Towards Intelligent Energy-Efficient Hyper-Dense Wireless Networks with Trillions of Devices

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TOHOKU UNIVERSITY

A Tutorial designed within the context of Project "JUNO : (1680301) Towards Energy-Efficient Hyper-Dense Wireless Networks with Trillions of Devices", a Commissioned Research of National Institute of Information and Communications Technology (NICT), JAPAN.

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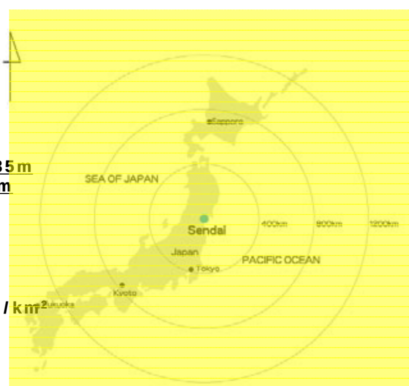
Location of Tohoku University

Location
- **In the North-East of Japan**
- **Distances from Sendai:**
  - **Tokyo 350 km**
  - **Osaka 700 km**
- **Travel time from Sendai:**
  - **Tokyo (by bullet train) 1h35m**
  - **Osaka (by air) 1h30m**

Size of The City
Area: 783.54km²
Population: 1,025,647
Population Density: 1,301 inhab./km²



Sendai City: Capital of Tohoku District

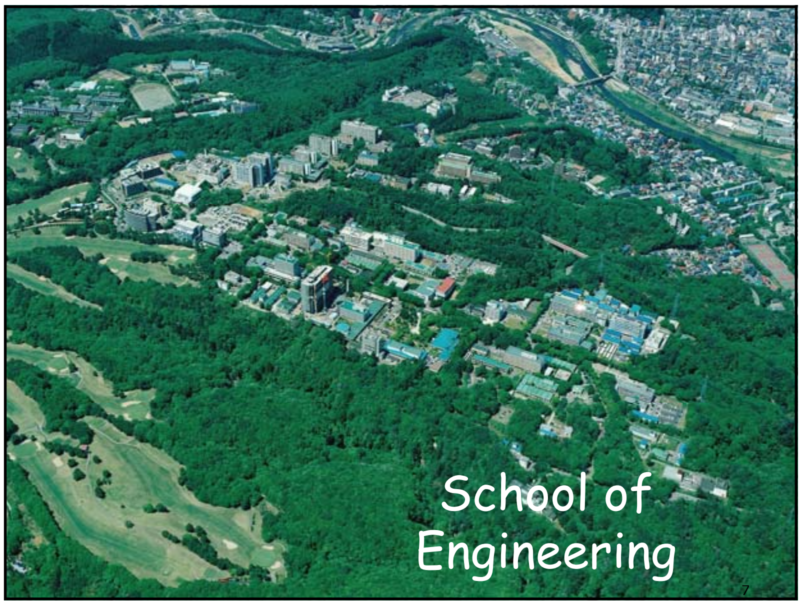
Sendai is called the city of forest

Main Campus of Tohoku University is located in the city of Sendai. Sendai is the largest city and the center of the Tohoku district. It is about 350 kilometers north of Tokyo, a two-hour bullet train ride from the metropolis. The city is called "Mori no miyako," the city of forest, since major streets in the city are lined with many trees. It is also referred to as the city of universities and colleges, since 15 colleges and universities are located in Sendai. The population is growing rapidly and has now reached about one million including the population in the Sendai suburbs.

Natural Scenery of Sendai

TOHOKU UNIVERSITY: Sendai, Japan

Founded in 1907 as the 3rd Imperial University



2011 Earthquake and recovery

Comm. Eng. Department (Old Bldg. Before Earthquake)

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Comm. Eng. Department (New Bldg.)

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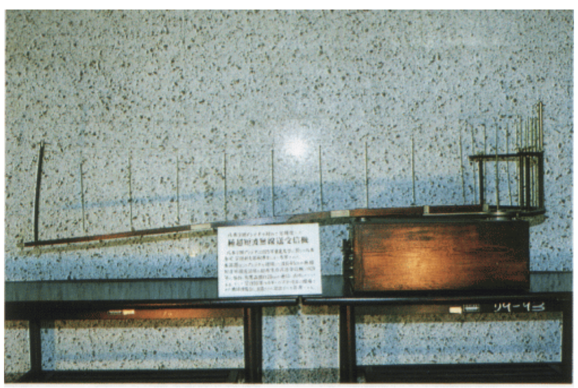
Yagi-Uda Antenna Was Invented At Tohoku University

600 MHz transceiver using Yagi-Uda antenna.



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Wireless Signal Processing & Networking (WSP&N) Lab.,

- **Supervisors**
  - Prof. F. Adachi
  - Assistant Prof. A. Mehbodniya

- **Structure**

Graduate School of Eng. — Comm. Eng.

Under graduate — Comm. Eng.

12 graduate students, 4 undergraduate students, and 2 research student

Close collaboration in research

IT21 Center @Research Institute of Elec. Comm.

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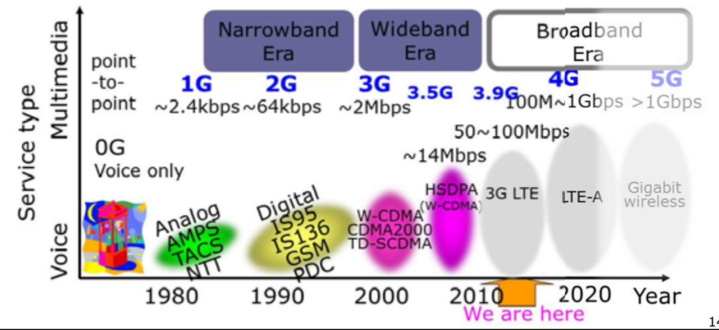
Wireless Evolution

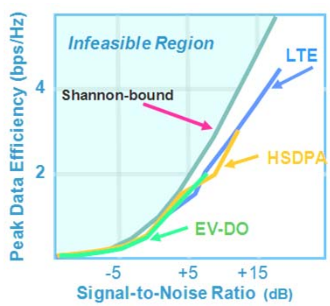
Wireless Evolution: Overview

- In early 1980's, communications systems changed from fixed "point-to-point" to wireless "anytime, anywhere" communication.
- Every 10 years, new generation appeared.
- Cellular systems have evolved from narrowband network of around 10kbps to wideband networks of around 10Mbps.
- Now on the way to broadband networks of 100Mbps (LTE).



Wireless Evolution: Direction 1:

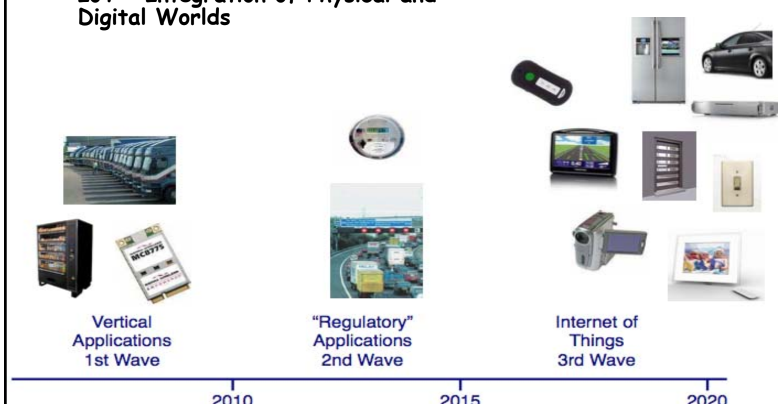
- Bandwidth efficiency
  - Mobile internet and smart phones
  - **Bandwidth and data traffic boost (Cisco)**
    - Data traffic increases 2 times/per year, 1000 times by 2020
  - Wireless network cannot support that!
  - **Information aggregate to hotspot and local area**
    - 70% in office and hotspot, over 90% in future
  - Hotspot QoS cannot be guaranteed!



Bandwidth demand over 1200MHz,
ITU assignment less than 600MHz

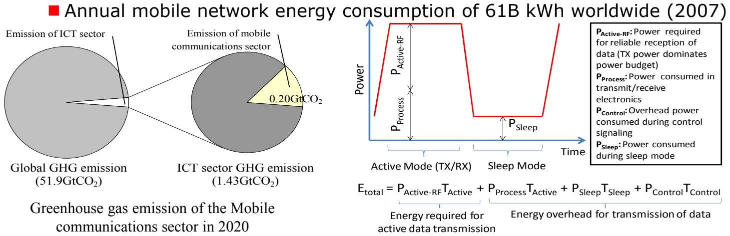
Wireless Evolution: Direction 2:

IoT – Integration of Physical and Digital Worlds



Wireless Evolution: Direction 3:

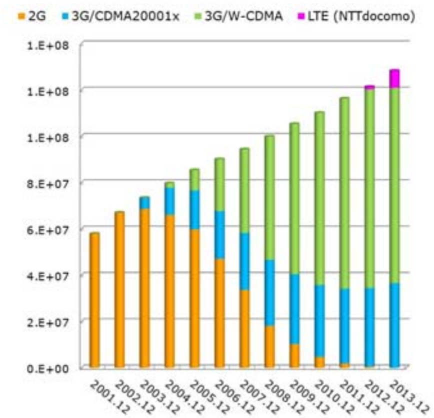
- Energy efficiency
  - Total energy consumption for a network of 20,000 3G base stations is 58MW (equivalent to **a large wind farm**) resulting in annual electricity costs of $62M.
  - A carbon footprint of 11 tons of carbon dioxide per **cell site, each year**.
  - Annual mobile network energy consumption of 61B kWh worldwide (2007)



- **The ICT industry is responsible for 2% to 2.5% of global greenhouse gas emissions. This value is expected to double in the next decade.**
- **Mobile telecommunications contribute by 9%.**

Wireless Evolution: On-going Shift To LTE (Japan)

- Total no. of cellular subscribers@end of Dec. 2013(TCA)
  - 135,832,000 (penetration: 106.5%)
- 2G has disappeared
- 3G dominates the Japanese market
- LTE is rapidly spreading



*Japanese population estimate@1 Aug. 2012:127.48M

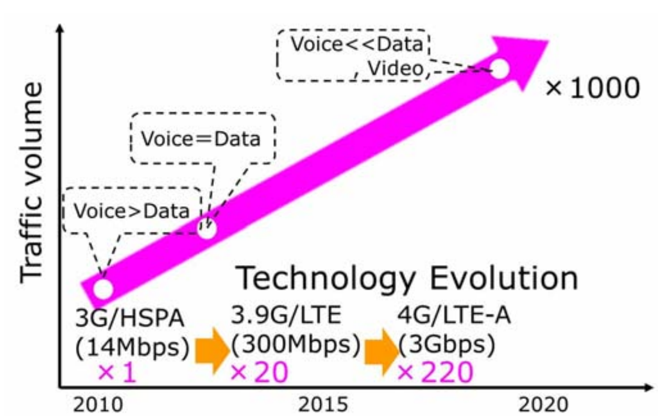
Wireless Evolution: LTE-Advanced is Not Sufficient

- LTE-advanced (4G) networks are expected to provide broadband packet data services of up to 1Gbps/BS
  - In December 2007, ITU allocated 3.4~3.6GHz band for 4G services. Only 200MHz is available for global use.
  - Although one-cell reuse of 100MHz is possible, an effective bandwidth (around 25% of total) which can be used at each BS is only around 12.5MHz/link. 1Gbps/12.5MHz is equivalent to 80bps/Hz/BS!!
- 5G networks may require >>1Gbps/BS capability.
  - Development of advanced wireless techniques that achieve a spectrum efficiency of >>80bps/Hz/BS is demanded.

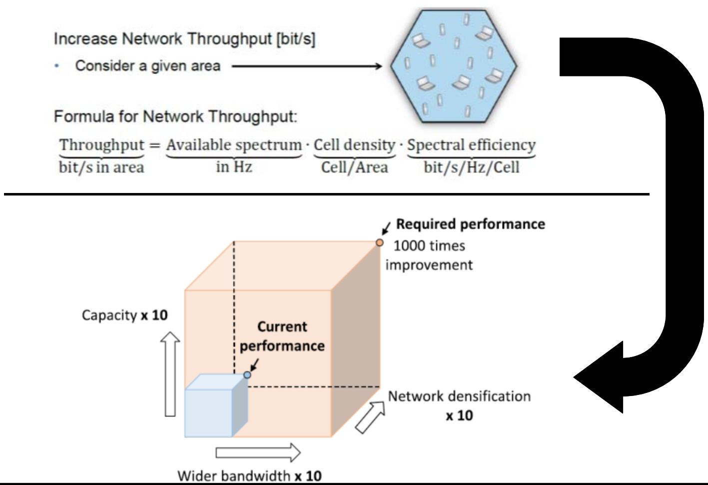
3.5G (HSPA,5MHz)		3.9G (LTE,~20MHz)		4G (LTE-A, ~100MHz)	
Up	Down	Up	Down	Up	Down
14.4 Mbps	14.4 Mbps	75 Mbps	300 Mbps	15bps/ Hz	30bps/ Hz

Wireless evolution: Explosive Growth of Traffic

Traffic growth (x1,000 in 10 years)



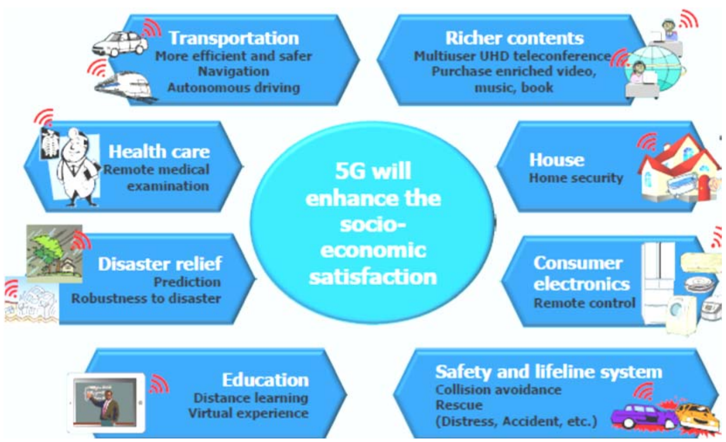
Wireless evolution: How to Achieve x1000 Capacity



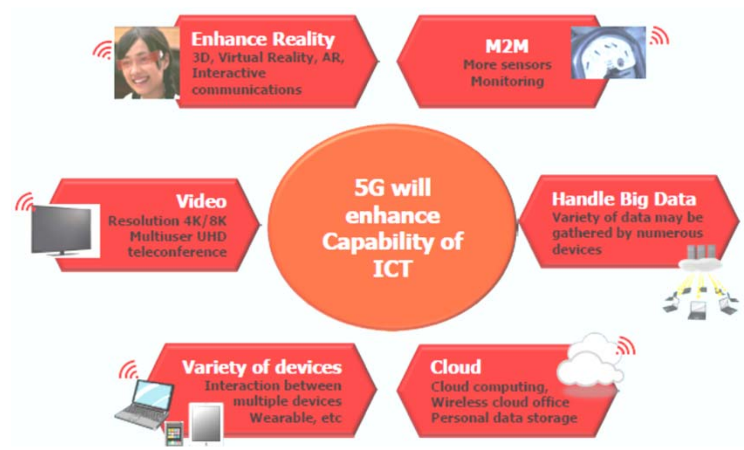
Challenges For 5G Wireless

- Spectrum Issue
- Energy Issue
- Channel Issue

Challenges for 5G: Socio-Economic Perpective



Challenges for 5G: Capability of ICT Perpective

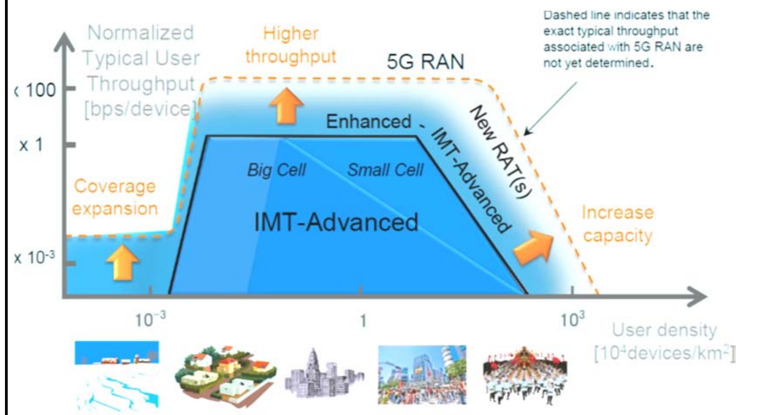


5G: A paradigm shift of cellular communications

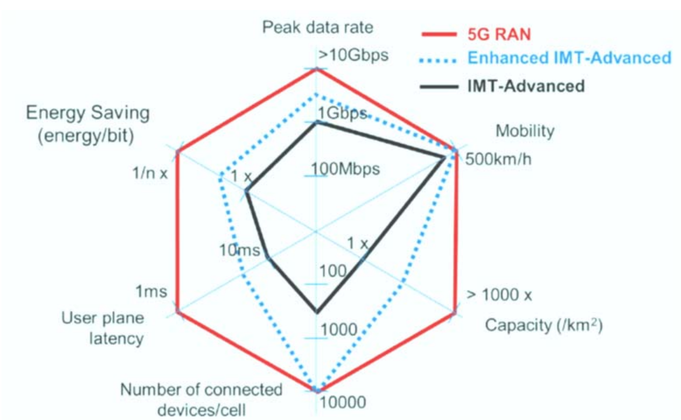
- 1G ('80s): Analog, Voice, FDMA, Macro *(Coverage-oriented)*
- 2G ('90s): Digital, Voice, TDMA, Macro *(Coverage-oriented)*
- 3G ('00s): Digital, Data, CDMA, Micro *(SE-oriented)*
- 4G ('10s): Digital, Video, OFDMA, Pico/Femto *(SE-oriented)*
- 5G ('20s): Digital, Video/M2M, BDMA?, ????? *(SE/EE-oriented)*

