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Effective Exploitation of Spatial Domain for 5G Small-cell Structured Mobile Networks

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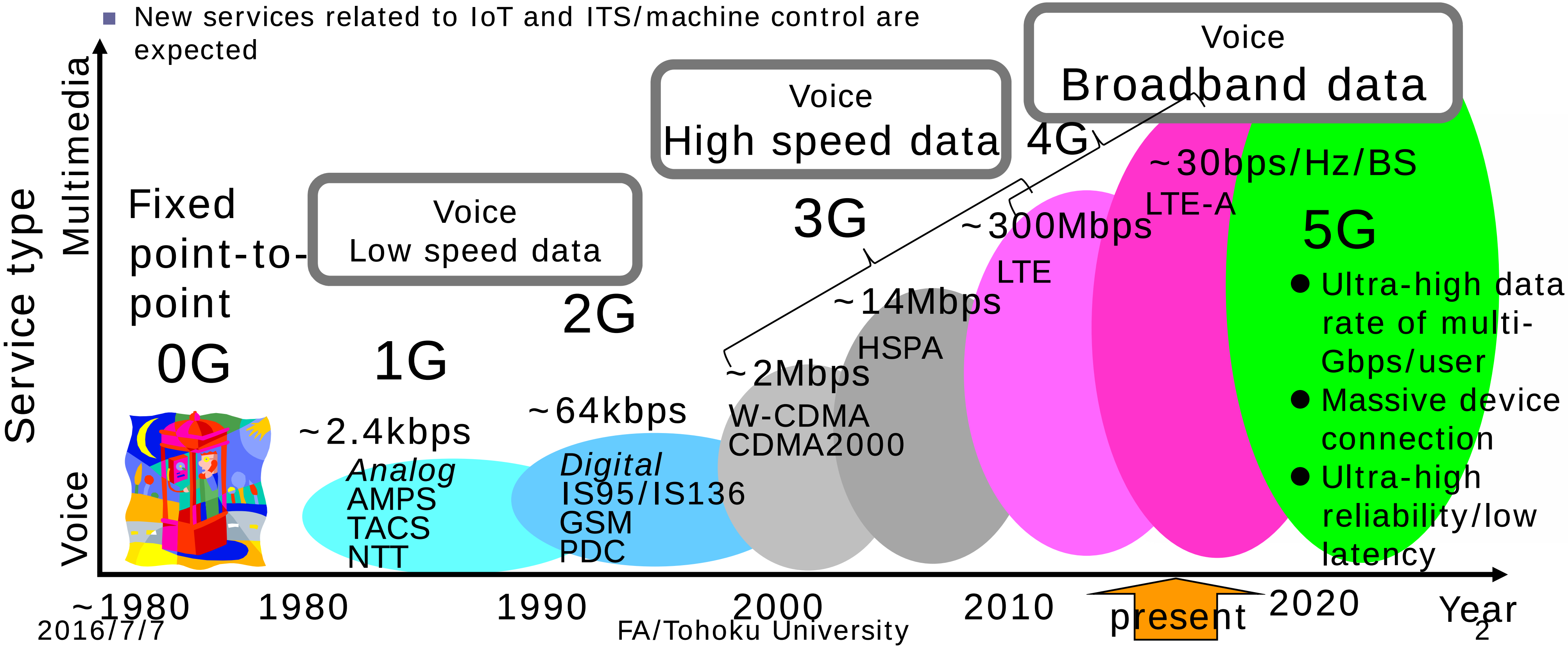
OUTLINE

- ☐ Mobile Wireless Evolution
  - ■ Evolution into 5G
  - ■ Cell Densification
  - ■ User-centric Virtual Small-cell
- ☐ Distributed Antenna Cooperative Signal Transmission
  - ■ Space-time Block Coded Diversity
  - ■ Multiuser MIMO
  - ■ Blind SLM
- ☐ Concluding Remarks

Evolution Into 5G

F. Adachi, "Wireless past and future - evolving mobile communications systems," IEICE Trans. Fundamentals, vol. E84-A, pp.55-60, Jan. 2001

- Taking 35 years (1980~2015), mobile wireless networks have evolved from 1G of few kbps (voice) to 4G of a few giga bps (data)
  - 4G/LTE-A started in March 2015 in Japan
  - 4G/LTE-A is designed to achieve a spectrum efficiency per BS of 30bps/Hz/BS
- Mobile wireless networks have become an important infrastructure of our modern society
  - Almost every one is connected to Internet via 3G/4G and WiFi networks
- 5G network is not just a broadband network
  - New services related to IoT and ITS/machine control are expected



Service type

Multimedia

Voice

Fixed point-to-point

0G

1G

~2.4kbps

Analog
AMPS
TACS
NTT

Voice
Low speed data

2G

~64kbps

Digital
IS95/IS136
GSM
PDC

Voice
High speed data

3G

~2Mbps
W-CDMA
CDMA2000

~14Mbps
HSPA

4G

~300Mbps
LTE

~30bps/Hz/BS
LTE-A

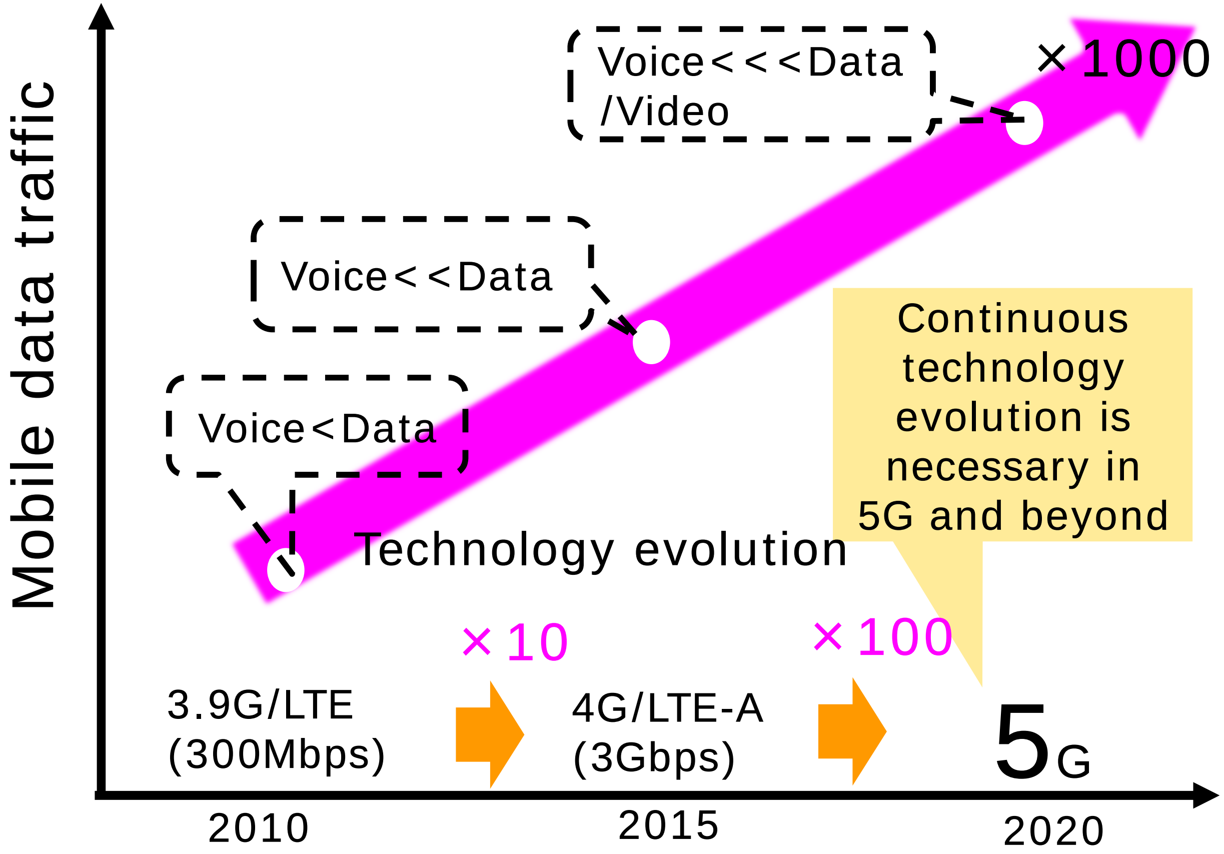
Voice
Broadband data

5G
- Ultra-high data rate of multi-Gbps/user
- Massive device connection
- Ultra-high reliability/low latency

~1980 1980 1990 2000 2010 present 2020 Year

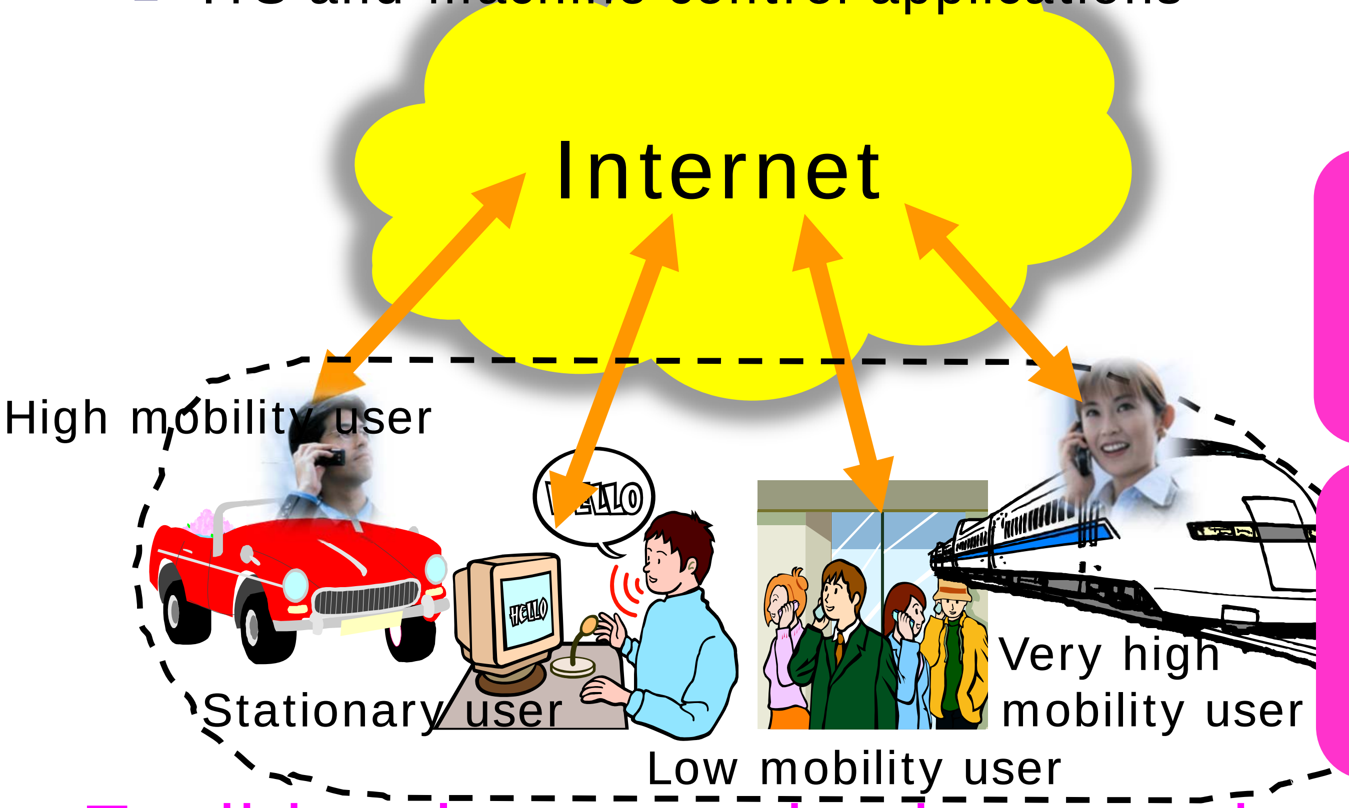
Explosive Growth of Mobile Data Traffic (1,000 times in 10 years)

- Due to rapid popularity of smart phones, mobile data traffic is growing at a rate of close-to-2 times per year
  - This growth rate leads to about 1,000 times of 2010 traffic volume by 2020
  - Present 4G networks cannot cope with this rapid growth
- Traffic gathers in hotspots and local areas
  - 70% in offices and hotspots, over 90% in future
  - QoS cannot be guaranteed in hotspots!



New Services in 5G

- Broadband mobile data services will become more and more popular
- New services will come out in the near future
  - IoT related massive devices connection
  - ITS and machine control applications



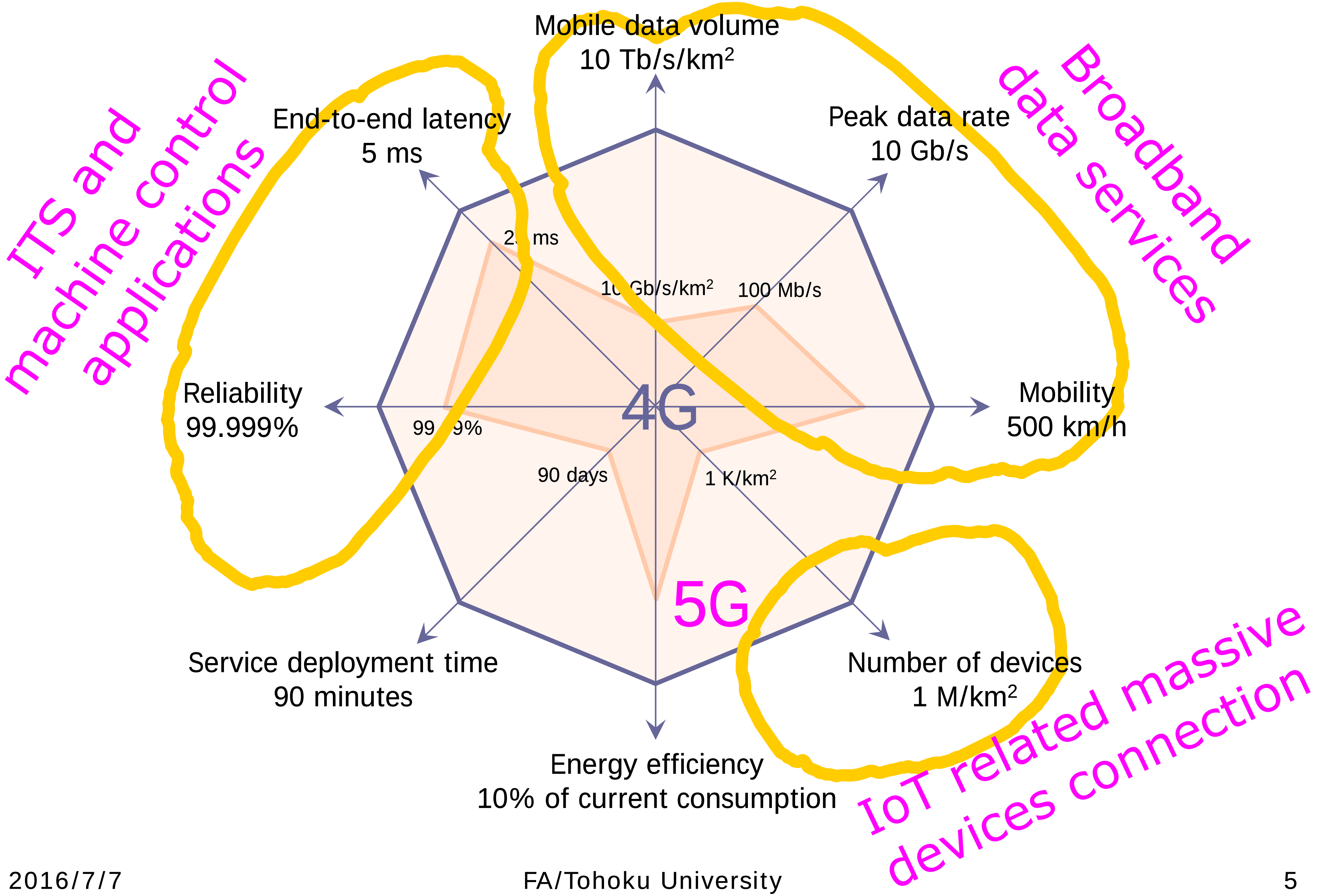
IoT related massive devices connection: M2M, D2D

