,++++,+-+-)$
$\mathbf{x}_1^{(3)} : (+--+,--++,-+-+,++++)$
$\mathbf{x}_1^{(4)} : (-+-+,++++,-++-,++--)$

$\mathbf{x}_2^{(1)} : (+-+-,++++,+--+,++--)$
$\mathbf{x}_2^{(2)} : (-++-,--++,+-+-,++++)$
$\mathbf{x}_2^{(3)} : (++--,-++-,----,+-+-)$
$\mathbf{x}_2^{(4)} : (----,+-+-,--++,+--+)$

$\mathbf{x}_3^{(1)} : (++--,+--+,++++,+-+-,)$
$\mathbf{x}_3^{(2)} : (----,-+-+,++--,+--+)$
$\mathbf{x}_3^{(3)} : (-+-+,++++,+--+,--++)$
$\mathbf{x}_3^{(4)} : (+--+,--++,+-+-,----)$

$\mathbf{x}_4^{(1)} : (+--+,++--,+-+-,++++)$
$\mathbf{x}_4^{(2)} : (-+-+,----,+--+,++--)$
$\mathbf{x}_4^{(3)} : (----,+-+-,++--,-++-)$
$\mathbf{x}_4^{(4)} : (++--,-++-,++++,-+-+)$

MIMO-enabled next generation CDMA (10/10)

Properties of chip-level space-time-frequency complementary coding (CL-STFCC)

- CL-STFCC provides both spatial diversity and spatial multiplex at the same time. This unique feature is due to the use of chip-level space-time-frequency coding, different from traditional bit-level S-T coding, which only supports either spatial diversity or spatial multiplex, but not both.

- CL-STFCC offers MAI-free and MI-free operation for both up-link and down-link transmissions. Thus, both base-station and mobiles can use CL-STFCC technique.

- CL-STFCC works based on the integral design of system-architecture and 3-dimensional signaling, making the design for a truly optimal system possible.

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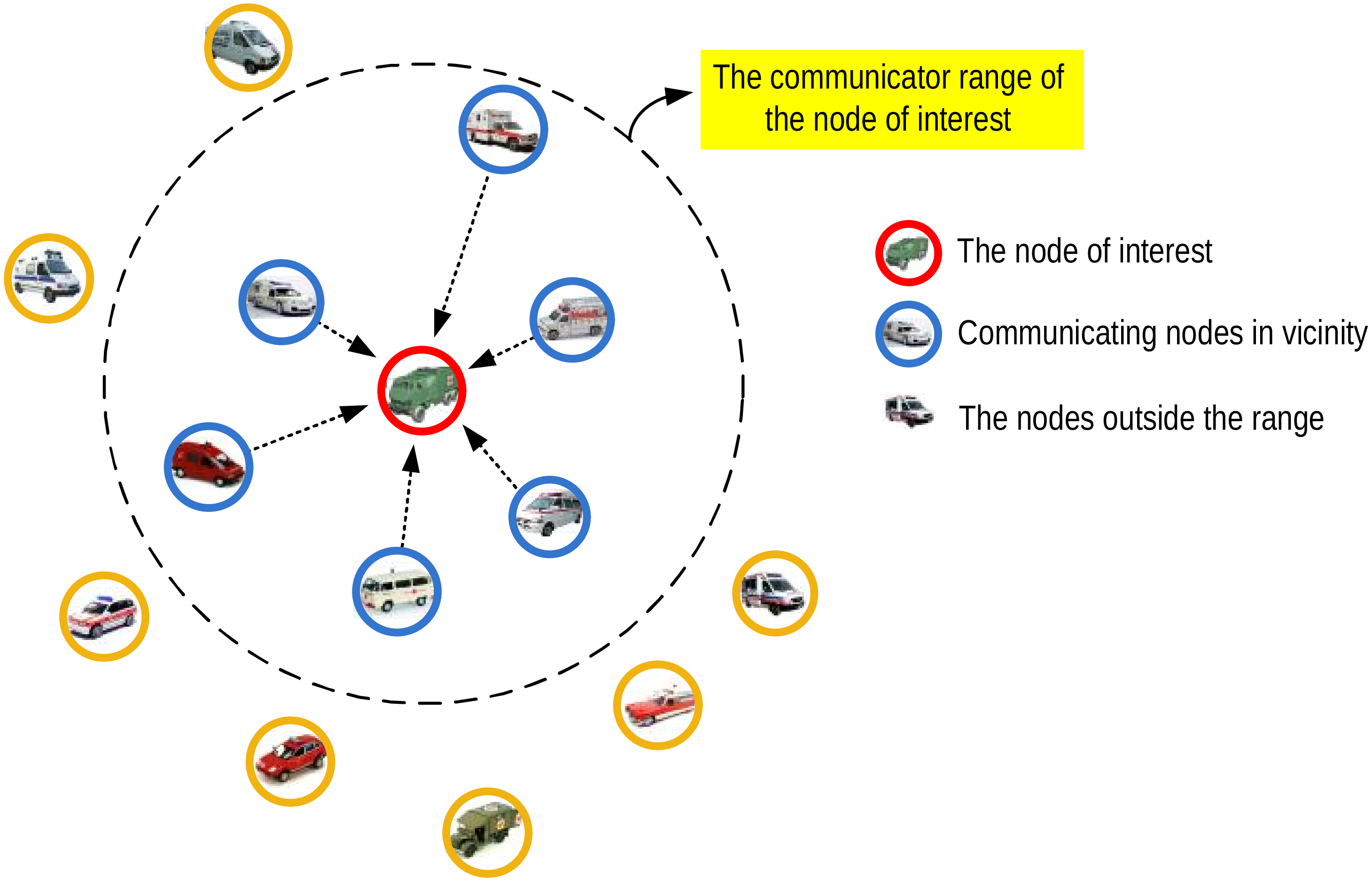
Applications of next generation CDMA (1/7)