Cell densification is trying to further improve SE, *but is it also good for EE and smart enough to support M2M?*

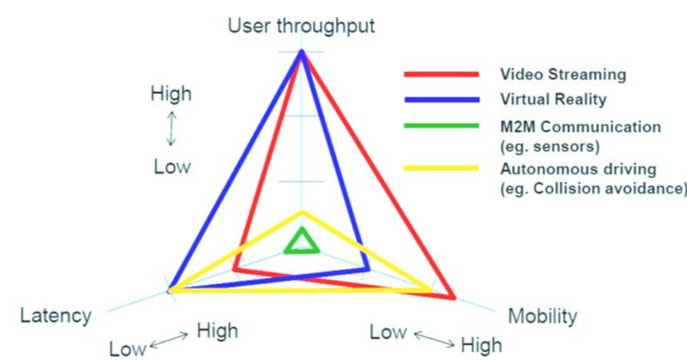
Challenges for 5G: Requirements (1)



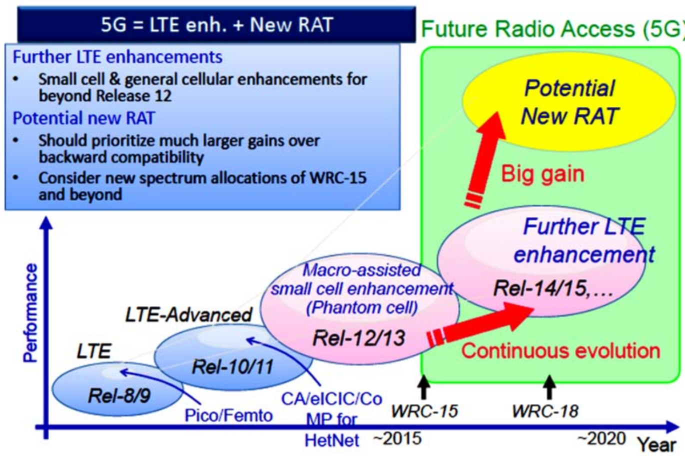
Challenges for 5G: Requirements (2)



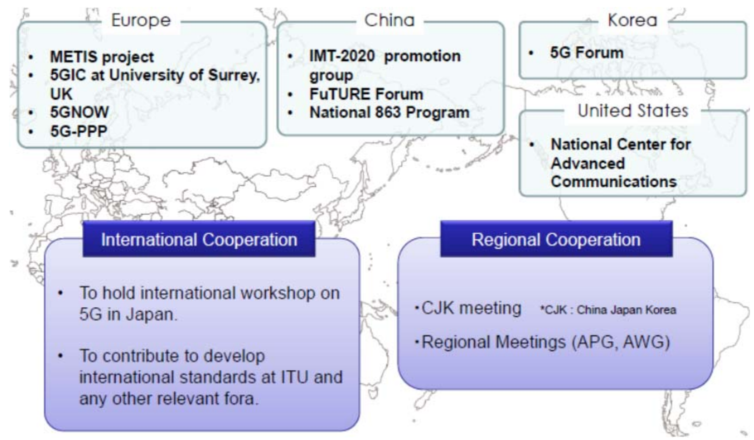
Challenges for 5G: Requirements (3)



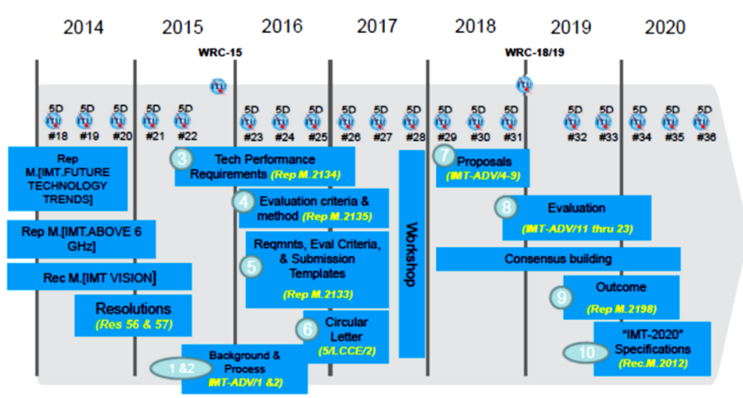
Challenges for 5G: Road Map Towards 4G



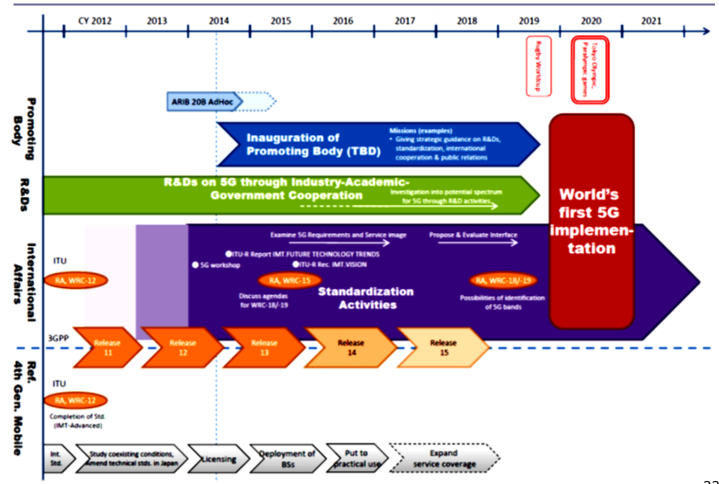
Challenges for 5G: Ongoing projects



Challenges for 5G: ITU Timeline for 5G

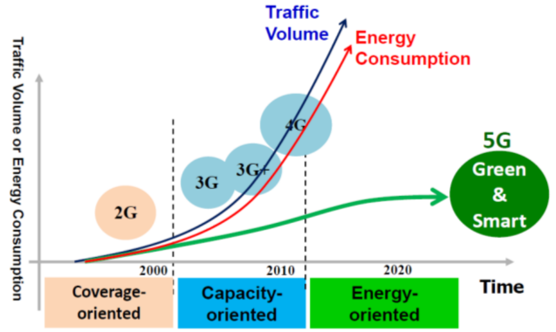


Challenges for 5G: Japan MIC Timeline for 5G



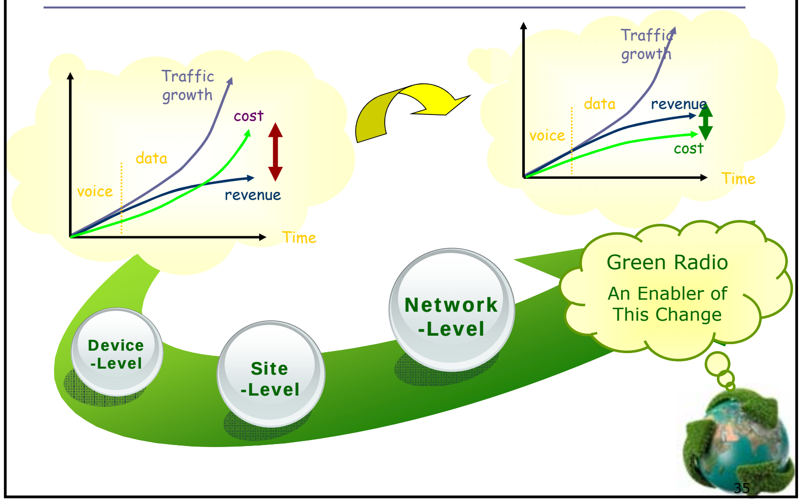
Energy-efficiency in Wireless Networks (Green Radio)

Green Radio: A Key Enabler

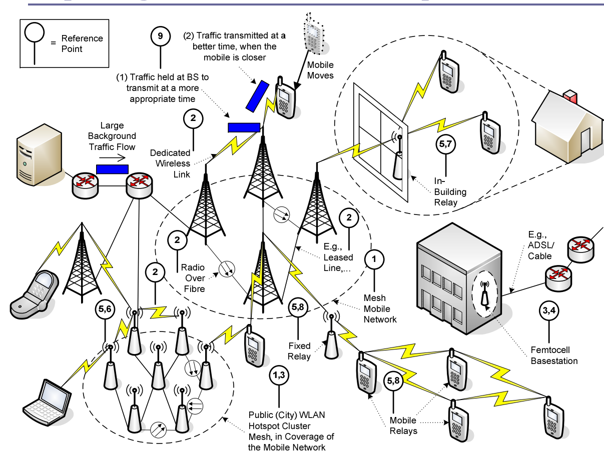


- Trends
  - Exponential growth in data traffic
  - Number of base stations / area increasing for higher capacity
  - Revenue growth constrained and dependent on new services
  - Carriers under pressure to dramatically reduce TCO and energy bill

Green Radio : Vision



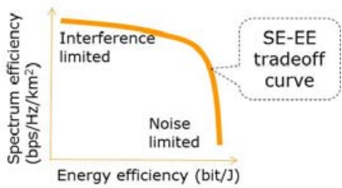
Green Radio : Network Element Deployment Perspective



Wide scope: Macro-cells, relays, backhaul, WLAN. Also consider **Embodied (Equipment Fabrication) Energy**.

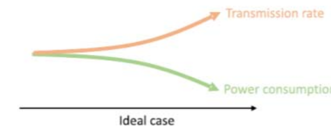
Key Enabler For 5G

- Until LTE, much effort has been paid to improve to the spectrum efficiency
- As broadband services are getting popular, energy efficiency is becoming more and more important
- Unfortunately, spectrum and energy efficiencies are in a tradeoff relationship
- Improving both spectrum and energy efficiencies at the same time is an important technical issue



- Will the cellular concept disappear?

How to Improve EE



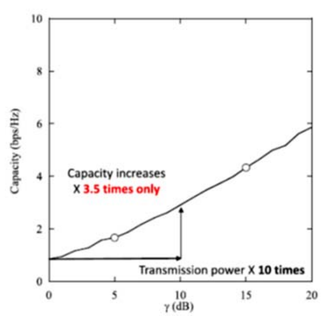
- Transmission rate increases
- Power consumption reduces

- Transmission rate increases
- Power consumption keeps same

- Transmission rate keeps same
- Power consumption reduces

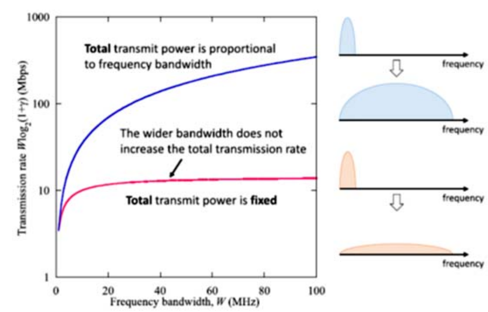
A simple Example : SISO

- $R = \log_2(1 + \text{SNR}_1)$, i.e., $W = 1$ & $Q = 1$.
- Capacity increases logarithmically in power.
- Does wider frequency bandwidth provide higher transmission rate?



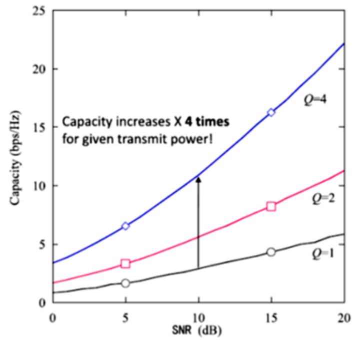
A simple Example : Effect of Bandwidth Increase

- $R = W \log_2(1 + \text{SNR}_1/W)$ (bps), i.e., $Q = 1$.
- R does not increase as W increases. But it requires the same power.



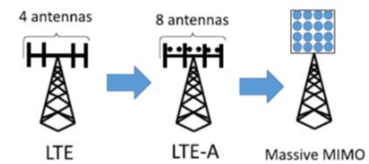
A simple Example : MIMO

- $R = \sum_{q=1}^{Q} \log_2(1+\mathsf{SNR}_q)$, i.e., $W = 1$ and $\mathsf{SNR}_q = \frac{\lambda_q \mathsf{SNR}}{N_t}$.
- As Q increases, capacity increases significantly.
- Less transmission power is required to achieve the same rate.



A simple Example : Massive MIMO

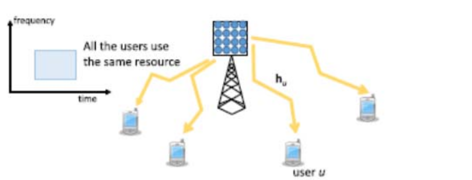
- LTE:# of Tx: 4 $\rightarrow$ LTE-A: # of Tx:8
- What's next?
- In Massive MIMO system, up to ~ 100 antenna elements are deployed at base station (BS) [Marzetta'10].
- What is the merit of such a large # of antennas?



Downlink transmission in Massive MIMO (1)

- Each user terminal is equipped with single antenna.
- BS is equipped with N_t antennas.

$$\begin{aligned} y_u &= \mathbf{h}_u^H \mathbf{W}\mathbf{s} + n_u \\ &= \underbrace{\mathbf{h}_u^H \mathbf{w}_u s_u}_{\text{desired signal}} + \underbrace{\sum_{u' \neq u} \mathbf{h}_u^H \mathbf{w}_{u'} s_{u'}}_{\text{inter-user interference}} + \underbrace{n_u}_{\text{noise}} \end{aligned}$$



Downlink transmission in Massive MIMO (2)

- The received signal-to-interference plus noise power ratio becomes as $N_t \rightarrow \infty$:

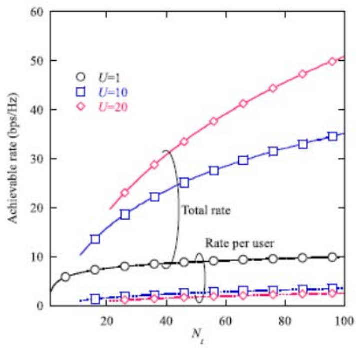
$$\begin{aligned} \mathsf{SINR}_u &= \frac{|\mathbf{h}_u^H \mathbf{w}_u s_u|^2}{\sum_{u' \neq u} |\mathbf{h}_u^H \mathbf{w}_{u'} s_{u'}|^2 + \sigma^2} \\ &\approx \frac{P_t}{\frac{1}{N_t} \sum_{u' \neq u} P_t + \sigma^2} \end{aligned}$$

- Total capacity of U user Massive MIMO scenario:

$$R_{\text{sum}} = \sum_{u=1}^{U} \log_2 \left(1 + \mathsf{SINR}_u\right)$$

Downlink transmission in Massive MIMO (3)

- Capacity (bps/Hz) increases as N_t increases even though the total transmission power is fixed!



Downlink transmission in Massive MIMO (4)

- Why is Massive MIMO important?
- The capacity of Massive MIMO system can be approximated as [Yang'13, Ngo'13]

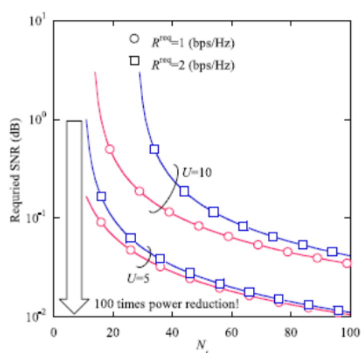
$$R \approx \log_2 \left(1 + \frac{(N_t - 1)P_{\mathrm{tx}}}{(U-1)P_{\mathrm{tx}} + 1}\right)$$

- The required transmission power required for target rate R^{req} (bps/Hz) becomes

$$P_{\mathrm{tx}} = \frac{2^{R^{\mathrm{req}}} - 1}{(N_t - 1) - (2^{R^{\mathrm{req}}} - 1)(U-1))}$$

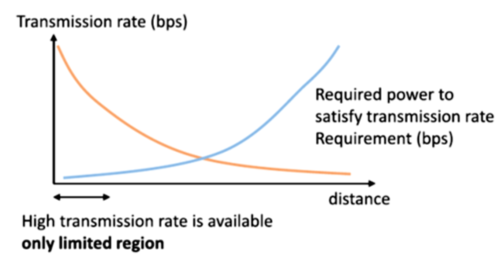
Downlink transmission in Massive MIMO (5)

- Required transmission power significantly reduced by increasing N_t.



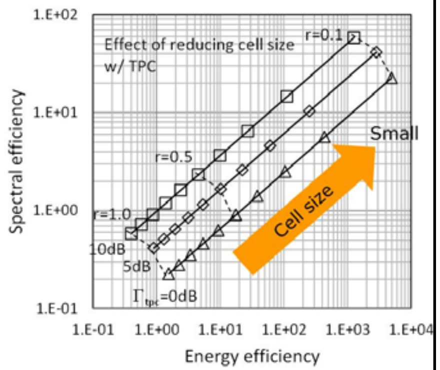
Path Loss Effect

- State-of-the-art technologies, e.g., OFDM/SC-FDE and MIMO, significantly increase the transmission rate.
- However, it is only true for limited region. Why?
- The signal attenuates as it propagates over the wireless channel.