ITS and machine control applications: ultra low latency and high reliability

Traditional communications services

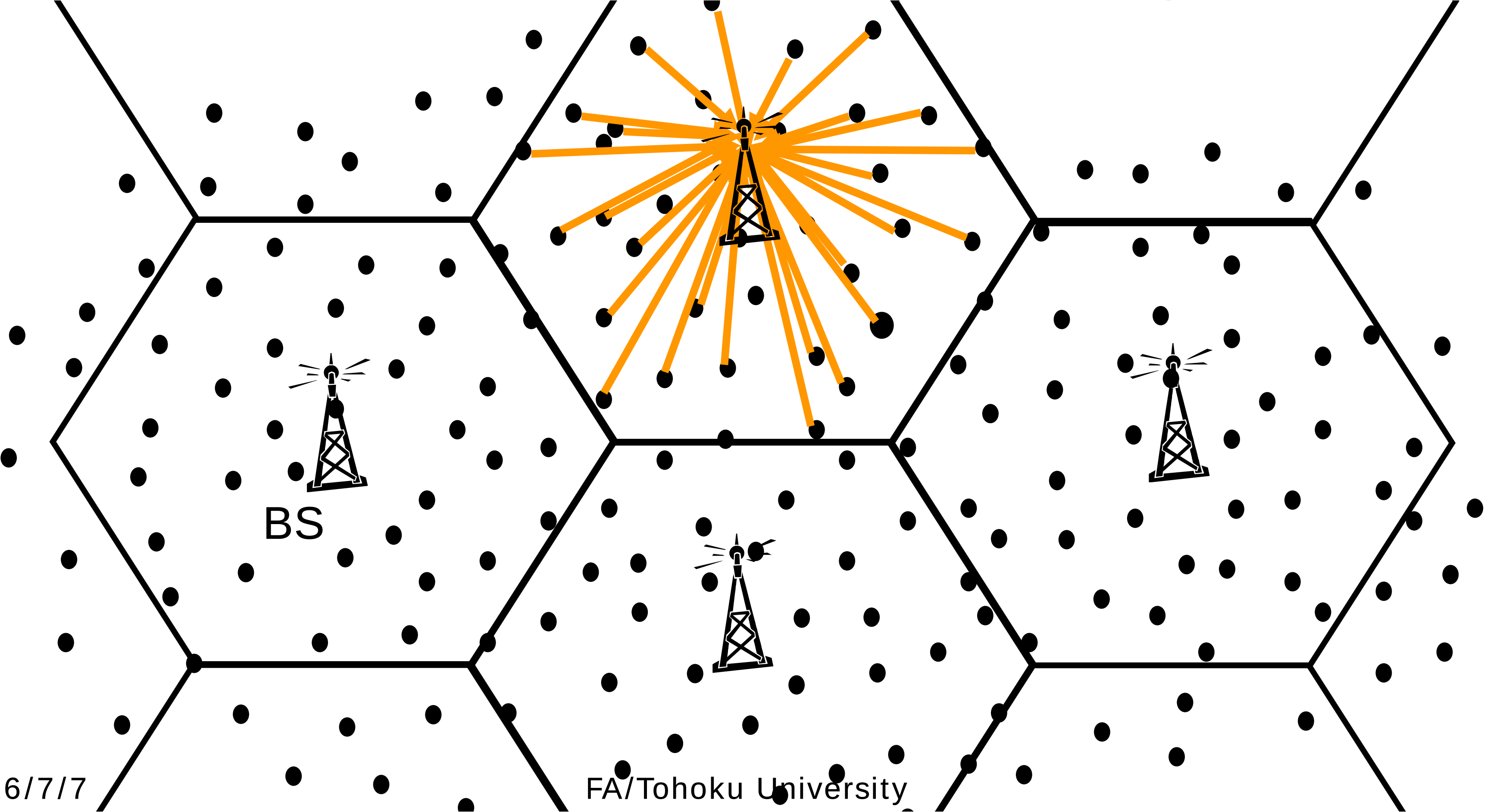
5G Requirements

“5G Vision – The 5G Infrastructure Public Private Partnership (5G-PPP): the next generation of communication networks and services,” available at www.5g-ppp.eu, Feb. 2015.



Cell-densification

- Transmission capability of BS (bps/BS) is limited
- The spatial distribution of users/devices should be more exploited
  - This is within the context of cellular concept



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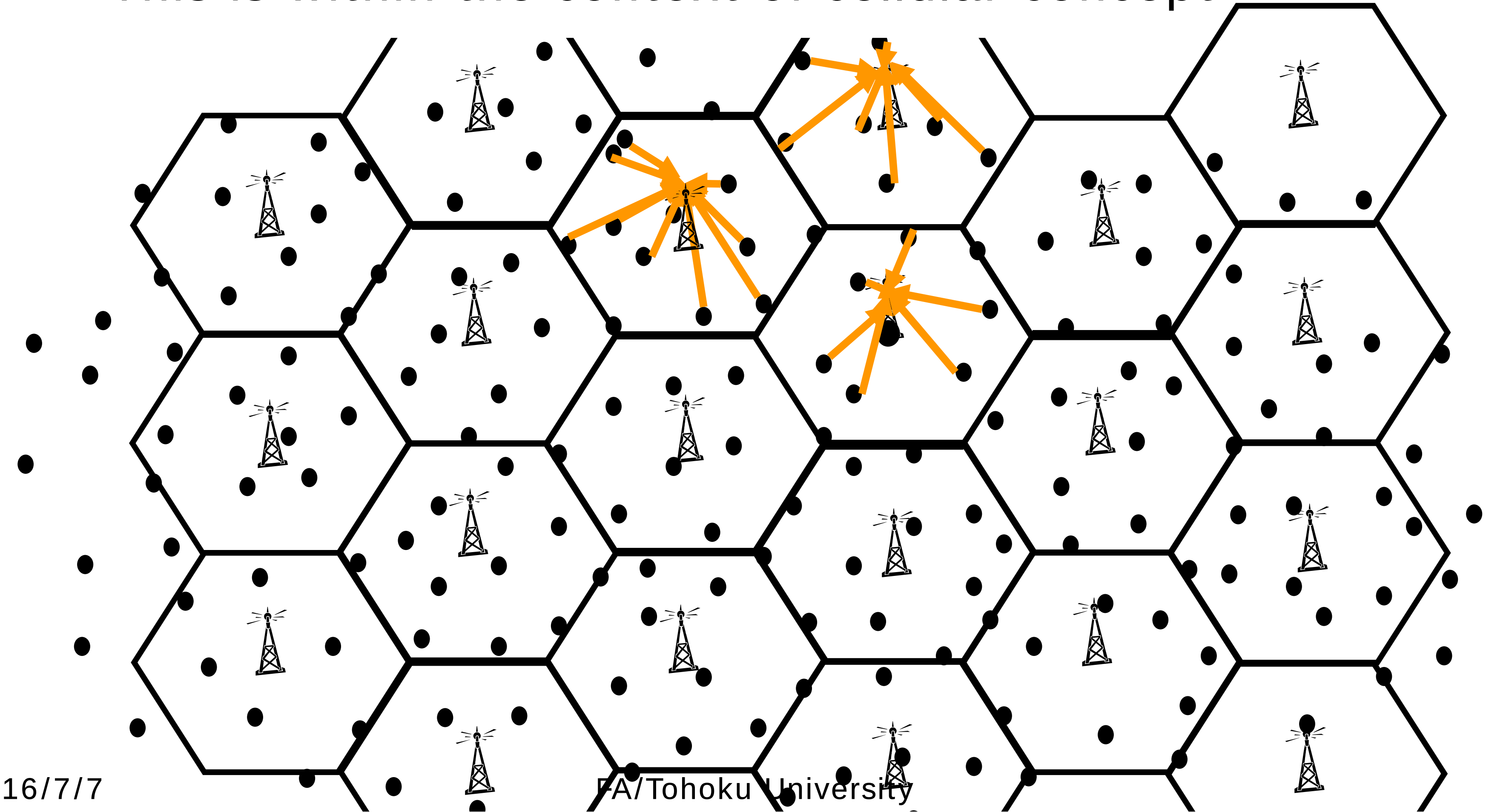


5G Technical Issues Toward Mobile Broadband Services

- How to achieve a peak data rate *C* of 10Gbps/BS and a bit rate density η of 10 Tbps/km^2 in a strong CCI environment?
  - BS capacity *C* (bps/BS) and capacity density η (bps/km^2) w/ MIMO using N_t transmit and N_r receive antennas

$$\begin{cases} C = \left(B \times \dfrac{1}{F}\right) \times N_r \times \log_2(1+\Lambda) \quad \text{if } N_t = N_r >> 1 \\ \eta = C / A \end{cases}$$

where

$$\begin{cases} B = \text{system bandwidth}, \ F = \text{frequency reuse factor}, \\ N_r = N_t = \text{no. of antennas}, \ \Lambda = \text{cell edge SINR} \\ A = \text{BS coverage area} \end{cases}$$

- Promising approaches
  - Reducing *F*→1: dynamic reuse of the same freq. (scheduling)
  - Increasing *B*: >>100MHz
  - Increasing N_r: N_r>>1 (massive MIMO)
  - Reducing *A*: cell densification (small-cell networks)

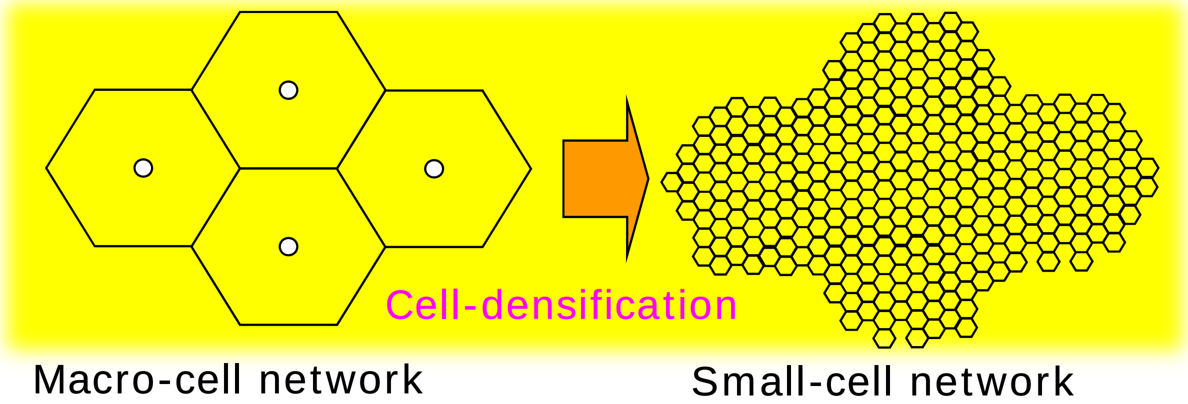
5G Technical Issues Toward Mobile Broadband Services

- One design example

$$\begin{cases} B = 400\text{MHz},\ F = 1,\ N_r(=N_t) = 4,\ \Lambda = 20\text{dB} \\ A = 1{,}000\text{m}^2 (\text{cell radious} = 12.6\text{m}) \end{cases}$$

provides

$$\begin{cases} C \approx 10\ \text{Gbps/BS} \\ \eta \approx 10\ \text{Tbps/km}^2 \end{cases}$$

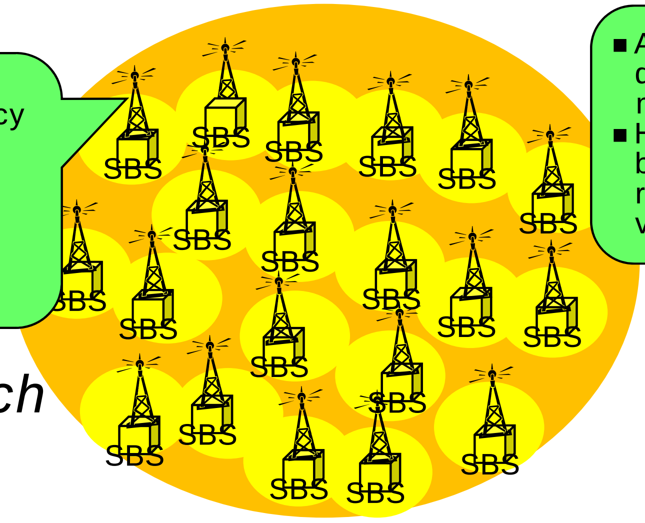


- Small-cell structured network by cell densification
  - Because of near single-user access/BS, a user is able to occupy the whole bandwidth if *F*→1 and accordingly, to increase the user data rate significantly
  - Higher frequency bands, where abundant bandwidths remain unused, can be used, e.g., centimeter wave, millimeter wave, and even visible light bands, can be used

Two Approaches for Small-cell Network

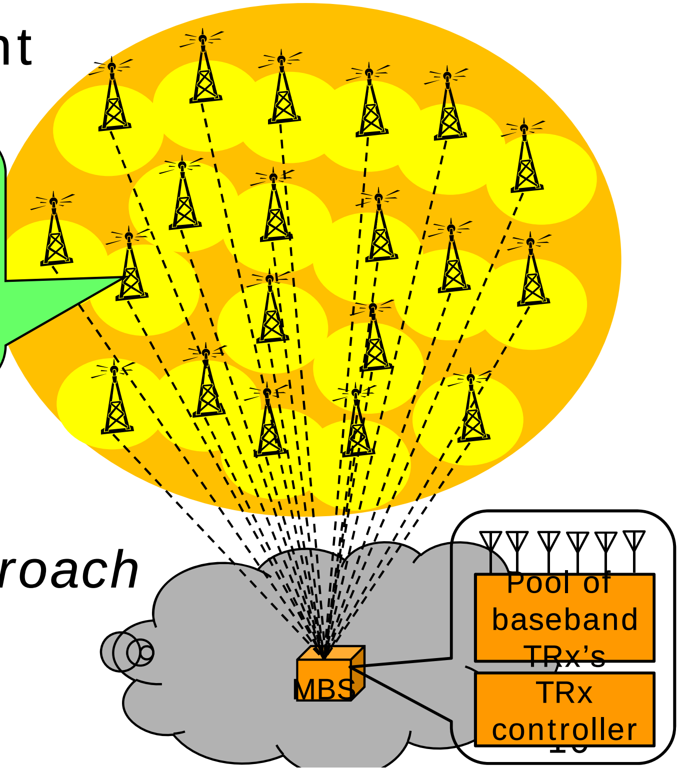
- Distributed antenna approach
  - A large number of antennas are deployed in a macro-cell area instead of using massive MIMO at macro-cell BS
  - A group of distributed antennas nearby a user forms a virtual small-cell
- Small-cell base station (SBS) approach
  - A number of loosely coordinating small-cell BSs (SBSs) are deployed in a macro-cell area
  - Decentralized radio resource management