Vehicular ad hoc networks (VANETs)



NG CDMA can be applied to vehicular ad hoc networks (VANETs) to improve their performance due to dominant asynchronous transmissions

Applications of next generation CDMA (2/7)

Applications in fast-fading channels

- All NG CDMA systems work based on two-dimensional spreading using different sub-carriers to send *M* different element codes.
- Many complementary codes have been found. One particular type is called column-wise complementary codes, whose ideal correlation property is based only on frequency-domain orthogonality, which will not be affected by time-variant 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 and V2V communications.

Applications of next generation CDMA (3/7)

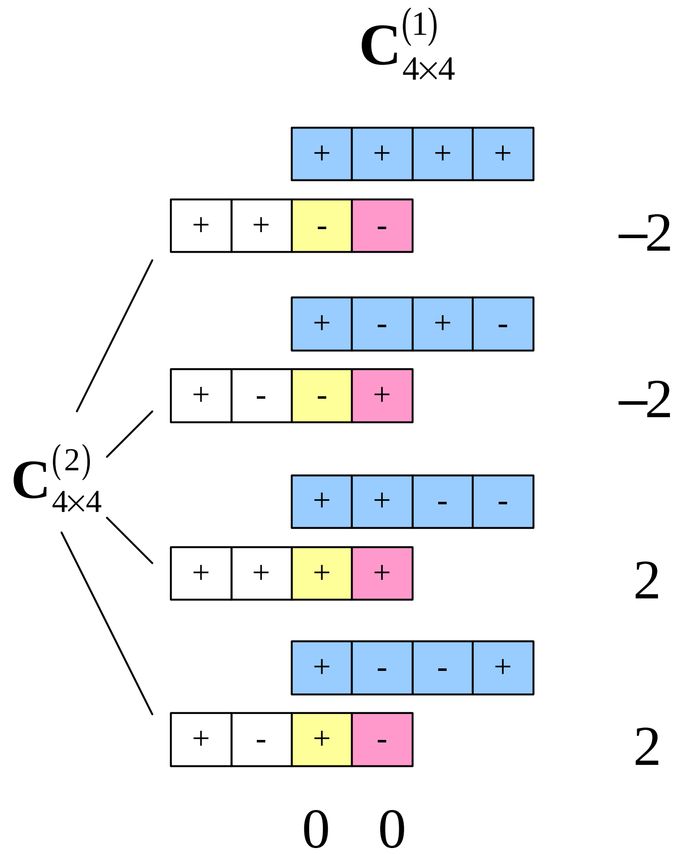
Applications in fast-fading channels

Frequency-domain orthogonality:

