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

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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.

Table of Contents

1. Wireless Communications’ Evolution
   - Introduction to WSP&Networking Lab
   - Wireless Evolution History
   - 5G 1000x Capacity ideas: spectrum/densification/smallcell
   - Challenges for 5G
   - 5G specifications, projects and timeline

2. Introduction to Energy-Efficiency in wireless
   - Introduction
   - A simple example
   - Massive MIMO
   - Small cells/ HetNet/ densification from EE point of view
   - BS energy consumption and on/off switching problem

3. More details on current ongoing projects in 5G and some candidate technologies
   - Docomo Proposals
   - MiWEBA 5G project at Osaka University
   - JUNO Project
   - An example uplink RRM and scheduling algorithm with application for 5G

4. Conclusion

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.

TOHOKU UNIVERSITY: Sendai, Japan

Founded in 1907 as the 3rd Imperial University

2011 Earthquake and recovery

School of Engineering

Comm. Eng. Department (New Bldg.)

Yagi-Uda Antenna Was Invented At Tohoku University

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

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

- **Structure**
  - Graduate School of Eng.
    - 12 graduate students
    - 4 undergraduate students
    - 2 research students
  - Undergraduate
    - 4 research students

600 MHz transceiver using Yagi-Uda antenna.

Close collaboration in research
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/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

Vertical Applications 1st Wave

"Regulatory" Applications 2nd Wave

Internet of Things 3rd Wave

- 2010
- 2015
- 2020
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

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.

<table>
<thead>
<tr>
<th>Technology</th>
<th>3.5G (HSPA,5MHz)</th>
<th>3.9G (LTE,~20MHz)</th>
<th>4G (LTE-A, ~100MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up</td>
<td>14.4 Mbps</td>
<td>75 Mbps</td>
<td>300 Mbps</td>
</tr>
<tr>
<td>Down</td>
<td>14.4 Mbps</td>
<td>300 Mbps</td>
<td>30bps/Hz</td>
</tr>
</tbody>
</table>

Wireless evolution: Explosive Growth of Traffic
Wireless evolution: How to Achieve x1000 Capacity

- Increase network throughput [bit/s]
  - Consider a given area

Formula for network throughput:
Throughput = Available spectrum \cdot Cell density \cdot Spectral efficiency

\[
\text{bit/s in area} \quad \text{in Hz} \quad \text{Cell/Area} \quad \text{bit/s/Hz/Cell}
\]

Challenges for 5G:
- Spectrum Issue
- Energy Issue
- Channel Issue

Challenges for 5G: Socio-Economic Perspective

5G will enhance the socio-economic satisfaction

- Richer contents
  - Multimedia 
  - Interactive communications

- More efficient and safer
  - Transportation
  - Autonomous driving

- Navigation

- Health care
  - Remote medical examination

- Disaster relief
  - Prediction
  - Robustness to disaster

- Education
  - Distance learning
  - Virtual experience

- Safety and lifeline system
  - Collision avoidance
  - Rescue (Distress, Accident, etc.)

Challenges for 5G: Capability of ICT Perspective

- 5G will enhance capability of ICT
- 4K/8K video resolution
- Multiuser MIMO teleconference

- M2M
  - More sensors Monitoring

- Handle Big Data
  - Cloud computing
  - Wireless, cloud office
  - Personal data storage
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)

- Normalized Typical User Throughput [bps/device]
- Coverage expansion
- Higher throughput

Challenges for 5G: Requirements (2)

- Peak data rate >10Gbps
- Energy Saving (energy/bit)
- 1/n x 100Bps
- 5G RAN
- Enhanced IMT-Advanced
- IMT-Advanced

Challenges for 5G: Requirements (3)

- User throughput
- Video Streaming
- Virtual Reality
- M2M Communication (eg. sensors)
- Autonomous Communication (eg. Collision avoidance)

- Latency
- Mobility
- Low
- High

- Low
- High
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: 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?

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**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**

- \( R = \log_2(1 + SNR) \), 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**

- \( R = W \log_2(1 + SNR/W) \) (bps), i.e., \( Q = 1 \).
- \( R \) does not increase as \( W \) increases. But it requires the same power.
**A simple Example : MIMO**

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

![Graph showing capacity increases 3-4 times for given transmit power](image)

**Downlink transmission in Massive MIMO (1)**

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

\[ y_u = h_u^H W s + n_u \]

\[ = h_u^H w_u s_u + \sum_{u' \neq u} h_{u'}^H w_{u'} s_{u'} + n_u \]

desired signal

inter-user interference

noise

**A simple Example : Massive MIMO**

- LTE: # of Tx: 4 → 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?

