Broadband Packet Wireless Access for Systems Beyond IMT-2000

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- **Requirements and targets for broadband packet wireless access**
- **Proposed broadband wireless access based on VSF-Spread OFDM and VSCRF-CDMA**
- **MIMO multiplexing techniques and design of 1-Gbps transceiver**
- **Field experimental results on broadband packet wireless access**

Number of FOMA Subscribers and Coverage by DoCoMo

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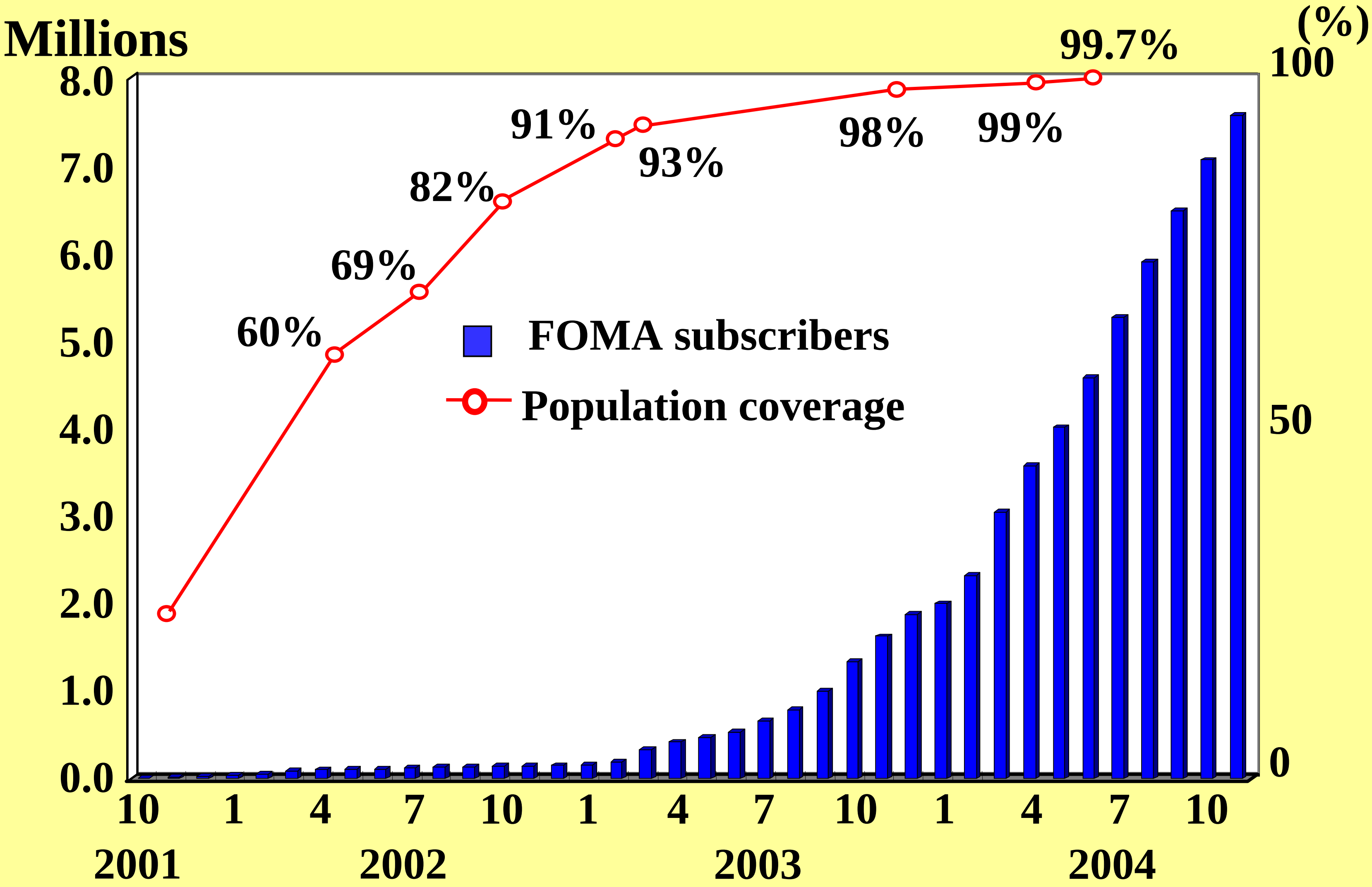
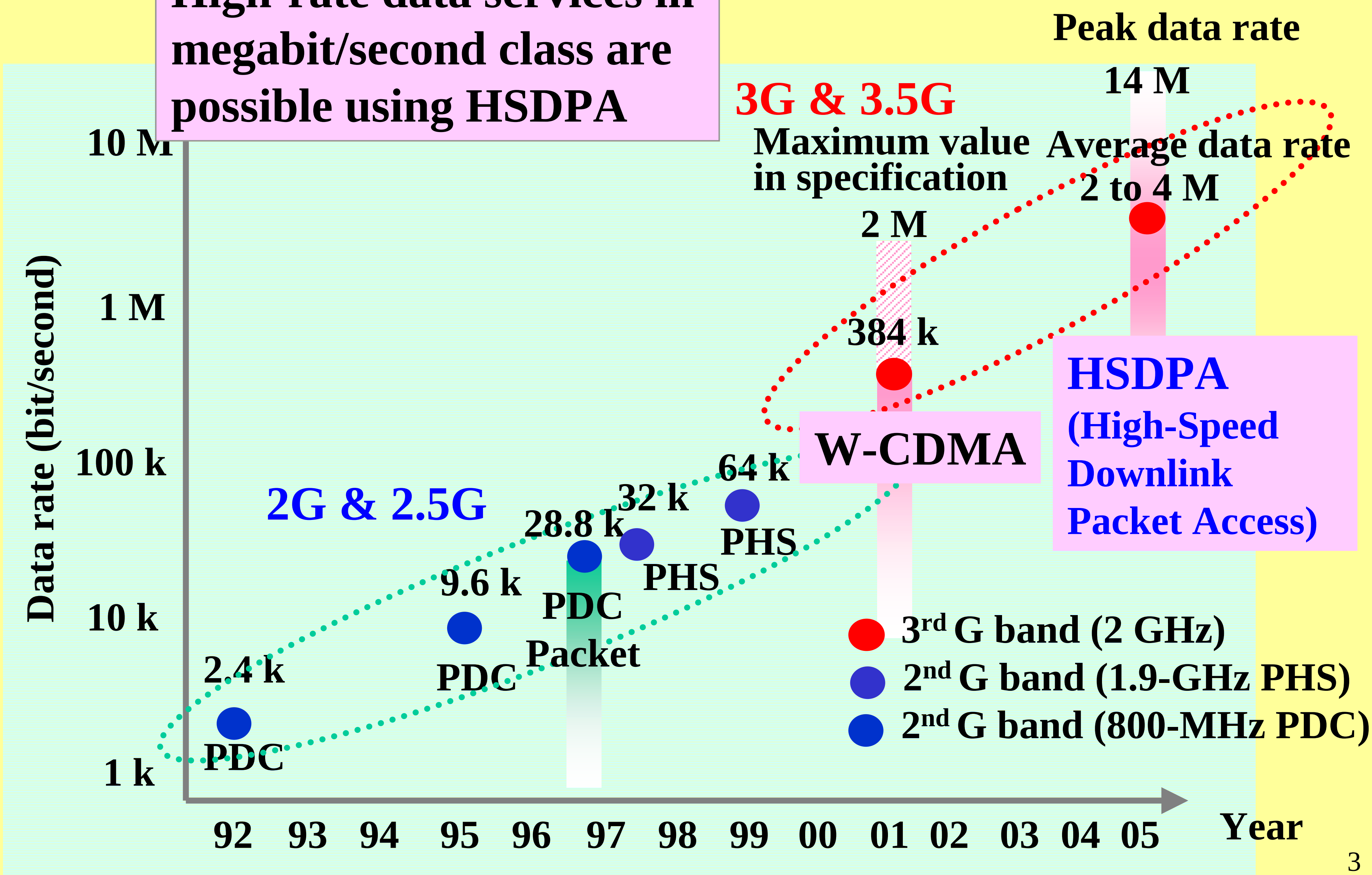


➔ **Global spread of 3G (W-CDMA) services**

Achievable Data Rate in Cellular Systems in Japan

High-rate data services in megabit/second class are possible using HSDPA



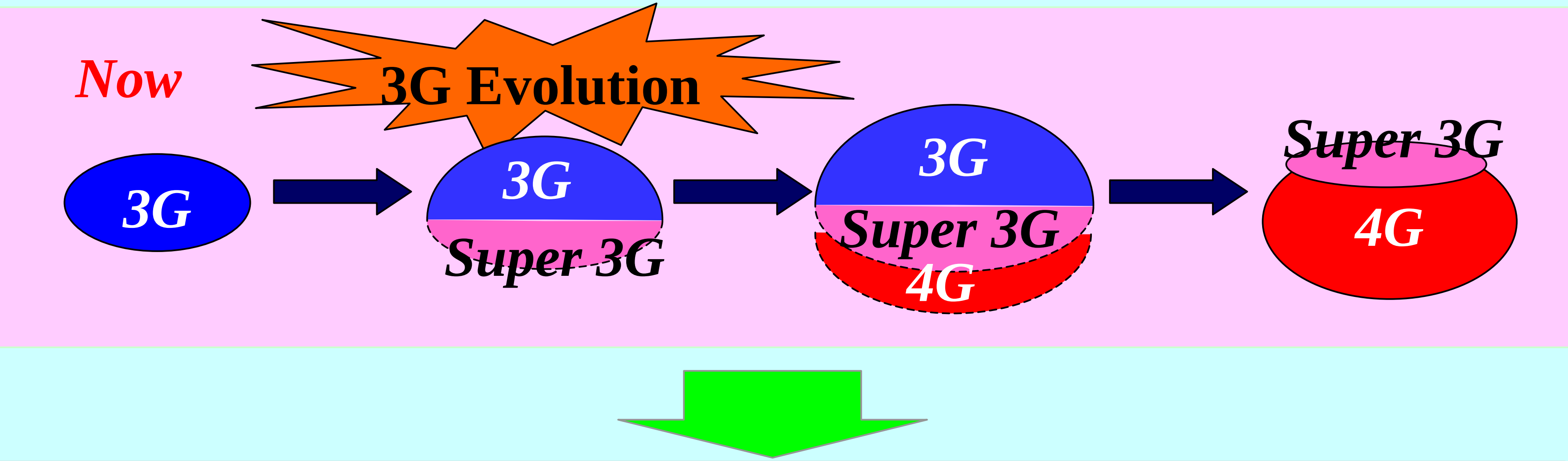
Migration to 4G Broadband Radio Access Network

◆ **Mid-term 3G RAN evolution:**
HSDPA, uplink enhancement, MBMS, etc.

◆ **Long-term 3G RAN evolution (Super 3G)**

✓ **3G system provides support for full IP capabilities including air interface**

✓ **Smooth introduction of future 4G system**



◆ **Real 4G using new spectrum with broad bandwidth such as 100 MHz**

Future 4G Broadband Radio Access Networks

◆ **Real wireless Internet**

➔ **High-speed data services via wireless Internet anytime and anywhere at low cost**

IP-based radio access networks (RANs) with low latency (delay) and with precise QoS controls (QoS: Delay, residual packet error rate, etc.)

➔ **Flexible packet-based access with affinity to IP-based core networks**

◆ **Technical requirements**

✓ **Very low latency (connection and transmission delays)**

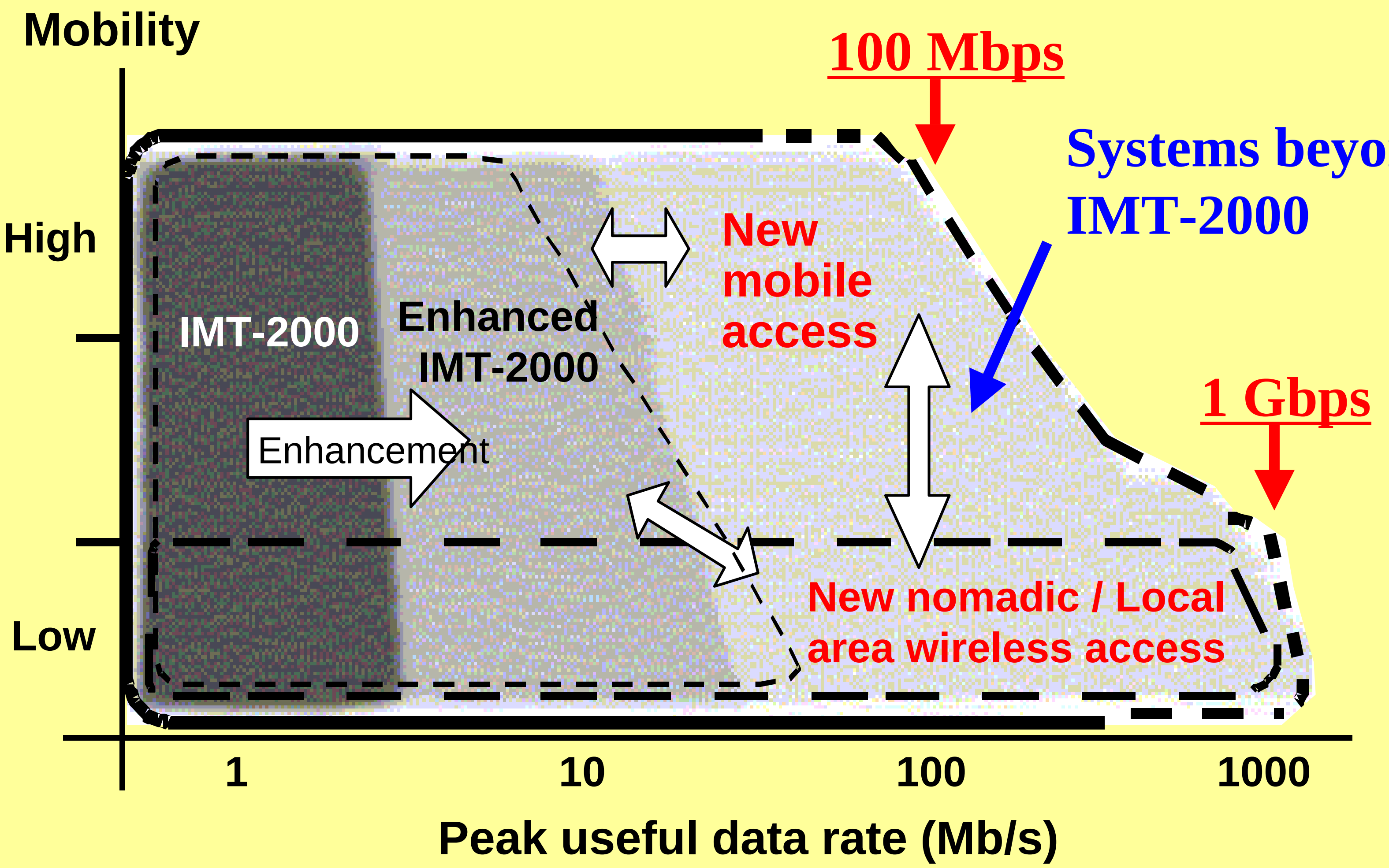
✓ **High user data rate and high capacity (high sector throughput)**