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

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

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



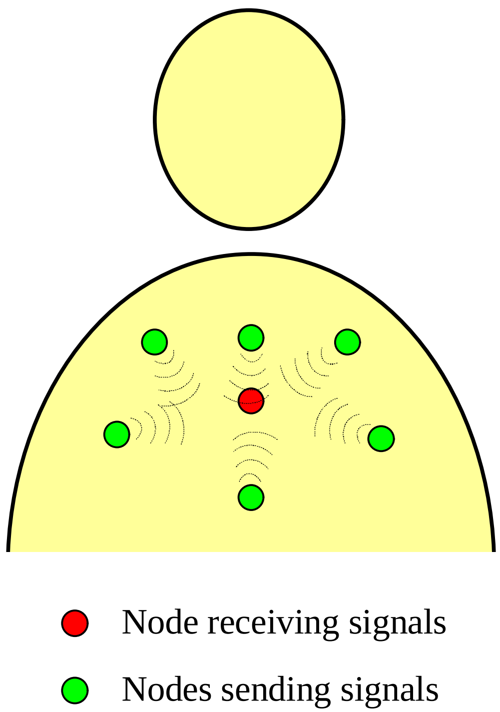
Applications of next generation CDMA (4/7)

Cooperative wireless networks

- Cooperative wireless networking works as a virtual MIMO system to provide spatial diversity gain.
- All relays always transmit asynchronously to a base-station.
- NG CDMA based on complementary codes offer perfect orthogonality for asynchronous transmissions.
- Signal separation can be done nicely to achieve the highest possible spatial diversity gain.

Applications of next generation CDMA (5/7)