![Diagram showing transition from 4 antennas LTE to 8 antennas LTE-A to Massive MIMO](image)

**Downlink transmission in Massive MIMO (2)**

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

\[ \text{SINR}_u = \frac{|h_u^H w_u s_u|^2}{\sum_{u' \neq u} |h_{u'}^H w_{u'} s_{u'}|^2 + \sigma^2} \]

\[ \approx \frac{1}{N_t} \sum_{u' \neq u} \frac{P_t}{P_t + \sigma^2} \]

- Total capacity of $U$ user Massive MIMO scenario:

\[ R_{\text{sum}} = \sum_{u=1}^{U} \log_2 \left(1 + \text{SINR}_u\right) \]
**Downlink transmission in Massive MIMO (3)**

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

![Graph showing capacity vs. $N_t$](image)

**Downlink transmission in Massive MIMO (4)**

- Why is Massive MIMO important?
- The capacity of Massive MIMO system can be approximated as $[\text{Yang'13, Ngo'13}]
  \[ R \approx \log_2 \left( 1 + \frac{(N_t - 1)P_{TX}}{(U - 1)P_{TX} + 1} \right) \]
- The required transmission power required for target rate $R^{\text{req}}$ (bps/Hz) becomes
  \[ P_{TX} = \frac{2^{R^{\text{req}}} - 1}{(N_t - 1) - (2^{R^{\text{req}}} - 1)(U - 1)} \]

**Downlink transmission in Massive MIMO (5)**

- Required transmission power significantly reduced by increasing $N_t$.

![Graph showing required power vs. $N_t$](image)

**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 x100 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.
  - Macro-cell layer: High mobility users, Cell control, D2D, M2M data.
  - Small-cell layer: Near stationary users, High speed data, D2D, M2M data.
  - Baseband processing layer: Equivalent to present BS TRx.
Heterogeneous scenario

- Cell size and SE-EE trade-off

- 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

Definition of SE and EE (1/3)

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

\[
\eta_{SE} = \frac{C_{total}}{S_{total} \cdot B_{total}} = \frac{N \cdot C}{(N \cdot S) \cdot (N \cdot B)} = \frac{c}{N \cdot S}
\]

Definition of SE and EE (2/3)

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

\[
\eta_{EE} = \frac{C_{total}}{P_{total}} = \frac{N \cdot C}{N \cdot P_{t}} = \frac{c}{B}
\]

Objective

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

Contents

- Background
- Objective
- Definition of SE and EE
- DAN downlink system model
- Numerical results
- Conclusion

Definition of SE and EE

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

\[
\eta_{SE} = \frac{C_{total}}{S_{total} \cdot B_{total}} = \frac{N \cdot C}{(N \cdot S) \cdot (N \cdot B)} = \frac{c}{N \cdot S}
\]

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

\[
\eta_{EE} = \frac{C_{total}}{P_{total}} = \frac{N \cdot C}{N \cdot P_{t}} = \frac{c}{B}
\]
Definition of SE and EE (3/3)

- **Relationship between SE and EE**
  - Shannon capacity (bps/Hz) assuming OFDM and SC-FDE
    \[ c = \sum_{n=1}^{N_c} \log_2 \left( 1 + \frac{P_r(k)}{G(k)} \right) \]
  - **SE** (bps/Hz/km²)
    \[ \eta_S = \frac{1}{N} \sum_{n=1}^{N} \log_2 \left( 1 + \frac{P_r(k)}{G(k)} \right) \]
  - **EE** (bits/J)
    \[ \eta_E = \frac{1}{N} \sum_{n=1}^{N} \log_2 \left( 1 + \frac{P_r(k)}{G(k)} \right) \]

- SE increases with \( P_t \) (is saturated eventually)
- EE decreases with \( P_t \)

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

Numerical results

- **Numerical evaluation condition**
  - Path loss exponent \( \alpha = 3.0 \)
  - Shadowing: Log-normal w/ standard deviation \( \sigma = 7.0 \) (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
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 $N$

- **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 be considered.