✓ **Wide coverage area**

✓ **Low network cost**

✓ **Backward compatibility with existing cellular systems**

Targets for Systems Beyond IMT-2000



Extracted from ITU-R.1645

Proposed 4G Broadband Wireless Access Concept

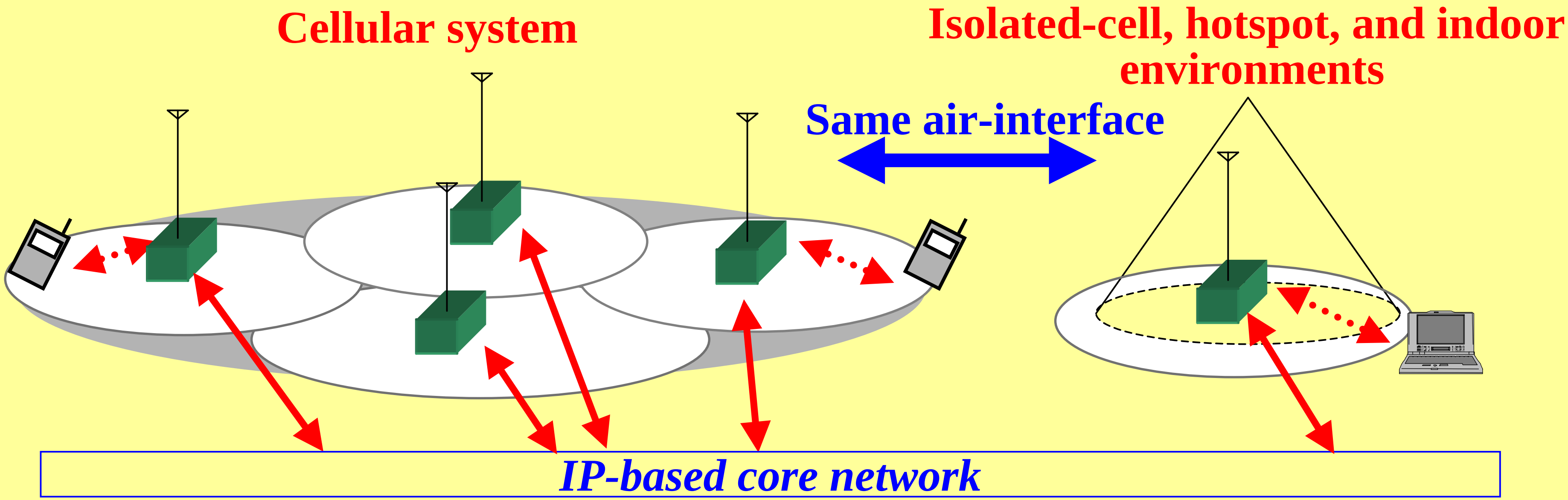
Our proposed concept

➔ **4G broadband wireless access must flexibly support**

- **Cellular systems with multi-cell configuration**
- **Local area environments such as very-small-cell (hotspot), isolated-cell, and indoor environments**

with the same air interface by changing radio parameters

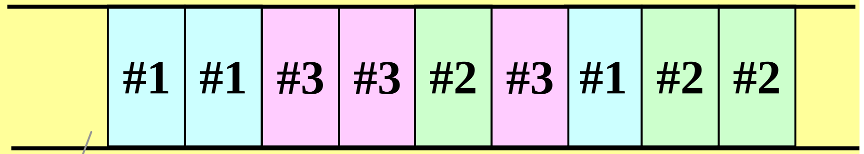
➔ **Flexible system deployment and reduction in network cost**



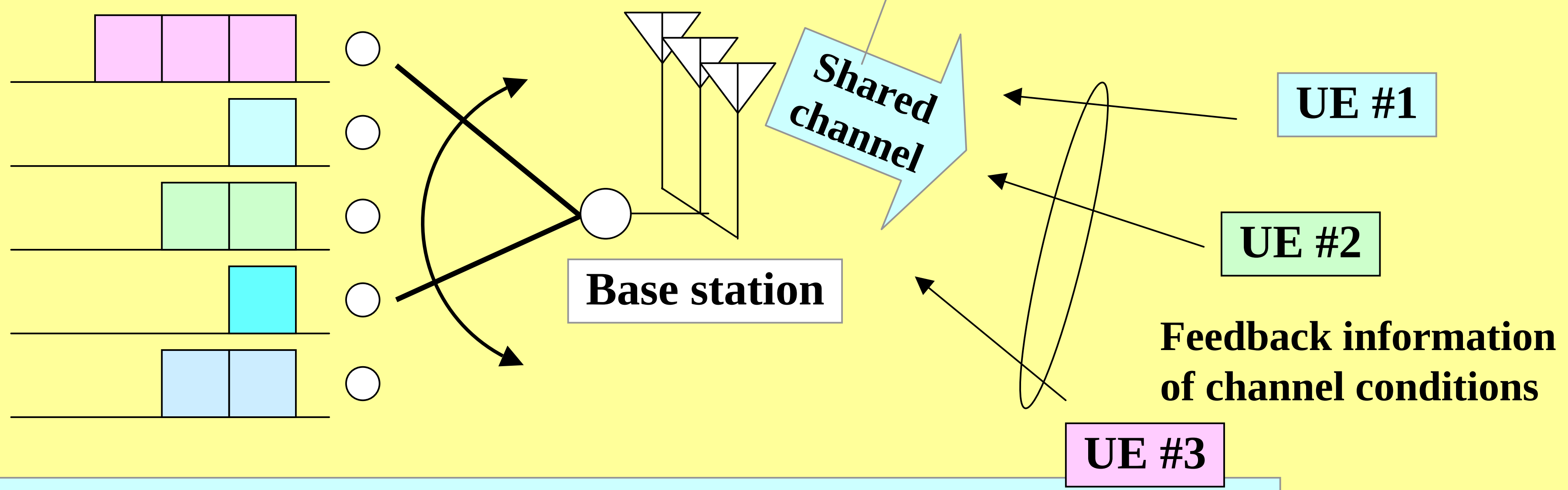
Packet-Based Wireless Access

Shared channel is used to transmit various types of data in packet format

Transmission slot assignment in shared channel in downlink



Information of QoS, data size, …



Transmission slot assignment is based on

- ◆ QoS (Delay) requirements
- ◆ Traffic (IP packet size)
- ◆ Channel conditions
- ◆ Initially transmitted packet or retransmitted packet, etc.

Targets for 4G Broadband Wireless Access

◆ **Support very high data rates (User throughput)**

Target peak data rate (Forward link)

➢ **Greater than 100 Mbps in wide area cellular system**

using 16QAM with coding rate of *R* = 1/2, which is defined as *"Supportable data rate"*

➢ **Greater than 1 Gbps in local area under special propagation conditions, *i.e.*, short distance and short time dispersion**

(16QAM (64QAM) with higher coding rate, MIMO multiplexing, etc.)

◆ **High capacity (Sector throughput)**

Target is more than twice that of HSDPA

◆ **Very short air interface delay**

Short TTI (Transmission Time Interval), fast link connection setup, etc.

◆ **Support of various data types with various QoS requirements**

QoS: Delay, residual packet error rate, …

◆ **Wide coverage**

Wide coverage area is very important in particular for cellular systems

◆ **Support of low-to-high mobility**

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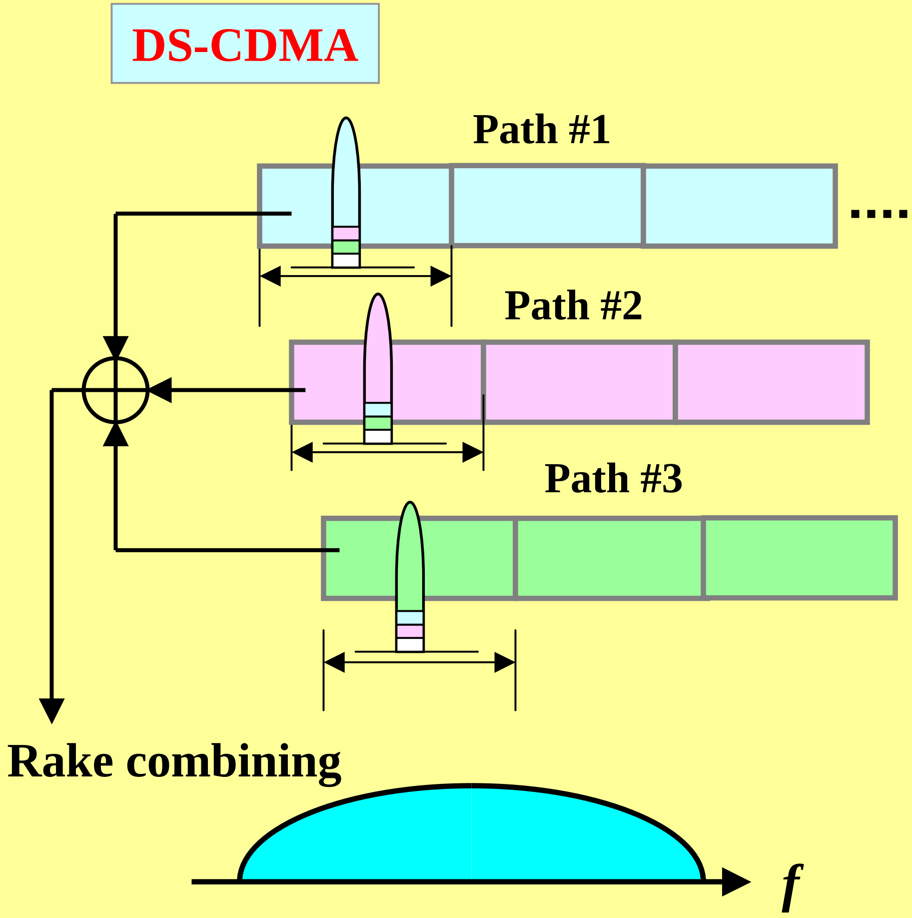
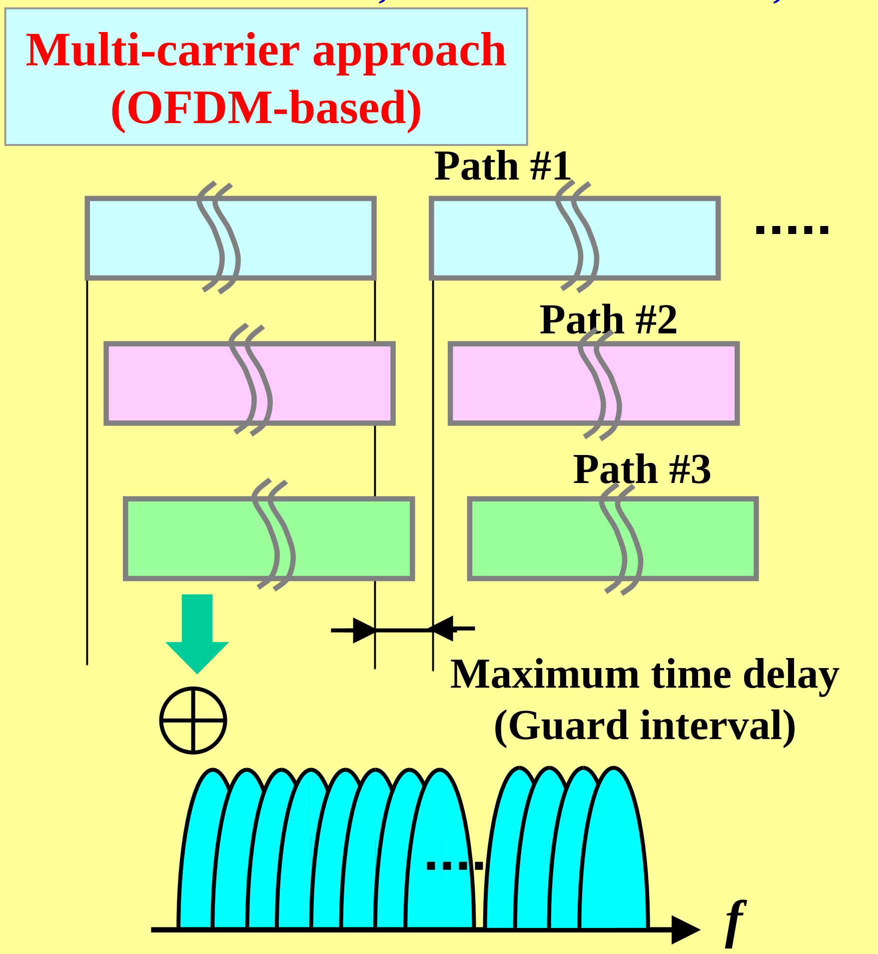
Wireless Access Scheme in Forward Link Based on VSF-Spread OFDM

VSF-Spread OFDM:
Variable Spreading Factor-
Spread Orthogonal Frequency Division Multiplexing

Why Multi-carrier Approach is Better in Broadband Channel?





- Multipath interference (MPI) increases as the bandwidth becomes wider
- MPI offsets Rake path diversity effect

- Lower symbol rate with a large number of sub-carriers mitigates severe MPI
- Guard interval insertion avoids inter-symbol interference

OFDM Based Broadband Wireless Access in Forward Link

◆ **Orthogonal Frequency Division Multiplexing (OFDM)-based wireless access is promising**

- ➢ **Robust against multipath interference (time dispersion)**
- ➢ **Large frequency diversity effect**

◆**Full use of "Diversity" in frequency domain**

✧ **Common channels ➔ Frequency diversity (Interleaving and spreading in frequency domain)**

✧ **Shared Channel ➔ Multi-user diversity (Frequency-domain scheduling in addition to time-domain scheduling) or Frequency diversity**

- ➢ **Must verify effects considering QoS (delay)**
- ➢ **Increase in number of control signaling bits should be considered**

VSF-Spread OFDM Wireless Access in Forward Link

◆**One-cell frequency reuse is essential in cellular environments**

Spreading gain including channel coding gain is inevitable for suppressing other-cell interference

✧ **Application of very-low-rate channel coding such as *R* = 1/8-1/16**

✧ **Combination of channel coding and spreading (particularly in frequency domain)**

◆**Efficient radio resource usage, i.e. required high data rate with high geometry environments is necessary in local areas**

Proposed:

Variable Spreading Factor-Spread OFDM (VSF-Spread OFDM)

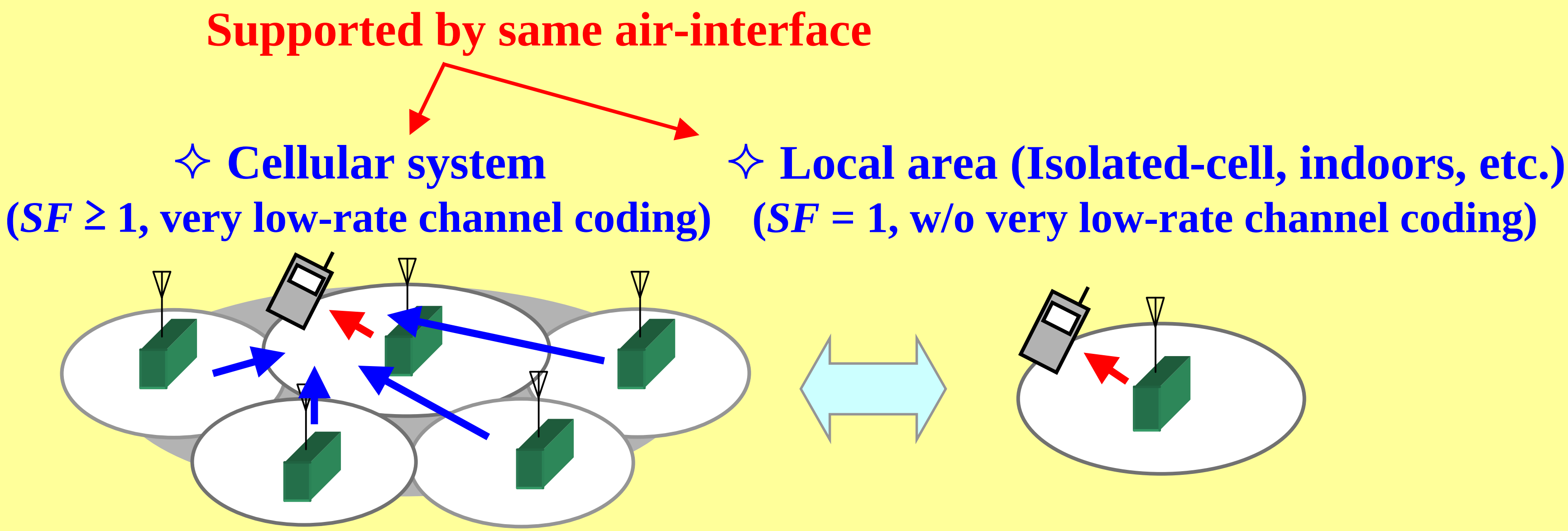
➢ **Variable control of channel coding rate (including very low-rate channel coding) and spreading factor in spreading**