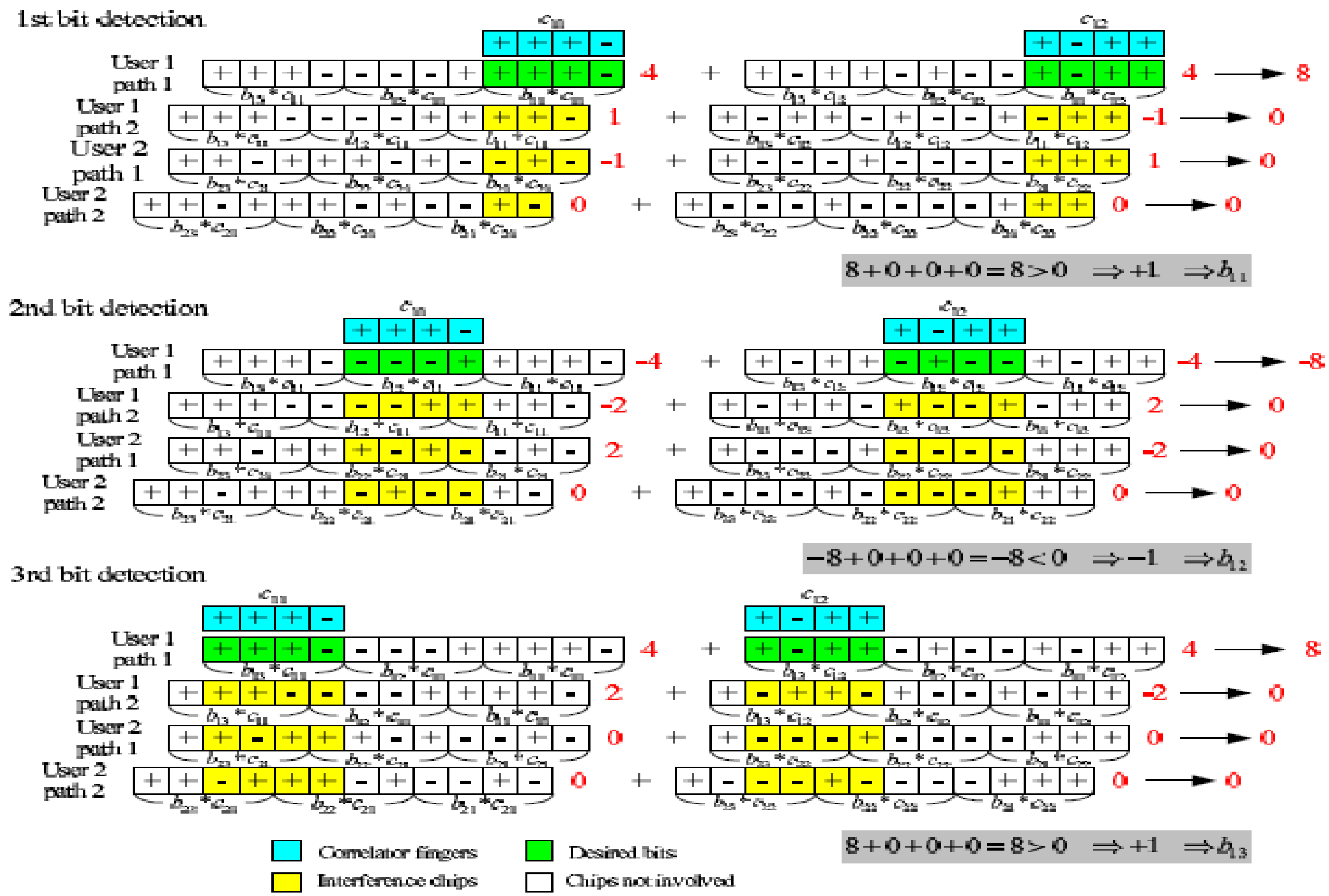
BodyNets or wireless sensor networks



- Only asynchronous transmission exists in all sensor networks, and thus the use of the next generation CDMA technology can provide ideal interference-free operation.
- The relatively low average transmission power of CDMA makes it the right choice for Bodynets, where a strict requirement on the RF emission level may apply.
- MI-free operation of the next generation CDMA is important to mitigate multipath interference in bodynets working in an indoor environment

Applications of next generation CDMA (6/7)