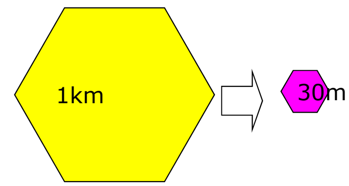
SE-EE Tradeoff w/ TPC

- With TPC, reducing the cell size is quite effective to improve both SE and EE
  - Reducing the cell size by a factor of 10 leads to about x 100 improvement of SE
  - EE improvement is more than SE improvement (x1,000)



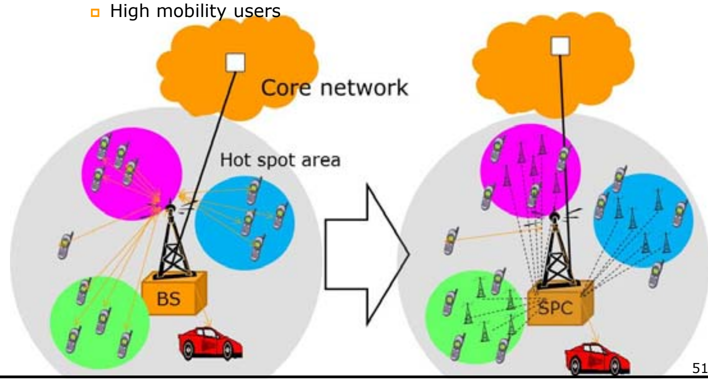
Small-cell Network

- Simultaneous improvement of SE and EE is possible
- Reducing the cell radius by a factor of 30 (1,000m → 30m) leads to
  - X1,000 capacity increase
  - reduced transmit power by a factor of 150,000



Heterogeneous Network

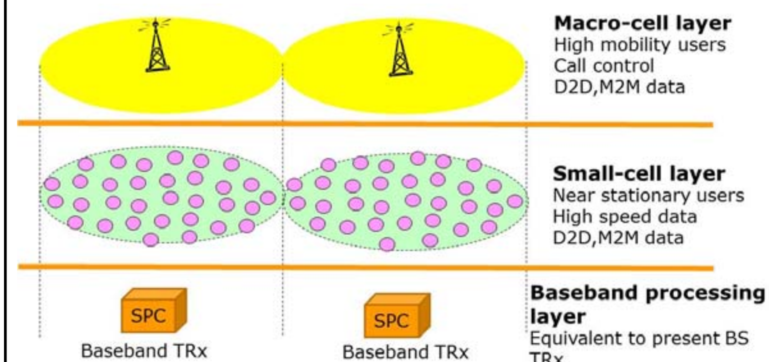
- Heterogeneous network is a realistic approach
  - Small-cell network (e.g., DAN) to cover hot-spot area
  - Large-cell network (3G, LTE) to cover wide area
    - Access control
    - High mobility users



Heterogeneous Network

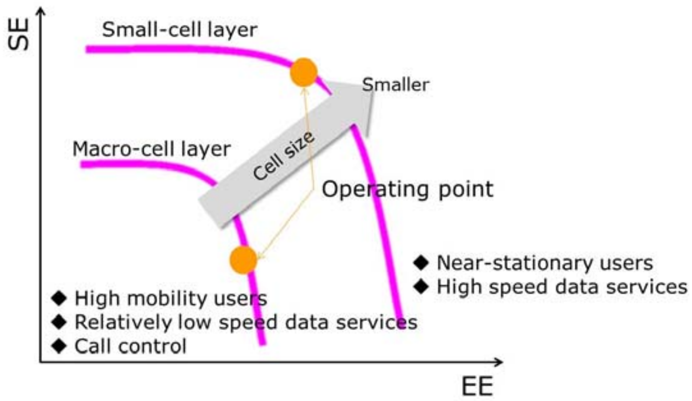
- 2-layer Heterogeneous DAN

Transmit power can be adaptively controlled according to traffic



Heterogeneous scenario

- Cell size and SE-EE trade-off



Hidetoshi Kaji Shinya Kumagai Katsuhiro Temma and Fumiyuki Adachi, ***in Proc APWCS 2014@Taiwan***

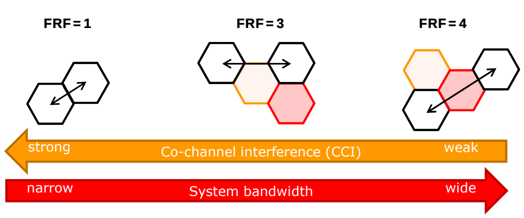
Spectrum-Energy Efficiency Tradeoff of Distributed Antenna Network

Background (1/3)

- Broadband data services have been demanded in wireless networks
  → **Higher data rate requires more bandwidth and transmit power**

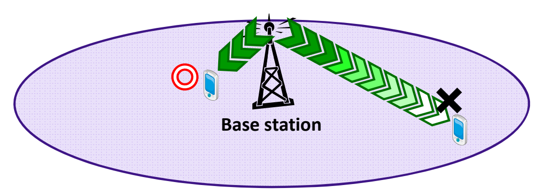
Efficient use of spectrum and energy resources in broadband wireless communications has been a hot topic

- **Spectrum efficiency (SE)** and **energy efficiency (EE)** of wireless network have a tradeoff relationship
  - **Cellular networks**: The same frequency is reused among a number of cells
    - **Frequency reuse factor (FRF)** affects the SE-EE tradeoff relationship



Background (2/3)

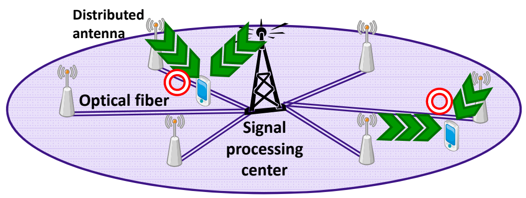
- **Broadband wireless channel**
  - Path loss
  - Shadowing loss
  - Frequency-selective fading
- **Conventional cellular network (centralized antenna network (CAN))**
  - Antennas are co-located at the base station
    - Antenna diversity: Only the impact of fading can be mitigated



Background (3/3)

- **Distributed antenna network (DAN)**
  - Antennas are spatially distributed over the entire coverage area
    - Impacts of path loss and shadowing loss can be mitigated as well as fading
  - allows single frequency reuse and improves the SE compared with CAN
  - achieves higher received signal power than CAN even with significantly reduced transmit power

DAN can achieve higher EE compared with CAN while improving SE for the same FRF



Objective

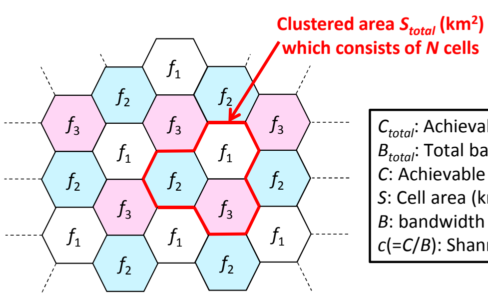
- To derive the SE-EE tradeoff of DAN taking FRF into account
- To discuss the impact of FRF on SE-EE tradeoff

Contents

Definition of SE and EE (1/3)

- **SE: Channel capacity /Hz/km²** (bps/Hz/km²)

$$\eta_s \equiv \frac{C_{total}}{S_{total}\cdot B_{total}} = \frac{N\cdot C}{(N\cdot S)\cdot(N\cdot B)} = \frac{c}{N\cdot S}$$



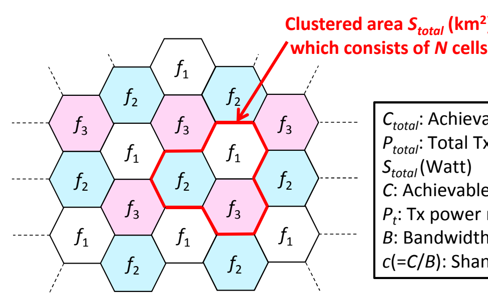
e.g. FRF, N=3

C_{total}: Achievable total capacity (bps)
B_{total}: Total bandwidth (Hz)
C: Achievable channel capacity per cell (bps)
S: Cell area (km²)
B: bandwidth of each cell (Hz)
c(=C/B): Shannon capacity (bps/Hz)

Definition of SE and EE (2/3)

- **EE: No. of bits transmitted per Joule** (bits/J)

$$\eta_e \equiv \frac{C_{total}}{P_{total}} = \frac{N\cdot C}{N\cdot P_t} = \frac{c}{P_t / B}$$



e.g. FRF, N=3

C_{total}: Achievable total capacity (bps)
P_{total}: Total Tx power radiated in the area S_{total} (Watt)
C: Achievable channel capacity per cell (bps)
P_t: Tx power radiated in each cell (Watt)
B: Bandwidth of each cell (Hz)
c(=C/B): Shannon capacity (bps/Hz)

Definition of SE and EE (3/3)

- **Relationship between SE and EE**
  - Shannon capacity (bps/Hz) assuming OFDM and SC-FDE

$$c=\frac{1}{N_c}\sum_{k=0}^{N_c-1}\log_2\left\{1+\frac{P_r(k)}{G(k)}\right\}$$

N_c: No. of subcarriers
$P_r(k)$: Instantaneous received signal power
$G(k)$: CCI plus background noise power
N: FRF
P_t: Tx power radiated in each cell (Watt)
B: Bandwidth of each cell (Hz)

  - **SE** (bps/Hz/km²)

$$\eta_s=\frac{1}{N\cdot S}\frac{1}{N_c}\sum_{k=0}^{N_c-1}\log_2\left\{1+\frac{P_r(k)}{G(k)}\right\}$$

◀ **SE increases with P_t (is saturated eventually)**

  - **EE** (bits/J)

SE and EE have a tradeoff relationship

$$\eta_e=\frac{\frac{1}{N}\frac{1}{N_c}\sum_{k=0}^{N_c-1}\log_2\left\{1+\frac{P_r(k)}{G(k)}\right\}}{P_t/B}$$

◀ **EE decreases with P_t**

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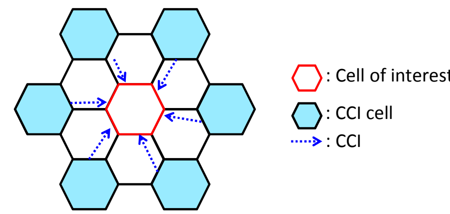
DAN downlink system model (1/2)

- **Cellular network model**
  - Downlink broadband SISO transmission
  - Cell of interest: center cell
  - CCI cells: 6 cells in the first tier
  - Tx power is the same among cells



e.g. FRF, N=3

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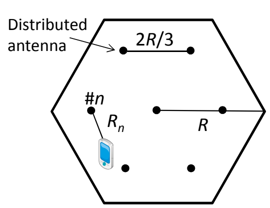
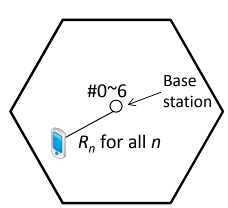
DAN downlink system model (2/2)

- **Cell model**
  - A single mobile terminal equipped with a single receive antenna is randomly located in each cell
  - A single antenna having the highest instantaneous received power is selected for transmission

DAN
7 antennas are distributed in each cell



CAN
7 antennas are co-located at base station



R: Cell radius

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Numerical results

- **Numerical evaluation condition**

Path loss exponent	α=3.0
Shadowing	Log-normal w/ standard deviation σ=7.0(dB)
Fading type	Frequency-selective block Rayleigh
No. of paths	L=16 w/ uniform power delay profile
Power delay profile	Sample-spaced uniform
DFT size (=No. of subcarriers)	N_c=128

- **Evaluation indicator**: x%-outage SE and EE
  - x% values of cumulative distribution function (CDF) of normalized SE and EE

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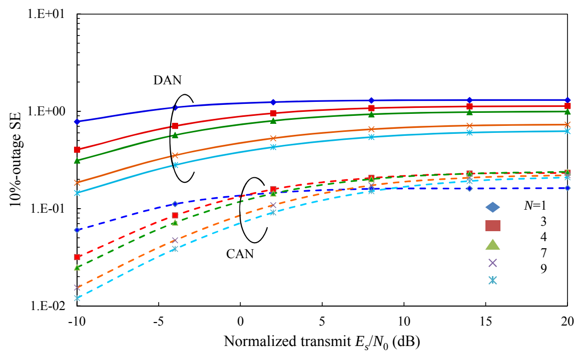
Numerical results (2/5)

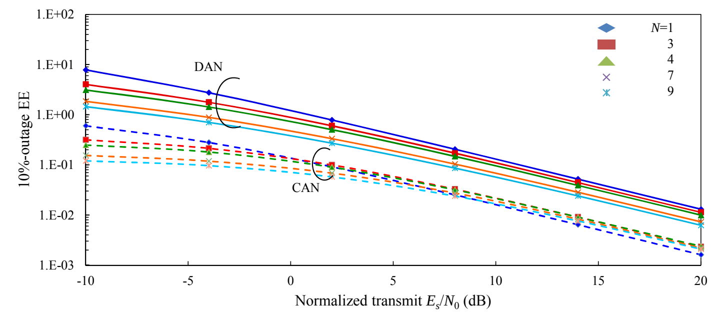
- **Outage SE**



- ***N*=1 always maximizes 10%-outage SE in DAN**
  - Short distance communication can improve the received SINR w/o increasing *N*

Numerical results

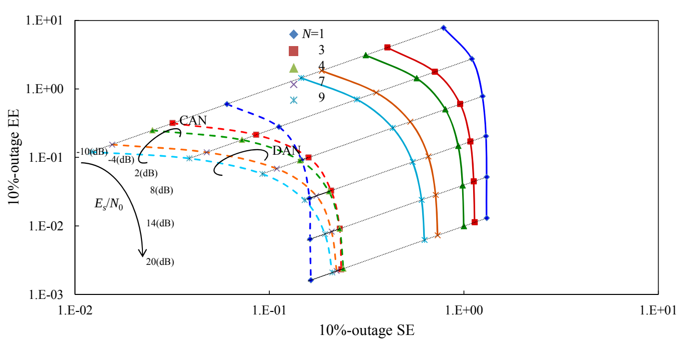
- **Outage EE**



- ***N*=1 always maximizes 10%-outage EE in DAN**
  - DAN can reduce Tx power → reduce CCI power w/o increasing *N*

Numerical results (4/5)

- **SE-EE tradeoff**

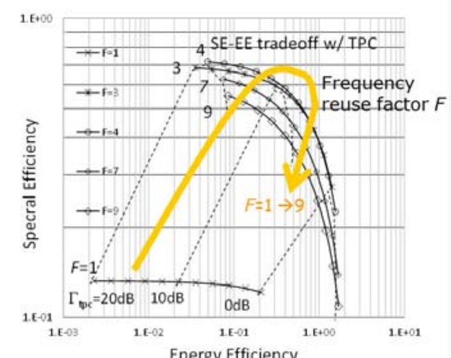


- **10%-outage**
  - DAN has better SE-EE tradeoff than CAN and allows *N*=1

Numerical results (5/5)

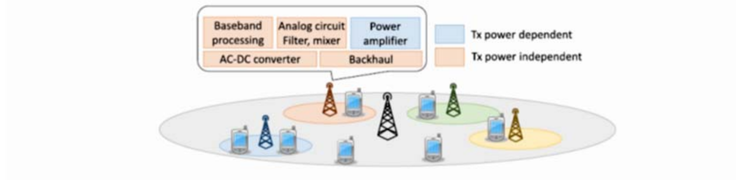
- SE-EE Tradeoff with TPC. TPC seems to improve the performance significantly.
- Frequency reuse factor *F*=4 seems to be the best

- Increasing TPC target improves the SE, however degrades the EE
- EE does not degrade so rapidly as far as too high SE is not demanded



A Broader Outlook (1)

- Massive MIMO technology and network densification can reduce the transmission power or equivalently increase transmission rate greatly.
- Do they have advantage only?
- So far we considered transmission power only.
- Fixed power consumption, circuit power consumption, base band processing power consumption should also considered.



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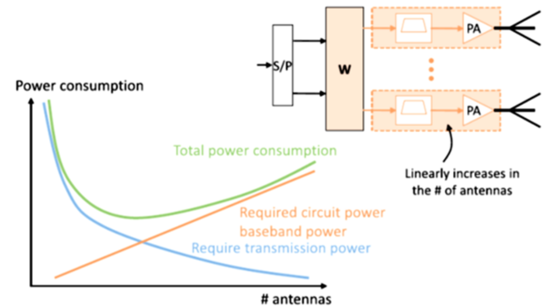
A Broader Outlook (2)

- Massive MIMO can reduce the transmission power greatly.
- However, power consumption overhead increases as N_t increases.



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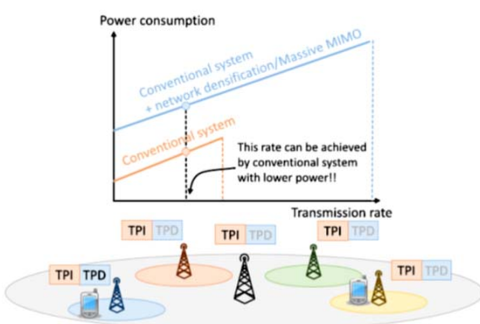
A Broader Outlook (3)

- Network densification targets the higher transmission rate.
- If all small cell BSs are necessary, it can gain.
- If a few small cell BSs provide the service, there is a loss.



