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<u>Effective Exploitation of Spatial</u> 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

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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



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

data

Vobile

- This growth rate leads to about 1,000 times of 2010 traffic volume by 2020
 Present 4G networks
- 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!



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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



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/km² in a strong CCI environment?
 - BS capacity C (bps/BS) and capacity density η (bps/km²) w/ MIMO using N_t transmit and N_r receive antennas

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

where

$$B =$$
 system bandwidth, $F =$ frequency reuse factor,

$$N_r = N_t$$
 = no. of antennas, Λ = cell edge SINR

A = BS coverage area

- Promising approaches
 - Reducing $F \rightarrow 1$: 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)

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5G Technical Issues Toward Mobile Broadband Services

One design example

$$\begin{cases} B = 400 \text{ MHz}, \ F = 1, \ N_r (= N_t) = 4, \ \Lambda = 20 \text{ dB} \\ A = 1,000 \text{ m}^2 (\text{cell radious} = 12.6 \text{ m}) \\ \text{provides} \\ \left\{ C \approx 10 \text{ Gbps/BS} \\ \eta \approx 10 \text{ Tbps/km}^2 \end{cases}$$

Macro-cell network

Small-cell network

- 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 FA/Tohoku University

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



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

Distributed antenna approach

baseband

TRx controlle

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It may be wise to exploit Near single-Macro-cell more the spatial domain area user access • 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 smallcell within a macro-cell area **User-centric** Handover problem can Pool of virtual be replaced with antenna baseband small-cell selection problem TRx's **Optical** TRx Path loss and shadowing loss controller link problems can be mitigated **ABS** Near single-user access is possible **MBS TRx Distributed** antenna small-cell network

Two types of virtual small-cell



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- 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.





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

Centralized massive MIMO

- Distributed massive MIMO
- □ Uplink access BS received signal $\mathbf{y} = \mathbf{w}_r \mathbf{H} \mathbf{d} + \mathbf{N}$ Signal detection $\hat{\mathbf{d}} = \mathbf{w}_r \mathbf{y}$ with $\mathbf{w}_r = (\mathbf{H}^H \mathbf{H})^{-1} \mathbf{H}^H$
- Downlink access Precoding $\mathbf{x} = \mathbf{w}_t^* \mathbf{d}$ with $\mathbf{w}_t = \mathbf{H} (\mathbf{H}^H \mathbf{H})^{-1}$ 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

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

 $H_{\scriptscriptstyle N-1,N-1}$

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Severely Frequencyselective 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_i(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 Frequencyselective Channel

- The transfer function H(f, t) of broadband channel at time t is not constant and varies over the signal bandwidth $H(f,t) = \sum_{l=1}^{L-1} h_l(t) \exp(-j2\pi f \tau_l)$
 - L=16 uniform power delay profile

l = 0

- *l*-th path time delay=100*l* + [-50,50)ns
- In such a severely frequency-selective channel, advanced equalization technique is necessary
 - OFDMA with frequencydomain equalization (FDE)
- Single-carrier access with FDE 2016/7/7 FA/Tohoku University



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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



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
 Space-time block coded
 Pool of baseband TRx's



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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
 No. of

Transmit signal processing	No. of transmit distributed antennas <i>N_{mbs}</i>	No. of UE receive antennas <i>N_{ue}</i>	J	Q	Coding rate		
time : :#		1	1	1	1		
	mbs ⁻ '	2	2	2	1		
		3	3	4	3/4		
	#0	4	3	4	3/4		
Transmit FDE		5	10	15	2/3		
		6	20	30	2/3		
When $J = Q = 2$ (Alamouti code) $\mathbf{X}(k) = \begin{bmatrix} D_0(k) & -D_1^*(k) \\ D_1(k) & D_0^*(k) \end{bmatrix}$ $\mathbf{W}_{txFDE}(k) = A \mathbf{H}_{\downarrow}^H(k)$ $\mathbf{H}_{\downarrow}(k) = \begin{bmatrix} H_{0,0}(k) & H_{0,1}(k) & \cdots & H_{0,N_{mbs}-1}(k) \\ H_{1,0}(k) & H_{1,1}(k) & \cdots & H_{1,N_{mbs}-1}(k) \end{bmatrix}$ 20							

STBC Diversity OFDM Downlink

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MU-MIMO w/ MMSE-SVD OFDN 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



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		<i>N_c</i> =128			
	GI length		N _g =32			
	No. of distributed antennas deployed in a macro-cell		N _{macro} =7			
	No. of UE antennas		<i>N_{ue}</i> =2			
	No. of distributed antennas to be selected		$N_{mbs} = 4$			
	Channel state information		Ideal			
Propag. Channel K facte De	Path loss exp	onent	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		<i>K</i> =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.

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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



OFDM Downlink Capacity Spatial Distribution



- 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.

1000,

800

600

400

200

1000

throughput

Jəsn 400 h

Downlink L

0

25

(Mbps/100MHz)

0

Downlink user throughput

100MHz

(Mbps/

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



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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
 Phase rotation



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



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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)



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



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



virtual

small-cell