- Fast resource management (frequency and time) for users within each SBS
- Slow (distributed) resource management (frequency) for SBSs within a macro-cell



SBS approach

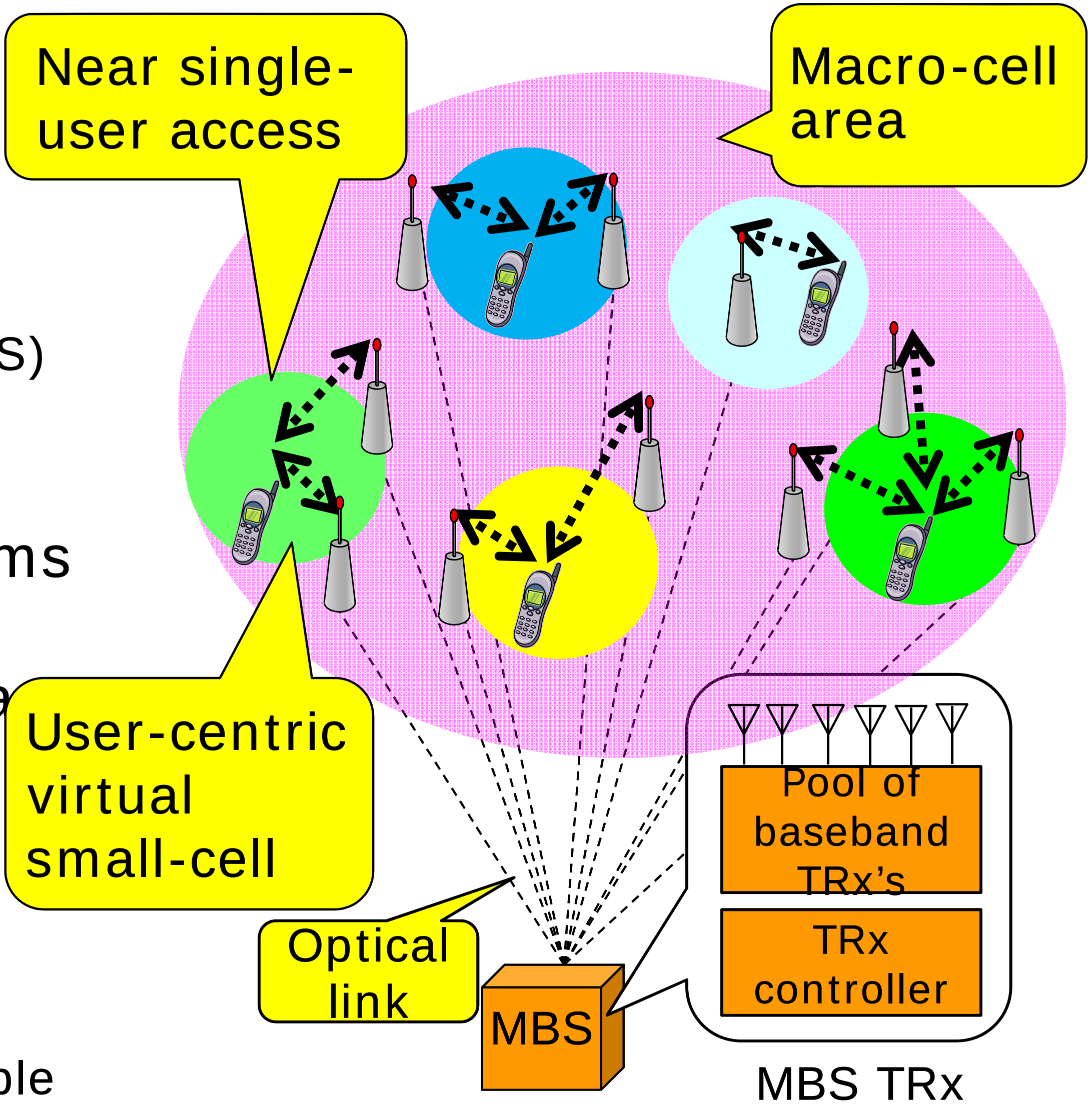
- Antenna becomes one dimension in resource management
- Handover is replaced by antenna reallocation within a virtual macro-cell



Distributed antenna approach

User-centric Virtual Small-cell
Centralized vs Distributed

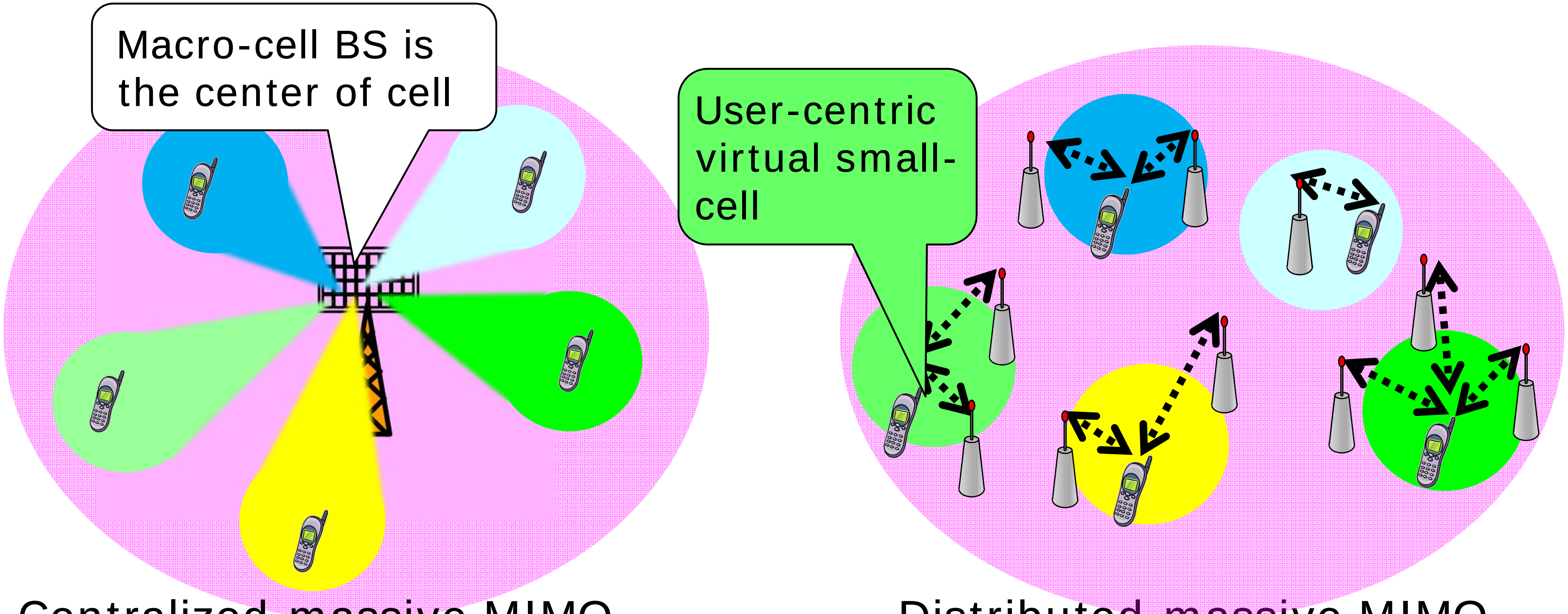
- It may be wise to exploit more the spatial domain
  - A large number of antennas are deployed in a macro-cell area
  - Each distributed antenna is connected to macro-cell BS (MBS) by optical link
- A group of distributed antennas nearby a user forms a user centric virtual small-cell within a macro-cell area
  - Handover problem can be replaced with antenna selection problem
  - Path loss and shadowing loss problems can be mitigated
  - Near single-user access is possible



Distributed antenna small-cell network

User-centric Virtual Small-cell
Centralized vs Distributed

- Two types of virtual small-cell



Centralized massive MIMO

- Path loss
  Shadowing loss
- Fading
- Near single-user access in each narrow beam

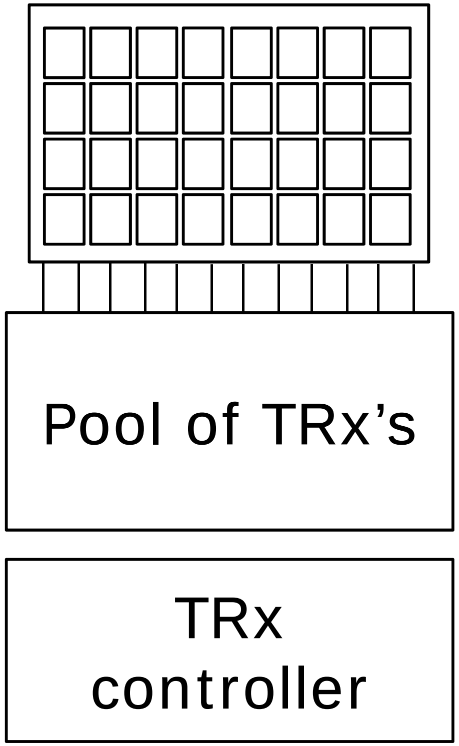
Distributed massive MIMO

- Path loss
- Shadowing loss
- Fading
- Near single-user access in each small-cell

User-centric Virtual Small-cell
Centralized vs Distributed

- The same received signal representation
- The channel matrix **H** is different
  - Centralized massive MIMO: dense **H**
  - Distributed massive MIMO: sparse **H**

F. Adachi, “Wireless Optical Convergence Enables Spectrum-Energy Efficient Wireless Networks,” Proc. 2014 International Topical Meeting on Microwave Photonics/the 9th Asia Pacific Microwave Photonics (MWP/APMP 2014), pp.51-56, Sapporo, Japan, 20-23 Oct. 2014.

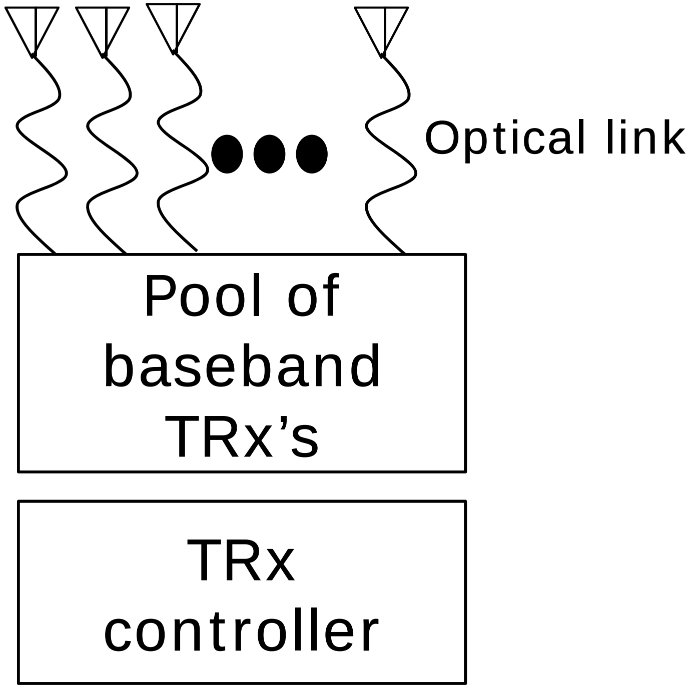


Pool of TRx’s

TRx controller

Centralized massive MIMO

$$\mathbf{Y} = \mathbf{H}\mathbf{X} + \mathbf{N}$$



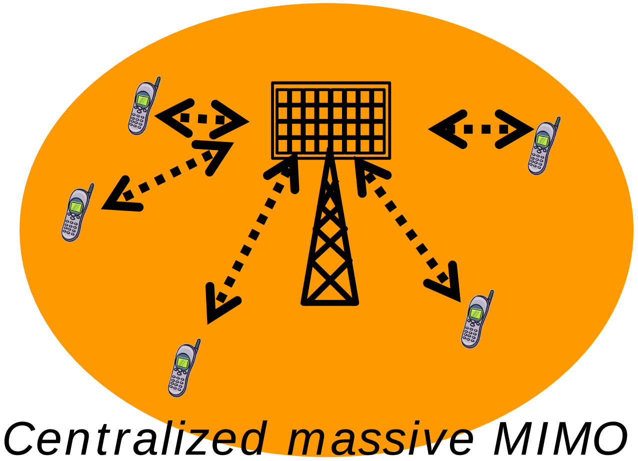
Optical link

Pool of baseband TRx’s

TRx controller

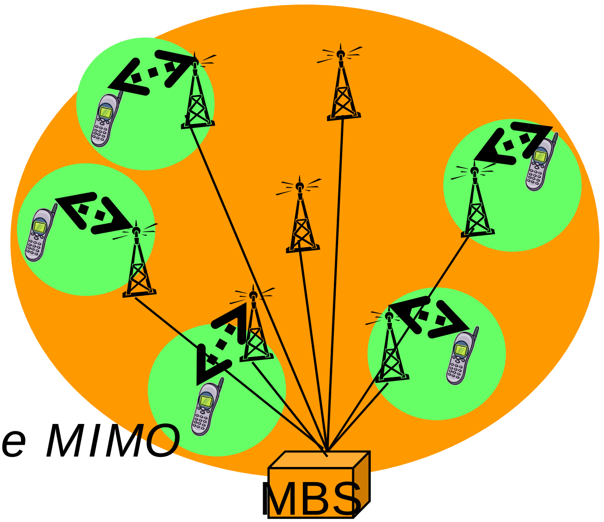
Distributed massive MIMO

User-centric Virtual Small-cell
Centralized vs Distributed



Centralized massive MIMO

- *N* BS antennas
- *N* users (equipped with single antenna)
- TDD



Distributed massive MIMO

- Uplink access

  BS received signal $\mathbf{y} = \mathbf{w}_{\mathrm{r}}\mathbf{H}\mathbf{d} + \mathbf{N}$

  Signal detection $\hat{\mathbf{d}} = \mathbf{w}_{\mathrm{r}}\mathbf{y}$

  with $\mathbf{w}_{\mathrm{r}} = \left(\mathbf{H}^H\mathbf{H}\right)^{-1}\mathbf{H}^H$

- Downlink access

  Precoding $\mathbf{x} = \mathbf{w}_t^*\mathbf{d}$

  with $\mathbf{w}_t = \mathbf{H}\left(\mathbf{H}^H\mathbf{H}\right)^{-1}$

  User received singal $\mathbf{y} = \mathbf{H}^T\mathbf{x} + \mathbf{N}$

- For centralized massive MIMO, computationally demanding signal processing (multi-user detection and precoding) is required