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Utility Function for EE RRM (1)

1. Difference of data rate and cost term

$$u(\mathbf{p}) = r(\mathbf{p}) - c(\mathbf{p}) = r(\mathbf{p}) - \sum_{k=1}^{n} p_k \mu_k$$

2. Ratio of data rate and energy consumed

$$u(\mathbf{p}) = \frac{r(\mathbf{p})}{p_c + \sum_{k=1}^{n} p_k}$$

System output over the consumed goods

3. Throughput (goodput) divided by energy

$$u(\mathbf{p}) = \frac{Rf(\mathbf{p})}{p_c + \sum_{k=1}^{n} p_k}$$

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Utility Function for EE RRM (2)

Capacity
EE = ------------------------------
Power Consumption

Network Throughput
NEE = ----------------------------------
Total Energy Consumption

- **Exploiting traffic dynamics** *(reduce energy consumption when traffic is low)*
  - Targeting **THROUGHPUT** rather than **CAPACITY** per joule
- **Exploit energy model** *(much energy is consumed at BB/PA/AC rather than RF, therefore BS **sleeping** is the most efficient way for energy saving)*
  - Targeting **TOTAL ENERGY** rather than **RF** power reduction only
- **Exploit cell collaboration** *(cell densification and HetNet make cell collaboration possible, helping to turn more BSs off)*
  - Targeting **NETWORK** rather than **LINK/CELL** performance

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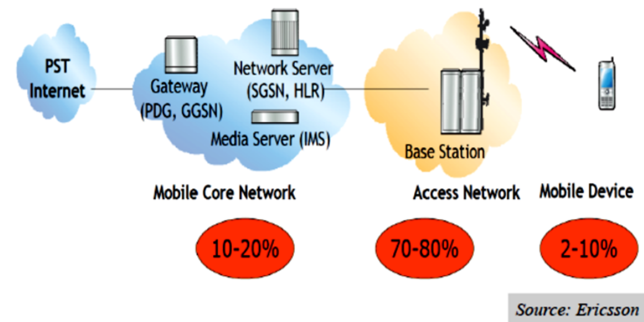
Energy Consumption for Network Elements

- **70~80% energy consumed by BSs in a cellular network**
  - Reducing the power consumption of BSs is the key!



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BS Energy Consumption (1)

Why so many BSs under-utilized, while still need to be densely deployed in some area?

- Mobile traffic is highly dynamic!

Why lightly-loaded BSs can't be switched off (*sleep*)?

- BSs need to provide data services as well as network coverage simultaneously

Existing cellular is neither smart nor green

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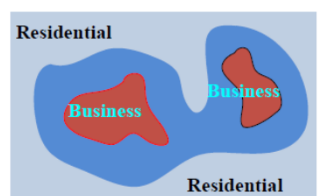
BS Energy Consumption (2)

- All BSs are ON *(active)* all the time *(in order to keep coverage)*, although traffic is almost zero in many areas
- Each BS almost transmits in *peak* power, although peak traffic only lasts for a very short time in most cells
- Multi-BSs (*small cells, HetNet*) are *densely* deployed in many areas without any collaboration *(work almost independently)*
- As cell size is getting *smaller* AND traffic dynamics more *bursty*, energy waste is getting more serious



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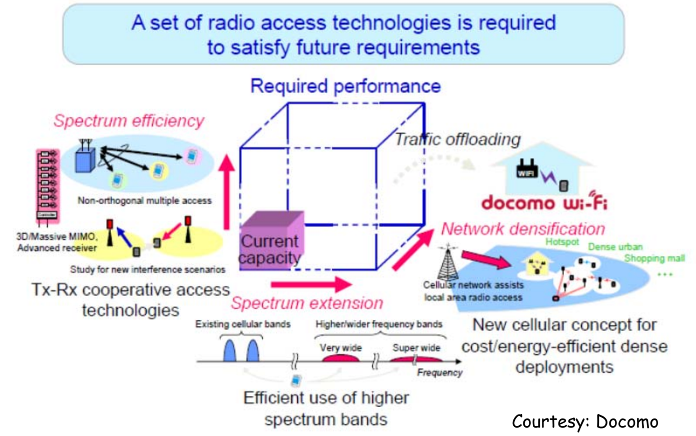
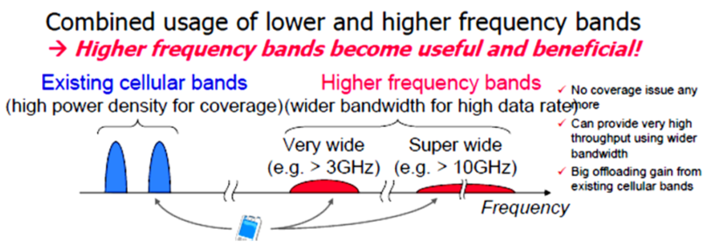
Potential Ideas for Capacity improvement in 5G

Docomo Point of view for 1000x capacity improvement

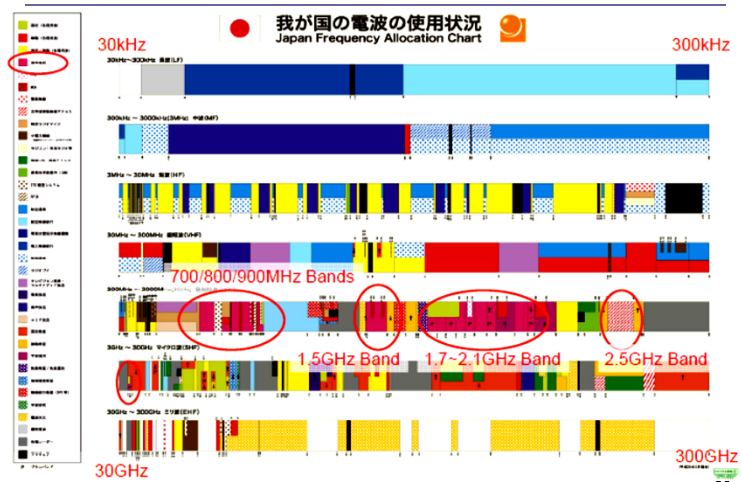


Capacity Improvement in 5G: Spectrum Extension (1)

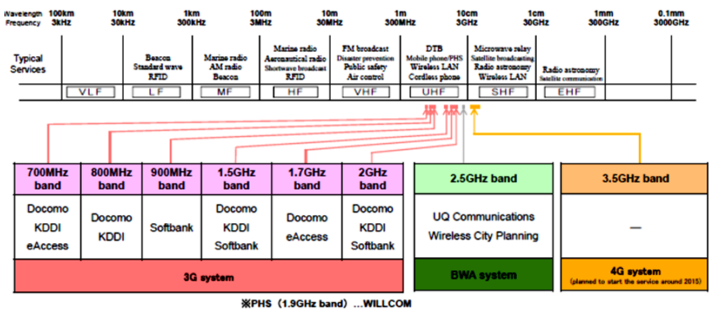


Courtesy: Docomo

Capacity Improvement in 5G: Spectrum Extension (2)



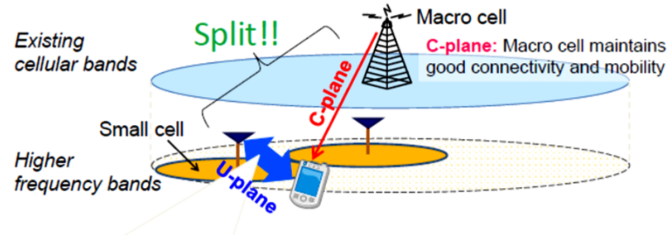
Capacity Improvement in 5G: Spectrum Extension (3)



- The Information and Communications Council reported technical conditions for LTE-Advanced, a new cellular networking standard for previously assigned IMT bands and 3.4-3.6 GHz band (Jul. 2013). MIC developed amended technical regulations in accordance with the report.
- Regarding the introduction of LTE-Advanced in 3.4-3.6GHz band, it is planned to assign the band to operators this year.

Capacity Improvement in 5G: Spectrum Extension (4)

- NW architecture to utilize higher frequency bands
  "Phantom cell" – Split of C-plane & U-plane between macro and small cells in different frequency bands [1, 2]

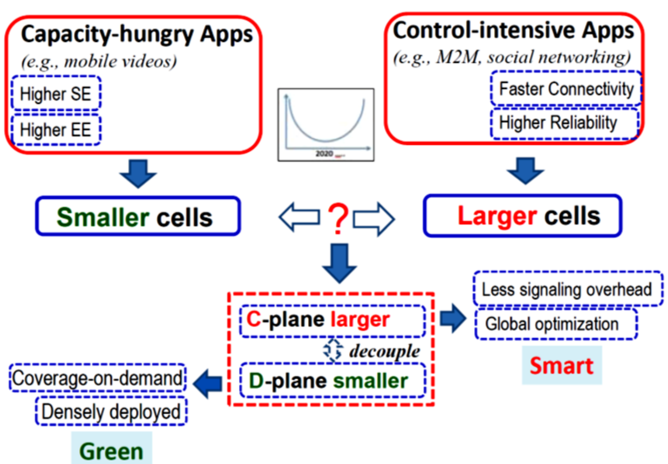


Higher data rate and more flexible & cost-energy efficient operations ← e.g., Small Cell Coordination
New RAT could be considered to exploit higher frequency bands ← e.g., NOMA, Massive MIMO

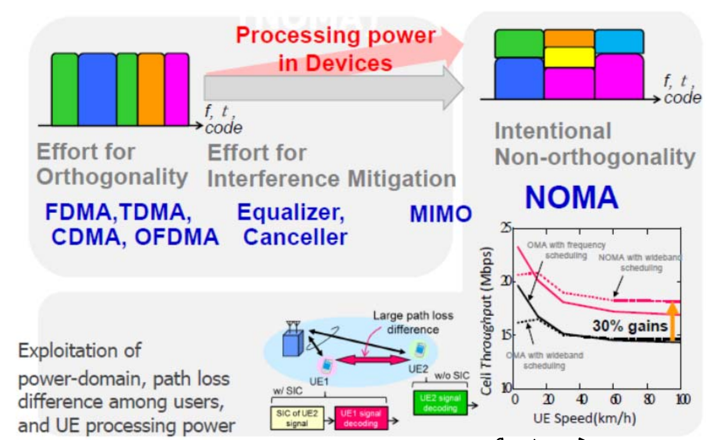
[1] NTT DOCOMO, 3GPP RWS-120010, June 2012.
[2] H. Ishii et al., IEEE Globecom 2012 Workshop, Dec. 2012.

Courtesy: Docomo

Capacity Improvement in 5G: Spectrum Extension (5)



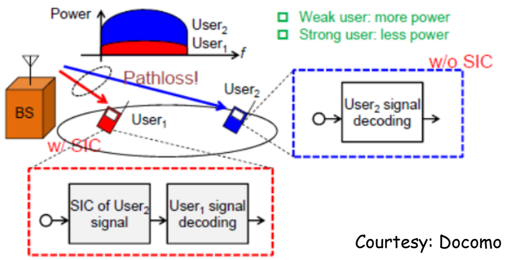
Potential Candidates for 5G: NOMA concept by Docomo(1)



Courtesy: Docomo

Potential Candidates for 5G: NOMA concept by Docomo (2)

- **Principle of non-orthogonal multiple access**
  - **Utilize power domain for user multiplexing**
    - **Strong user and weak user are multiplexed on the same radio resource but assigned with different transmission power**
  - **Utilize SIC receiver for user separation**
    - **Strong user first detects signals of weak user, and then conducts SIC to remove the interference of weak user from the received signal. After that, strong user detects its desired signal with improved SINR**



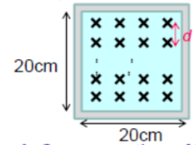
Courtesy: Docomo

Principle of NOMA: Exploit power domain and advanced receiver.

Massive MIMO prototype developed by Docomo

- **Massive MIMO** – Beamforming using massive antenna elements in higher frequency bands
  - *Essential technology to extend effective cell range*

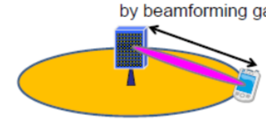
Example 2D antenna configuration



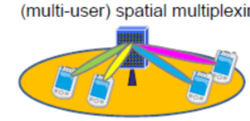
	LTE 3D-MIMO	Massive MIMO	
Antenna element spacing (d)	3.5 GHz (λ = 8.6 cm)	10 GHz (λ = 3 cm)	20 GHz (λ = 1.5 cm)
0.5 λ	16	169	676
0.7 λ	9	81	361

→ Compensation of increased path loss & Improved spectrum efficiency

Cell range extension by beamforming gain



Improved spectrum efficiency with (multi-user) spatial multiplexing

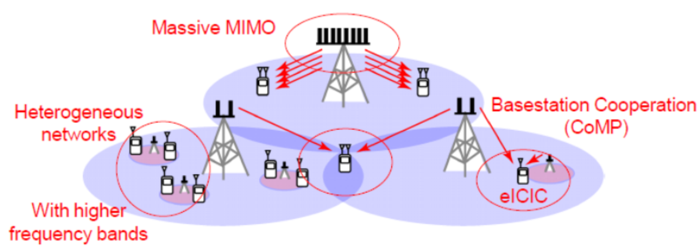


Courtesy: Docomo

MiWEBA 5G project at Osaka University (1)

- MIMO enhancement to improve average spectral efficiency
- CoMP to improve outage rate
- Heterogeneous network for traffic offloading
- Higher frequency band (3GHz, 60GHz) to enhance bandwidth

Focus of MiWEBA project (the last two items)



MiWEBA 5G project at Osaka University (2)

- **How to *decouple* signaling from data coverage? How to *integrate* the signaling functions of HetNets?**
  - *Complete* decoupling may lead to new bottleneck and delays due to frequent visits to signaling-BSs (main difference from BCG2), but which functions should be left into the data-BSs?
- **How to guarantee signaling coverage *highly reliable*?**
  - Need new protocol for S-BSs. Also, tradeoff between reliability and delay
- **How to detect user behaviors, QoS requests, terminal capability, and provide *services in an EE manner*?**
  - Data mining, cognitive radio, on-line learning, …
- **How to locate users and associate them to the *best* D-BS?**
  - The best cells may be in sleeping state, activate or not?
- **How to *balance* the EC of network parts and user terminals?**
  - User terminals need to keep associations with S-BS in a wider scope
- **……**

MiWEBA 5G project at Osaka University (3)

- Inter Macro & small cell interference management is necessary
- Spectrum splitting loss occurs in single-band HetNet (e.g. ABS)
- Multi-band HetNet achieves BW enhancement without interference

Single-Band

2GHz band
Macro:
Center freq: 2GHz
BW: $\rho \times$ 10MHz
Tx power: 46dBm
Small cell:
Center freq: 2GHz
BW: $(1-\rho) \times$ 10MHz
Tx power: 24dBm

Multi-band

3GHz band
Macro:
Center freq: 2GHz
BW: 10MHz
Tx power: 46dBm
Small cell:
Center freq: 3.5GHz
BW: 100MHz
Tx power: 30dBm

60GHz band
Macro:
Center freq: 2GHz
BW: 10MHz
Tx power: 46dBm
Small cell:
Center freq: 60GHz
BW: 2.16GHz
Tx power: 10dBm

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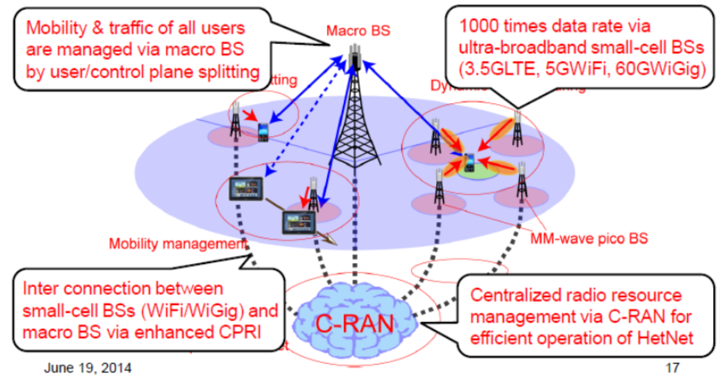
MiWEBA 5G project at Osaka University (4)

- HetNet consists of small-cell BSs for data plane & macro BS for control plane
- Efficient operation of HetNet by C-RAN (seamless handover, dynamic cell, ...)



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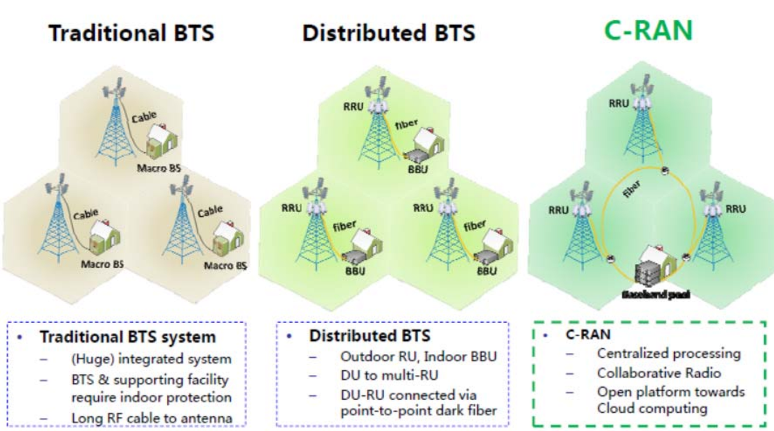
Cloud Cooperated HetNet



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C-RAN

It was first introduced by China Mobile Research Institute in April 2010 in Beijing, China. Simply speaking, C-RAN is a centralized, cloud computing based new radio access network (commonly known as cellular network) architecture that can support 2G, 3G, 4G system and future wireless communication standards. Its name comes from the four 'C's in the main characters of C-RAN system, which are "Clean, Centralized processing, Collaborative radio, and real-time Cloud Radio Access Network".