➔ **Achieve high system capacity in various wireless environments**

VSF-Spread OFDM Wireless Access in Forward Link

- **Application of spreading (symbol repetition) and very low-rate channel coding**
- **Adaptively changes the spreading factor (coding rate) value according to cell structure, radio link conditions, and modulation parameters, etc.**

  ➔ **High capacity in respective radio conditions using the same air interface**



Wireless Access Scheme in Reverse Link Based on VSCRF-CDMA

VSCRF-CDMA:

Variable Spreading and Chip Repetition Factor-CDMA

Wireless Access in Reverse Link

◆ **Single-carrier based access**

DS-CDMA with spreading and IFDMA without spreading

◆ **Multi-carrier based access**

OFDMA and MC-CDMA

✧ **Full use of frequency diversity is necessary**

Frequency diversity / Frequency-domain scheduling

➔ **Single-carrier and multi-carrier approaches can achieve both configurations**

✧ **Multi-carrier approach has advantage in mitigating multipath interference ➔ Superior performance in MIMO application**

✧ **Single-carrier approach has advantage in enabling low PAPR ➔ low power consumption of UE terminal**

DS-CDMA Based Access in Reverse Link

DS-CDMA wireless access is advantageous in reverse link

- **Flexibly achieve one-cell frequency reuse in cellular system**
- **Lower transmission power associated with lower PAPR (peak-to average power ratio)**

However, in multipath fading channels, multiple access interference and multipath interference destroy orthogonality among access users

DoCoMo' s proposal

Apply *orthogonality in frequency domain* to achieve normalized capacity of nearly 100%

(Essentially use TDMA-based packet access with packet scheduling)

VSCRF-CDMA Wireless Access

VSCRF (Variable Spreading and Chip Repetition Factor) - CDMA

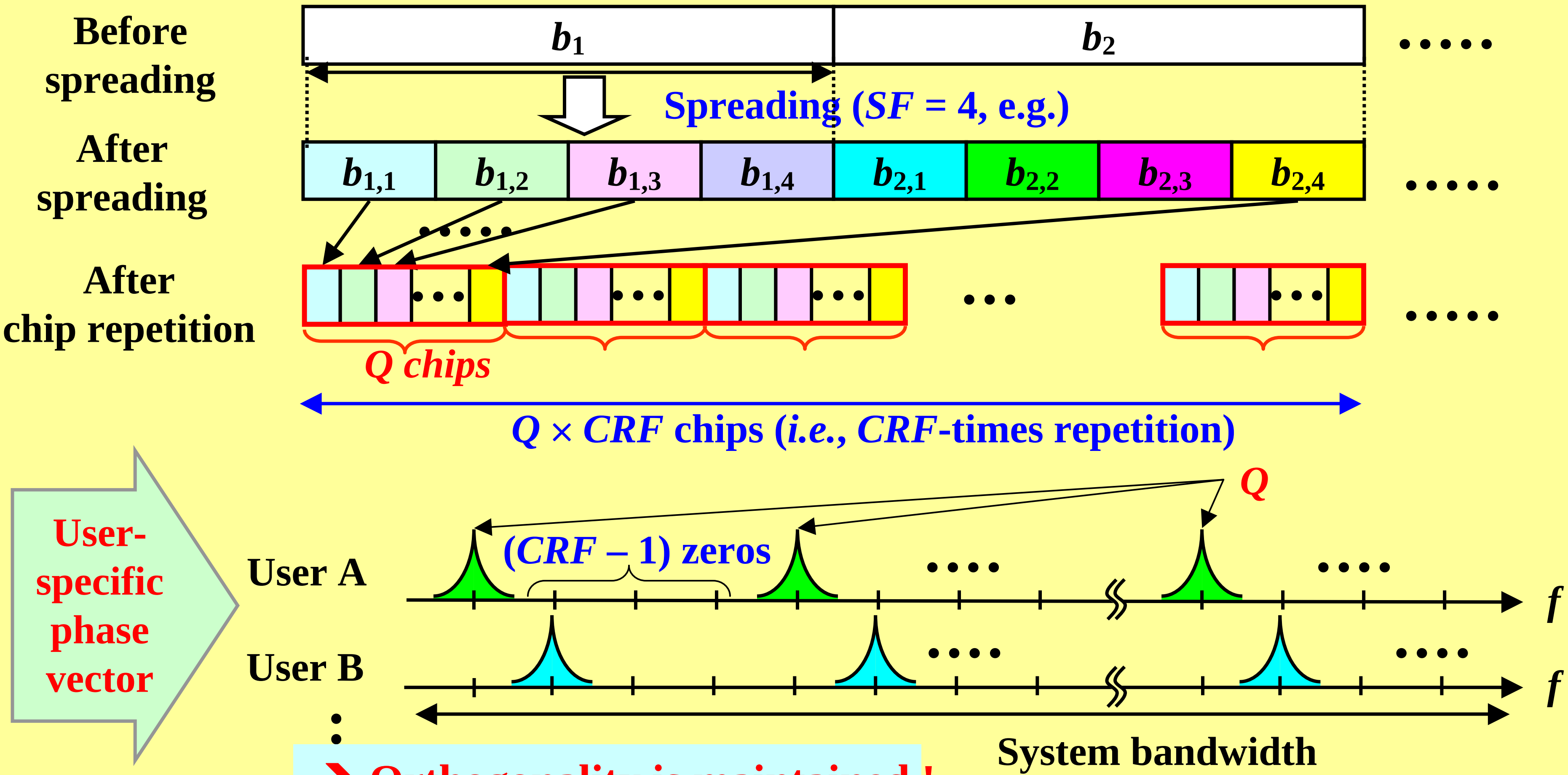
(1) Application of symbol repetition principle to chip signal after spreading ➔ Chip repetition
(Symbol repetition was proposed by Dr. Schnell in ICC'98)

(2) Optimum control of spreading factor (*SF*) and chip repetition factor (*CRF*) according to various wireless access conditions

- **Cell structure**
- **Other-cell interference**
- **Channel propagation conditions**
- **Number of accessing users**

Principle of Chip Repetition

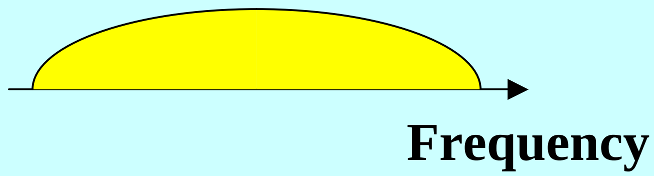
- After spreading, *Q* chips are **compressed and repeated *CRF*-times**.
- By assigning a user specific phase vector, **a set of sub-carriers that is orthogonal to the others is obtained.**



➔ **Orthogonality is maintained !**

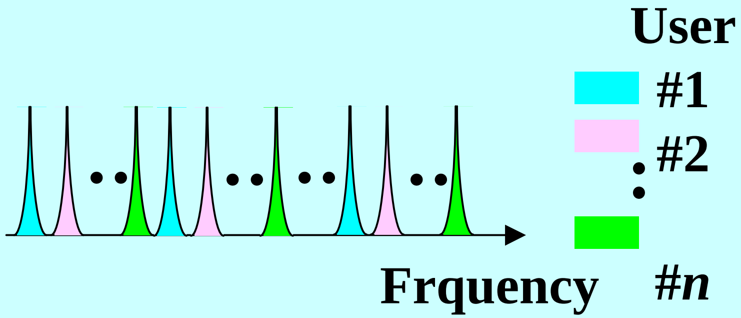
VSF-Spread OFDM Wireless Access

◆ **Single-user environment**



✧ **W/o chip repetition**
(*SF* ≥ 1, *CRF* = 1)

◆ **Multi-user environment**



✧ **W/ chip repetition (*CRF* > 1) and spreading (*SF* ≥ 1)**
➔ **By using chip repetition, orthogonality among simultaneously accessing users is maintained.**

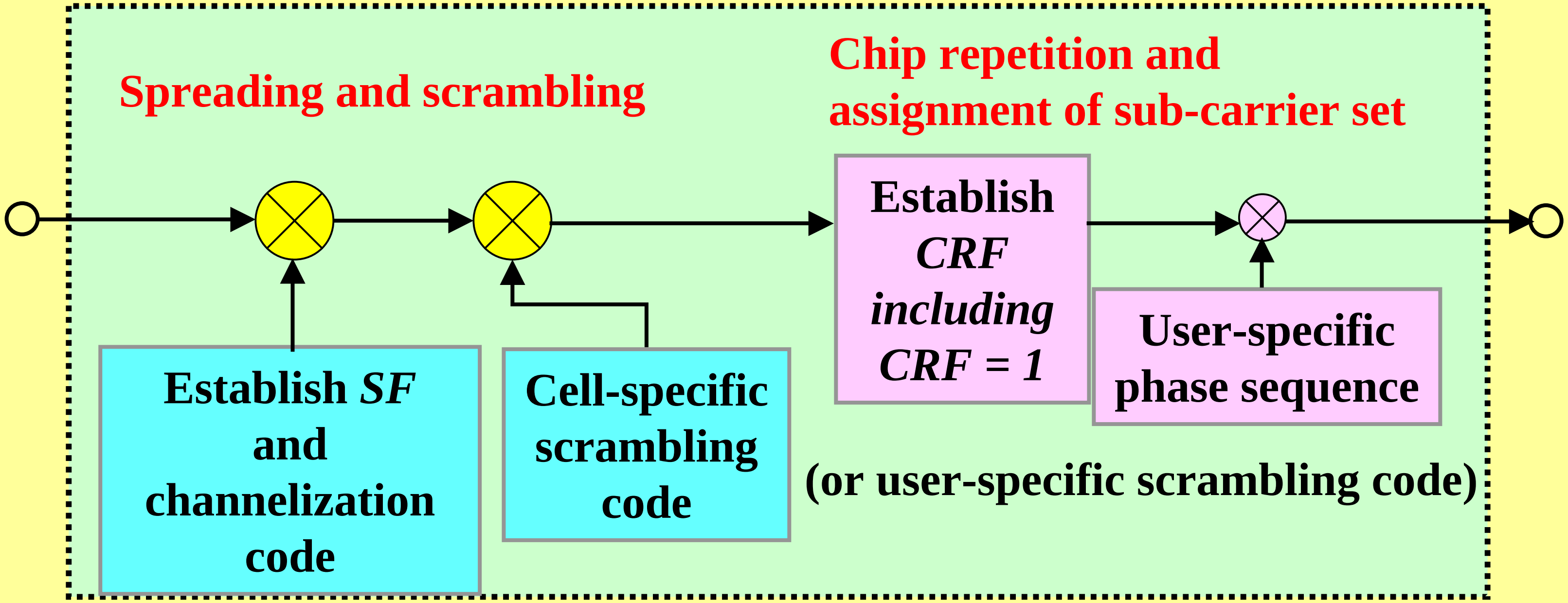
Variable Spreading and Chip Repetition Factors (VSCRF) Control
➔ **High system capacity for respective environments by using one air interface**

Processing Operation of VSCRF-CDMA

- **Chip repetition function is easily incorporated into DS-CDMA signals**

➔ Adaptive control of *SF* and *CRF* is possible based on the same air-interface

- **Coarse adaptive transmission timing control (ATTC) is applied so that the received timings of all accessing users are aligned within the guard interval**



◆ **Orthogonality among accessing users is achieved in frequency domain based on single-carrier approach, *i.e.*, without increase in PAPR**

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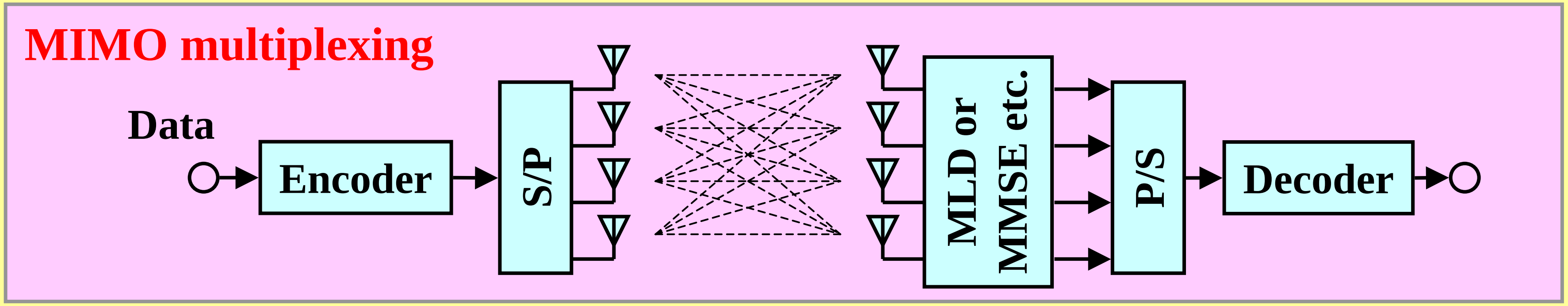
Multiple-Antenna Transmission Techniques for 1-Gbps Data Transmission in Local Areas (Isolated-cell and Indoor Environments)

MIMO Multiplexing

◆ **Signal transmission utilizing MIMO channel**
➔ **Information bit rate is increased by different simultaneous parallel data stream transmissions from multiple antennas.**

➢ **MIMO multiplexing (*i.e.*, BLAST*, SDM) is a promising candidate for achieving high-rate packet transmission**

*** G. J. Foschini, Jr., Bell Labs Tech. J., 1996.**



MLD: Maximum likelihood detection
MMSE: Minimum mean squared error

Signal Separation Algorithms in MIMO Multiplexing

	Features	Computational complexity
MLD (Maximum Likelihood Detection)	➢ Good signal separation performance (Channels with the same frequency, time, and code resources) ➔ Reduction in the required E_b/N_0 ➔ High achievable throughput	Very high
MMSE (Minimum Mean Squared Error)	➢ Signal separation ability is worse than MLD	Low - High
V-BLAST (Combination of beam nulling and successive interference cancellers)	➢ Signal separation ability is worse than MLD and MMSE	Low

Throughput that MMSE (V-BLAST) can achieve is too low to apply to actual wireless system with 16QAM with high coding rate.
➔ MLD based approach is the most promising candidate.

Computational complexity of MLD must be reduced to apply it to future UE terminals.