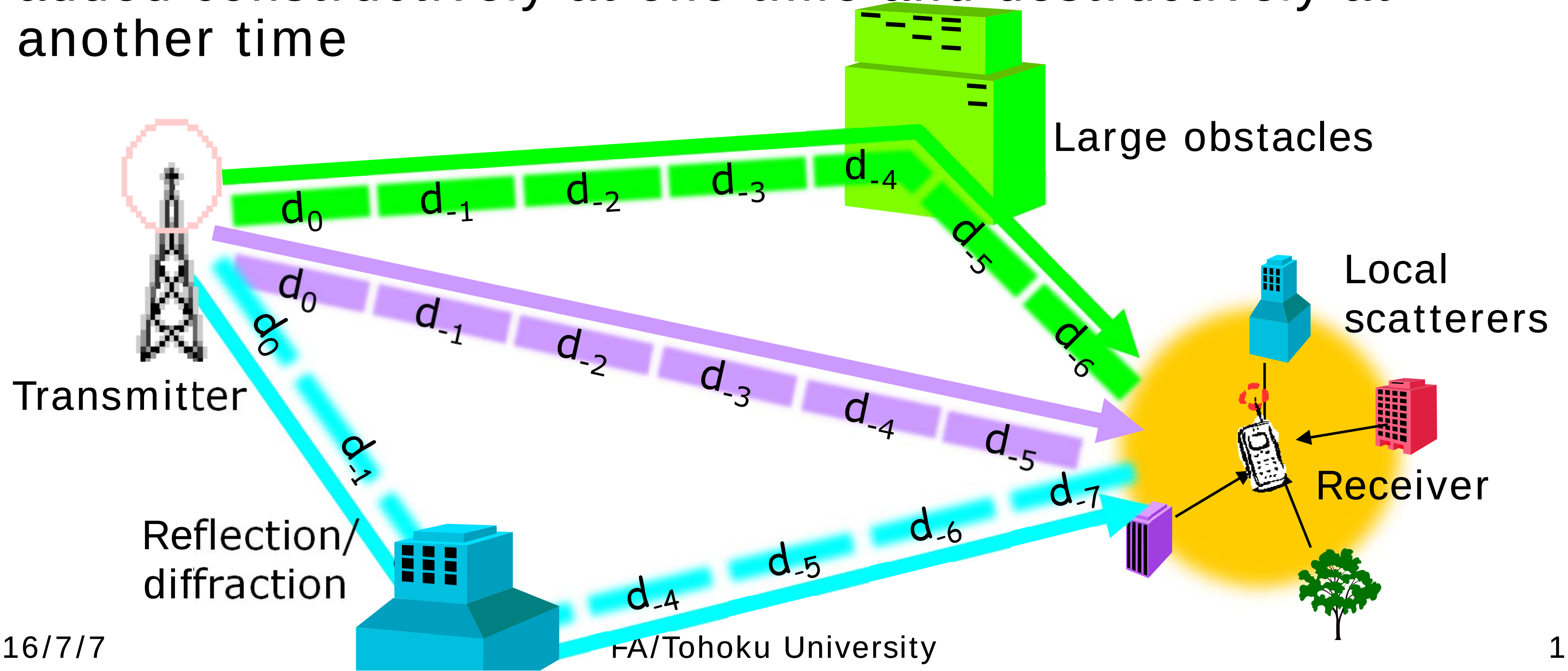
$$\mathbf{H} = \begin{pmatrix} H_{0,0} & \cdots & H_{0,N-1} \\ \cdots & \ddots & \cdots \\ H_{N-1,0} & \cdots & H_{N-1,N-1} \end{pmatrix}$$

- For distributed massive MIMO, by exploiting the sparsity of channel matrix, multi-user detection problem can be reduced to near single-user detection problem

$$\mathbf{H} = \begin{pmatrix} H_{0,0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \ddots & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & H_{N-1,N-1} \end{pmatrix}$$

Severely Frequency-selective Channel

- Transmitted radio waves are reflected or diffracted by some large buildings, creating resolvable paths having time delays of multiple of (signal bandwidth)$^{-1}$
- Each resolvable path is the sum of irresolvable paths created by local scatterers surrounding a mobile
- The path gain $h_l(t)$ varies in time according to the movement of mobile terminal since resolvable paths are added constructively at one time and destructively at another time

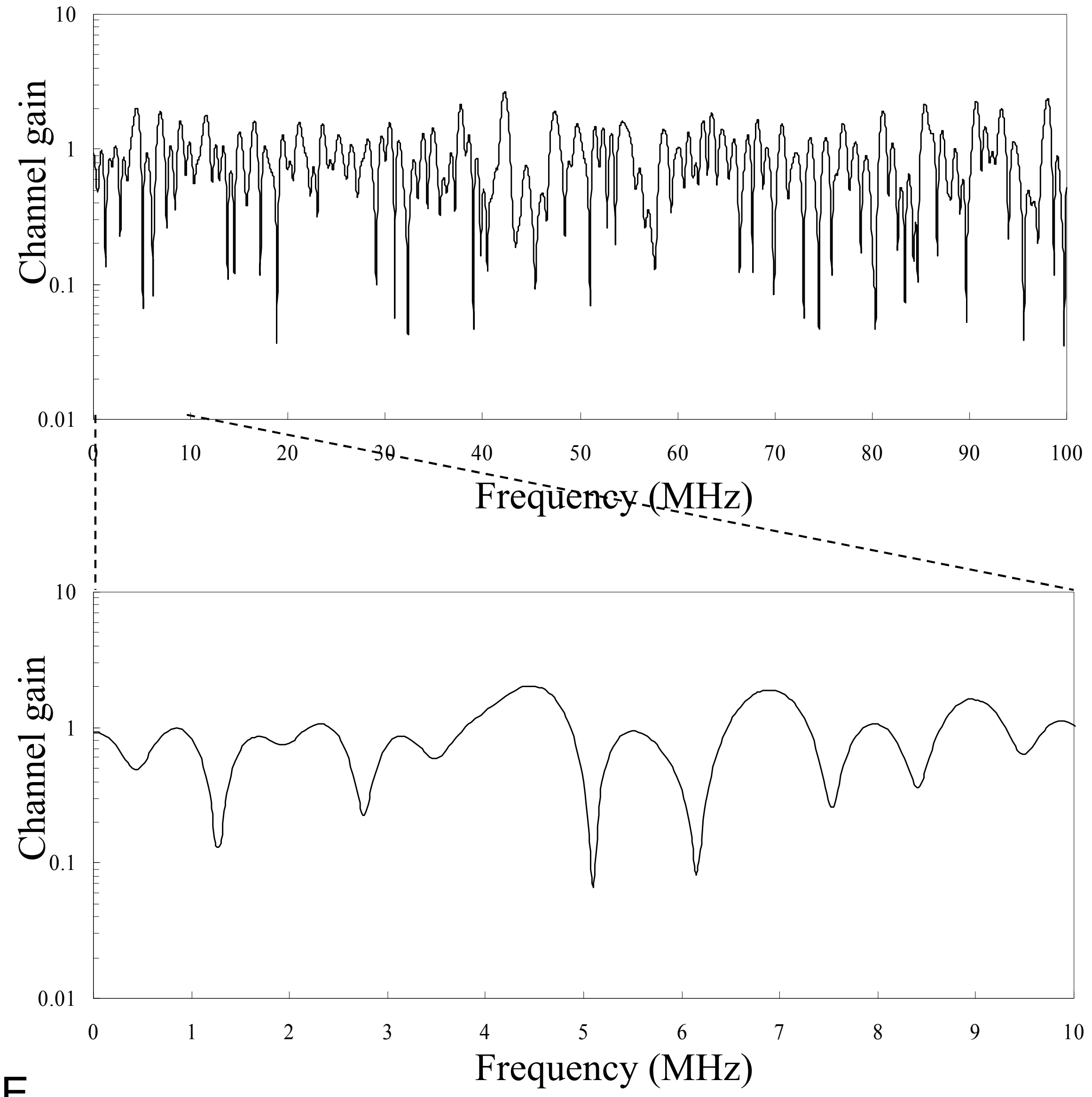


Severely Frequency-selective Channel

- The transfer function $H(f, t)$ of broadband channel at time t is not constant and varies over the signal bandwidth

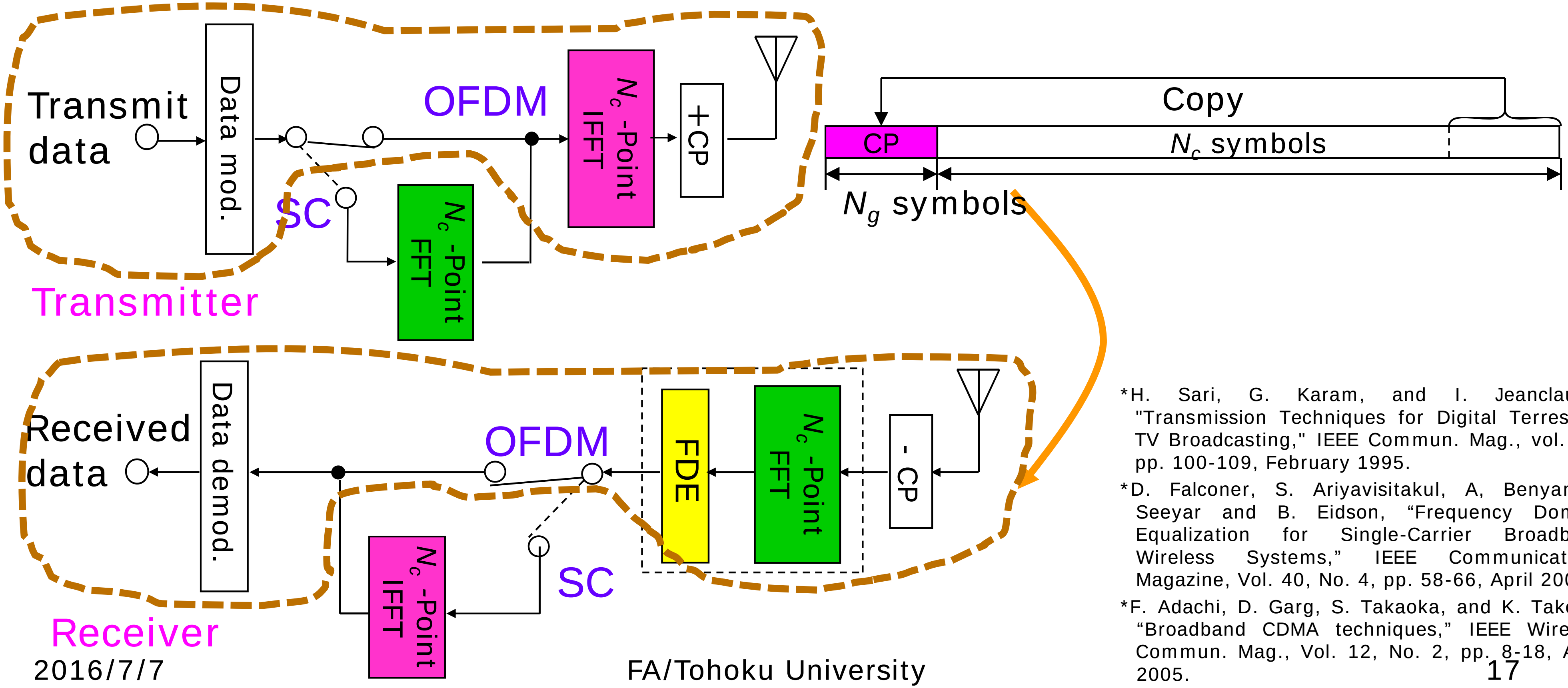
$$H(f,t)=\sum_{l=0}^{L-1}h_l(t)\exp(-j2\pi f\tau_l)$$

  - L=16 uniform power delay profile
  - l-th path time delay=100l + [-50,50)ns
- In such a severely frequency-selective channel, advanced equalization technique is necessary
  - OFDMA with frequency-domain equalization (FDE)
  - Single-carrier access with FDE



Frequency-domain Equalization (FDE)

- SC is a family of OFDM
  - SC transceivers can be designed based on OFDM
  - FFT at transmitter acts as the precoder of OFDM
  - There may be different precoders which generate many different waveforms between OFDM and SC



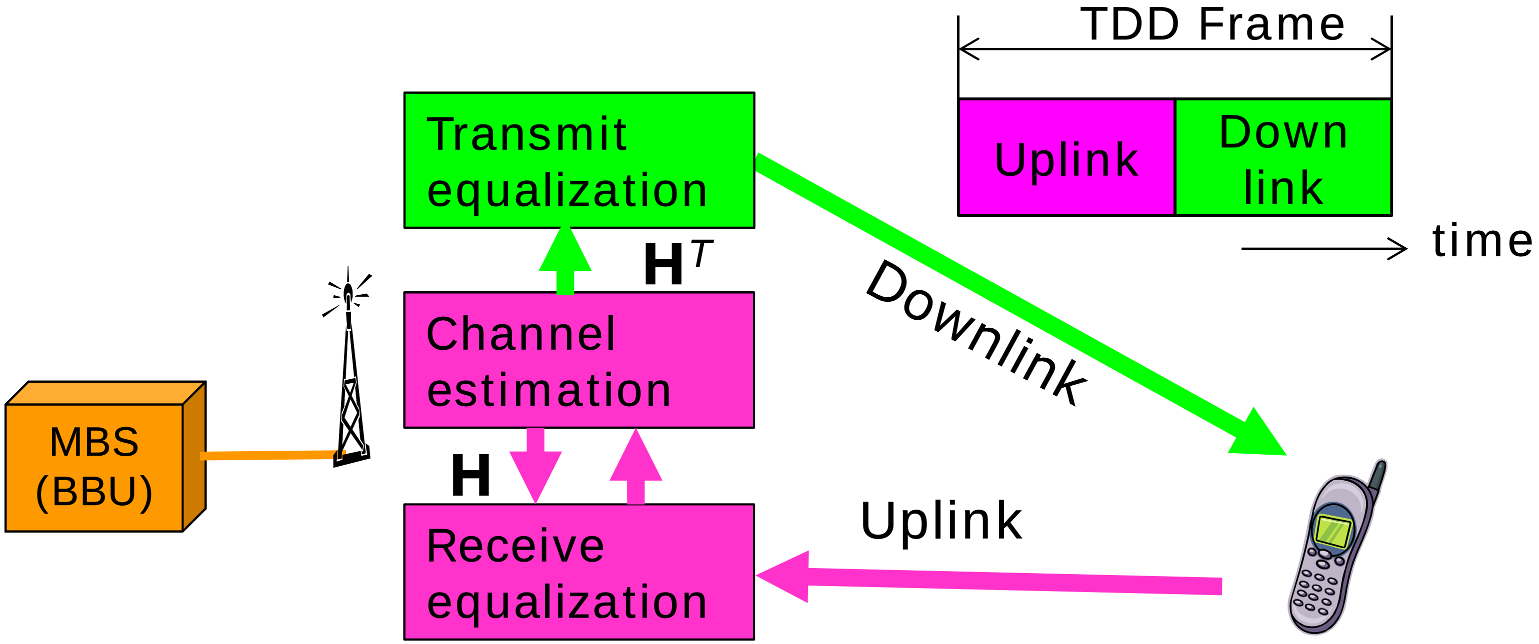
*H. Sari, G. Karam, and I. Jeanclaude, "Transmission Techniques for Digital Terrestrial TV Broadcasting," IEEE Commun. Mag., vol. 33, pp. 100-109, February 1995.

*D. Falconer, S. Ariyavisitakul, A, Benyamin-Seeyar and B. Eidson, “Frequency Domain Equalization for Single-Carrier Broadband Wireless Systems,” IEEE Communications Magazine, Vol. 40, No. 4, pp. 58-66, April 2002.

*F. Adachi, D. Garg, S. Takaoka, and K. Takeda, “Broadband CDMA techniques,” IEEE Wireless Commun. Mag., Vol. 12, No. 2, pp. 8-18, April 2005.