Similar Architecture and Systems:

1) Korean Telecom's has introduced Cloud Computing Center (CCC) system in their 3G (WCDMA/HSPA) and 4G (LTE/LTE-A) network in 2011 and 2012. The concept of CCC is basically same to C-RAN.
2) SK Telecom's has also deployed Smart Cloud Access Network (SCAN) and Advanced-SCAN in their 4G (LTE/LTE-A) network in Korean no late than 2012.

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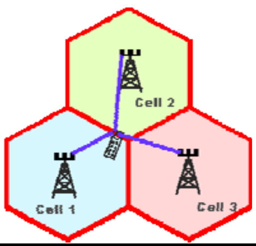
COMP

4G LTE CoMP, Coordinated Multipoint requires close coordination between a number of geographically separated eNBs. They dynamically coordinate to provide joint scheduling and transmissions as well as proving joint processing of the received signals. In this way a UE at the edge of a cell is able to be served by two or more eNBs to improve signals reception / transmission and increase throughput particularly under cell edge conditions.



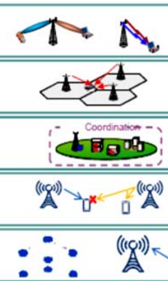
One of the key requirements for LTE is that it should be able to provide a very low level of latency. The additional processing required for multiple site reception and transmission could add significantly to any delays. This could result from the need for the additional processing as well as the communication between the different sites.
To overcome this, it is anticipated that the different sites may be connected together in a form of centralised RAN, or C-RAN.

A Summary of future Technologies for 5G

- **Massive MIMO and dense small cell networks** *(for throughput improvement)*
- **Highly flexible/reliable and realtime MAC protocol** *(for efficient support of IoT applications)*
- **Advanced interference and mobility management**
- **Cognitive or smart radio technologies** *(for spectrum efficiency)*
- **Single frequency full duplex radio technologies**
- **mmWave** *(for wireless backhaul and/or access)*
- **Pervasive networks** *(for multihoming or multiple concurrent data transmission)*
- **Multi-hop networks and D2D communications** *(for coverage extension)*
- **IPv6** *(for seamless handover and roaming)*
- **Virtualized and cloud-based radio access infrastructure** *(for network flexibility: different slices of the network with different technologies for different applications)*
- ***World wide wireless web* (WWWW)** *(for comprehensive wireless-based web applications that include full multimedia capability beyond 4G speeds)*
- **Wearable devices with AI capabilities** *(for augmented reality)*

5G: PHY *vs* NET Solution

- Multi-antenna transmission/reception
- Multi-site transmission/reception
- Multi-layer coordination
- Interference suppression
- Full duplex, network coding, …



Physical-layer evolution will remain important

But the main aim for the PHY evolution will be to enable more advanced system-level features

Martin T.H. Sirait, Yuki Matsumura, Katsuhiro Temma, Koichi Ishihara, B. A Hirantha Sithira, Abeysekera Tomoki Kumagai and Fumiyuki Adachi, IEEE 25th PIMRC in Washington D.C.

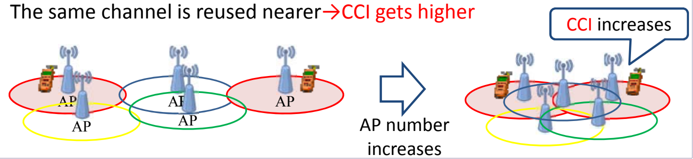
Distributed RRM *vs* C-RAN

AP Cooperative Diversity for Wireless Network Using Interference-Aware Channel Segregation Based Dynamic Channel Assignment

Background (1/4)

CCI Problem in Wireless Network

- Total number of channels is limited
  - Channel reuse → Co-channel interference (CCI)
- Recently, density of wireless network has been higher due to rapidly increasing number of access points (APs)
  - The same channel is reused nearer → CCI gets higher



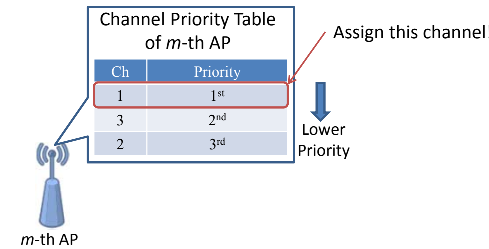
CCI Mitigation Method

- Channel Assignment
  - Dynamic Channel Assignment (DCA) → able to dynamically minimize CCI
    - Interference-Aware Channel Segregation Based Dynamic Channel Assignment (IACS-DCA)[1][2]

Background (2/4)

IACS-DCA[1][2]

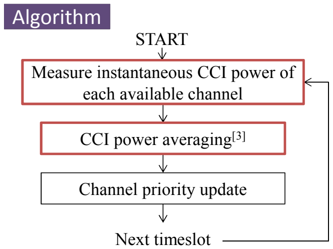
- Every AP has its own channel priority table
- AP updates its own channel priority table periodically
- AP assigns channel with the highest priority



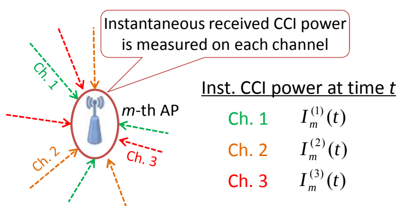
Background (3/4)

IACS-DCA[1][2]

Algorithm



- We utilize beacon signal(s) transmitted by each AP on the selected channel(s) for the instantaneous CCI power measurement



- The first order filtering is used for CCI power averaging[3]
  (At c-th channel of m-th AP)

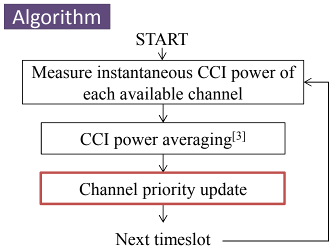
$$\bar{I}_m^{(c)}(t) = (1-\beta)\cdot I_m^{(c)}(t) + \beta\cdot \bar{I}_m^{(c)}(t-1)$$

filter forgetting factor $(0 \le \beta < 1)$; $\bar{I}_m^{(c)}(t)$: average CCI power; $I_m^{(c)}(t)$: instantaneous CCI power

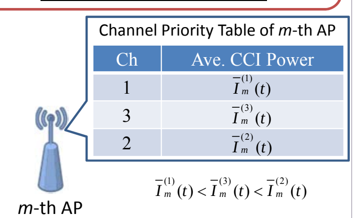
Background (3/4)

IACS-DCA[1][2]

Algorithm



A channel reuse pattern with a low CCI condition can be formed in a distributed manner[1][2]



- The first order filtering is used for CCI power averaging[3]
  (At c-th channel of m-th AP)

$$\bar{I}_m^{(c)}(t) = (1-\beta)\cdot I_m^{(c)}(t) + \beta\cdot \bar{I}_m^{(c)}(t-1)$$

filter forgetting factor $(0 \le \beta < 1)$; $\bar{I}_m^{(c)}(t)$: average CCI power; $I_m^{(c)}(t)$: instantaneous CCI power

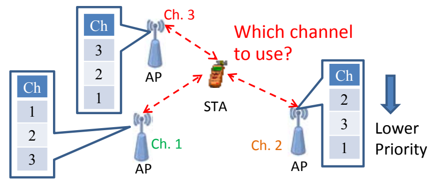
Background (4/4)

AP Cooperative Diversity in Wireless Network

- Transmission quality of mobile stations (STAs) located far from any APs degrades due to path loss and shadowing loss
- Cooperatively using multiple adjacent APs for an STA can solve this problem

Applying AP Cooperative Diversity for Wireless Network Using IACS-DCA

- The cooperating APs in a group need to use the same channel
- IACS-DCA operates so as to assign different channels to APs located nearby each other (i.e., each AP has its own channel priority table different from others)
  →AP cooperative diversity is difficult to apply



Objective

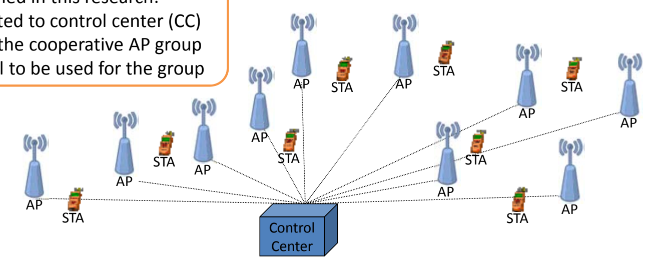
Objective

✓ To introduce AP cooperative diversity to wireless network using IACS-DCA

Proposal

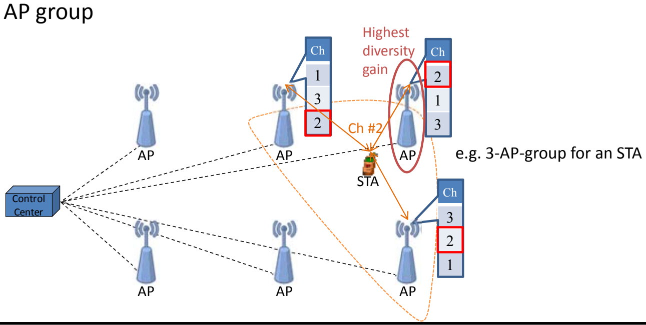
✓ AP grouping and channel selection method for AP cooperative diversity based on collaboration among APs, STAs, control center (CC)

Network assumed in this research:
- APs connected to control center (CC)
- CC decides the cooperative AP group and channel to be used for the group



AP Cooperative Diversity for Network with IACS-DCA

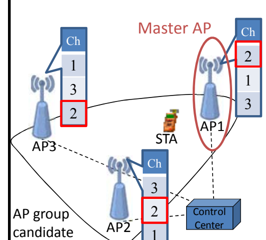
- AP Grouping and Channel Selection Method (w/o Channel Overlap Prevention)
  - Select a group of N_t AP(s) with the highest diversity gains for an STA
    - Highest received beacon signal powers
  - Select the highest-priority channel of AP with the highest diversity gain for the AP group



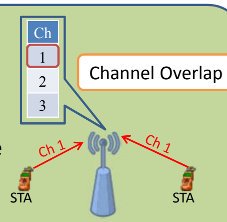
AP Cooperative Diversity for Network with IACS-DCA

Proposed AP Grouping and Channel Selection Method

- For every STA, CC makes a group candidate of N_t APs with the highest received beacon signal powers
- CC decides AP grouping and channel assignment for STAs' groups respectively from STA with the lowest received beacon signal power
  1. AP w/ highest received beacon power among candidates is set as master AP
  2. Vacant channel w/ highest priority on master AP is selected for the group



In our proposed method, channel overlap (condition when 1 channel of AP is allocated to multiple STAs) is prevented



AP Cooperative Diversity for Network with IACS-DCA

AP Grouping and Channel Selection Method

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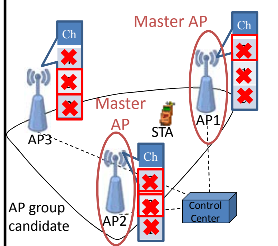


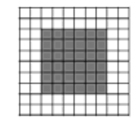
Problems & the Algorithm's Solving

- Master AP does not have any vacant channels → the next nearest AP is set as master AP
- Selected channel is not vacant on the other AP candidate(s) (i.e., channel overlap occurs) → the AP is removed from the group
- There is not any vacant channels on the APs in group candidate → the STA's request is blocked

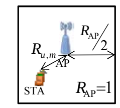
Computer Simulation

System Model

- A total of 100 rectangular cells with 36 cells of interest
- 1 AP (w/ 1 antenna) located on each cell's center
- 1 STA is located on each cell randomly
- OFDM[6] transmission is assumed
  - All cells are synchronously transmitting in TDD
  - STA communicates with transmission request probability p_u (uplink)
- MRC diversity[7] carried out on network side
- 1 simulation run contains t=1~2000 timeslots of IACS-DCA
- STA position and fading do not change on each simulation run



Cell of interest



Cell model

Computer Simulation

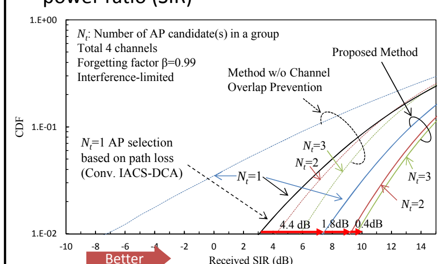
- Simulation Conditions

Channel (both for beacon signal and uplink STA-AP)	Shadowing loss Standard Deviation	σ=5 (dB)
	Path loss exponent	α=3.5
	Fading type	L=16-path static frequency-selective Rayleigh
	Power delay profile	Sampling interval-spaced uniform
	Number of channels	N_{ch} = 4
IACS-DCA	Forgetting factor of first order averaging filter	β=0.99
	Timeslots of each simulation run	2000
	Number of simulation runs	1000 (on each simulation run, path loss & shadowing conditions are set constant)
System	Total cellular areas	100 areas (36 areas of interest)
	Transmission	OFDM with N_c=64 subcarriers
	Transmit power	∞ (interference-limited)
	STA per cell	1 (randomly generated in each cell)
	No. of AP candidate(s) per STA	N_t=1,2,3 (each AP has 1 antenna)
	Transmission request probability	p_u=1

Proposed Algorithm vs. Conv. IACS-DCA

SIR Performance

- Cumulative distribution function (CDF) of average received signal-to-interference power ratio (SIR)



w/o AP cooperative diversity (N_t=1)
- AP is selected based on path loss (distance) or instantaneous received beacon power

w/ AP cooperative diversity (N_t>1)
- AP selection based on instantaneous beacon power (path loss & shadowing loss are considered)
- MRC diversity with max diversity order N_t (>1)

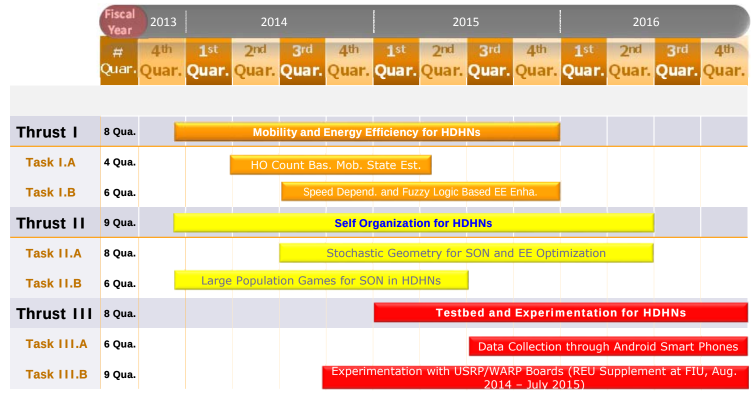
- Even when AP candidate N_t=1 (w/o AP cooperative diversity), AP selection based on instantaneous beacon power can improve the SIR performance compared to the AP selection based on path loss (i.e., distance)
- The SIR performance is improved more with AP cooperative diversity (N_t>1)
  - ✓ Because of antenna diversity gain and channel overlap prevention

Networking Technology and Systems: Japan-US Network Opportunity (NeTS: JUNO)

Energy-Efficient Hyper-Dense Wireless Networks with Trillions of Devices

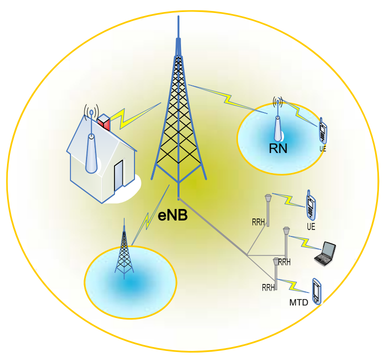
NSF NICT Virginia Tech FIU TOHOKU UNIVERSITY

JUNO Project Timeline

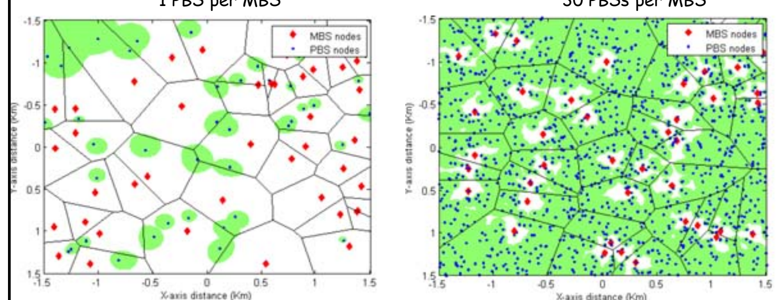


Key Research Challenges to be Addressed in JUNO Project

- Density, due to trillions of base stations and connected devices
- Network dynamics, due to mobility
- Heterogeneity, at both base station and device levels, e.g., concurrent existence of machine type devices (MTDs) and users equipment's (UEs) connections
- Inherent spectral-energy efficiency tradeoff and energy efficiency issue