A Broader Outlook (2)

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

Utility Function for EE RRM (1)

1. Difference of data rate and cost term
   \[ u(p) = r(p) - c(p) = r(p) - n \sum_{k=1}^{n} p_k \mu_k \]

2. Ratio of data rate and energy consumed
   \[ u(p) = \frac{r(p)}{P_c + \sum_{k=1}^{n} p_k} \]

3. Throughput (goodput) divided by energy
   \[ u(p) = \frac{Rf(p)}{P_c + \sum_{k=1}^{n} p_k} \]
Utility Function for EE RRM (2)

<table>
<thead>
<tr>
<th>Capacity</th>
<th>Network Throughput</th>
</tr>
</thead>
<tbody>
<tr>
<td>EE =</td>
<td>NEE =</td>
</tr>
<tr>
<td>Power Consumption</td>
<td>Total Energy Consumption</td>
</tr>
</tbody>
</table>

- 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

Energy Consumption for Network Elements

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

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

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
Potential Ideas for Capacity improvement in 5G

Docomo Point of view for 1000x capacity improvement

Capacity Improvement in 5G: Spectrum Extension (1)

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 3.4-3.6 GHz band, it is planned to assign the band to operators this year.

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

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

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]

Capacity Improvement in 5G: Spectrum Extension (5)

- Capacity-hungry Apps (e.g., mobile videos):
  - Higher SE
  - Higher EE

- Control-intensive Apps (e.g., M2M, social networking):
  - Faster Connectivity
  - Higher Reliability

- Smaller cells
- Larger cells
- C-plane larger
- D-plane smaller
- Coverage-on-demand
- Densely deployed
- Smart

Processing power in Devices

Effort for Orthogonality
FDMA, TDMA, CDMA, OFDMA
Equalizer, Canceller, MIMO

Intentional Non-orthogonality

Exploitation of power-domain, path loss difference among users, and UE processing power
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

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

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Antenna element spacing (λ)</th>
<th>Cell range extension</th>
<th>Improved spectrum efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5 (λ = 8.6 cm)</td>
<td>0.7 λ</td>
<td>9</td>
<td>81</td>
</tr>
<tr>
<td>10 (λ = 3 cm)</td>
<td>0.7 λ</td>
<td>9</td>
<td>81</td>
</tr>
</tbody>
</table>

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

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 bottlenecks due to frequent visits to signaling-BSs (main difference from BCGN2), 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?
  - 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

<table>
<thead>
<tr>
<th>Single-Band</th>
<th>Multi-band</th>
</tr>
</thead>
<tbody>
<tr>
<td>2GHz band</td>
<td>60GHz band</td>
</tr>
<tr>
<td>Macro:</td>
<td>Macro:</td>
</tr>
<tr>
<td>Center freq:2GHz</td>
<td>Center freq:2GHz</td>
</tr>
<tr>
<td>BW: 2GHz 10MHz</td>
<td>BW: 10GHz 10MHz</td>
</tr>
<tr>
<td>Tx power: 46dBm</td>
<td>Tx power: 46dBm</td>
</tr>
<tr>
<td>Small cell:</td>
<td>Small cell:</td>
</tr>
<tr>
<td>Center freq:2GHz</td>
<td>Center freq:60GHz</td>
</tr>
<tr>
<td>BW: (1-p)10MHz</td>
<td>BW: 2.16GHz</td>
</tr>
<tr>
<td>Tx power: 24dBm</td>
<td>Tx power: 10dBm</td>
</tr>
</tbody>
</table>

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, ...)

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.
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 improvements)
- 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 multi-homing 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 (W3WWW) (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

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
START
Measure instantaneous CCI power of each available channel
CCI power averaging[3]
Channel priority update
Next timeslot

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

\[ \text{Inst. CCI power at time } t \]

Ch Ave. CCI Power

Channel Priority Table of m-th AP

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

Background (3/4)
IACS-DCA[1][2]
Algorithm
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Measure instantaneous CCI power of each available channel
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Ch Ave. CCI Power

Channel Priority Table of m-th AP

A channel reuse pattern with a low CCI condition can be formed in a distributed manner[1][2]
**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 \( N \) 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 \( N \) 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.
### 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 \(r=1\text{~}2000\) timeslots of IACS-DCA
- STA position and fading do not change on each simulation run