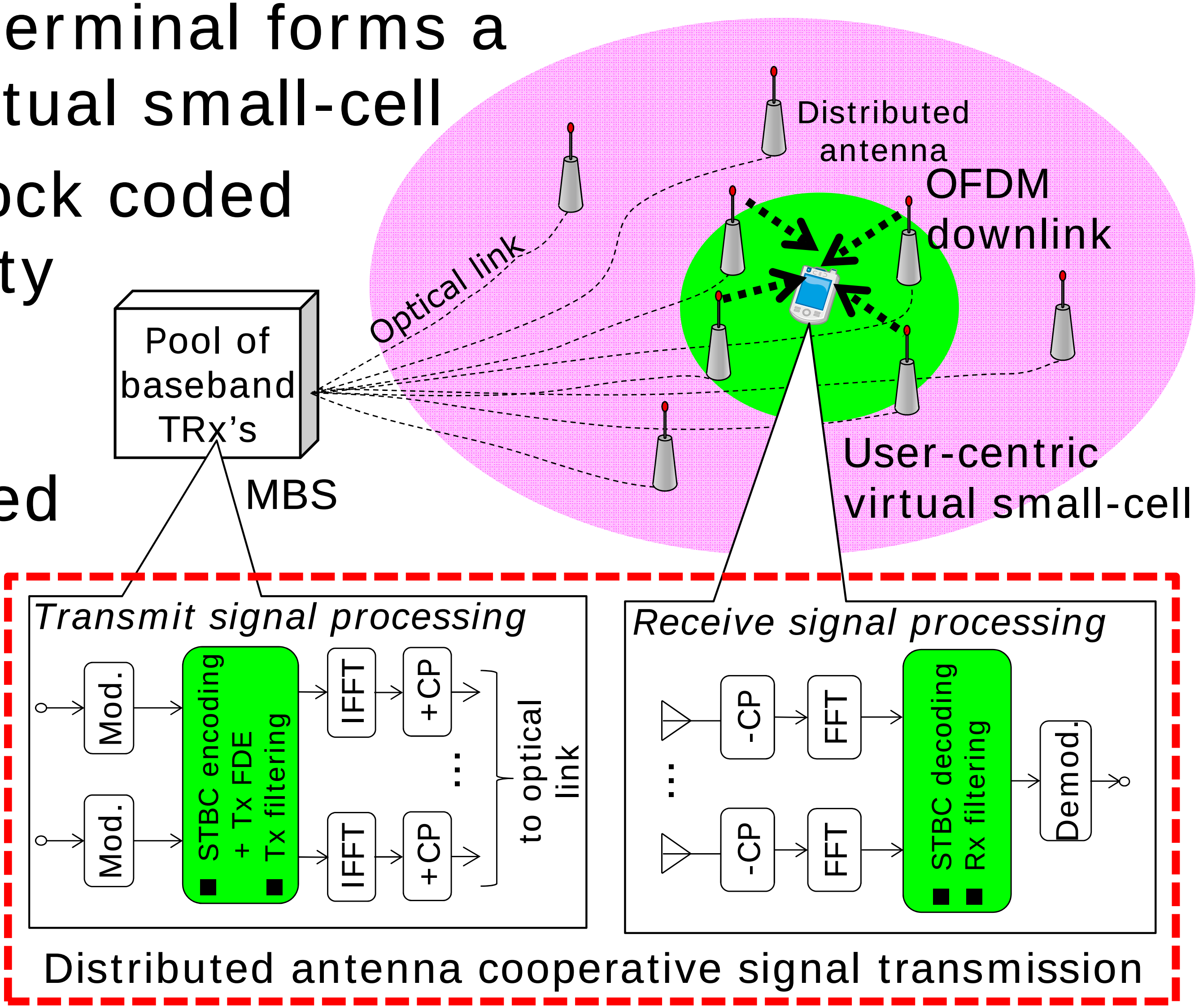
TDD Allows Transmit Equalization

- TDD can exploit the channel reciprocity to introduce the transmit equalization without the feedback of channel state information (CSI) from user equipments (UEs)
- Computationally demanding signal processing can be done at a virtual MBS, thereby alleviating the complexity problem of UEs



Distributed Antenna Cooperative Signal Transmission

- A group of distributed antennas nearby a user terminal forms a user-centric virtual small-cell
- Space-time block coded (STBC) diversity and multiuser spatial multiplexing are used to improve the throughput in the virtual small-cell

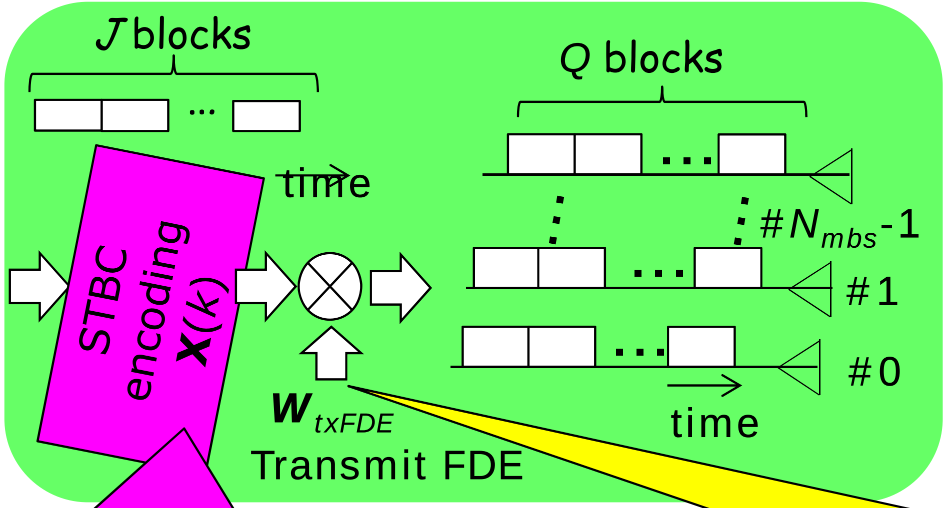


STBC Diversity OFDM Downlink

- H. Tomeba, K. Takeda and F. Adachi, "Space-Time Block Coded Joint Transmit/Receive Diversity in a Frequency-Nonselective Rayleigh Fading Channel," IEICE Trans. Commun., Vol.E89-B, No.8, pp.2189-2195, Aug. 2006.
- H. Tomeba, K. Takeda, and F. Adachi, "Space-Time Block Coded-Joint Transmit/Receive Antenna Diversity using more than 4 Receive Antennas, 2008 IEEE 68th Vehicular Technology Conference (VTC-Fall), Calgary, Canada, 21-25 September 2008.
- R. Matsukawa, T. Obara, and F. Adachi, "Frequency-Domain Space-Time Block Coded Transmit/Receive Diversity For Single-Carrier Distributed Antenna Network," IEICE Communications Express (ComEX), Vol. 2, No. 4, pp. 141-147, 15 April, 2013. http://dx.doi.org/10.1587/comex.2.141.

- STBC diversity with MMSE transmit FDE
  - It allows an arbitrary number of transmit antennas although the number of receive antennas at a user equipment (UE) is limited to 6
  - Transmit FDE is used to obtain frequency-diversity gain
  - Simple addition/subtraction and complex conjugation operations required at UE

Transmit signal processing



When $J = Q = 2$
(Alamouti code)

$$\mathbf{X}(k) = \begin{bmatrix} D_0(k) & -D_1^*(k) \\ D_1(k) & D_0^*(k) \end{bmatrix}$$

$$\mathbf{W}_{txFDE}(k) = \mathbf{A}\mathbf{H}_{\downarrow}^{H}(k)$$

$$\mathbf{H}_{\downarrow}(k) = \begin{bmatrix} H_{0,0}(k) & H_{0,1}(k) & \cdots & H_{0,N_{mbs}-1}(k) \\ H_{1,0}(k) & H_{1,1}(k) & \cdots & H_{1,N_{mbs}-1}(k) \end{bmatrix}$$

No. of transmit distributed antennas N_{mbs}	No. of UE receive antennas N_{ue}	J	Q	Coding rate
Arbitrary	1	1	1	1
	2	2	2	1
	3	3	4	3/4
	4	3	4	3/4
	5	10	15	2/3
	6	20	30	2/3

STBC Diversity OFDM Downlink

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- H. Tomeba, K. Takeda, and F. Adachi, "Space-Time Block Coded-Joint Transmit/Receive Antenna Diversity using more than 4 Receive Antennas, 2008 IEEE 68th Vehicular Technology Conference (VTC-Fall), Calgary, Canada, 21-25 September 2008.
- R. Matsukawa, T. Obara, and F. Adachi, "Frequency-Domain Space-Time Block Coded Transmit/Receive Diversity For Single-Carrier Distributed Antenna Network," IEICE Communications Express (ComEX), Vol. 2, No. 4, pp. 141-147, 15 April, 2013. http://dx.doi.org/10.1587/comex.2.141.

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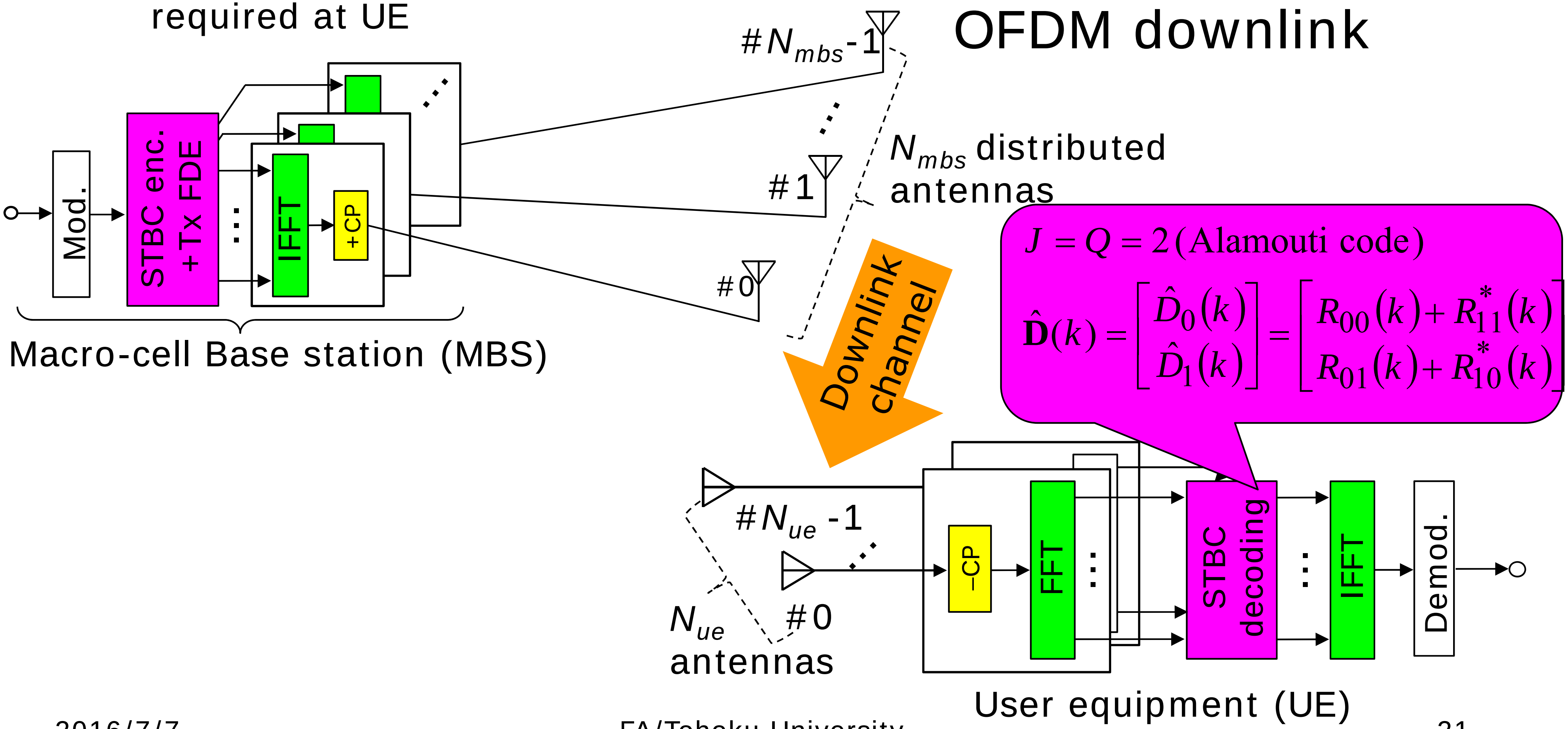


$J = Q = 2$ (Alamouti code)

$$\hat{\mathbf{D}}(k)=\begin{bmatrix}\hat{D}_0(k)\\ \hat{D}_1(k)\end{bmatrix}=\begin{bmatrix}R_{00}(k)+R_{11}^{*}(k)\\ R_{01}(k)+R_{10}^{*}(k)\end{bmatrix}$$

MU-MIMO w/ MMSE-SVD OFDM Downlink

- Shinya Kumagai, Yuta Seki, and Fumiyuki Adachi, "Joint Tx/Rx Signal Processing for Distributed Antenna MU-MIMO Downlink," to be presented at 2016 IEEE 84th Vehicular Technology Conference (IEEE VTC2016-Fall), Montréal, Canada, 18–21 Sept. 2016.