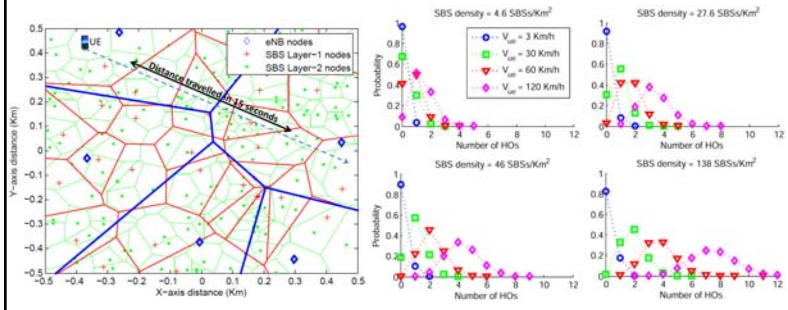


Thrust-I: Mobility and Energy Efficiency for HDHNs



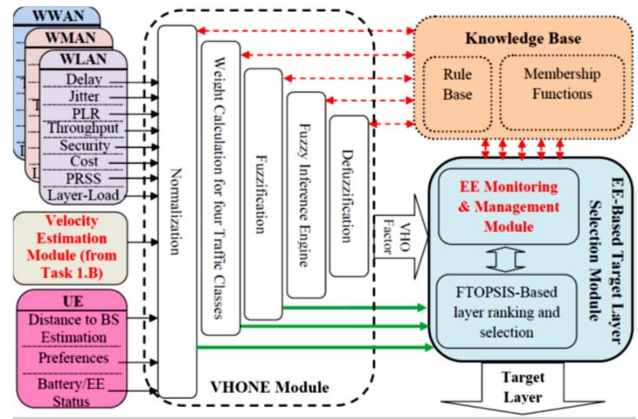
- Interference and mobility challenges will be more and more severe
- Self organization/optimization is the key for good performance

Mobility State Estimation



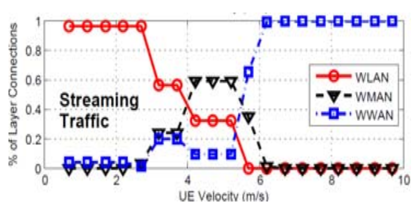
- Estimating the mobility states of user equipment (UE) is instrumental for interference and mobility management
- Commonly handled through handover counts in existing standards
- HDHNs allow more accurate estimation for a UE's mobility state
- Goal: to derive fundamental bounds on mobility state estimation accuracy through stochastic geometry

Fuzzy Logic for Vertical Handover (1)



Fuzzy Logic for Vertical Handover (2)

- An intelligent, flexible, and scalable scheme to perform
  - Handoff necessity estimation
  - Handoff target network selection
- A Fuzzy Logic Based Handoff Necessity Estimation scheme
- A Fuzzy TOPSIS MADM scheme to select the best target network
- Network Types that are considered: WLAN, WMAN, WWAN
- Traffic Types that are considered: Conversational, Streaming, Background, Interactive



Thrust II: Self-Organization for HDHNs

- Traditional ways of network optimization using base station controlled processes, staff monitoring, maps, trial and error, ...**is difficult in HDHNs!**
  - Self-organization is now a **necessity** not a privilege!

- Popular buzzword ☺ but…
  - …we view it as a distribution of intelligence throughout the network's nodes, each depending on its capability and features
  - Simply: **smarter devices and smarter network**
- Most importantly, self-organizing resource management to exploit the HDHNs features with minimal overhead!
  - How to enable self-organization? **Game Theory!**

Game Theory: What? Why?

- What is Game Theory?
  - Has nothing to do with PS3 or Medal of Honor ☺
  - Distributed optimization of environments where **multiple players** interact and make coupled decisions
- Heard of it before?
  - In Movies
  - Childhood games
  - You have done at least one game-theoretic decision in your life without knowing!
- For HDHNs
  - Noncooperative vs. cooperative

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Game-Theoretic Framework for HDHNs

- **Step 1:** Basic noncooperative games as building blocks
  - Players: base stations (if downlink) or devices (if uplink)
  - Actions: sleep mode, resource allocation, mobility decisions, etc.
  - Utilities: emphasis on tradeoffs between network performance and energy-efficiency
- **Step 2:** Learning as a means to achieve equilibria or desirable operating points
  - Focus on learning with minimal information
  - **Preliminary work:** IEEE ICC (June 2014) and IEEE ISWCS (August 2014). Extension to IEEE Transactions ongoing.
- **Step 3:** Incorporate dynamics and build stochastic games
  - Game meets stochastic geometry
- **Step 4:** The "trillions" dimension
  - Large population games (e.g., mean-field and evolutionary games)

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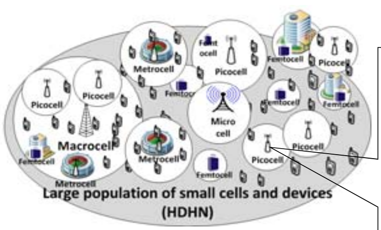
To Sleep or Not To Sleep?



- How to maintain energy efficiency?
  - **Put BS to sleep?**
  - **Wake BS up?**
  - **When to do what?**

- Each BS faces a tradeoff between increasing its rate/reducing load (in terms of fractional time needed to service users) and the associated increase in the power consumption
- We formulate a noncooperative game:
  - **Players:** BSs both MBSs and SBSs.
  - **Strategies:** State (sleep or active), power level, and cell bias
  - **Utilities:** tradeoff between energy and load (fractional time)

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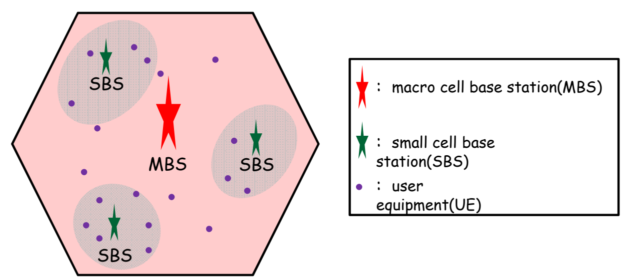
System model

- Each SBS have 3 state. (ON mode, OFF mode, Extended Power mode)
- During the OFF mode, each BS consumes power to sense UEs in it's coverage.



Our goal is to the realize energy efficient self-organizing dense HetNets using non-cooperative games.

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Power Consumption Model

- Power consumption includes:

$$P_b^{Total} = \begin{cases} P_b^{Idle} = \frac{P_{RF}+P_{BB}}{(1-\sigma_{DC})(1-\sigma_{MS})(1-\sigma_{cool})} = \frac{P_{RF}+P_{BB}}{\sigma} & \text{if } S_b = 0, \\ (P_b^{Work} + P_b^{Idle}) = \frac{P_b}{\eta\sigma(1-\sigma_{feed})} + P_b^{BCK} + P_b^{Idle} & \text{if } S_b = 1, \end{cases}$$

Backhaul power consumption

Transmit power

Power of RF and baseband components

σ terms are loss fractions in feeders, DC-DC conversion, etc.

- We look at games in **mixed** strategies where players choose an action probabilistically (a certain frequency)
- The goal is to find an equilibrium solution that can be reached in a self-organizing manner
  - Epsilon-equilibrium, where no BS can improve by unilaterally changing its strategy (within ϵ)

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Load

The load of BS b is given by following expression.

the load of BS b : $\rho_b(t) = \int_{\mathbf{x}\in\mathcal{L}_b} Q_b(\mathbf{x})d\mathbf{x}$

$\mathbf{x}$: location of UE

$\mathbf{x} \in \mathcal{L}_b$ ($\mathcal{L}_b$: coverage of BS b)

$Q_b(\mathbf{x})$: the load density in $\mathbf{x}$ $\quad Q_b(\mathbf{x}) = \frac{\lambda_b(\mathbf{x})}{\mu_b(\mathbf{x})R_b(\mathbf{x})}$

- $\lambda_b(\mathbf{x})$: the packet arrival rate in $\mathbf{x}$
- $1/\mu_b(\mathbf{x})$: the packet size of any UE in $\mathbf{x}$
- $R_b(\mathbf{x})$: the data rate in $\mathbf{x}$

$R_b(\mathbf{x}) = \omega \log_2(1+\gamma_b(\mathbf{x}))$

- ω : band width
- $\gamma_b(\mathbf{x})$: SINR

$$\gamma_b(\mathbf{x}) = \frac{P_b(t)S_b(t)h_b(\mathbf{x})}{\sum_{\forall b'\in\mathbf{B}/b} P_{b'}(t)S_{b'}(t)h_{b'}(\mathbf{x}) + N_0} \quad (if\ \ b: OFF \ \ \gamma_b(\mathbf{x}) = 0)$$

- $h_b(\mathbf{x})$: the channel gain from BS b to UE on location $\mathbf{x}$
- N_0 : the noise variance

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Cost function

The objective of this Algorithm is minimize each BS's cost function ,which is defined as follow.

cost function of BS b: $\Gamma_b(\boldsymbol{\rho}(t)) = \alpha_b P_b^{Total}(t) + \beta_b \rho_b(t) = -u_b(\boldsymbol{\rho}(t))$

$u_b(\boldsymbol{\rho}(t))$: utility $\quad (\alpha_b, \beta_b$: weight parameter $)$

$\boldsymbol{\rho}(t) = (\mathbf{P}(t), \boldsymbol{\zeta}(t), \mathbf{S}(t))$: network configuration

$\mathbf{P}(t) = (P_1(t),\cdots,P_B(t)), \quad P_1(t),\cdots,P_B(t)$: transmission power of BS1,⋯,B

$\boldsymbol{\zeta}(t) = (\zeta_1(t),\cdots,\zeta_{B_S}(t)), \quad \zeta_1(t),\cdots,\zeta_{B_S}(t)$: CREB of SBS1,⋯,B_S

CREB(cell range expansion bias):
CREB $\zeta_b(t)$ expands SBS b's coverage to absorb additional UEs.

$\mathbf{S}(t) = (S_1(t),\cdots,S_B(t)), \quad S_1(t),\cdots,S_B(t)$: state of BS1,⋯,B

- $S_b(t) = 0$ means that BS b is OFF. $(P_b^{Total}(t) = P_b^{Idle})$
- $S_b(t) = 1$ means that BS b is ON. $(P_b^{Total}(t) = P_b^{Work}(t) + P_b^{Idle})$
- $S_b(t) = 2$ means that BS b transmits extended power. $(P_b^{Total}(t) = P_b^{Work}(t) + P_b^{Idle} + P_b^{extended})$

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Definition of all parameters in the algorithm

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Define all parameters in the algorithm before explaining the algorithm.

parameter	definition
$\hat{u}_{b,i}(t)$	utility
$\hat{r}_{b,i}(t)$	regret ←calculated with $\hat{r}_{b,i}(t)$
$\pi_{b,i}(t)$	probability distribution ←calculated with $\hat{r}_{b,i}(t)$
$a_b(t)$	action ←decided by $\pi_{b,i}(t)$
$\hat{\rho}_b(t)$	load estimation ←This is like average of load.
$b(\mathbf{x},t)$	UE association
i	This is related to $a_b(t)$ as below table.

relationship of i and $a_b(t)$

i	action $a_b(t)$
1	OFF
2	ON
3	Extended Power

Algorithm

1. Input: utility $\hat{u}_{b,i}(t)$,regret $\hat{r}_{b,i}(t)$, probability distribution $\pi_{b,i}(t)$ for t=0
2. t→t+1
3. Select action $a_b(t)$ with $\pi_{b,i}(t-1)$
4. Calculate load estimation $\hat{\rho}_b(t)$
5. Calculate UE association $b(\mathbf{x},t)$
6. Calculate load $\rho_b(t)$, the consumption of energy $P_b^{Total}(\boldsymbol{\rho}(t))$, cost function $\Gamma_b(\boldsymbol{\rho}(t))$ and utility $u_b(t)$
7. Update utility $\hat{u}_{b,i}(t+1)$,regret $\hat{r}_{b,i}(t+1)$,probability distribution $\pi_{b,i}(t+1)$
8. Repeat 2-7
9. Finish

$$\begin{cases} a_b(t) = f(\max(\pi_{b,i}(t-1))) \\ \hat{\rho}_b(t) = \hat{\rho}_b(t-1) + \nu(t)(\rho_b(t-1) - \hat{\rho}_b(t-1)) \\ \hat{u}_{b,i}(t+1) = \hat{u}_{b,i}(t) + \tau_b(t)\mathbf{1}_{\{a_b=\rho_b(t+1)\}}(u_b(t+1) - \hat{u}_{b,i}(t)), i \in \mathbf{A_b} \\ \hat{r}_{b,i}(t+1) = \hat{r}_{b,i}(t) + \iota_b(t+1)(\hat{u}_{b,i}(t+1) - U_b(t+1) - \hat{r}_{b,i}(t)) \\ \pi_{b,i}(t+1) = \pi_{b,i}(t) + \varepsilon_b(t+1)(G_{b,i}(\hat{r}_{b,i}(t+1)) - \pi_{b,i}(t)) \end{cases}$$

- f : the mapping from probability distribution to action
- $\rho_b(t-1)$: instantaneous load
- $\nu(t)$: learning rate
- ε_b : offset $(\varepsilon_b = 1 - \rho_b^{Best})$,
- ρ_b^{Best} : the preferred load per BS b
- $P_b^{Rx}(t)$: the received signal power
- δ : the coefficient
- $\tau_b(t)$, $\iota_b(t+1)$, $\varepsilon_b(t+1)$: learning rate

Step 1: Initial Setting

At first initial setting is done as below.

$$\hat{u}_{b,i}(0) = 0,\ \hat{r}_{b,i}(0) = 0,\ ,t = 0$$

↑

BS b does not need to obey its initial action $a_b(0)$ for the rest of the simulation.
→ BS b can maximize the utility $u_b(\boldsymbol{\rho}(t))$

Step 3: Selection of action $a_b(t)$ with $\pi_{b,i}(t-1)$

BS b selects its action $a_b(t)$ based on its probability distribution $\pi_{b,i}(t-1)$.

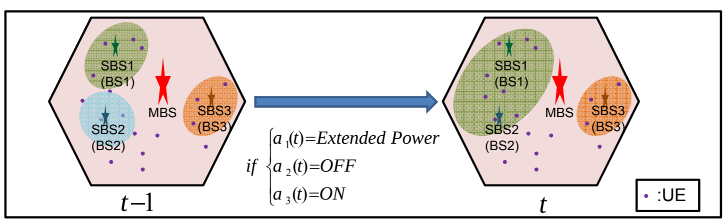
$$a_b(t) = f(\max(\pi_{b,i}(t-1)))$$ f : the mapping from probability distribution to action

$$\begin{cases} \pi_{b,1}(t-1) = 0.4 \\ \pi_{b,2}(t-1) = 0.5 \\ \pi_{b,3}(t-1) = 0.1 \end{cases} \Rightarrow \max(\pi_{b,i}(t-1)) = \pi_{b,2}(t-1) \Rightarrow a_b(t) = ON$$

Example of action selection

i	action $a_b(t)$
1	OFF
2	ON
3	Extended Power

relationship of i and $a_b(t)$



Example of action

Step 4: Calculation of $\hat{\rho}_b(t)$

The BSs calculate the accurate load estimation $\hat{\rho}_b(t)$ based on history as following and transmit this information to all UEs. → This is like average.

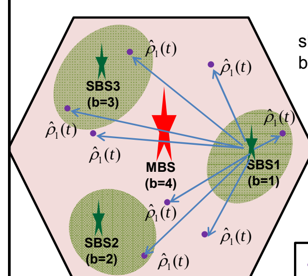
$$\hat{\rho}_b(t) = \hat{\rho}_b(t-1) + \nu(t)(\rho_b(t-1) - \hat{\rho}_b(t-1))$$

$\rho_b(t-1)$: instantaneous load

$\nu(t)$: the learning rate

$\nu(t)$ is selected such that the load estimation is much slower than the UE association and BSs can predict the load by balancing $\rho_b(t-1)$ and $\hat{\rho}_b(t-1)$.

∵ If load estimation changes rapidly, UEs start to change connected BSs rapidly and the estimated load is not accurate enough.



transmission of $\hat{\rho}_1(t)$

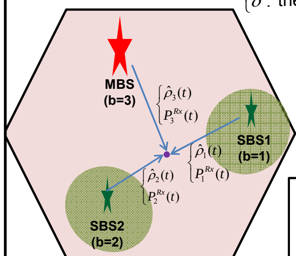
• : UE
$\hat{\rho}_1(t)$: transmitted information from BS1

Step5: Calculation of $b(\mathbf{x},t)$

UE at location **x** connects to BS $b(\mathbf{x},t)$ according to the following UE association rule.

$$b(\mathbf{x},t) = \arg\max_{b\in B} \left\{ \left(\hat{\rho}_b(t) + \varepsilon_b \right)^{-\delta} P_b^{Rx}(t) \right\}$$

- $\hat{\rho}_b(t)$: estimated load
- ε_b : offset $(\varepsilon_b = 1 - \rho_b^{Best})$, ρ_b^{Best} : the preferred load per BS b
- $P_b^{Rx}(t)$: the received signal power from BS b of the UE in location **x**
- δ : the coefficient
  →This determines the impact of load.