#### Proposed Algorithm vs. Conv. IACS-DCA

<table>
<thead>
<tr>
<th>Channel (both for beacon signal and uplink STA-AP)</th>
<th>Shadowing loss Standard Deviation</th>
<th>(\alpha=5) (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Path loss exponent</td>
<td>(\alpha=3.5)</td>
<td></td>
</tr>
<tr>
<td>Fading type</td>
<td>(L=16)-path static frequency-selective Rayleigh</td>
<td></td>
</tr>
<tr>
<td>Power delay profile</td>
<td>Sampling interval-spaced uniform</td>
<td></td>
</tr>
<tr>
<td>Number of channels</td>
<td>(N_c=4)</td>
<td></td>
</tr>
<tr>
<td>Forgetting factor of first order averaging filter</td>
<td>(\beta=0.99)</td>
<td></td>
</tr>
<tr>
<td>Timeslots of each simulation run</td>
<td>2000</td>
<td></td>
</tr>
<tr>
<td>Number of simulation runs</td>
<td>1000 (on each simulation run, path loss &amp; shadowing conditions are set constant)</td>
<td></td>
</tr>
<tr>
<td>Total cellular areas</td>
<td>100 areas (36 areas of interest)</td>
<td></td>
</tr>
<tr>
<td>Transmission</td>
<td>OFDM with (N_c=4) subcarriers</td>
<td></td>
</tr>
<tr>
<td>Transmit power</td>
<td>(interference-limited)</td>
<td></td>
</tr>
<tr>
<td>STA per cell</td>
<td>1 (randomly generated in each cell)</td>
<td></td>
</tr>
<tr>
<td>No. of AP candidate(s) per STA</td>
<td>(N_t=1,2,3) (each AP has 1 antenna)</td>
<td></td>
</tr>
<tr>
<td>Transmission request probability</td>
<td>(p_u=1)</td>
<td></td>
</tr>
</tbody>
</table>

### Computer Simulation

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

- 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

### AP Cooperative Diversity for Network with IACS-DCA

#### 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
  - 1 AP w/ highest received beacon power among candidates is set as master AP
  - 1 STA is located on each cell randomly
  - 1 STA with the lowest received beacon signal power
  - Vacant channel w/ highest priority on master AP is selected for the group

#### 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)
- AP is removed from the group
- There is not any vacant channels on the APs in group candidate
- The STA’s request is blocked

### MRC diversity

- MRC diversity\(^{[7]}\) carried out on network side

- 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

#### IACS-DCA

- AP selection based on instantaneous beacon power (path loss & shadowing loss are considered)
- MRC diversity with max diversity order \(N_t\)
Energy-Efficient Hyper-Dense Wireless Networks with Trillions of Devices

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

JUNO Project Timeline

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)

- 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.

Fuzzy Logic for Vertical Handover (2)

- 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

---

**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)

---

**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)

---

**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 its coverage.

*Our goal is to realize energy efficient self-organizing dense HetNets using non-cooperative games.*
Power Consumption Model

- Power consumption includes:
  - Backhaul power consumption
  - Transmit power and baseband components

- 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 $\epsilon$)

Cost function

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

- Utility function: $u_b(p(t))$ with weight parameters $\alpha_b, \beta_b$

- Network configuration: $P(t) = (P_1(t), \ldots, P_b(t), \ldots, P_B(t))$

- Transmission power of BS $b$: $P_b(t)$

- Load estimation: $S(t) = (S_1(t), \ldots, S_b(t), \ldots, S_B(t))$

- State of BS $b$: $S_b(t) = \{0, 1, 2\}$
  - $S_b(t) = 0$ means that BS $b$ is OFF.
  - $S_b(t) = 1$ means that BS $b$ is ON.
  - $S_b(t) = 2$ means that BS $b$ transmits extended power.

Load

The load of BS $b$ is given by following expression.

$$Q_b(x) = \int_{x \in L_b} Q_b(x) dx$$

- $Q_b(x)$: load density in BS $b$
- $\lambda_b(x)$: packet arrival rate in BS $b$
- $\mu_b(x)$: packet size of any UE in BS $b$
- $R_b(x)$: data rate in BS $b$
- $\gamma_b(x)$: channel gain from BS $b$ to UE on location $x$
- $h_b(x)$: noise variance from BS $b$ to UE on location $x$
- $N_b$ : noise variance

Definition of all parameters in the algorithm

Define all parameters in the algorithm before explaining the algorithm.