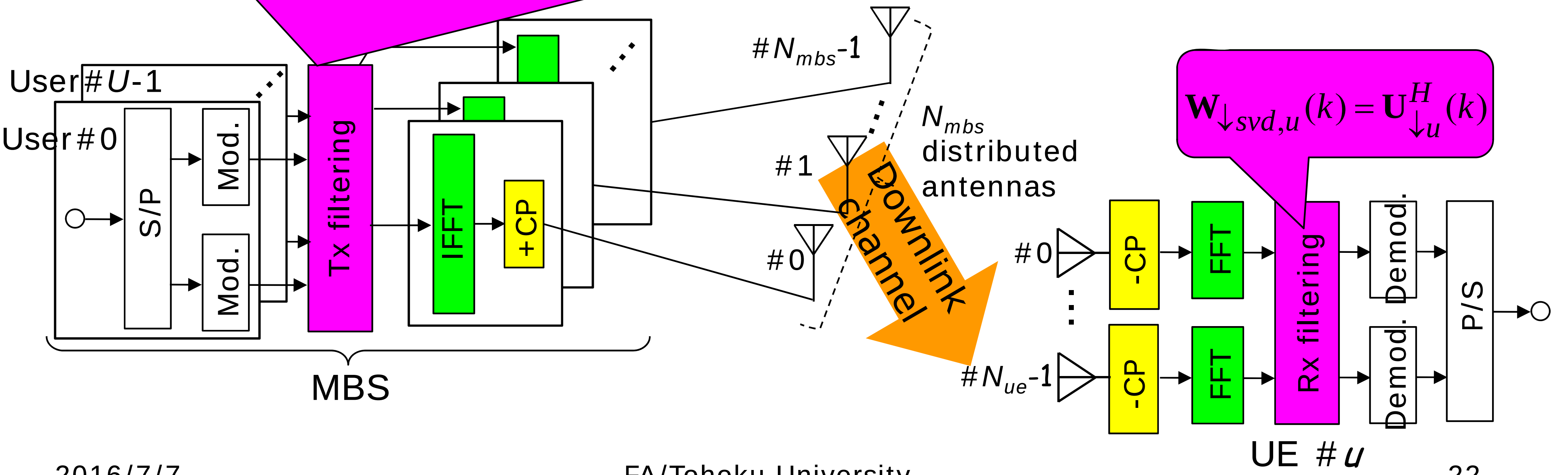
- Downlink MMSE-SVD
  - MMSE transmit filtering at MBS to suppress inter-user interference (IUI)
  - Eigenmode reception at UE to remove inter-antenna interference (IAI) at UE
  - Water-filling power allocation across eigenmodes and subcarriers for each UE at MBS

$$\mathbf{W}_{\downarrow mmse}(k)=\left(\left(\mathbf{U}_{\downarrow}^{\mathrm{H}}(k)\mathbf{H}_{\downarrow}(k)\right)^{H}\left(\mathbf{U}_{\downarrow}^{\mathrm{H}}(k)\mathbf{H}_{\downarrow}(k)\right)+U\cdot N_{ue}\left(\frac{E_s}{N_0}\right)^{-1}\mathbf{I}_{N_{mbs}}\right)^{-1}\times\left(\mathbf{U}_{\downarrow}^{\mathrm{H}}(k)\mathbf{H}_{\downarrow}(k)\right)^{H}\sqrt{\mathbf{P}_{wf}(k)}$$

$$\mathbf{U}_{\downarrow}(k)=\mathrm{diag}\left[\mathbf{U}_{\downarrow 0}(k)\cdots\mathbf{U}_{\downarrow U-1}(k)\right]$$

$$\mathbf{P}_{wf}(k)=\mathrm{diag}\left[\mathbf{P}_{wf,0}(k)\cdots\mathbf{P}_{wf,U-1}(k)\right]$$

Note : $\mathbf{P}_{wf,u}(k)$ is power allocation based on Water filing theory across eigenmodes and subcarriers



$$\mathbf{W}_{\downarrow svd,u}(k)=\mathbf{U}_{\downarrow u}^{H}(k)$$

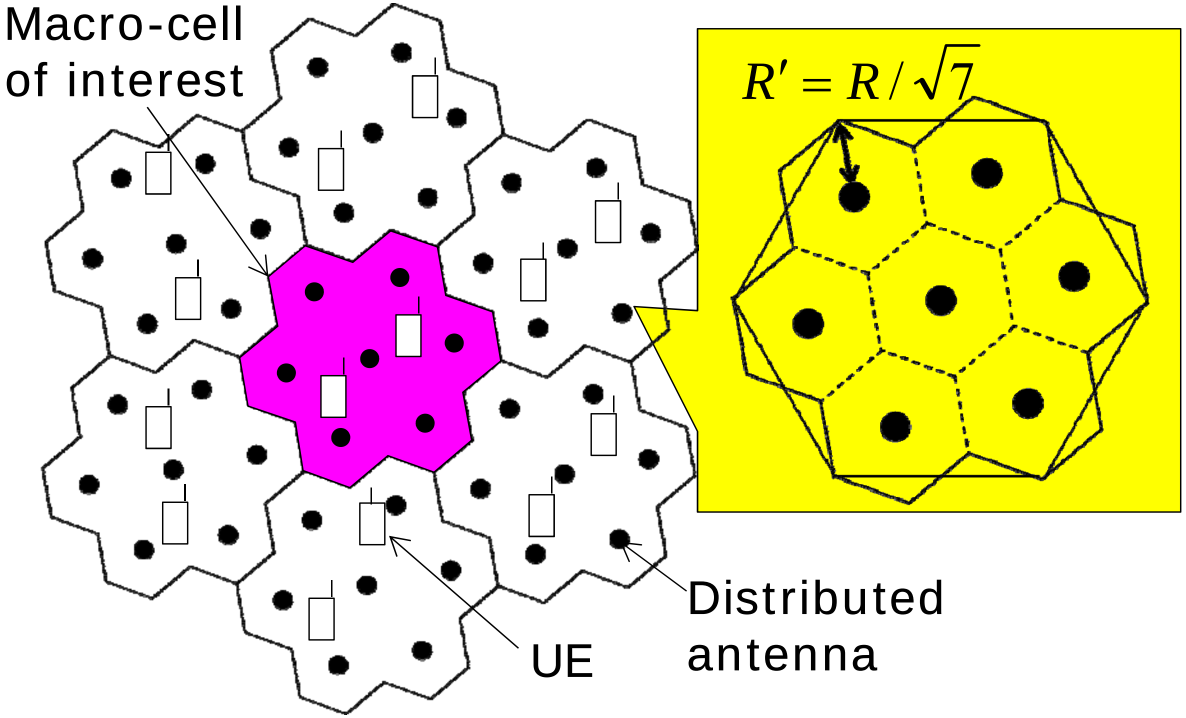
Simulation Setting up/downlinks

Tx/Rx	SC uplink	FDMA	STBC diversity w/Rx FDE [1]
		MU-MIMO	MMSE-SVD [2]
	OFDM downlink	FDMA	STBC diversity w/Tx FDE [3]
		MU-MIMO	MMSE-SVD [4]
	Total no. of subcarriers		N_c=128
	GI length		N_g=32
	No. of distributed antennas deployed in a macro-cell		N_{macro}=7
	No. of UE antennas		N_{ue}=2
	No. of distributed antennas to be selected		N_{mbs}=4
	Channel state information		Ideal
Propag. Channel	Path loss exponent		α=3.5
	Shadowing loss standard deviation		σ=7.0(dB)
	Type of fading		Frequency-selective block Nakagami-Rice and Rayleigh
	K factor of Nakagami-Rice		K=10dB
	Delay profile shape		L=16 - uniform

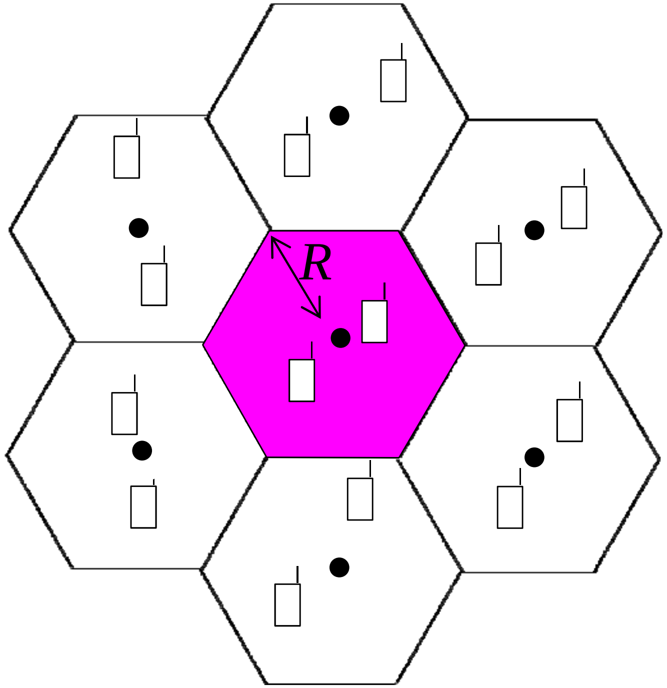
[1] K. Takeda, T. Itagaki, and F. Adachi, IEE Proc. –Commun., Vol. 151, No. 6, pp. 627-632, Dec. 2004.
[2] S. Kumagai, S. Yoshioka, and F. Adachi, ICICS2015, Singapore, 2-4 Dec. 2015.
[3] H. Tomeba, K. Takeda, and F. Adachi, IEICE Trans. Commun., Vol.E89-B, No.8, pp.2189-2195, Aug. 2006.
[4] S. Kumagai, Y. Seki, and F. Adachi, IEEE VTC2016-Fall, Montréal, Canada, 18–21 Sept. 2016.

Network Model

- SC uplink and OFDM downlink (2 UEs and N_c=128 subcarriers)
  - STBC diversity: $N_c/2$=64 subcarriers/UE
  - MMSE-SVD: N_c=128 subcarriers are shared by 2 UEs
- N_{mbs}=4 distributed antennas are selected from N_{macro}=7 distributed antennas deployed in a macro-cell area
- Interference-limited condition



Distributed antenna small-cell network (7 distributed antennas/macro-cell)



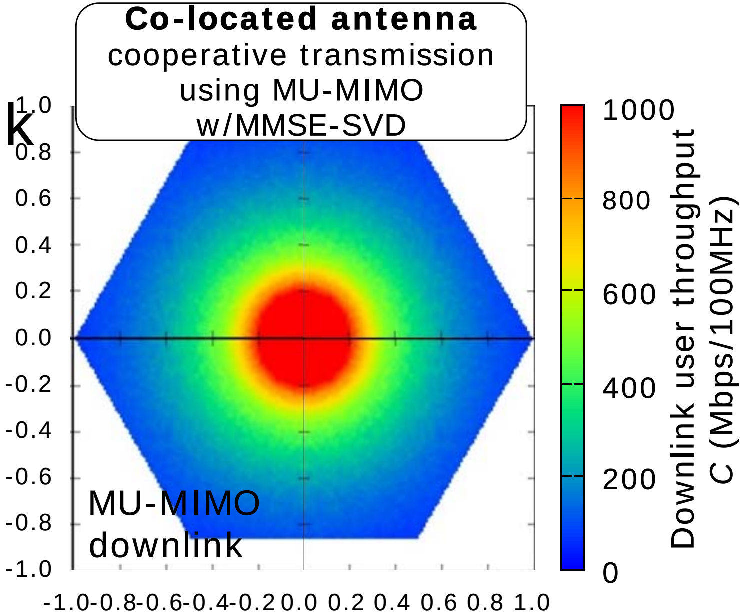
Traditional macro-cell (7 co-located antennas/macro-cell)

- H. Miyazaki and F. Adachi, “Effect of Macro-cell Cooperation on Distributed Antenna Space-Time Block Coded Diversity,” IEICE Technical Report, vol. 115, no. 369, RCS2015-273, pp. 175-180, Dec. 2015.
- S. Kumagai, S. Yoshioka, and F. Adachi, “Joint Tx/Rx Filtering for Distributed Antenna Network Uplink with Single-Carrier MU-MIMO,” IEICE Technical Report, vol. 114, no. 490, RCS2014-354, pp. 315-320, March 2015.
- S. Kumagai and F. Adachi, “Effect of Joint Tx/Rx Cooperative Signal Shinya Kumagai, Yuta Seki, and Fumiyuki Adachi, "Joint Tx/Rx Signal Processing for Distributed Antenna MU-MIMO Downlink," to be presented at 2016 IEEE 84th Vehicular Technology Conference (IEEE VTC2016-Fall), Montréal, Canada, 18–21 Sept. 2016.

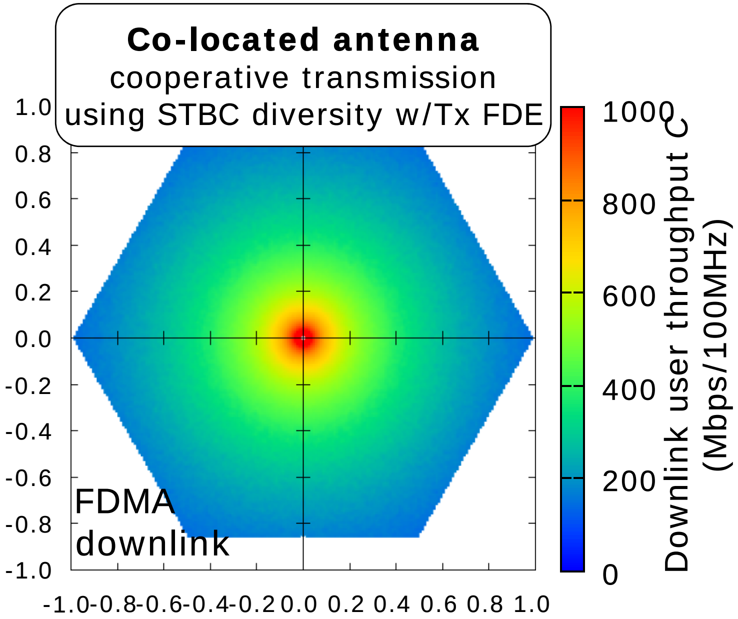
OFDM Downlink Capacity

Spatial Distribution

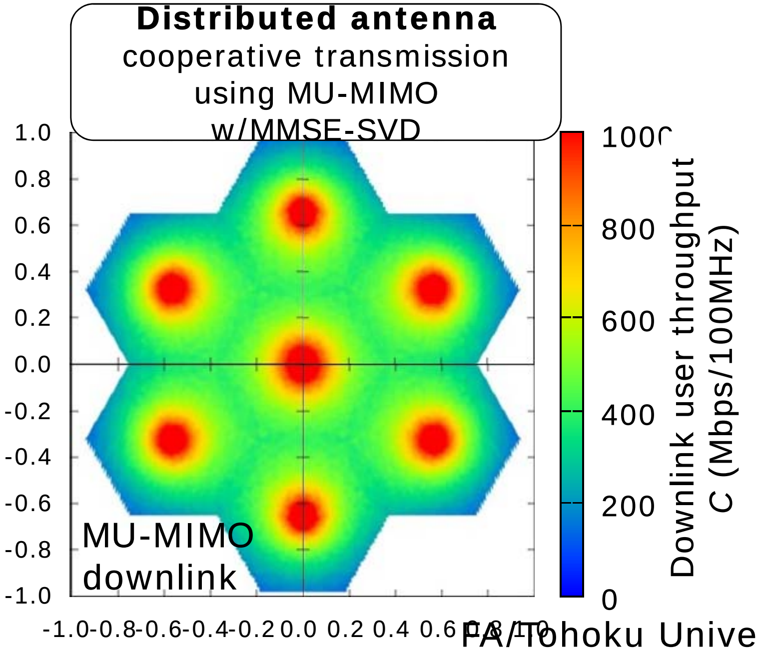
- OFDM downlink



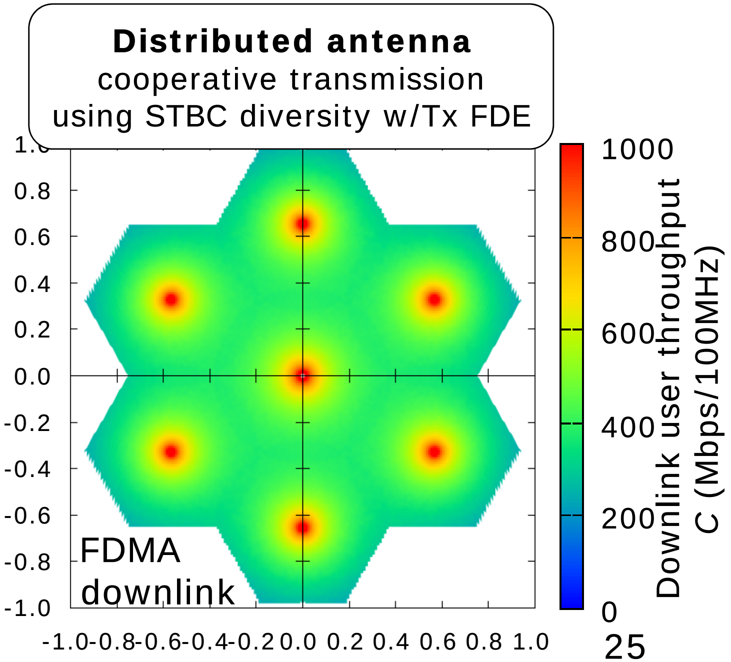
Co-located antenna
cooperative transmission
using MU-MIMO
w/MMSE-SVD