• : UE

$\left\{ \hat{\rho}_b(t), P_b^{Rx}(t) \right.$: transmitted information from BS b

the received information $\hat{\rho}_b(t)$ and $P_b^{Rx}(t)$ of one UE

Step 7: Update of $\hat{u}_{b,i}(t+1)$, $\hat{r}_{b,i}(t+1)$, $\pi_{b,i}(t+1)$

Each action's utility $\hat{u}_{b,i}(t+1)$, regret $\hat{r}_{b,i}(t+1)$ and probability distribution $\pi_{b,i}(t+1)$ are updated as follow.

$$\begin{cases} \hat{u}_{b,i}(t+1) = \hat{u}_{b,i}(t) + \tau_b(t)\mathbf{1}_{\{a_b=\rho_b(t+1)\}}\left(u_b(t+1) - \hat{u}_{b,i}(t)\right), i \in \mathbf{A_b} \\ \hat{r}_{b,i}(t+1) = \hat{r}_{b,i}(t) + \iota_b(t+1)\left(\hat{u}_{b,i}(t+1) - U_b(t+1) - \hat{r}_{b,i}(t)\right) \\ \pi_{b,i}(t+1) = \pi_{b,i}(t) + \varepsilon_b(t+1)\left(G_{b,i}(\hat{r}_{b,i}(t+1)) - \pi_{b,i}(t)\right) \end{cases}$$

$\longleftarrow \mathbf{A_b}$: set of actions

$\tau_b(t)$, $\iota_b(t+1)$, $\varepsilon_b(t+1)$: learning rate←The format is $1/t^c$. (c:exponent, 0.5<c<1.0)

$$\begin{cases} \lim_{t\to\infty}\sum_{n=1}^{t}\tau_b(n) = +\infty, \quad \lim_{t\to\infty}\sum_{n=1}^{t}\iota_b(n) = +\infty, \quad \lim_{t\to\infty}\sum_{n=1}^{t}\varepsilon_b(n) = +\infty \\ \lim_{t\to\infty}\sum_{n=1}^{t}\tau_b^{\,2}(n) < +\infty, \quad \lim_{t\to\infty}\sum_{n=1}^{t}\iota_b^{\,2}(n) < +\infty, \quad \lim_{t\to\infty}\sum_{n=1}^{t}\varepsilon_b^{\,2}(n) < +\infty \\ \lim_{t\to\infty}\frac{\iota_b(t)}{\tau_b(t)} = 0, \quad \lim_{t\to\infty}\frac{\varepsilon_b(t)}{\iota_b(t)} = 0 \end{cases}$$

$$G_b(\hat{r}_b(t)) = \frac{\exp(\kappa_b \hat{r}_{b,i}(t))}{\sum_{i'\in\mathbf{A_b}} \exp(\kappa_b \hat{r}_{b,i'}(t))}$$

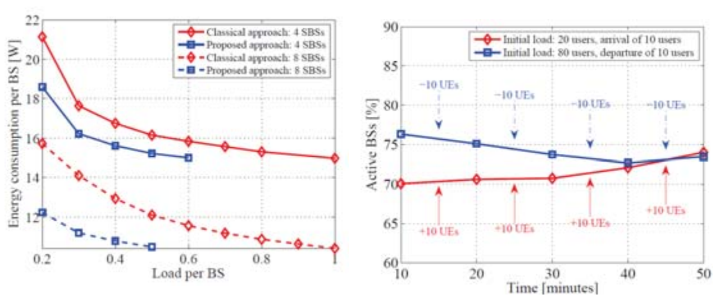
κ_b : temperature parameter

i	action
1	OFF
2	ON
3	Extended Power

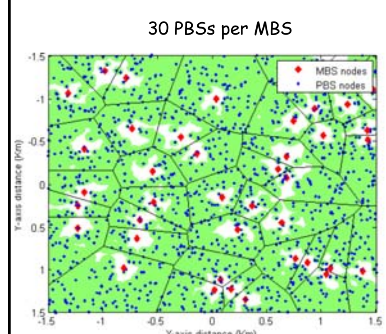
relationship of i and action

Simulation Results

- Fully distributed learning algorithm based on the Boltzman-Gibbs process reaches an equilibrium
  - Update utility and actions jointly with no information exchange
  - Small overhead, only measurements of the current utility

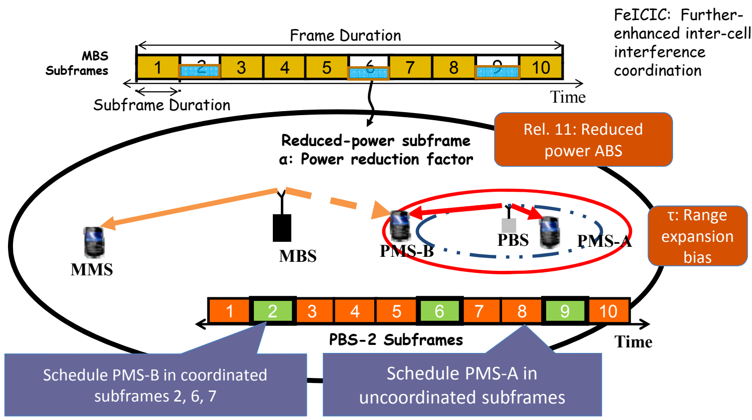


SON Analysis through Stochastic Geometry

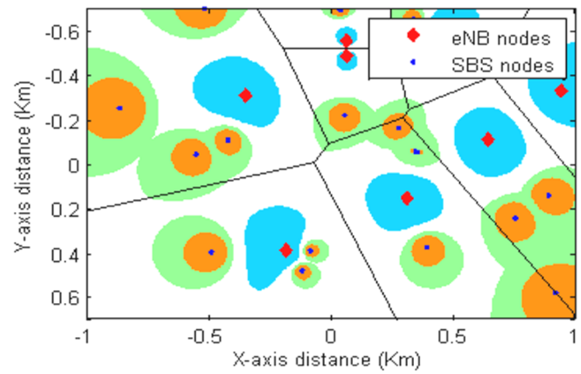


- Stochastic geometry: a popular tool to capture statistics of the interference in HDHNs
- Can analyze key network metrics (outage, capacity) in closed form under some assumptions
- We will use it to design and optimize interference coordination for HDHN deployments

Interference Coordination with LTE Release-11 (FeICIC)

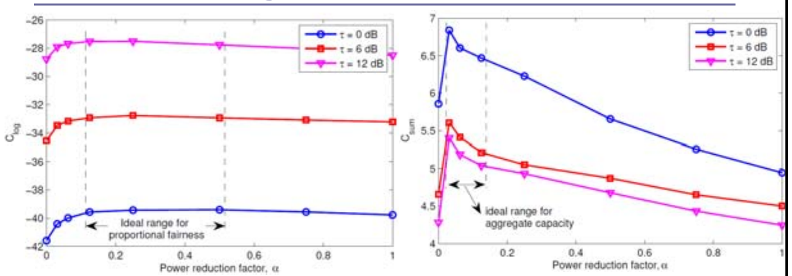


HDHN Coverage with Rel-11 FeICIC



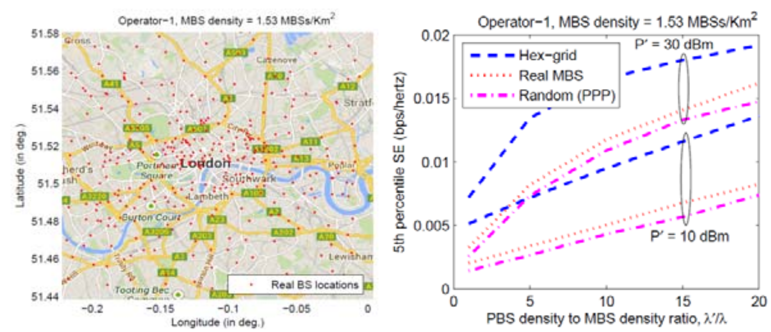
SBS: Small base station
eNB: Macrocell base station

FeICIC Optimization -- Preliminary Results



- Preliminary work: optimize ICIC for spectral efficiency
- Reasonable range of power reduction in blank subframes is between 0.1-0.4
- Larger range expansion bias improves fairness, but hurts aggregate capacity
- Future work: design and optimize FeICIC by jointly considering energy and spectral efficiency

How does Stochastic Geometry Analysis Compare to Real Deployments?



- Compared performance with stochastic geometry, hex. grid, and real BS locations
- Stochastic geometry (PPP) gives much closer 5th percentile results to real BS deployments when compared with hex-grid

Considers Rel-11 FeICIC with the following parameters: τ = 6 dB, α = 0.5, β = 0.5, ρ = 4 dB, ρ' = 12 dB, and P_{tx} = 46 dBm

Thrust III – Testbed and Experimentation for HDHNs

- Experimentation with USRPs, WARP boards, CORENET testbed, and software simulations
  - To verify the feasibility of our proposed RRM algorithms
  - To emulate our massive deployment scenarios
  - Optimizing the algorithms designed in Thrusts I and II with conjunction to physical layer parameters and designing experiments to verify them on our USRP testbed
- Data collection via Android smartphones
  - To verify the developed algorithms for mobility management through a massive data collection campaign

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Abolfazl Mehbodniya, Wei Peng, Fumiyuki Adachi,

ICC 2014, Sydney, Audtralia

Radio Resource Management for Next Generation Wireless Networks : Uplink SIMO SC-FDMA Scheduling

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Outline

1. Introduction to multiuser SIMO SC-FDMA and resource allocation
2. Research Objective
3. Transceiver model
4. SINR expression for multiuser SIMO SC-FDMA
5. Receive correlation and DOC
6. Proposed Suboptimal Scheduling and RA Algorithm
7. Results
8. Conclusion and future work

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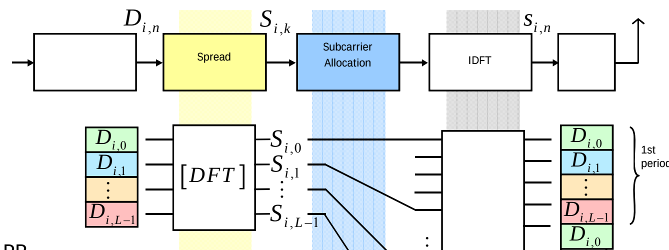
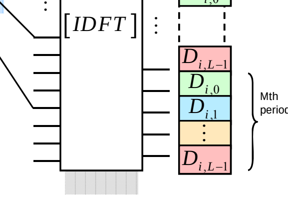
Background / SC-FDMA (1)





- Low PAPR
- Cyclic prefix guard interval: enable cost-effective frequency domain block processing at receiver side
- Two types of SC transmission
  - Localized transmission: multi-user scheduling gain in frequency domain
  - Distributed transmission: robust transmission for control channels and high mobility UE

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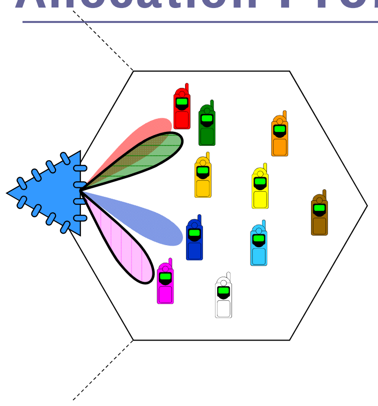
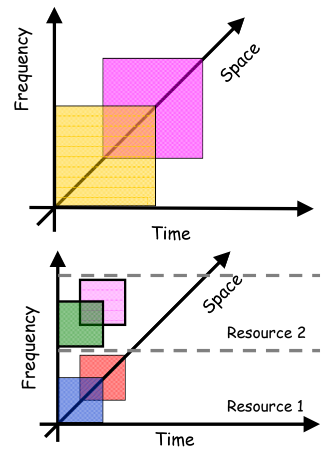
Background / Resource Allocation Problem



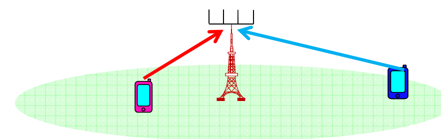


Objective → Maximize the capacity of the system

Background / Objective

Objective

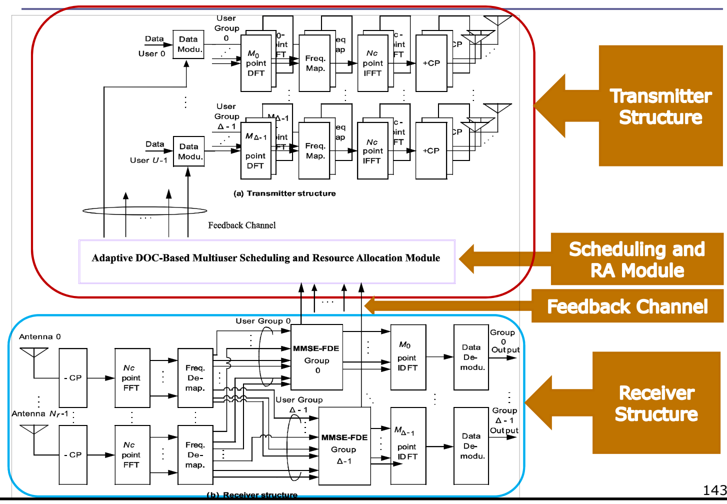
Maximizing the system capacity for uplink multiuser SC-FDMA with multiple received antenna by means of an effective scheduling and user grouping, while considering fairness among users.



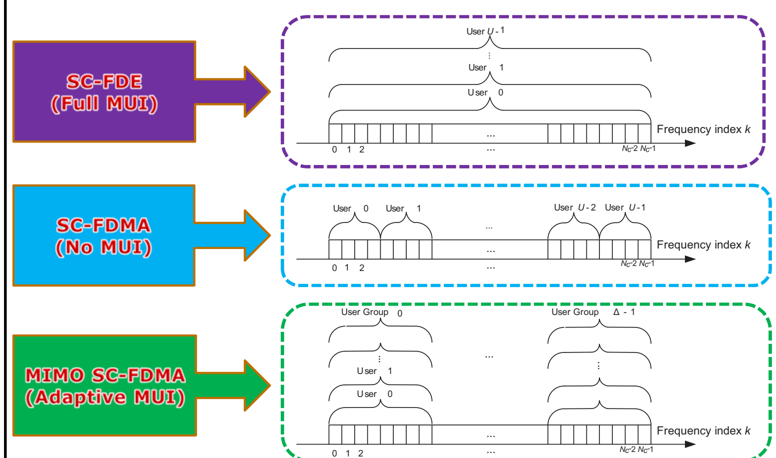
Challenges

- Uplink MIMO channel is a MAC channel and different than available literature which mainly emphasize on downlink MIMO-BC channels.
- In Uplink interference is caused by MUI rather than imperfect BF.
- Optimization should be done in conjunction with all other parameters.