Complexity Reduced MLD Using QR Decomposition with M-algorithm (QRM-MLD)

QRM-MLD

- **QR decomposition of Channel matrix *H***
- **Orthogonalization of received signal by multiplying Matrix Q^H with received signal vector (^{H} denotes Hermitian transpose)**

➔ **Orthogonality among transmission signals is achieved**

- **Application of M-algorithm from high-ranked transmit signal to low-ranked signal results in reduced number of symbol replica candidates for which squared Euclidian distances are to be calculated**

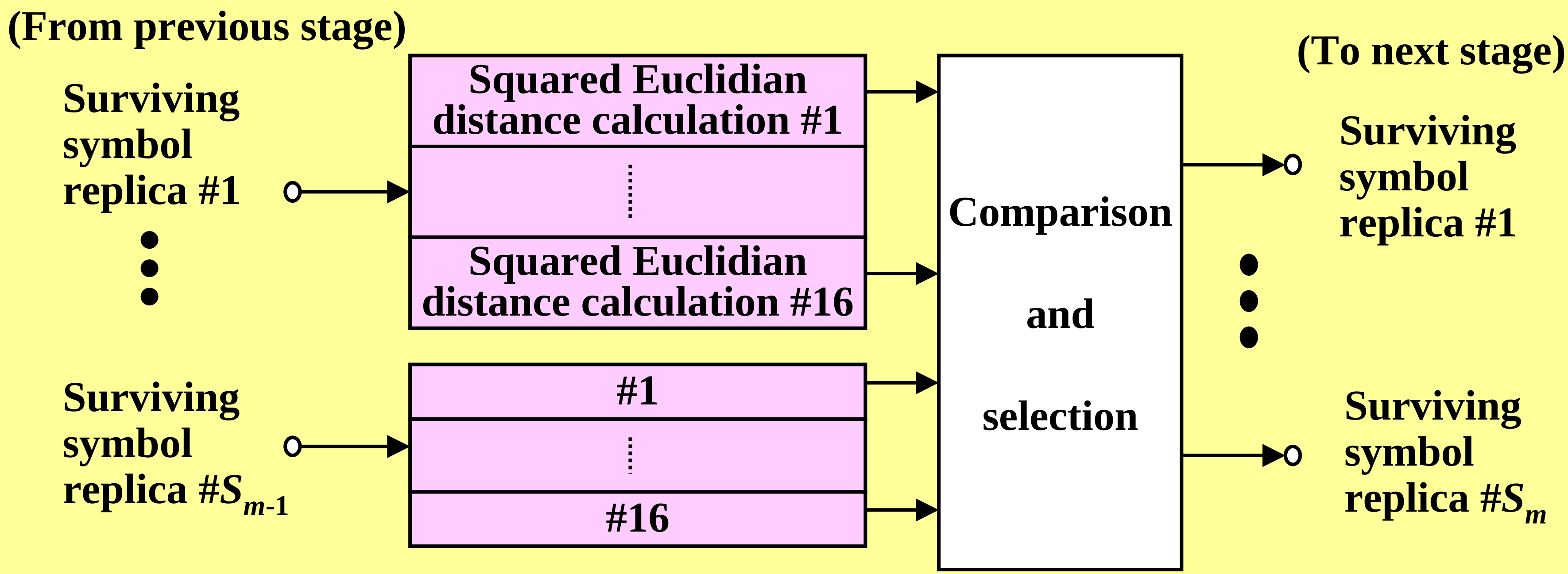
Received signal after Matrix Q^H multiplication — ***R* matrix** — **Transmitted signal** — **Noise component**

$$\mathbf{z} = \begin{bmatrix} z_1 \\ z_2 \\ z_3 \\ z_4 \end{bmatrix} = \begin{bmatrix} r_{11} & r_{12} & r_{13} & r_{14} \\ 0 & r_{22} & r_{23} & r_{24} \\ 0 & 0 & r_{33} & r_{34} \\ 0 & 0 & 0 & r_{44} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + \begin{bmatrix} n'_1 \\ n'_2 \\ n'_3 \\ n'_4 \end{bmatrix}$$

Upper triangle shape

✓**K. J. Kim *et al.*, "Joint channel estimation and data detection algorithms for MIMO-OFDM systems," in Proc. 36th Asilomar Conference on Signals, Systems and Computers, Nov. 2002.**

Original QRM-MLD Algorithm



✓S_m is the number of surviving symbol replicas at the m-th stage
✓16QAM modulation is assumed

Euclidian distance calculated for "all" remaining symbol candidates in the original QRM-MLD at each stage

➔ 16 × S_{m-1} squared Euclidian distance calculations are needed.

Proposed Adaptive Selection of Surviving Symbol Replica Candidates Based on Maximum Reliability

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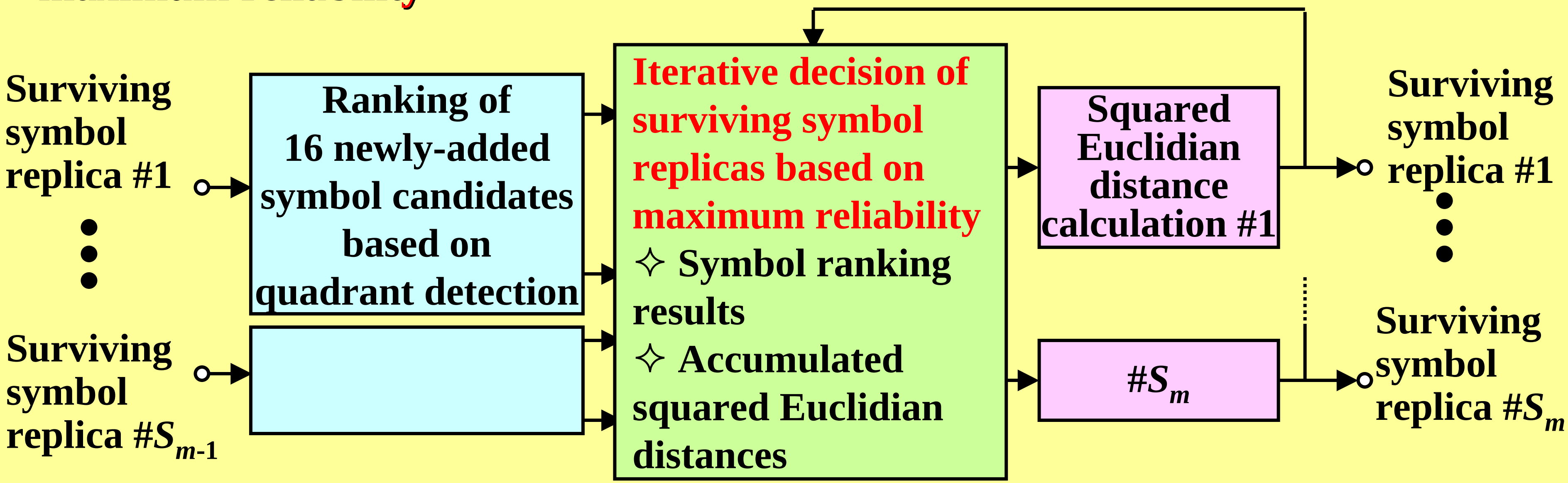
◆ **Adaptive selection of surviving symbol replica candidates based on maximum reliability**



✓S_m is the number of surviving symbol replicas at each stage

✓16QAM modulation is assumed

In the proposed algorithm,

Euclidian distance is calculated only for S_m remaining symbol replica candidates

➔ **Further reduction in computational complexity**

➢ **Ranking of 16 newly-added symbol replica candidates by quadrant detection**

➢ **Iterative decision of surviving symbol replicas with the highest reliability in decreasing order**

PER Performance of Adaptive Selection of Surviving Symbol Replica Candidates

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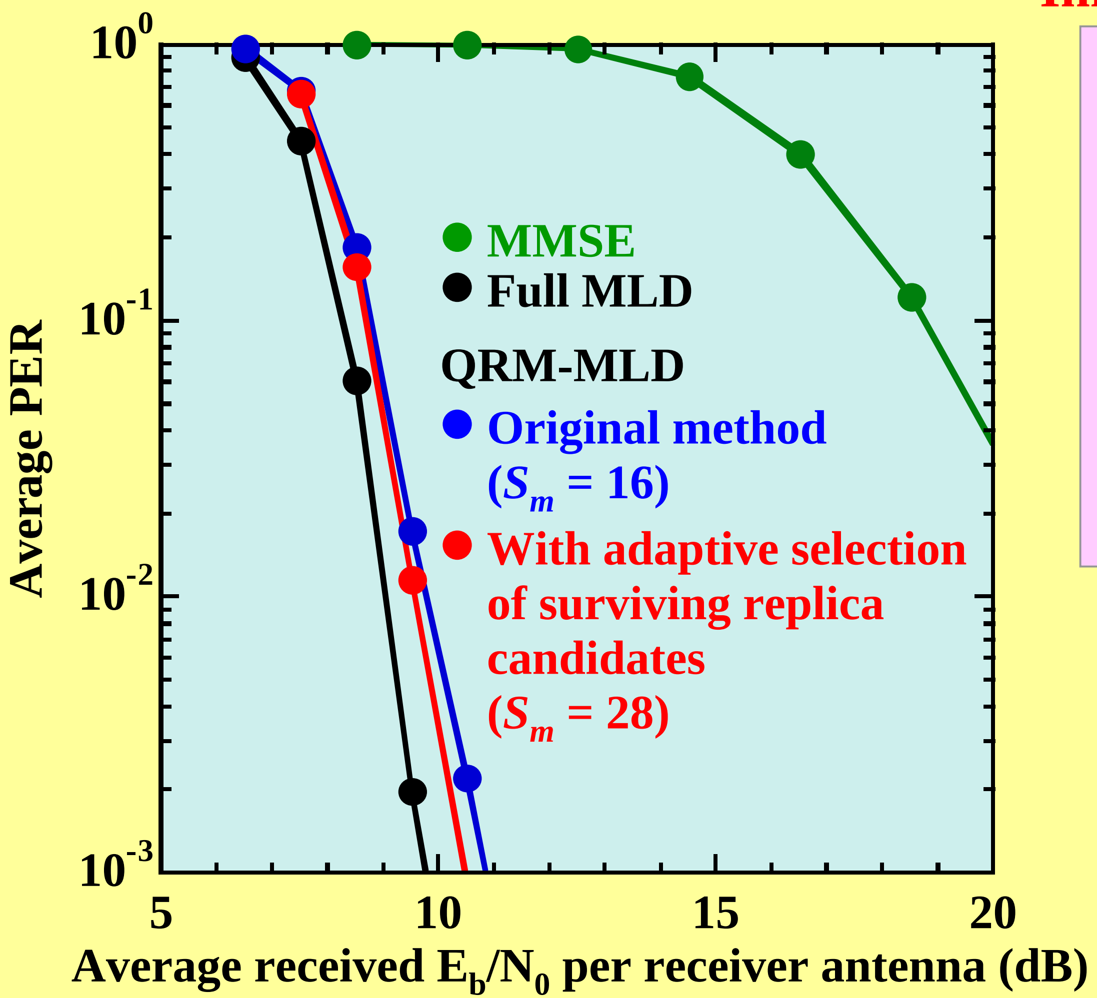


Information bit rate of 1.048 Gbps

- 4-by-4 MIMO multiplexing
- 16 QAM modulation
- Coding rate R = 8/9
- Number of multipaths L = 12
- Maximum Doppler frequency f_D = 20 Hz
- R.m.s. delay spread σ = 0.26 μsec
- Fading correlation factor ρ = 0
- With transmitted signal ranking

Achievable packet error rate (PER) employing proposed adaptive selection with S_m = 28 is almost identical to that of original QRM-MLD with S_m = 16

Average PER of 10^{-2} for 1.048 Gbps is achieved at the average received E_b/N_0 of approximately 10 dB

Comparison of Computational Complexity of Proposed Adaptive Selection Algorithm

Information bit rate of 1.048 Gbps

- **4-by-4 MIMO multiplexing**
- **16 QAM modulation**

Required number of multiplications per 0.5-msec packet frame

Full MLD		**1.9 x 10^{+10}**
QRM-MLD	**Original (S_m = 16)**	**6.1 x 10^{+7}**
	Proposed adaptive selection algorithm of surviving symbol replica candidates (S_m = 28)	**1.0 x 10^{+7}**
MMSE		**7.8 x 10^{+6}**

Computational complexity of the proposed adaptive selection method based on QRM-MLD is reduced to

- ✓**1/6 that of original QRM-MLD**
- ✓**1/1900 that of Full MLD**

Design Considerations for 1-Gbps Packet Transmission Transceiver

◆ **Major radio parameters**

- **Channel bandwidth: 100 MHz (Forward link)/ 40 MHz (Reverse link)**
- **TTI: 0.5 msec (1Gbps real-time processing is done within the TTI lenfth)**
- **Targets of peak frequency efficiency: 10 bits/sec/Hz (Forward link)/ 7 bits/sec/Hz (Reverse link)**

◆ **Techniques applied**

- **MIMO multiplexing and QRM-MLD based signal separation**

✓**Two-dimensional multi-slot and sub-carrier-averaging (MSCA) channel estimation filter using orthogonal pilot channel**

✓**Adaptive selection of surviving symbol replica candidates based on maximum reliability**

✓**LLR calculation of APP in QRM-MLD for soft-decision Turbo decoding**

- **Adaptive link adaptation appropriate to MIMO multiplexing**

Independent use of adaptive modulation and coding at each transmission antenna

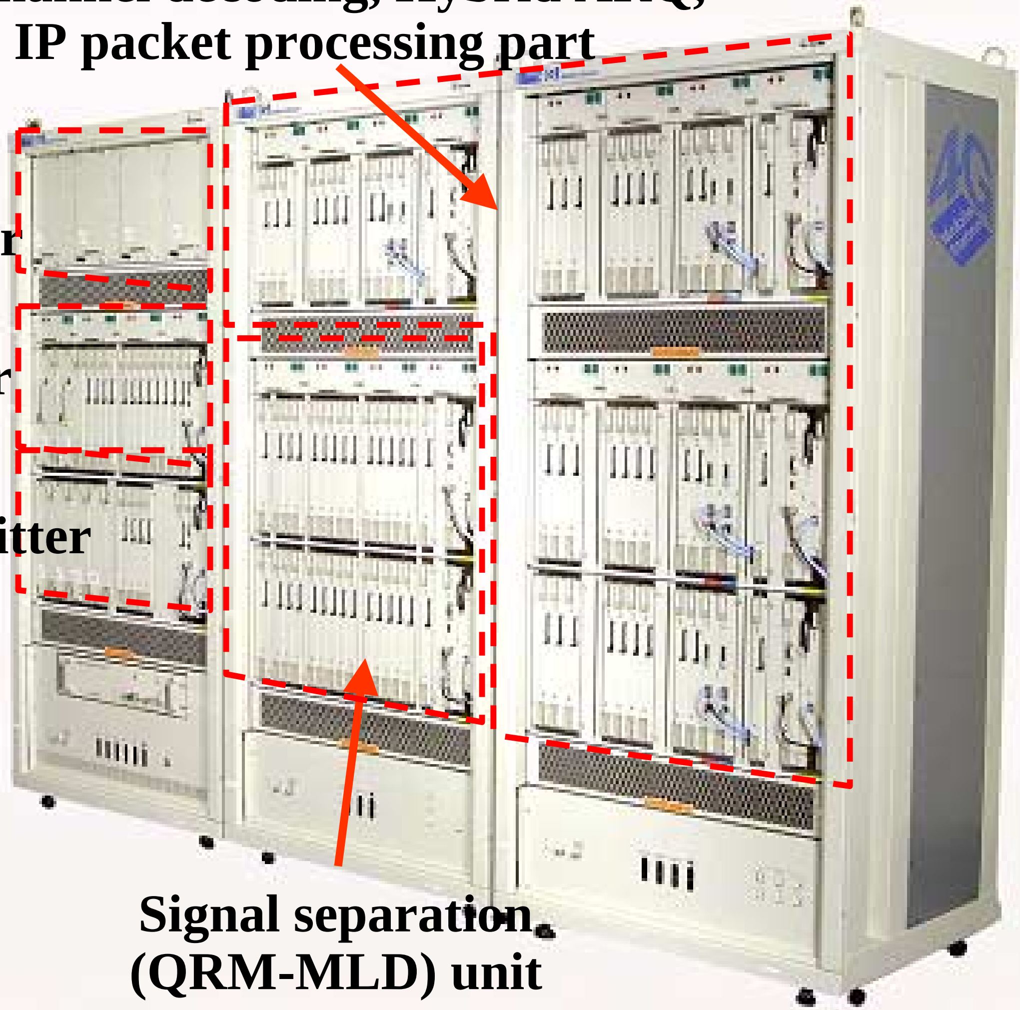
- **ARQ appropriate for MIMO multiplexing**