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\hat{u}_b(t)$</td>
<td>utility</td>
</tr>
<tr>
<td>$\hat{\pi}_b(t)$</td>
<td>regret ← calculated with $\hat{\pi}_b(t)$</td>
</tr>
<tr>
<td>$\pi_{b}(t)$</td>
<td>probability distribution ← calculated with $\hat{\pi}_b(t)$</td>
</tr>
<tr>
<td>$a_b(t)$</td>
<td>action ← decided by $\pi_{b}(t)$</td>
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<tr>
<td>$\hat{b}(x,t)$</td>
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</tr>
<tr>
<td>$b(x,t)$</td>
<td>UE association</td>
</tr>
</tbody>
</table>

relationship of $i$ and $a_b(t)$

1. $a_b(t)$
   - 1: OFF
   - 2: ON
   - 3: Extended Power
Algorithm

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

Step 1: Initial Setting

At first initial setting is done as below.

\[ \hat{u}_{b,j}(0) = 0, \quad \hat{r}_{b,j}(0) = 0, \quad t = 0 \]

BS $b$ does not need to obey its initial action $a_{b,0}(t)$ for the rest of the simulation.

\[ \rightarrow \text{BS } b \text{ can maximize the utility } u_b(\rho(t)) \]

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 $\pi_{b,i}(t-1)$.

\[ a_{b}(t) = f(\max(\pi_{b,i}(t-1))) \]

Example of action selection

Example of action

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

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

\[ \hat{\lambda}_b(t) = \hat{\lambda}_b(t-1) + v(t)(\rho_b(t-1) - \hat{\rho}_b(t-1)) \]

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

$\hat{\lambda}_b(t-1)$: transmitted information from BS1

$\hat{\lambda}_b(t)$: transmitted information from BS1
Step 5: Calculation of $b(x, t)$

UE at location $x$ connects to BS $b(x, t)$ according to the following UE association rule:

$$b(x, t) = \arg \max_{b \in B} \left( \delta_{b} + \epsilon_{b} \right) \beta_{b}(t)$$

- $\delta_{b}$: offset ($\epsilon_{b} = 1 - \rho_{b}^{\text{opt}}$)
- $\rho_{b}^{\text{opt}}$: the preferred load per BS $b$
- $\beta_{b}(t)$: the received signal power from BS $b$ of the UE in location $x$
- $\delta$: the coefficient

This determines the impact of load.

- $\rho_{b}^{\text{opt}}$: transmitted information from BS $b$
- $\beta_{b}(t)$: received information and estimated load

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)

FeICIC: Further-enhanced inter-cell interference coordination

PBS-2 Subframes

MBS Subframes

Reduced-power subframe
α: Power reduction factor

Schedule PMS-B in coordinated subframes 2, 6, 7

Schedule PMS-A in uncoordinated subframes

PBS-2 Subframes

Time

Frame Duration

Subframe Duration

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

HDHN Coverage with Rel-11 FeICIC

SBS: Small base station

eNB: Macrocell base station

FeICIC: Further-enhanced inter-cell interference coordination

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

Considered Rel-11 FeICIC with the following parameters: τ = 6 dB, α = 0.5, β = 0.5, ρ = 4 dB, ρ' = 12 dB, and P_t = 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

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

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
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
\[ R_n(k) = H_n(k)S(k) + N_n(k) \]
- \( H_n(k) \): The channel gain observed at \( m \)-th antenna
- \( S(k) \): The \( k \)-th subcarrier component of \( N_c \)-chip signal sequence
- \( N_n(k) \): The noise component

The equivalent channel gain after equalization
\[ \hat{H}(k) = \sum_{m=0}^{N_c-1} w_m(k)H_m(k) \]
- The channel gain observed at \( m \)-th antenna

The noise component after equalization
\[ \hat{N}(k) = \sum_{m=0}^{N_c-1} w_m(k)N_m(k) \]

Correlated Sources
- Assume that \( \{a_m^{(n)}(\alpha_m^{(n)})s_{n-m}, n = 1, \ldots, L_{p_i}\} \) is a cluster of \( L_{p_i} \) correlated sources impinging on the receiver antenna array where
  - \( a_m^{(n)}(\alpha_m^{(n)}) \): path gain of each correlated signal in the cluster
  - \( \alpha_m^{(n)} \): DOA of each correlated signal in the cluster

SINR Expression for Uplink SIMO SC-FDMA
The weight for user \( u_i \) at antenna \( n \) is given by
\[ W_{u_i,n}(\text{MMSE})(k) = \frac{H_{u_i,n}(k)}{\sum_{p=1}^{M_u-1} |H_{u_p,n}(k)|^2 + \frac{E_r}{N_0}} \]