Transceiver Model



RA and Scheduling Problem for Multiuser Uplink SIMO SC-FDMA



Joint use of FDE and receive antenna diversity

Received signal after FFT

$$R_m(k) = H_m(k)S(k) + N_m(k)$$

$H_m(k)$	:	The channel gain observed at mth antenna
$S(k)$	:	The kth subcarrier component of N_c-chip signal sequence
$N_m(k)$	:	The noise component

⇩ Joint use of FDE and receive antenna diversity

$$\widetilde{R}(k) = \sum_{m=0}^{N_r-1} w_m(k) R_m(k)$$

$$= \left(\sum_{m=0}^{N_r-1} w_m(k) H_m(k) \right) S(k) + \sum_{m=0}^{N_r-1} w_m(k) N_m(k)$$

The equivalent channel gain $\hat{H}(k)$

The noise component after equalization $\hat{N}(k)$

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SINR Expression for Uplink SIMO SC-FDMA

The weight for user u'_δ at antenna n_r *is given by*

$$W_{u'_\delta,n_r}^{(MMSE)}(k) = \frac{H^*_{u'_\delta,n_r}(k)}{\sum_{u=1}^{U_\delta-1} |H_{u'_\delta,n_r}(k)|^2 + E_c/N_0}$$

$$SINR^{Uplink} = \frac{\frac{P_{u'_\delta}}{M_\delta N_0} \left| \sum_{k=0}^{M_\delta-1} \hat{H}_{u'_\delta}(k) \right|^2}{\sum_{u_\delta=0}^{U_\delta-1} \frac{P_{u_\delta}}{M_\delta N_0} \sum_{k=0}^{M_\delta-1} \left| \hat{H}_{u_\delta}(k) \right|^2 - \frac{P_{u'_\delta}}{M_\delta N_0} \left| \sum_{k=0}^{M_\delta-1} \hat{H}_{u'_\delta}(k) \right|^2 + \sum_{k=0}^{M_\delta-1} \left| W_{u'_\delta,n_r} \right|^2}.$$

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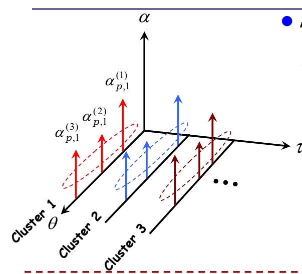
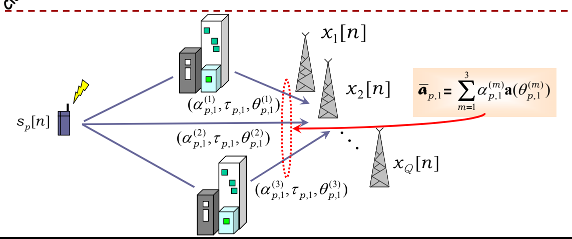
Correlated Sources



- Assume that $\{\alpha^{(m)}_{p,l}\mathbf{a}(\theta^{(m)}_{p,l}) s_p[n-\tau_{p,l}],\ m=1,\cdots L_{p,l}\}$ is a cluster of $L_{p,l}$ correlated sources impinging on the receiver antenna array where

$\alpha^{(m)}_{p,l}$: path gain of each correlated signal in the cluster

$\theta^{(m)}_{p,l}$: DOA of each correlated signal in the cluster



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Relationship between DOC and SINR Uplink

$$\sin^2\theta_{u_\delta} = 1 - \frac{1}{N_r^2} \left\| \bar{\mathbf{a}}^H_{u_\delta} \bar{\mathbf{a}}_{u'_\delta} \right\|^2 = \begin{cases} 1 - \frac{1}{N_r^2} \frac{1-\cos\left(\Phi_{N_r}\left(\sin(\phi^{u_\delta}) - \sin(\phi^{u'_\delta})\right)\right)}{1-\cos\left(\Phi_1\left(\sin(\phi^{u_\delta}) - \sin(\phi^{u'_\delta})\right)\right)} & \phi^{u_\delta} \neq \phi^{u'_\delta} \\ 0 & \phi^{u_\delta} = \phi^{u'_\delta} \end{cases}$$

$$\mathbf{E}\{\gamma_{u'_\delta}\} = \frac{P_{u'_\delta}\mathbf{E}\left\{\mathbf{W}_{u'_\delta}\mathbf{H}'^H_{u'_\delta}\right\}}{\sum_{u_\delta=0,u_\delta\neq u'_\delta}^{U_\delta-1} P_{u_\delta}\mathbf{E}\left\{\mathbf{W}_{u'_\delta}\mathbf{H}'^H_{u_\delta}\right\} + N_0\mathbf{E}\left\{\mathbf{W}_{u'_\delta}\mathbf{W}^H_{u'_\delta}\right\}}.$$

$$\mathbf{E}\{\gamma_{u'_\delta}\} = \frac{\frac{P^2_{u'_\delta} N_r^2}{N_r^2 \sum_{u_\delta=0}^{U_\delta-1} P_{u_\delta}}}{\sum_{u_\delta=0,u_\delta\neq u'_\delta}^{U_\delta-1} \frac{P_{u_\delta} P_{u'_\delta} \cos\delta_{u_\delta}}{N_r^2 \sum_{u_\delta=0}^{U_\delta-1} P_{u_\delta}} + \frac{N_0 P^2_{u'_\delta} N_r^2}{N_r^4 \left(\sum_{u_\delta=0}^{U_\delta-1} P_{u_\delta}\right)^2}} = \frac{N_r^2 P_{u'_\delta} \sum_{u_\delta=0}^{U_\delta-1} P_{u_\delta}}{\sum_{u_\delta=0}^{U_\delta-1} P_{u_\delta} \left(\sum_{u_\delta=0,u_\delta\neq u'_\delta}^{U_\delta-1} P_{u_\delta} \cos\theta_{u_\delta} \right) + N_0 P_{u'_\delta}}$$

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Formulation of the optimization problem

- Optimization problem:
- Subject to:

$$\max_{\Delta, M_\delta, U_\delta, u_\delta, P_{u_\delta}} \frac{1}{N_c} \sum_{\delta=0}^{\Delta-1} M_\delta \sum_{u_\delta=0}^{U_\delta} \log_2\left(1+\gamma_{u_\delta}\right)$$

$$(1) \sum_{\delta=0}^{\Delta-1} M_\delta = N_c, \ (2) \sum_{\delta=0}^{\Delta-1} U_\delta = U,$$

$$(3) \ 0 < U_\delta \le N_r,$$

$$(4) \sum_{u_\delta=0}^{U_\delta} P_{u_\delta} \le P_\delta, \ (5) \sum_{\delta=0}^{\Delta-1} P_\delta \le P$$

N_c : Total Number of Subcarriers
U : Total Number of Users
Δ : Number of Resource Blocks (RBs)
M_δ: Size of each RB
γ_{u_δ}: SINR of user u_δ
U_δ: Total number of users on δth RB
N_r : Number of receive antennas
P_{u_δ}: Total transmit power on δth RB
P : Total transmit power of the system

Very high computational complexity because of exhaustive search

Optimal and a few suboptimal techniques, e.g. those based on Hungarian search are proposed.

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Proposed adaptive scheduling and RA algorithm for $\hat{U}/\Delta^* \ge 1$

Input: Target E_b/N_0, U, $\mathbf{F}$, N_c, N_r and $\mathbf{H}' \in \mathbb{C}^{N_c \times N_r \times U}$
Output: Δ^*, M_δ^*, U_δ^* and Allocation Vector $\mathcal{S}_\delta$
$\hat{U} \leftarrow \mathcal{G}(E_b/N_0, \mathbf{F}, N_r)$
$\Delta^* \leftarrow \mathcal{F}(E_b/N_0, \hat{U}, N_r)$
$M_\delta^* \leftarrow N_c/\Delta^*$
Initialization: $\mathcal{B} = \{0, 1, ..., \Delta^* - 1\}$; $\mathcal{U} = \{0, 1, ..., U\}$;
$U_\delta^* \leftarrow \hat{U}/\Delta^*$
while do
  $\mathcal{S}_\delta \leftarrow \emptyset, \ \forall \delta \in \mathcal{B}$
  for $\forall \delta \in \mathcal{B}$ **do**
    Find $u_\delta^* = \arg\max_{j \in \mathcal{U}} \| \mathbf{H}_j^\delta \|^2$, where
    $\mathbf{H}_j^\delta \in \mathbb{C}^{(\delta M_\delta^*+1:(\delta+1)M_\delta^*) \times N_r \times j}$ is a subspace of $\mathbf{H}'$
    $\mathcal{S}_\delta \leftarrow \mathcal{S}_\delta \cup \{u_\delta^*\}$, $\mathcal{U} \leftarrow \mathcal{U} \setminus \{u_\delta^*\}$
    while $|\mathcal{S}_\delta| < U_\delta^*$ **do**
      $\bar{u}_\delta = \arg\min_{j \in \mathcal{U}} \sum_{i \in \mathcal{S}_\delta} \left(\| \mathbf{H}_i^\delta (\mathbf{H}_j^\delta)^H \|^2 / \| \mathbf{H}_i^\delta \|^2 \| \mathbf{H}_j^\delta \|^2 \right)$
      $\mathcal{S}_\delta \leftarrow \mathcal{S}_\delta \cup \{\bar{u}_\delta\}$, $\mathcal{U} \leftarrow \mathcal{U} \setminus \{\bar{u}_\delta\}$
    end while
  end for
  Calculate the fairness factor $\mathbf{F}^*$ and $\epsilon = |\mathbf{F}^* - \mathbf{F}|$
  if $\epsilon \le \epsilon^*$ **then**
    EXIT While
  else
    Adjust $\hat{U}$ accordingly
  end if
end while

Step 1
Find optimum values for number of RBs, their size and number of users on each RB.

Step 2
Find the users to be assigned to each RB based on their mutual DOC factor .

Step 3
Fairness adjustment.

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Proposed adaptive scheduling and RA algorithm for $\hat{U}/\Delta^* < 1$

Input: Target E_b/N_0, U, $\mathbf{F}$, N_c, N_r and $\mathbf{H}' \in \mathbb{C}^{N_c \times N_r \times U}$
Output: Δ^*, M_δ^*, U_δ^* and Allocation Vector $\mathcal{S}_u$
$\hat{U} \leftarrow \mathcal{G}(E_b/N_0, \mathbf{F}, N_r)$
$\Delta^* \leftarrow \mathcal{F}(E_b/N_0, \hat{U}, N_r)$
$M_\delta^* \leftarrow N_c/\Delta^*$
Initialization: $\mathcal{B} = \{0, 1, ..., \Delta^* - 1\}$; $\mathcal{U} = \{0, 1, ..., U\}$;
while do
  $\mathcal{S}_u \leftarrow \emptyset$, $C_u \leftarrow \emptyset \ \forall u \in \mathcal{U}$
  for $\forall \delta \in \mathcal{B}$ **do**
    Find $u^* = \arg\max_{j \in \mathcal{U}} \| \mathbf{H}_j^\delta \|^2$.
    $\mathcal{S}_{u^*} \leftarrow \mathcal{S}_{u^*} \cup \{\delta\}$.
  end for
  Calculate each user achieved capacity, C_u
  $\mathcal{K} = \{0, 1, ..., U\}$;
  for $u = 1 : \hat{U}$ **do**
    Find $u^* = \arg\max_{u \in \mathcal{K}} C_u$.
    $\mathcal{K} \leftarrow \mathcal{K} \setminus \{u^*\}$
    if $|\mathcal{S}_{u^*}| = \hat{U}/\Delta^*$ **then**
      EXIT
    else if $|\mathcal{S}_{u^*}| > \hat{U}/\Delta^*$ **then**
      while $|\mathcal{S}_{u^*}| > \hat{U}/\Delta^*$ **do**
        Find $\delta^* = \arg\min_{\delta \in \mathcal{S}_{u^*}} \| \mathbf{H}_{u^*}^\delta \|^2$.
        Find $\bar{u}^* = \arg\max_{j \in \mathcal{U}} \| \mathbf{H}_j^{\delta^*} \|^2$.
        $\mathcal{S}_{\bar{u}^*} \leftarrow \mathcal{S}_{\bar{u}^*} \cup \{\delta^*\}$, Update $C_{\bar{u}^*}$
        $\mathcal{S}_{u^*} \leftarrow \mathcal{S}_{u^*} \setminus \{\delta^*\}$, Update C_{u^*}
      end while
    else if $|\mathcal{S}_{u^*}| < \hat{U}/\Delta^*$ **then**
      while $|\mathcal{S}_{u^*}| < \hat{U}/\Delta^*$ **do**
        Find $\delta^* = \arg\max_{\delta \in \mathcal{S}_u \, \forall u \ne u^*} \| \mathbf{H}_{u^*}^\delta \|^2$.
        Find the user $\bar{u}^*$ to which δ^* belongs to
        $\mathcal{S}_{u^*} \leftarrow \mathcal{S}_{u^*} \cup \{\delta^*\}$, Update C_{u^*}
        $\mathcal{S}_{\bar{u}^*} \leftarrow \mathcal{S}_{\bar{u}^*} \setminus \{\delta^*\}$, Update $C_{\bar{u}^*}$
      end while
    end if
  end for
  Calculate the fairness factor $\mathbf{F}^*$ and $\epsilon = |\mathbf{F}^* - \mathbf{F}|$
  if $\epsilon \le \epsilon^*$ **then**
    EXIT While
  else
    Adjust $\hat{U}$ accordingly
  end if
end while

Fairness Index

$$\mathbf{F} = \left(\sum_{u=0}^{U-1} C_u \right)^2 / \left(U \cdot \sum_{u=0}^{U-1} C_u^2 \right)$$

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Simulation Parameters

Transmitter	Data modulation	QPSK,
	Number of resource blocks	$\Delta = 1 \sim 8$
	FFT/IFFT size	$N_c = 256$
	Total Number of users	$U = 1 \sim 16$
	Total Transmit SNR	$E_s/N_0 = 0 \sim 20$dB
	Transmit Power Control	Slow TPC
Channel	Fading type	Frequency-selective block Rayleigh
	Power delay profile	L = 16-path uniform power delay profile
	Time delay	$\tau_{u,l} = l, \ l = 0 \sim L-1$
Receiver	Number of receive antennas	$N_r = 1 \sim 8$
	Equalization Type	MMSE-FDE
	Channel estimation	Ideal

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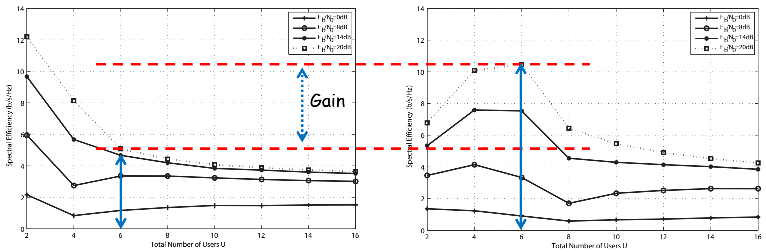
Simulation results 1

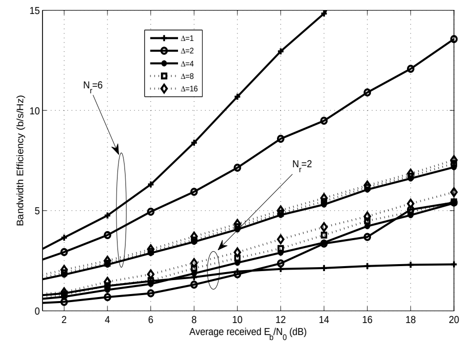
➢ Based on the values for target SNR, Number of simultaneous accessing users and number of receive antennas, there is an optimum value for number of RB, Δ , for which spectral efficiency maximizes.



Spectral efficiency *vs* different total number of users and SNRs for Nr=4 and Δ =1 (without scheduling)

Spectral efficiency *vs* different total number of users and SNRs for Nr=4 and Δ =2 (without scheduling)

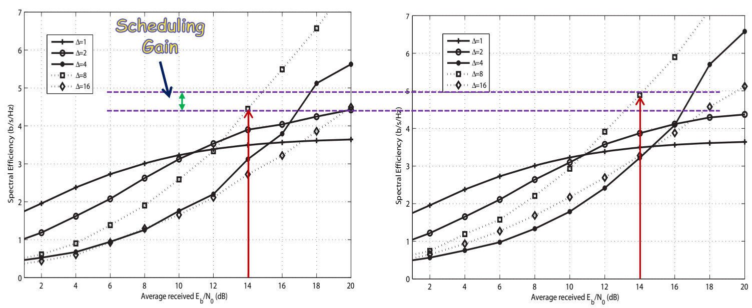
Simulation results 2



Spectral efficiency *vs* number of received antennas for different RB sizes, Nr=2,6 and U=4 (without scheduling)

Simulation results 3

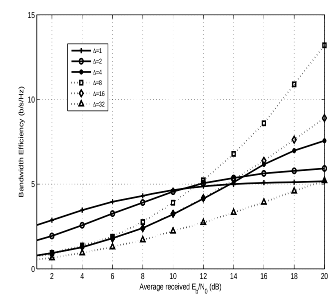
❑ Our algorithm provides 10 % gain in SE when optimum value for number of RBs is chosen.
❑ As number of RBs increase, the SE gain achieved by our algorithm increase due to multiuser diversity



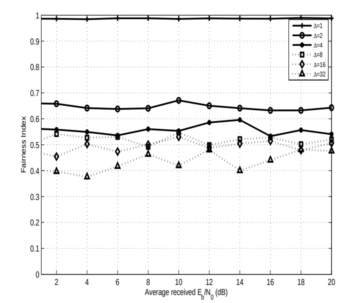
Spectral efficiency *vs* average received SNR for different RB sizes and Nr=4, U=16 (without scheduling).

Spectral efficiency *vs* average received SNR for different RB sizes and Nr=4, U=16 (with scheduling).

Simulation results 4

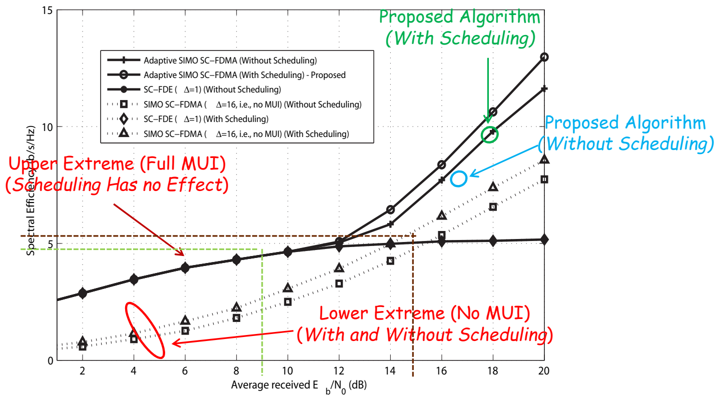


Spectral efficiency *vs* average received SNR for different RB sizes and Nr=6, U=32 (with scheduling).



Fairness index *vs* average received SNR for different RB sizes and Nr=6, U=32 (with scheduling).

Simulation results 5



Spectral efficiency *vs* average received SNR for different resource allocation scenarios and Nr=6, U=32 and target F=0.8.

Concluding Remarks

- 5G requires energy & spectrum efficient network
- Heterogeneous network is a realistic approach
  - Small-cell layer (e.g. DAN) to provide short range communications
    - High speed data services
    - Significantly reduced signal energy
    - New frequency bands, e.g., centimeter & millimeter wave bands
  - Macro-cell layer is still necessary
    - Call control signaling
    - High mobility users
    - M2M and D2D data services (low data rates but millions of devices)
  - Improved reliability
    - Simultaneous operation of multiple networks

- *Acknowledgment*
  - *Special thanks to members of Wireless Signal Processing & Networking (WSP&N) Lab as well as JUNO Project team*

Thank You
Q&A

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