Independent use of hybrid ARQ with packet combining at each transmission antenna

- **TCP/IP affinity ➔ Ethernet based interface for external equipment**

Base Station and Mobile Station Equipment for 1-Gbps Packet Transmission

Base station transceiver (Transmitter only)



Mobile station transceiver

Laboratory Experimental Results on PER Performance of 1 Gbps

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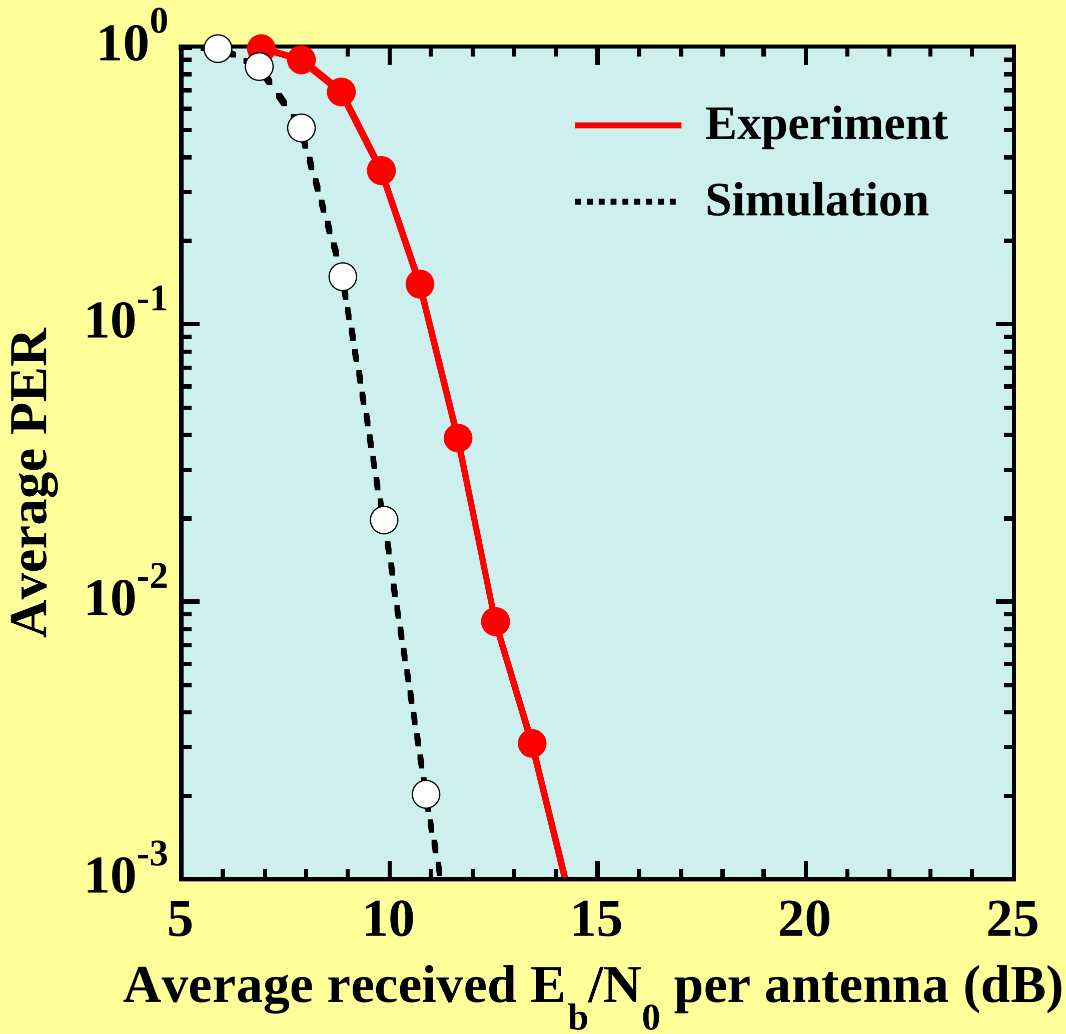
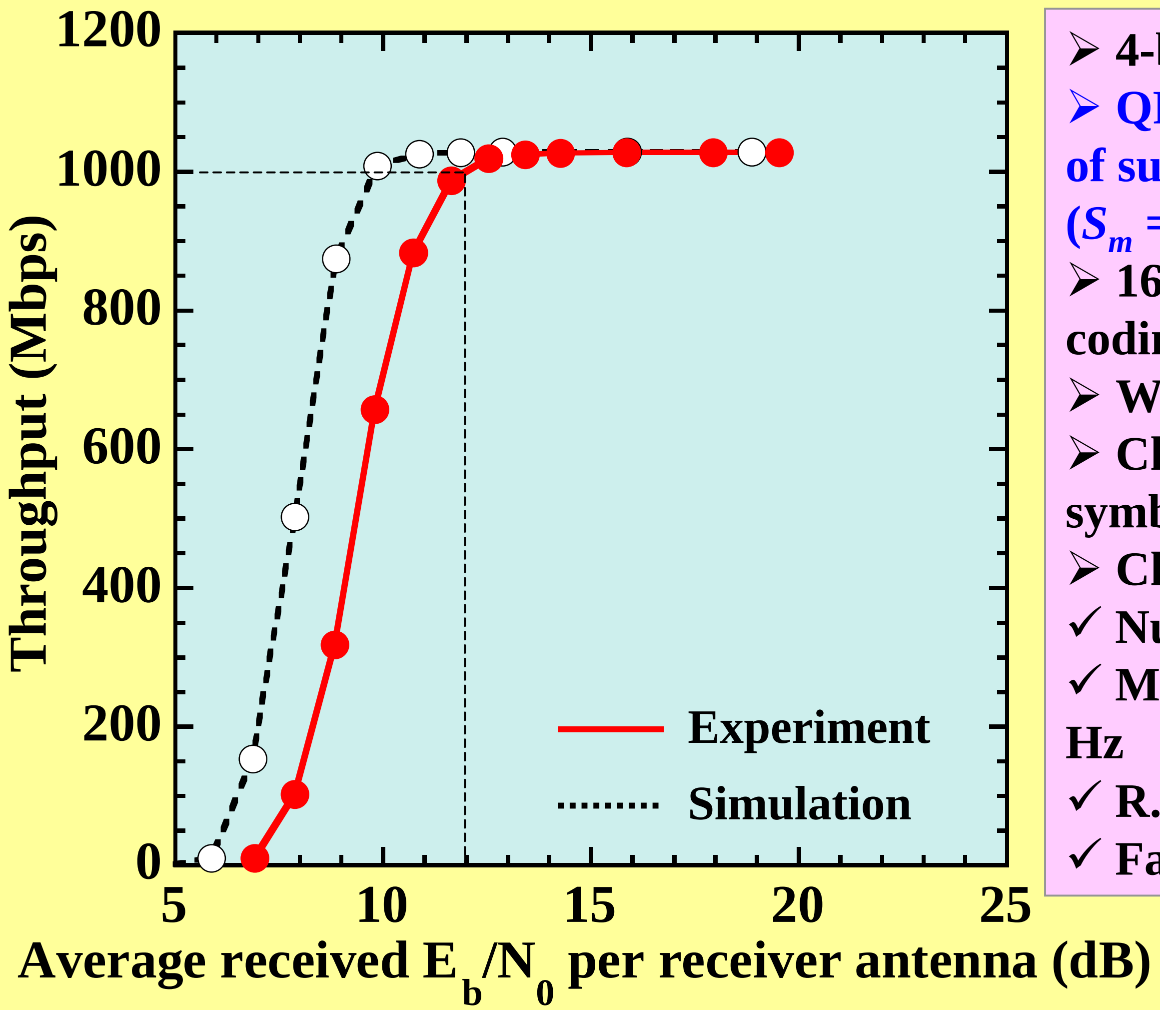


- 4-by-4 MIMO multiplexing
- QRM-MLD with adaptive selection of surviving symbol replica candidates (S_m = 28)
- 16 QAM modulation and Turbo coding with R = 8/9
- With transmitted signal ranking
- Channel estimation using pilot symbols (2-dimentional MSCA)
- Channel model
  - ✓ Number of multipaths L = 6
  - ✓ Maximum Doppler frequency f_D = 20 Hz
  - ✓ r.m.s. delay spread σ = 0.26 μsec
  - ✓ Fading correlation factor ρ = 0

Average PER of 10^{-2} for 1.048 Gbps is achieved at the average received E_b/N_0 of approximately 12 dB

Laboratory Experimental Results on Throughput Performance of 1 Gbps



- ➢ 4-by-4 MIMO multiplexing
- ➢ QRM-MLD with adaptive selection of surviving symbol replica candidates (S_m = 28)
- ➢ 16 QAM modulation and Turbo coding with R = 8/9
- ➢ With transmitted signal ranking
- ➢ Channel estimation using pilot symbols of each packet and sub-carrier
- ➢ Channel model
  - ✓ Number of multipaths L = 6
  - ✓ Maximum Doppler frequency f_D = 20 Hz
  - ✓ R.m.s. delay spread σ = 0.26 μsec
  - ✓ Fading correlation factor ρ = 0

Real time 1-Gbps throughput was achieved by laboratory experiments in multipath Rayleigh fading channels

Field Experimental Results on Broadband Packet Wireless Access (Over 100 Mbps in Wide Area Environment)

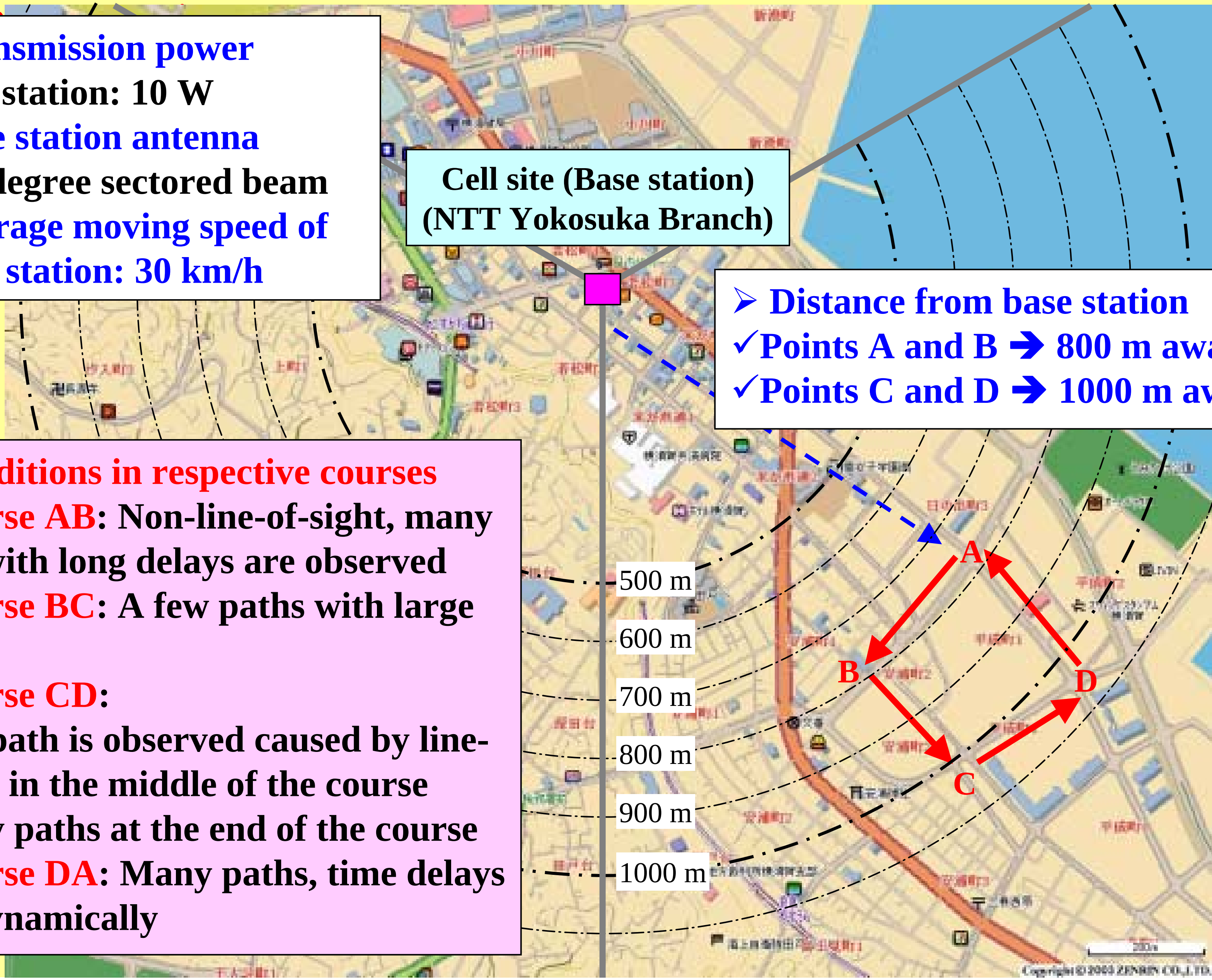
Major Radio Parameters of Implemented Equipment

	Forward link	Reverse link
Carrier frequency	4.635 GHz	4.900 GHz
Bandwidth (MHz)	101. 5	40
Number of sub-carriers	768 (131.836 kHz sub-carrier separation)	2
Symbol duration	7.585 μsec + GI 1.674 μsec (1024 + 226 samples)	
Chip rate		16.384 Mcps
Spreading factor (*SF*)	DSPDCH: Maximum 128 (Two-dimensional spreading Time domain: Maximum 16) DDPCCH: 128	UDPDCH: 4, 8, 16 UDPCCH: 64 RACH: 16
TTI	0.5 msec	
Data modulation	QPSK, 16QAM, 64QAM	
Channel coding/decoding	Turbo coding (*R* = 1/3 – 5/6, 1/8, 1/16) / Max-Log-MAP decoding	

DSPDCH: Downlink shared packet data channel
DDPCCH: Downlink dedicated packet control channel
UDPDCH: Uplink dedicated packet data channel
UDPCCH: Uplink dedicated packet control channel