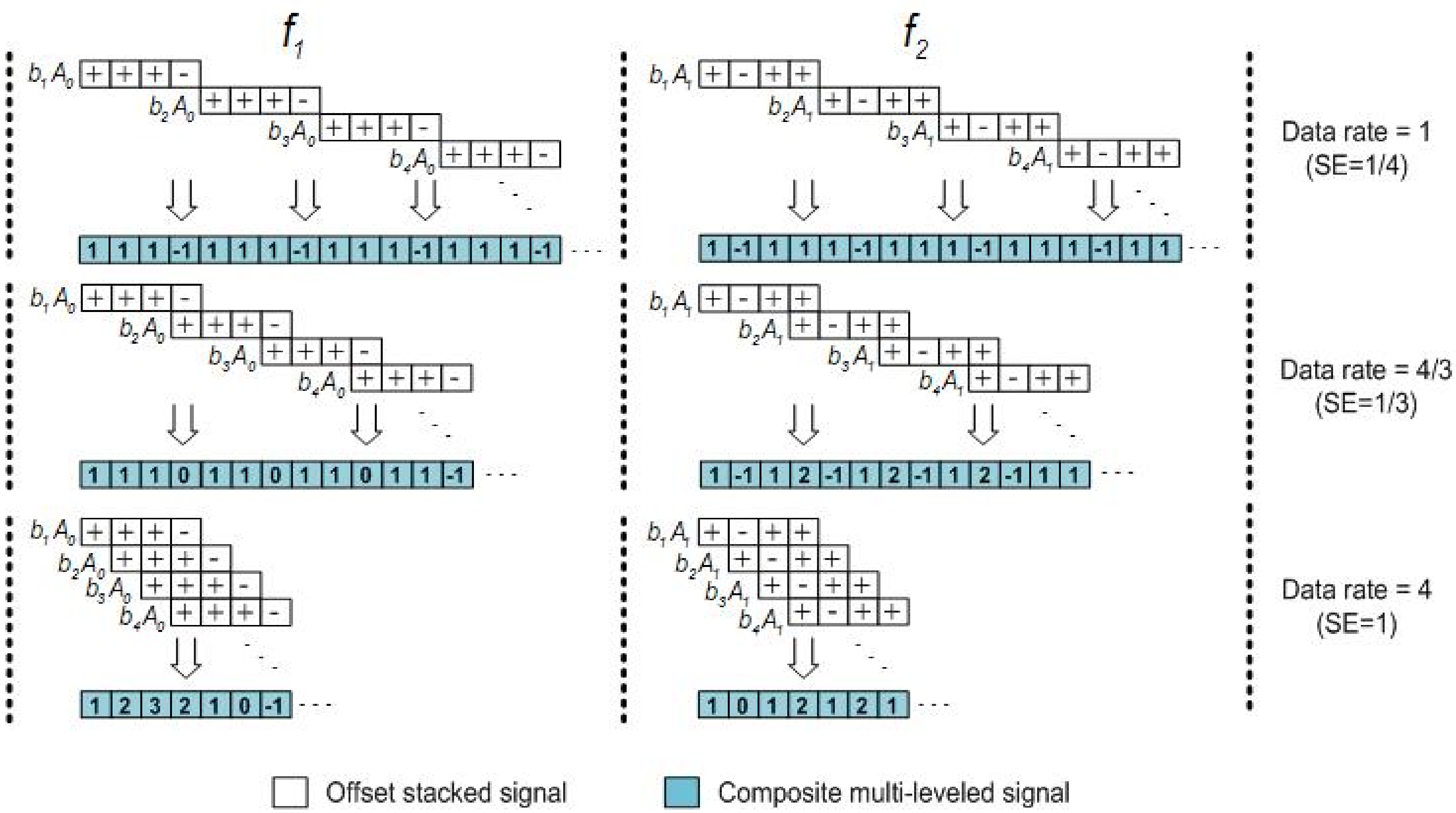
All-IP wireless networks



NG CDMA supports all-IP wireless high-speed burst-traffic. 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 both inter-path delay and inter-user delay being one chip for illustration simplicity.

Applications of next generation CDMA (7/7)

Offset-stacking (OS) spreading: rate-on-demand



Variable SE figures and agility in changing transmission rate in NG CDMA system based on offset-stacking (OS) spreading, where only two short element codes are shown and sent via two different carriers f_1 and f_2 .

Outline

- Introduction
- What's wrong with CDMA?
- What is next generation CDMA?
- Multi-dimensional spreading code design
- MIMO-enabled next generation CDMA
- Applications of next generation CDMA
- Summary
- References

Summary

Next generation CDMA offers:

- MAI-free operation
- MI-free operation
- Support high-speed burst-traffic
- Homogenous performance in synchronous and asynchronous transmissions
- MIMO-enabling capability (CL-STFCC)
- Multi-dimensional spreading (more degree-of-freedoms)
- Suitable for fast-fading applications
- Easy to implement by OFDM

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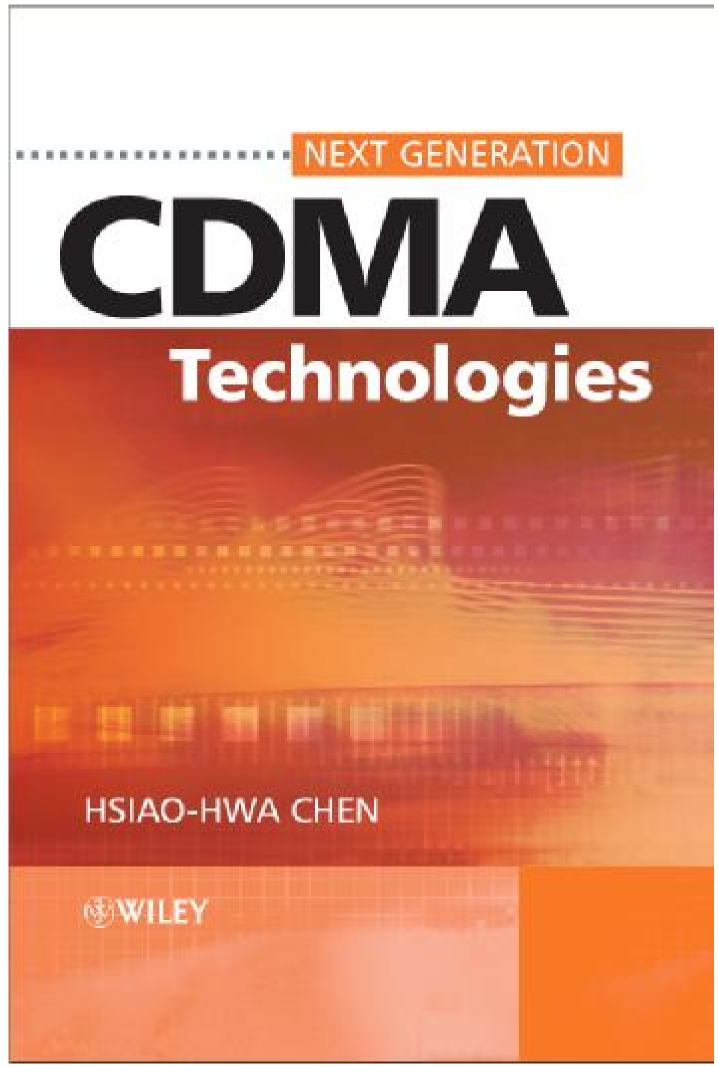

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Thank you !