SINR\text{\textsuperscript{Prk}} =
\[ \frac{P_{u_j}}{M_uN_0} \left| \sum_{i=0}^{M_u-1} \hat{H}_{u_i}(k) \right|^2 \]
\[ \sum_{i=0}^{M_u-1} \frac{P_{u_j}}{M_uN_0} \left| \sum_{k=0}^{M_u-1} \hat{H}_{u_i}(k) \right|^2 \]

Relationship between DOC and SINR Uplink
\[ \sin^2 \theta_{u_i} = 1 - \frac{1}{N_{p_i}} \mathbb{E}\left[ x_{u_i}^2 \right] \]
\[ = \frac{1}{N_{p_i}} \left[ 1 - \cos \left( \Phi_{u_i} \left( \sin(\phi^r) - \sin(\phi^s) \right) \right) \right] \]
\[ \Phi_{u_i} = \Phi_{u_i}^s = \Phi_{u_i}^r \]
\[ = 0 \]
\[ \mathbb{E}\left[ y_{u_i} \right] = \frac{P_{u_i} \mathbb{E}\left[ W_{u_i} H_{u_i}^t \right]}{\sum_{x_j \neq u_i, x_j \in G} P_{x_j} \mathbb{E}\left[ W_{x_j} H_{x_j}^t \right] + N_i \mathbb{E}\left[ W_{u_i} W_{u_i}^t \right]} \]
\[ = \frac{P_{u_i} \mathbb{E}\left[ W_{u_i} H_{u_i}^t \right]}{N_i \sum_{x_j \neq u_i} P_{x_j} + \sum_{x_j \neq u_i} \sum_{x_k \neq x_j, x_k \in G} P_{x_k} \cos \theta_{x_k}} + N_i P_{u_j} \]
Formulation of the optimization problem

- Optimization problem:

\[ \max \left\{ \frac{1}{N_c} \sum_{\delta \in \Delta} \sum_{\nu \in M_{\delta}} \log_2(1 + \gamma_{\delta,\nu}) \right\} \]

- Subject to:

\[ \begin{align*}
M_{\delta} &= N_{\delta}, & \text{(1)} \\
U_{\delta} &= U, & \text{(2)} \\
0 &< U_{\delta} \leq N_{\delta}, & \text{(3)} \\
P_{\nu} &\leq P_{\delta}, & \sum_{\nu \in M_{\delta}} P_{\nu} \leq P & \text{(4)} \\
\end{align*} \]

- Total number of subcarriers
- Total number of users
- Size of each RB
- SINR of user \( u_i \)
- Total number of users on \( \delta \)th RB
- Total transmit power on \( \delta \)th RB
- Total transmit power of the system

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

Very high computational complexity because of exhaustive search.

Proposed adaptive scheduling and RA algorithm for \( U/\Delta \geq 1 \)

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

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

3. **Step 3**
   - Fairness adjustment.

Simulation Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data modulation</td>
<td>QPSK</td>
</tr>
<tr>
<td>Number of resource blocks</td>
<td>( \Delta = 1 \sim 8 )</td>
</tr>
<tr>
<td>FFT/IFFT size</td>
<td>( N_c = 256 )</td>
</tr>
<tr>
<td>Total Number of users</td>
<td>( U = 1 \sim 16 )</td>
</tr>
<tr>
<td>Total Transmit SNR</td>
<td>( E_s/N_0 = 0 \sim 20dB )</td>
</tr>
<tr>
<td>Transmit Power Control</td>
<td>Slow TPC</td>
</tr>
<tr>
<td>Fading type</td>
<td>Frequency-selective block Rayleigh</td>
</tr>
<tr>
<td>Power delay profile</td>
<td>( L = 16 )-path uniform power delay profile</td>
</tr>
<tr>
<td>Time delay</td>
<td>( \tau_{ij} = I, I = 0 \sim L - 1 )</td>
</tr>
<tr>
<td>Number of receive antennas</td>
<td>( N_r = 1 \sim 8 )</td>
</tr>
<tr>
<td>Equalization Type</td>
<td>MMSE-FDE</td>
</tr>
<tr>
<td>Channel estimation</td>
<td>Ideal</td>
</tr>
</tbody>
</table>
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, \( \Delta \), for which spectral efficiency maximizes.

Simulation results 2

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.

Simulation results 4

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

Fairness index vs average received SNR for different RB sizes and \( N_r=6, \ U=32 \) (with scheduling).
Simulation results 5

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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