Field Experiment Course

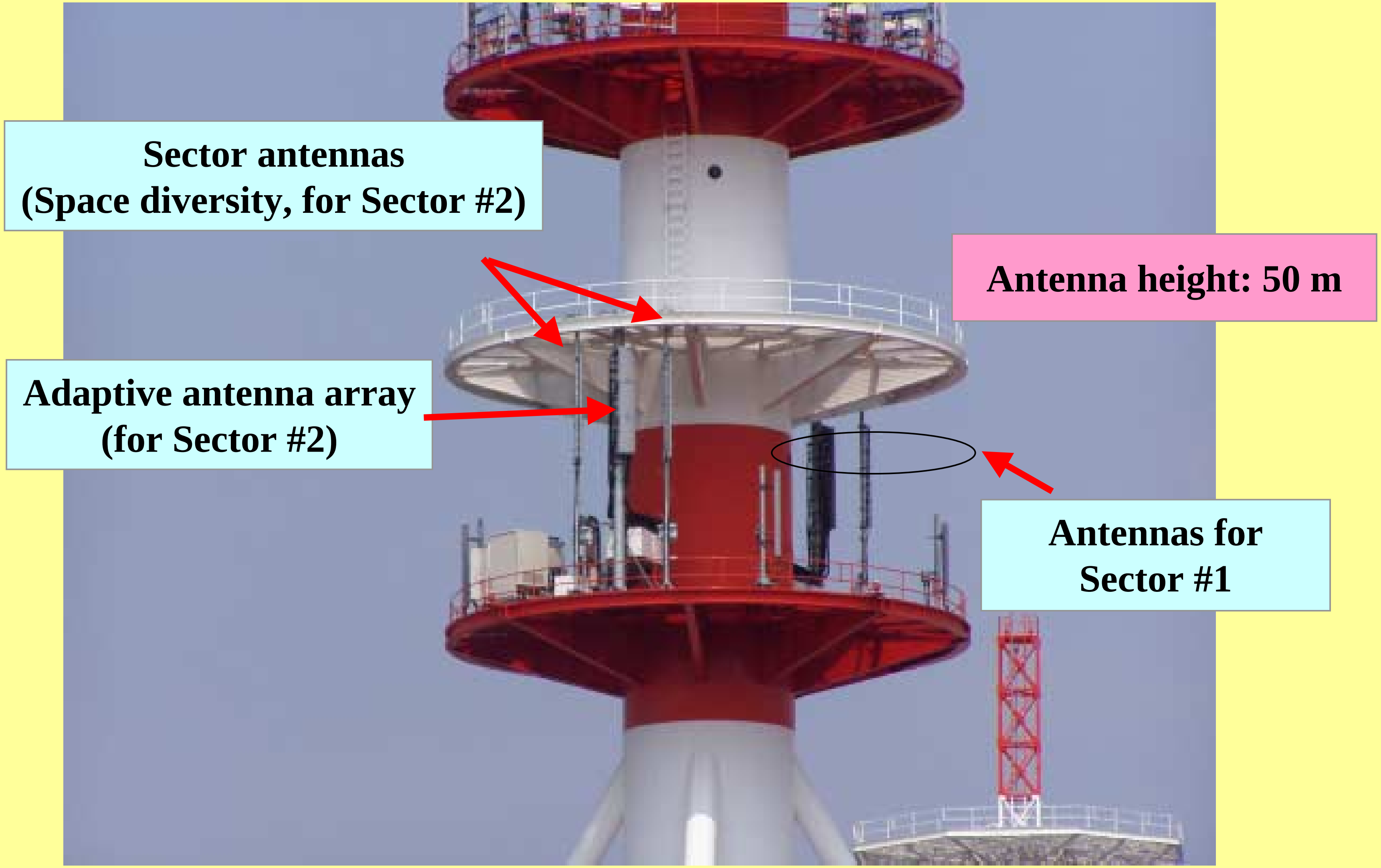
✧ **Transmission power**
✓**Base station: 10 W**
✧ **Base station antenna**
✓**120-degree sectored beam**
✧ **Average moving speed of mobile station: 30 km/h**



➢ **Distance from base station**
✓**Points A and B → 800 m away**
✓**Points C and D → 1000 m away**

◆ **Conditions in respective courses**
➢ **Course AB: Non-line-of-sight, many paths with long delays are observed**
➢ **Course BC: A few paths with large powers**
➢ **Course CD:**
✓**One path is observed caused by line-of sight in the middle of the course**
✓**Many paths at the end of the course**
➢ **Course DA: Many paths, time delays vary dynamically**

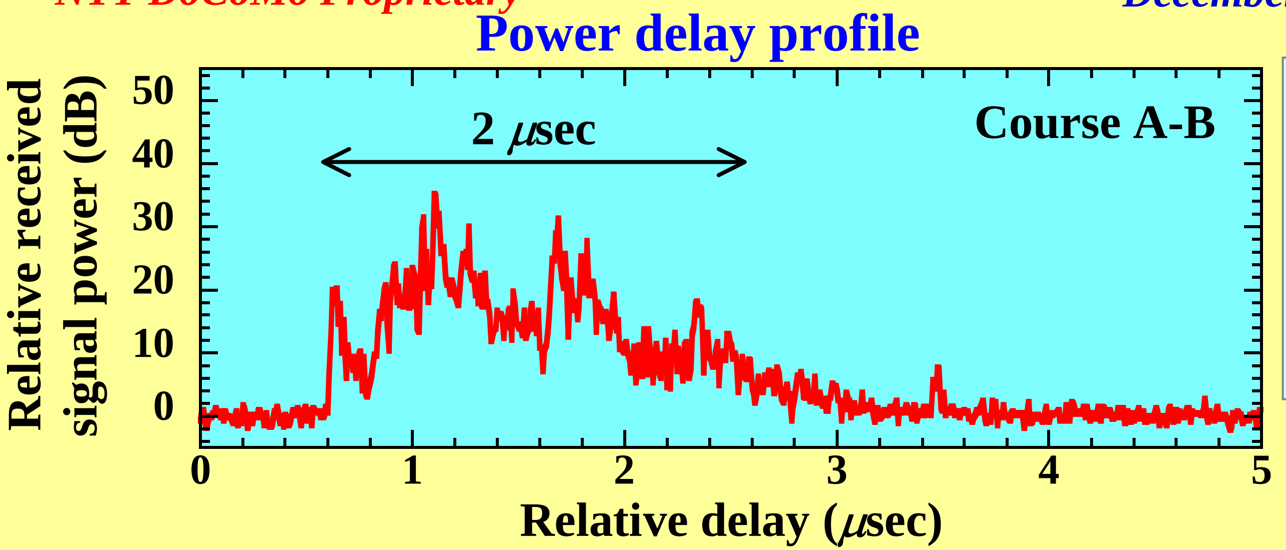
Base Station Antenna



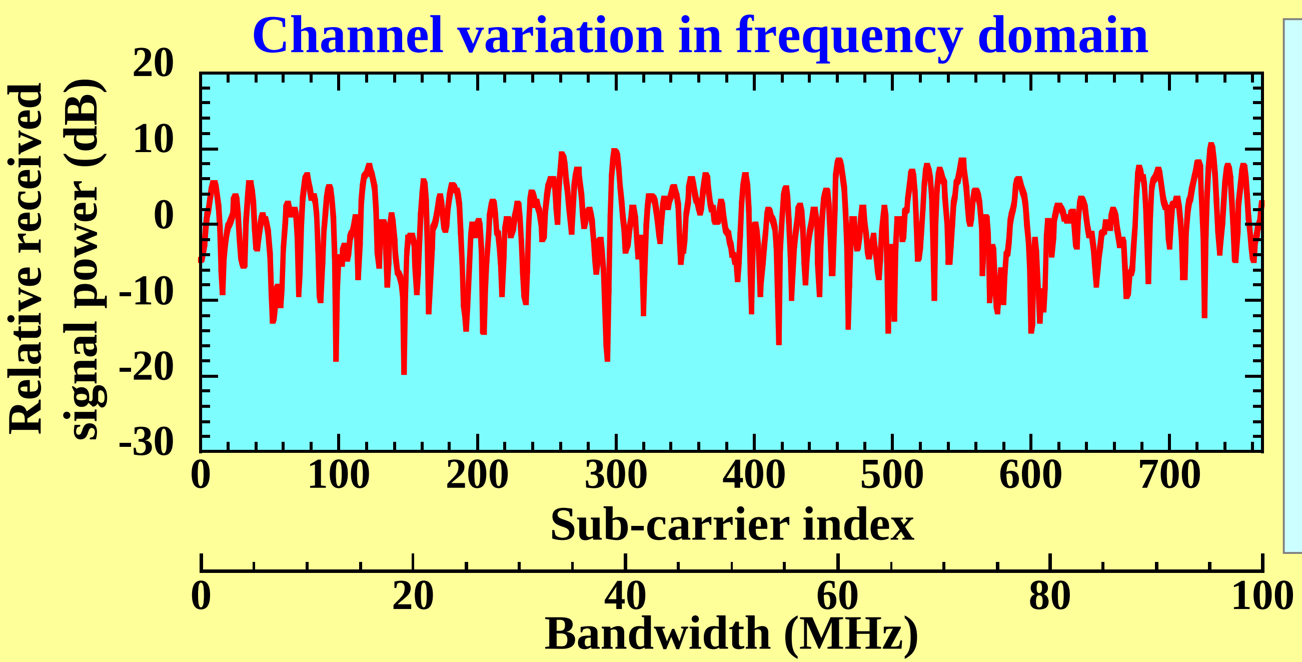
Van Equipped with Mobile Station

Mobile station antenna
- **Dipole antenna**
- **Gain: 2 dBi/branch**
- **Size: 70 mm x 10 mm ϕ**

Propagation Channel Measurement



- **Many paths within approximately 2-μsec duration**
  ➔ **R.m.s. delay spread = 0.35 μsec**



- **Large received signal power variation in frequency domain**
  ➔ **Fluctuation over the entire bandwidth is reduced owing to path (frequency) diversity effect.**

Measured Cumulative Distribution Function of Received SINR

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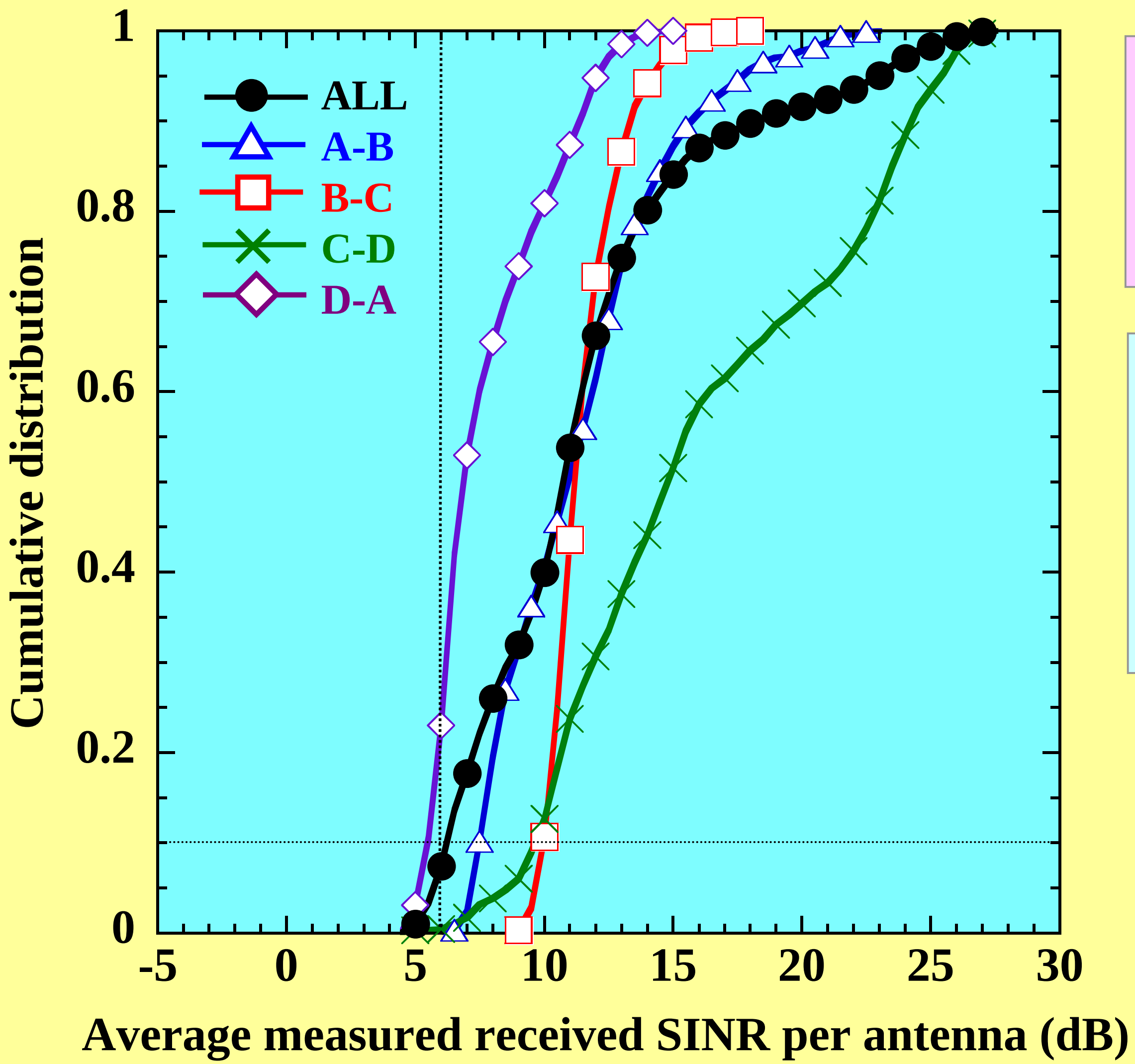
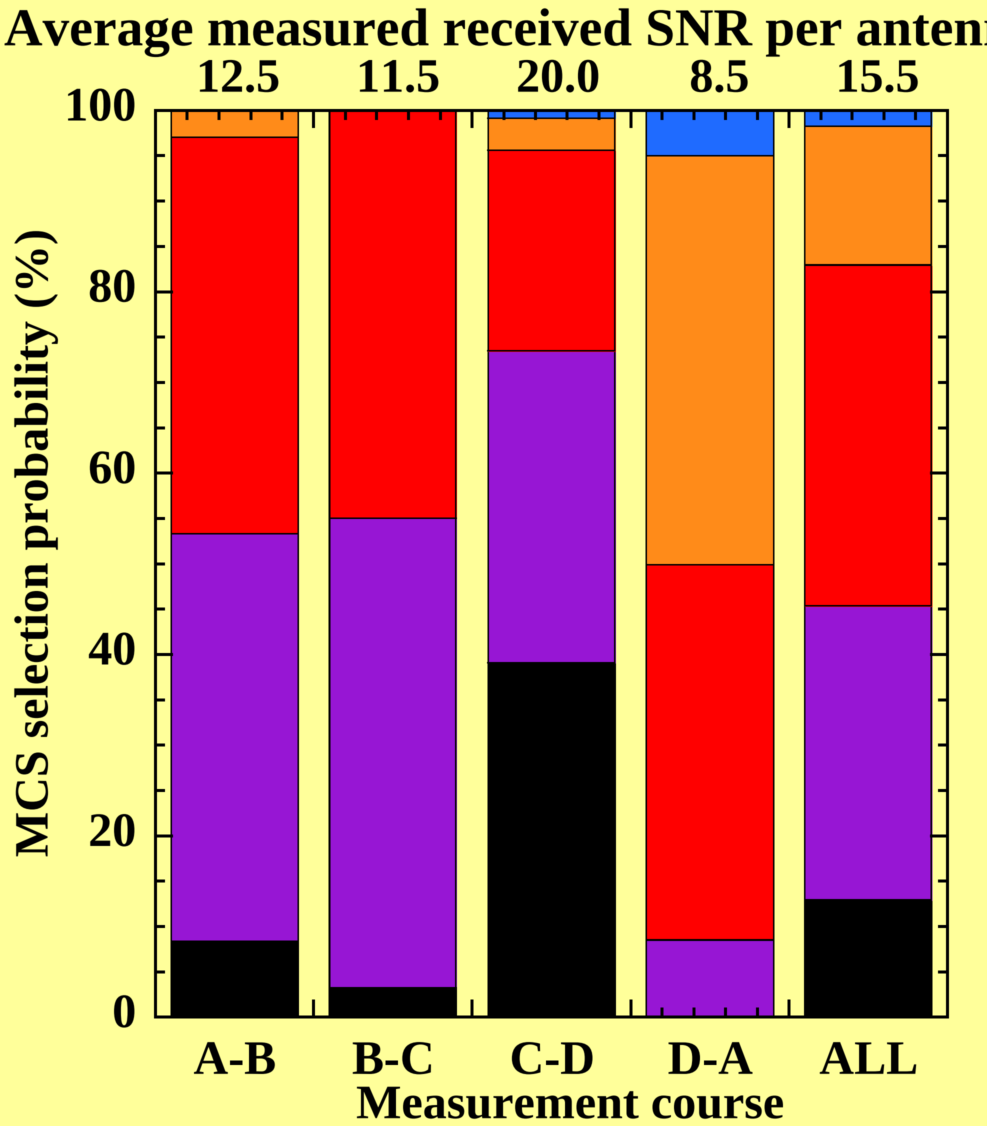


- **Measured SINR averaged over 100 msec along Course ABCD**
- **Two-branch antenna diversity reception at mobile station**

◆ Received SINR is greater than 6.0 dB
➔ For approximately 90% of locations over the measurement course.