Co-located antenna
cooperative transmission
using STBC diversity w/Tx FDE



Distributed antenna
cooperative transmission
using MU-MIMO
w/MMSE-SVD



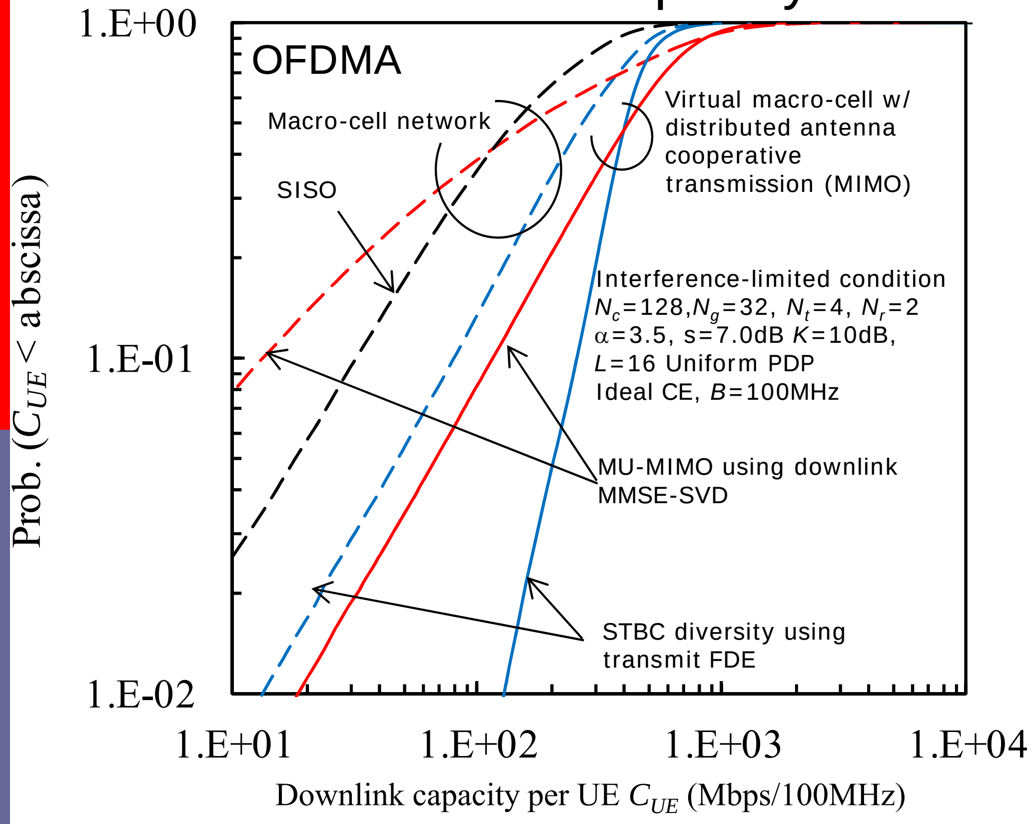
Distributed antenna
cooperative transmission
using STBC diversity w/Tx FDE

OFDM Downlink Capacity

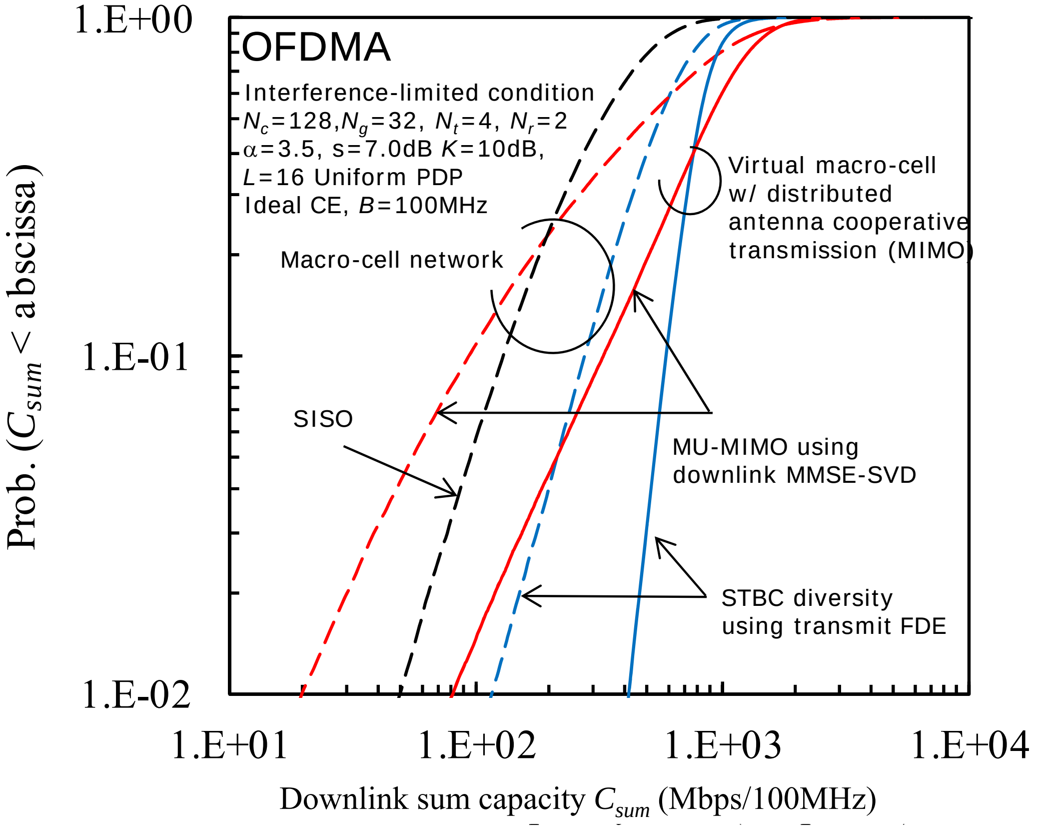
- H. Miyazaki and F. Adachi, “Effect of Macro-cell Cooperation on Distributed Antenna Space-Time Block Coded Diversity,” IEICE Technical Report, vol. 115, no. 369, RCS2015-273, pp. 175-180, Dec. 2015.
- S. Kumagai, S. Yoshioka, and F. Adachi, “Joint Tx/Rx Filtering for Distributed Antenna Network Uplink with Single-Carrier MU-MIMO,” IEICE Technical Report, vol. 114, no. 490, RCS2014-354, pp. 315-320, March 2015.
- S. Kumagai and F. Adachi, “Effect of Joint Tx/Rx Cooperative Signal Processing on Downlink Broadband MU-MIMO Transmissions in Distributed Antenna Network,” IEICE Technical Report, vol. 115, no. 369, RCS2015-274, pp. 181-186 Dec. 2015.

- Distributed antenna cooperative signal transmission can significantly improve the up/downlink capacities compared to the traditional macro-cell network using co-located antennas

- OFDM downlink capacity distribution



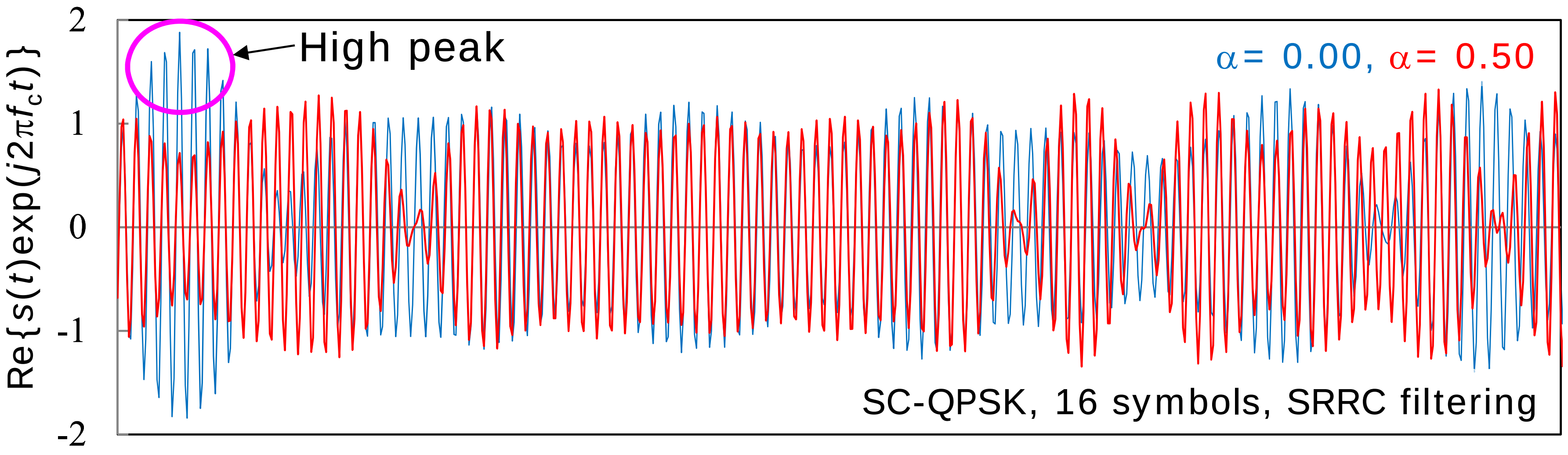
Downlink user capacity (Mbps/100MHz)



Downlink sum capacity (Mbps/100MHz)

PAPR Problem

- Low PAPR signal waveform design is still necessary for the uplink
  - Single-carrier based waveform is attractive because of its low PAPR property, but its PAPR grows when transmit filtering is employed
- E.g. square root Nyquist transmit filtering case
  - Roll-off factors of $\alpha=0$ and 0.5
  - QPSK data modulation and 16-symbol block transmission

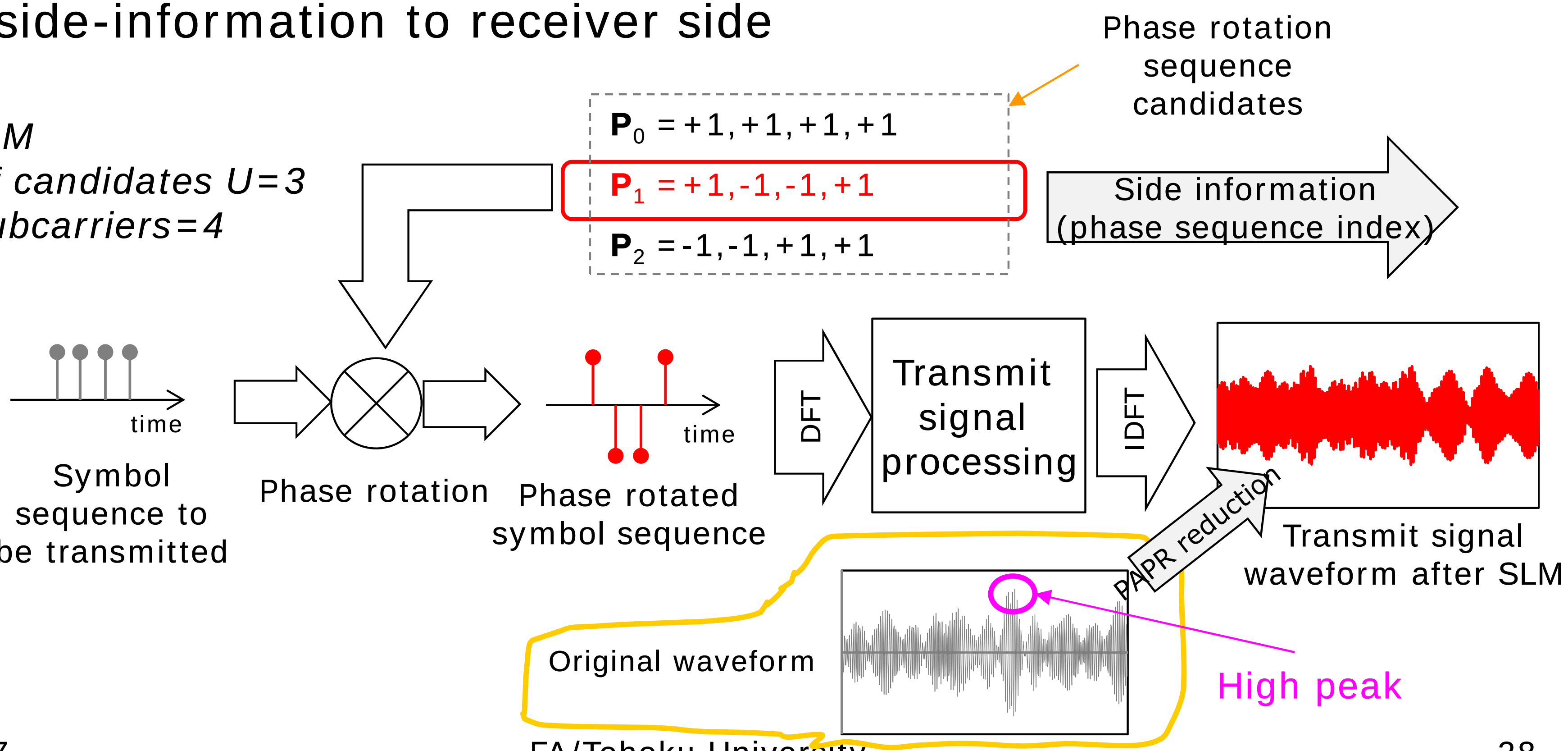


Selected Mapping (SLM)

- A. Boonkajay et al., “Selective Mapping for Broadband Single-Carrier Transmission Using Joint Tx/Rx MMSE-FDE,” Proc. PIMRC 2013, London, UK, Sept. 2013.
- A. Boonkajay et al., “Low-PAPR Joint Transmit/Received SC-FDE Transmission using Time-Domain Selected Mapping,” Proc. APCC 2014, Pattaya, Thailand, Oct. 2014.