(Note) Multipath interference, which exceeded guard interval, is included in the interference power

MCS Selection Probability When Employing AMC

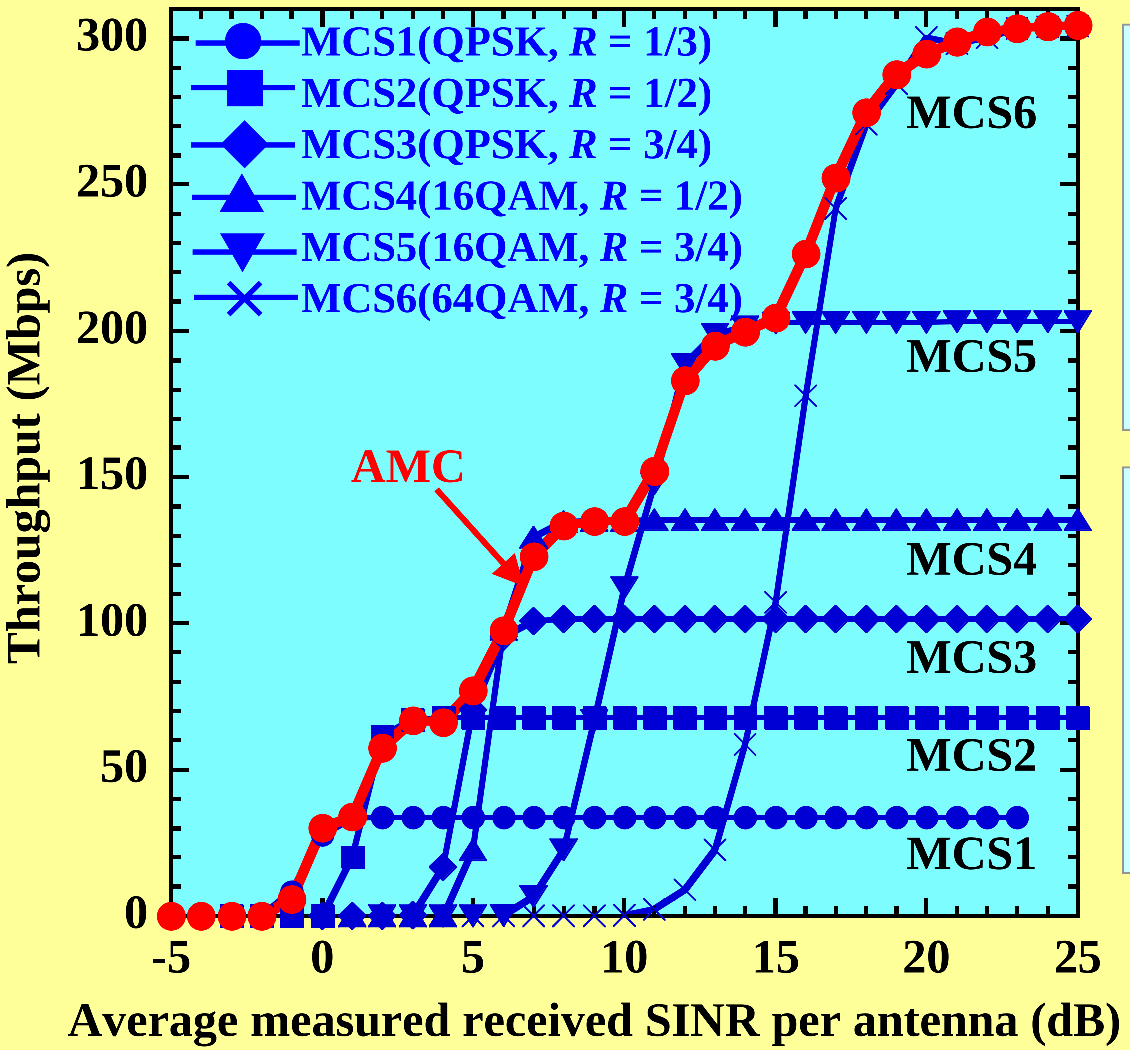


MCS	Modulation	*R*	Data rate
1	QPSK	1/3	33.84 Mbps
2		1/2	67.68 Mbps
3		3/4	101.52 Mbps
4	16QAM	1/2	135.36 Mbps
5		3/4	203.04 Mbps
6	64QAM	3/4	304.56 Mbps

- **AMC is applied in the measurement course.**
- **Instantaneous SNR is reported to BS from MS every 0.5 msec for AMC.**

- **According to the received SNR, appropriate MCS is selected to maximize the throughput.**
- **In Course CD, MCS6 (304.56 Mbps) is selected for approximately 40% of the course.**

Throughput Performance in Forward Link



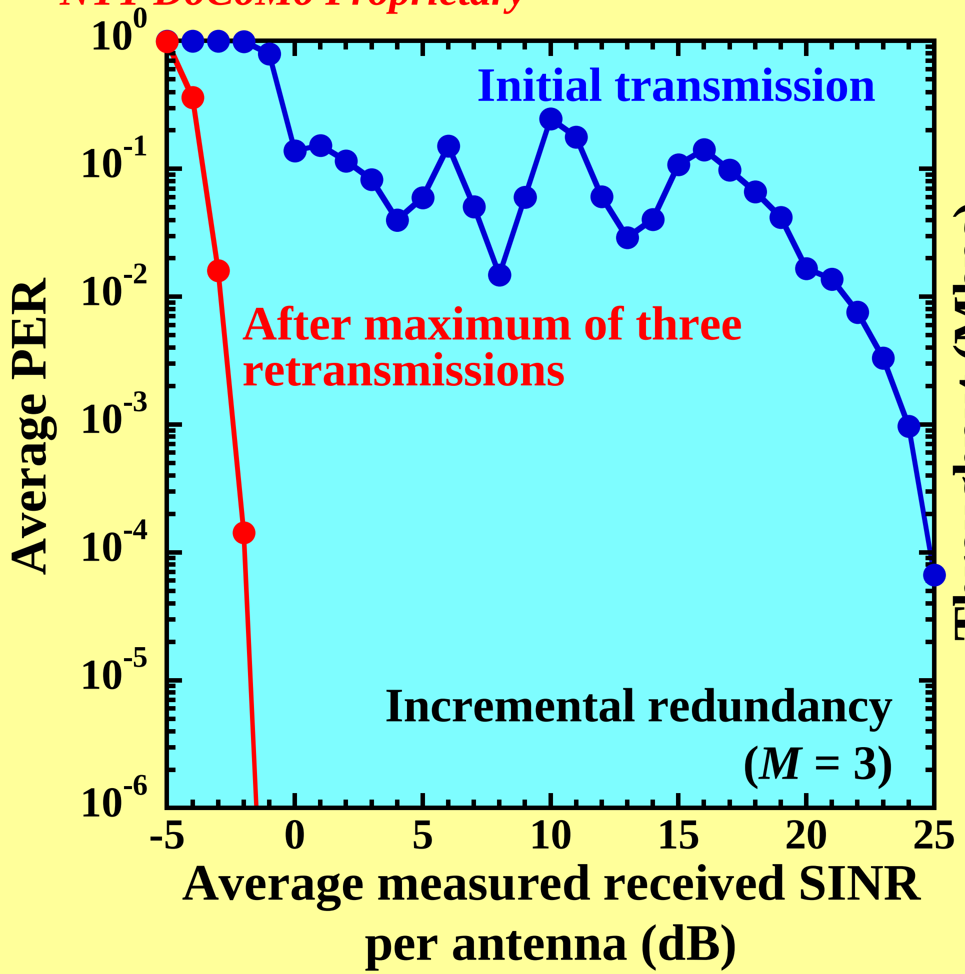
- **Throughput of 100 Mbps is achieved at average received SINR of approximately 6.0 dB**
  ➔ **For approximately 90% of locations over the measurement course**

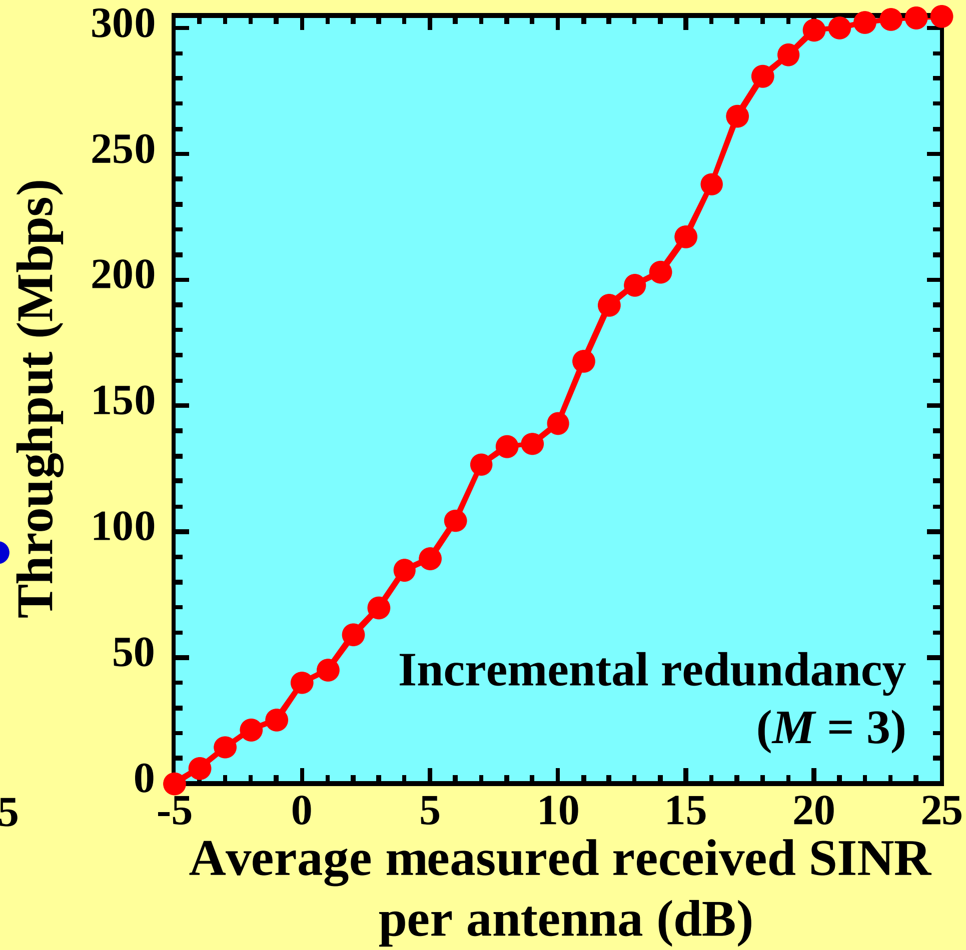
- **Throughput values of 200 and 300 Mbps are achieved when the average received SINRs are approximately 14.0 (30% locations) and 22.0 dB (6% locations), respectively.**

Effect of Hybrid ARQ with Packet Combining in Forward Link Employing 100-MHz Bandwidth

NTT DoCoMo Proprietary

December 10, 2004 / NTT DoCoMo, Inc.



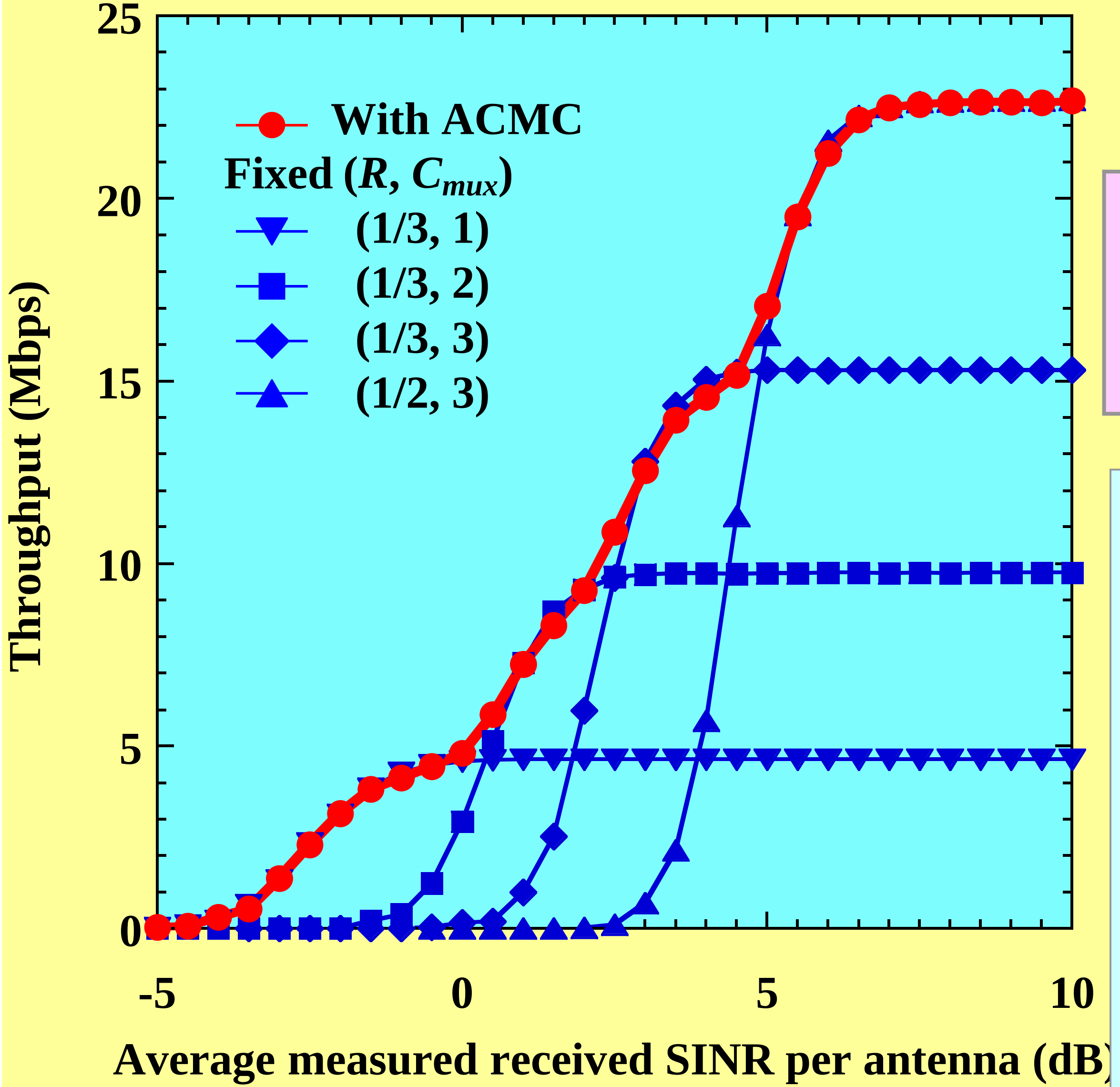


➢ **By applying Incremental redundancy with the maximum number of retransmission of *M* = 3, error-free transmission (average PER of less than 10^{-6}) is achieved at the average received SINR of greater than -1.5 dB.**

Throughput Performance Employing ACMC (Adaptive Coding and Multiplexed Codes) in Reverse Link

NTT DoCoMo Proprietary

December 10, 2004 / NTT DoCoMo, Inc.



DS-CDMA access

***SF* = 4**

- **Measured SINR averaged over 100 msec along Course ABCD**
- **Two-branch antenna diversity reception at base station**

- **According to increase in the received SINR, the most efficient combination of (R, C_{mux}) is selected appropriately.**

- **Throughput values of 10, 20, and 22 Mbps are achieved when the average received SINRs are approximately 2.5, 5.5, and 6.5 dB, respectively.**

Conclusion

◆ **Long-term 3G evolution is needed to achieve smooth migration to future 4G cellular system**

◆ **4G broadband wireless access must flexibly support both cellular systems and local areas using the same air interface**

- **Forward Link**
  VSF-Spread OFDM utilizing spreading and low-rate channel coding
- **Reverse Link**
  VSCRF-CDMA utilizing chip repetition

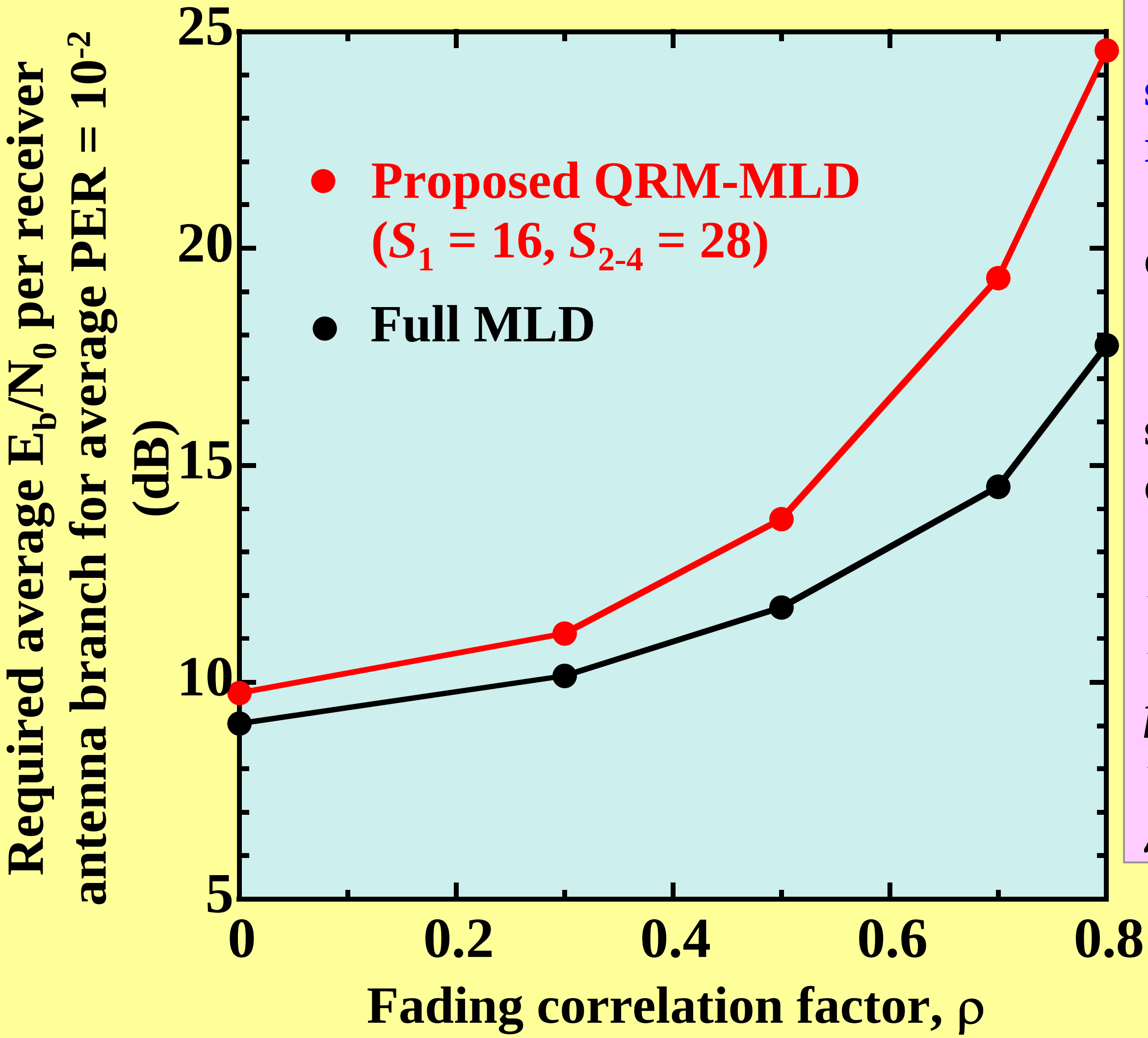
◆ **MIMO multiplexing to achieve 1 Gbps employing 100-MHz bandwidth**

- **Proposal of techniques based on QRM-MLD**
  - ✧ **Application of two-dimensional multi-slot and sub-carrier averaging (MSCA) channel estimation filter using orthogonal pilot channel**
  - ✧ **Adaptive selection of surviving symbol replica candidates based on maximum reliability**
  - ✧ **LLR calculation of APP in QRM-MLD for soft-decision Turbo decoding**
- **Design considerations of 1-Gbps packet transmission transceiver**

◆ **Field experiments demonstrated that 100-Mbps throughput is provided with wide coverage area**

Influence of Fading Correlation Factor

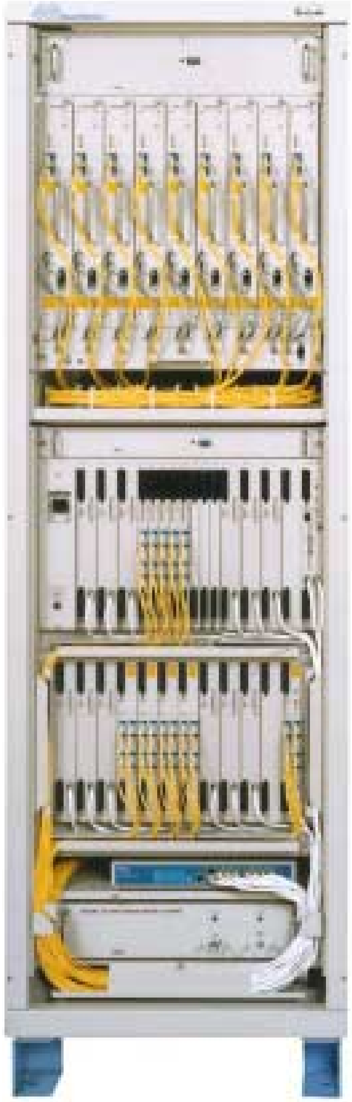
Information bit rate of 1.048 Gbps



- 4-by-4 MIMO multiplexing
- QRM-MLD with adaptive selection of surviving symbol replica candidates (S_m = 28)
- 16 QAM modulation and Turbo coding with R = 8/9
- With transmitted signal ranking
- Channel estimation using pilot symbols of each packet and sub-carrier
- Channel model
  - ✓ Number of multipaths L = 6
  - ✓ Maximum Doppler frequency f_D = 20 Hz
  - ✓ R.m.s. delay spread σ = 0.26 μsec

Experimental Testbed

Base station

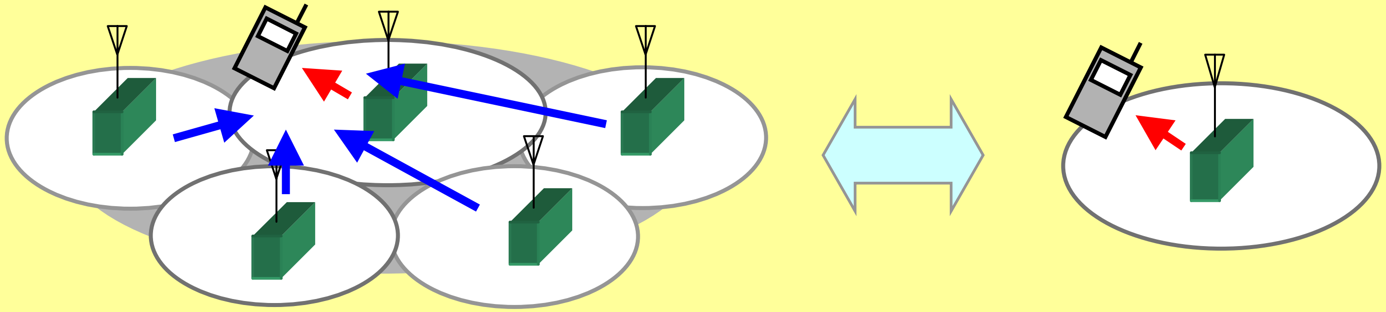


Mobile station

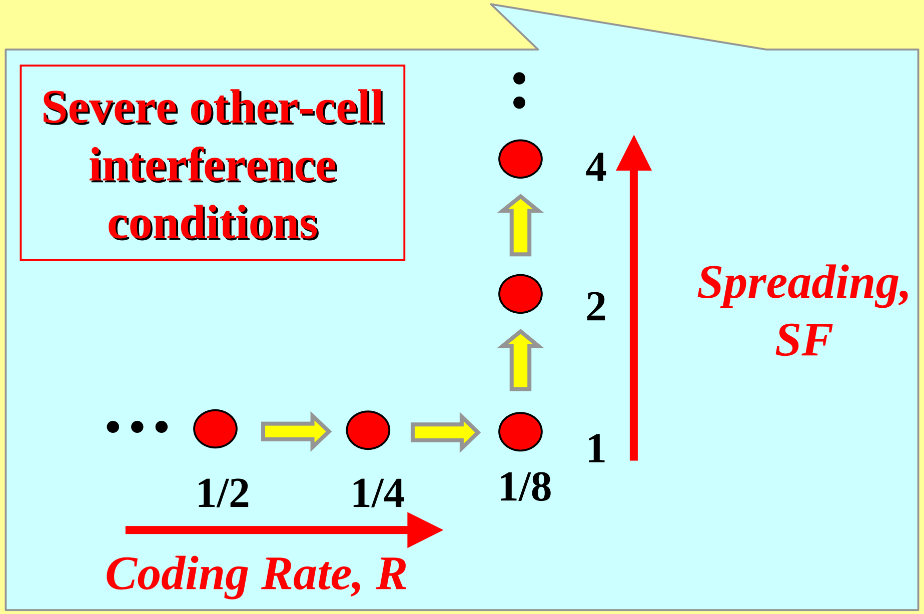
VSF-Spread OFDM Wireless Access

Supported by same air-interface

✧ **Cellular system** ✧ **Local area (Isolated-cell, indoors, etc.)**

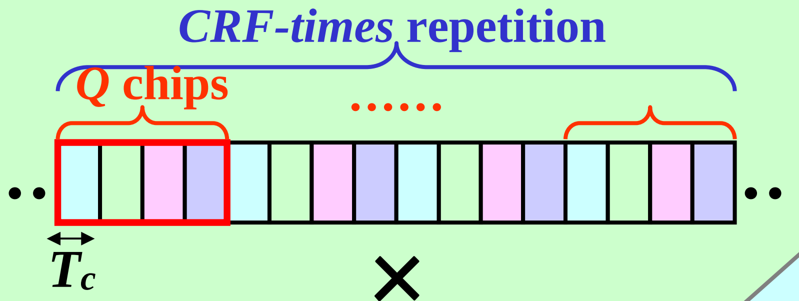


SF **≥ 1, Very low-rate channel coding** ***SF*** **= 1, w/o very low-rate channel coding**



Configuration of User Specific Phase Vector

Chip sequence after repetition

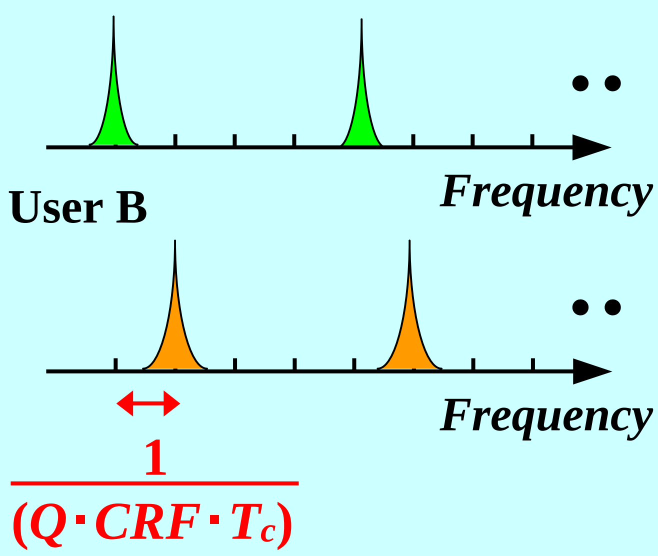


×

$$\exp[-j \cdot \Phi^{(k)} \cdot t]$$

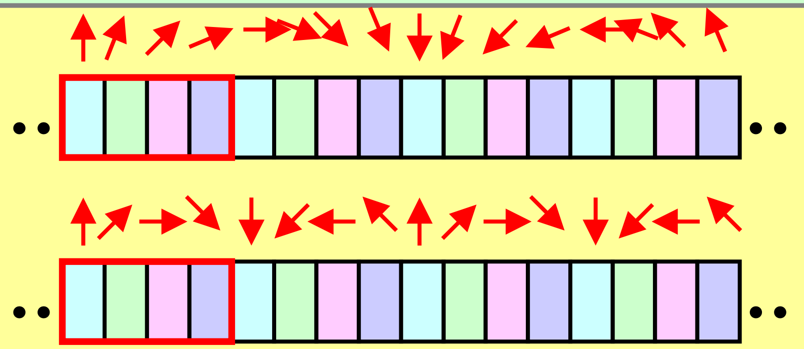
$$\Phi^{(k)} = \frac{k \times 2\pi}{Q \cdot CRF \cdot T_c}$$

→ Orthogonality is maintained in the frequency domain



User A (k = 1)

User B (k = 2)



Key Techniques in 4G Wireless Access Experiments