- A number of transmit signal waveform candidates are generated by using phase rotation sequences
- Phase rotation can be applied either in frequency-domain (FD-SLM) or time-domain (TD-SLM)
- The signal waveform candidate having the lowest PAPR is selected
- Simple and distortionless PAPR reduction, but needs transmission of side-information to receiver side

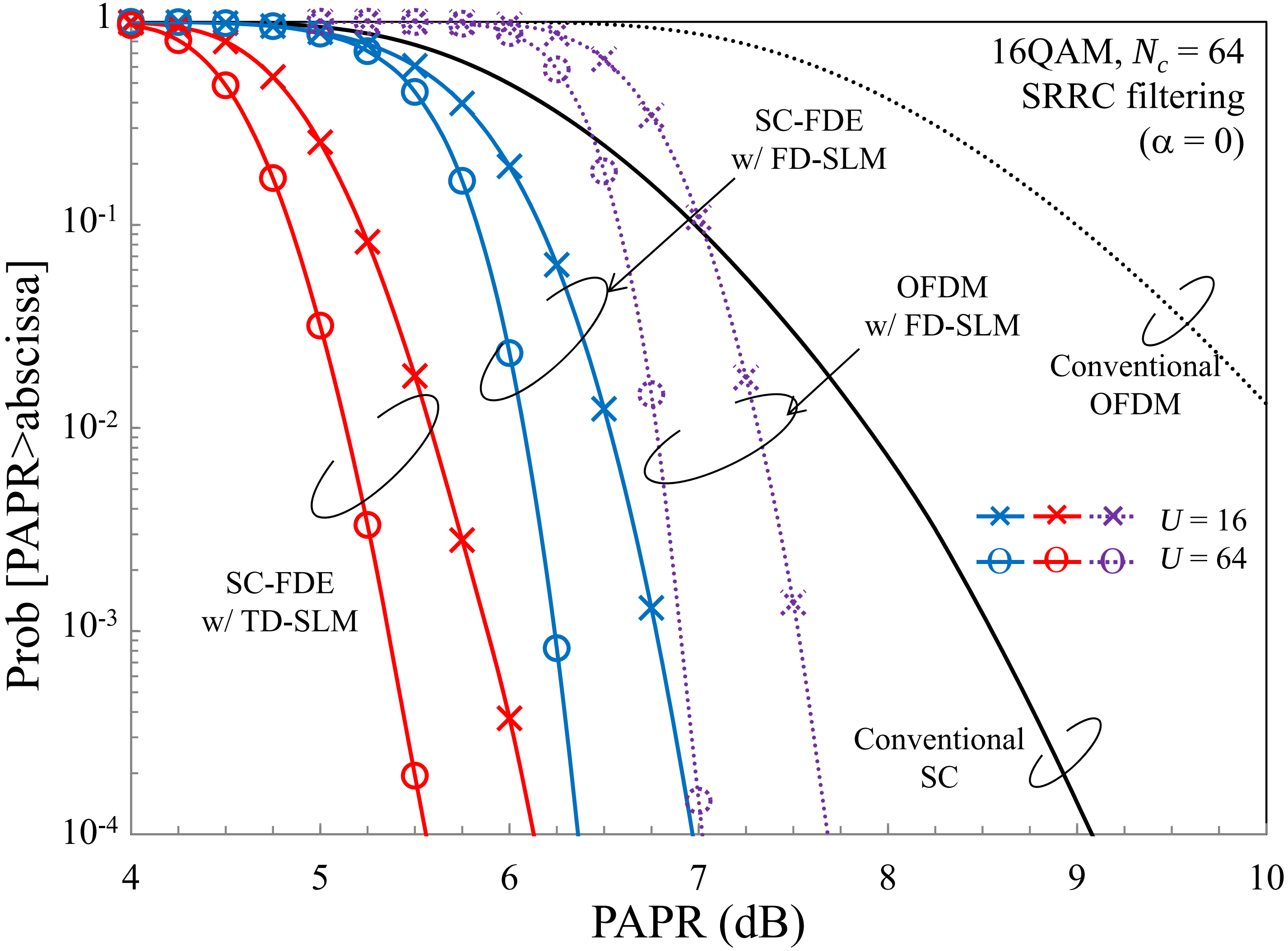
TD-SLM
No. of candidates U=3
No. subcarriers=4



Selected Mapping (SLM)

- ☐ A. Boonkajay et al., “A Blind Selected Mapping Technique for Low-PAPR Single-Carrier Signal Transmission,” Proc. ICICS2015, Singapore, Dec. 2015.
- ☐ A. Boonkajay et al., “Frequency-Domain Blind Selected Mapping Technique for Space-Time Block Coded Low-PAPR SC-FDE,” IEICE Tech. Rep. Radio Commun. Syst. (RCS), Dec. 2015.

- Comparison between FD-SLM and TD-SLM
  - Random binary phase rotation

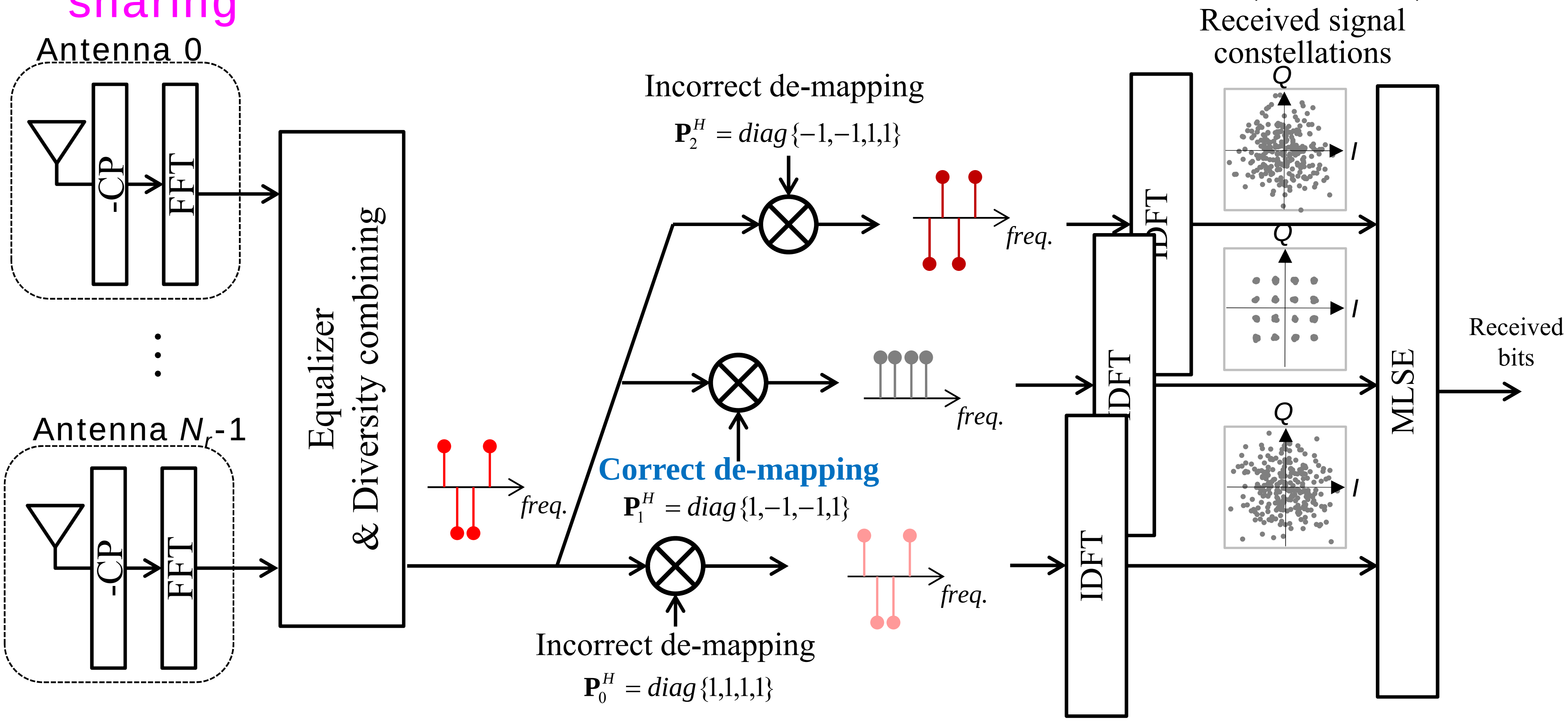


Blind SLM

- A. Boonkajay et al., “A Blind Selected Mapping Technique for Low-PAPR Single-Carrier Signal Transmission,” Proc. ICICS2015, Singapore, Dec. 2015.

- Blind SLM exploits the fact that the received signal constellation patternl with correct de-mapping and incorrect de-mapping are significantly different
- No need of side-information (phase rotation pattern) sharing

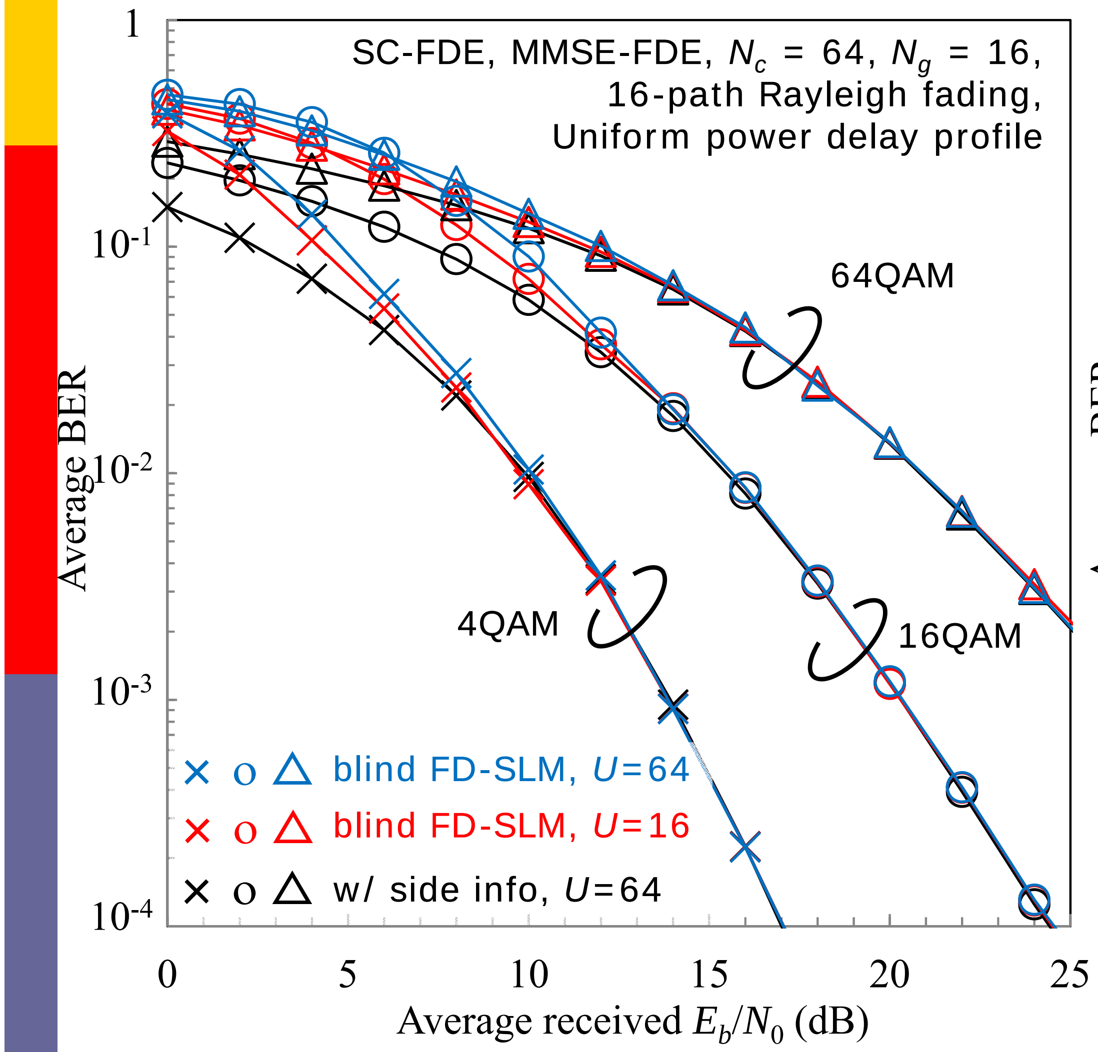
※ U=3 candidates , 4 subcarriers, FD-SLM



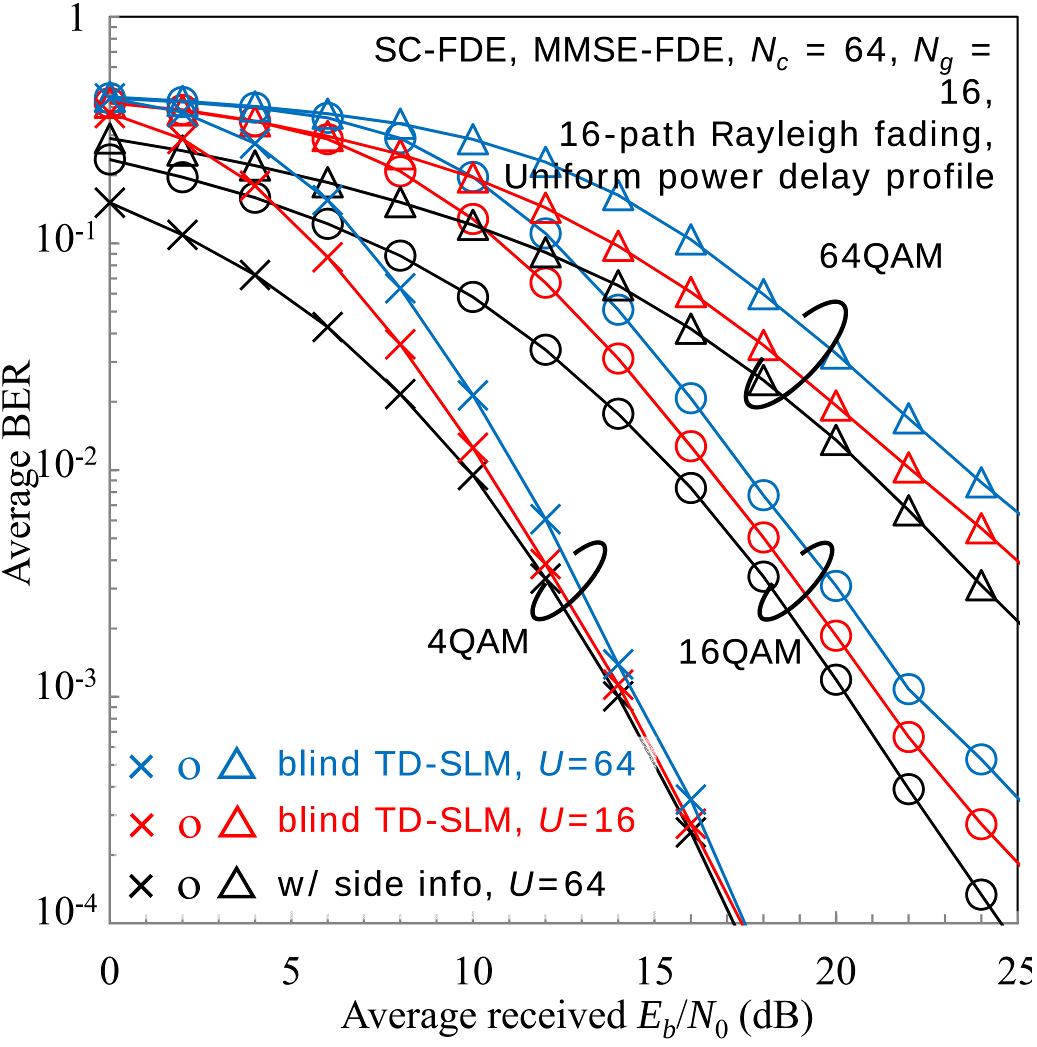
Blind SLM

- ☐ A. Boonkajay et al., "A Blind Selected Mapping Technique for Low-PAPR Single-Carrier Signal Transmission," Proc. ICICS2015, Singapore, Dec. 2015.
- ☐ A. Boonkajay et al., "Frequency-Domain Blind Selected Mapping Technique for Space-Time Block Coded Low-PAPR SC-FDE," IEICE Tech. Rep. Radio Commun. Syst. (RCS), Dec. 2015.

☐ Uncoded BER performance comparison



Blind FD-SLM
with random binary phase (0°, 180°)



Blind TD-SLM
with polyphase (0°, 120°, 240°)

Concluding Remarks

- After 35 years from the birth of 1G network in Dec. 1979 in Japan, mobile wireless communications networks have evolved into 4G networks
- 5G requires simultaneous improvement of spectrum efficiency and energy efficiency
  - 5G networks will be a small-cell network
- Distributed antenna small-cell network is a promising 5G network
  - User-centric virtual small-cell
  - Cooperative signal transmission
- Radio and optical link convergence plays an important role in 5G beyond
  - Fully coherent optical transmission