Spectrum-Energy Efficiency of Wireless Networks

Fumiyuki Adachi (安達文幸), Distinguished Professor
Wireless Signal Processing & Networking (WSP&N) Lab.,
Dept. of Communications Engineering, Graduate School of Engineering,
Tohoku University, Japan
E-mail: adachi@ecei.tohoku.ac.jp
http://www.mobile.ecei.tohoku.ac.jp/

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OUTLINE
- Wireless Evolution
- Challenges for 5G Wireless
- Toward Green Wireless
- Concluding Remarks
Wireless Evolution
Wireless Has Been Continuously Evolving

- In early 1980’s, communications systems changed from fixed “point-to-point” to wireless “anytime, anywhere” communication.
- 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).

**Diagram:***

- **0G**: Voice only, point-to-point communication.
- **1G**: Narrowband Era, ~2.4kbps ~64kbps.
- **2G**: Wideband Era, ~2Mbps.
- **3G**: 3.5G ~14Mbps, 3.9G 50~100Mbps.
- **4G**: 100M~1Gbps >1Gbps.
- **5G**: Gigabit wireless.

**Timeline:**

- 1980: Analog AMPS TACS NTT
- 1990: Digital IS95 IS136 GSM PDC
- 2000: W-CDMA (W-CDMA)
- 2010: HSDPA 3G LTE
- 2020: We are here (LTE-A)
Wireless Has Been Continuously Evolving

- There was a big technical leap from 2G to 3G systems.

**Voice + data**

- 1G Analog (FDMA) ~2.4kbps
- 2G Digital (TDMA) ~64kbps

**Voice + Data**

- 3G/3.5G Digital (CDMA) ~2Mbps ~14Mbps
- 3.9G (3G LTE) 4G (LTE-A)

Improved frequency utilization

- **Narrowband** Increased no. of voice-band channels
- **Broadband** Increased peak rate (increased throughput)

<table>
<thead>
<tr>
<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>Down</td>
<td>Up</td>
</tr>
<tr>
<td>14.4 Mbps</td>
<td>14.4 Mbps</td>
<td>75 Mbps</td>
</tr>
</tbody>
</table>
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
Networked Society

- People are always connected to networks
- Society is relying on communications networks
- Unlimited desire for data rate, but limited wireless resources and a wide range of mobility
Future Wireless Services

Cloud Computing Network

A variety of data services through Internet

Wireless Access Network

Gigabit wireless pipe (>1Gbps/user)

User terminals with high quality display and gigabit wireless processing

Problems
- Limited bandwidth
- Limited power
Explosive Growth of Mobile Traffic (x1,000 in 10 years)

Traffic volume

2010 2015 2020

3G/HSPA (14Mbps) ×1
3.9G/LTE (300Mbps) ×20
4G/LTE-A (3Gbps) ×220

Technology Evolution

Voice << Data
Voice = Data
Voice >> Data

Video

×1000
5G Target

- The available bandwidth and power are limited
- The ultimate goal of wireless technology is to provide high data rate services uniformly over an area with as narrow bandwidth and low energy as possible

<table>
<thead>
<tr>
<th>1G Analog (FDMA)</th>
<th>2G Digital (TDMA)</th>
<th>Big leap</th>
<th>3G/3.5G Digital (CDMA)</th>
<th>3.9G (3G LTE)</th>
<th>4G (LTE-A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>~2.4kbps</td>
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<td>~14Mbps</td>
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<td>14.4 Mbps</td>
<td>14.4 Mbps</td>
<td>75 Mbps</td>
</tr>
<tr>
<td>15bps/Hz</td>
<td>30bps/Hz</td>
<td></td>
</tr>
</tbody>
</table>

5G
Spectrum and energy efficient green wireless
Important Technical Issues

- **Spectrum issue**
  - MIMO antenna multiplexing to increase bps/Hz
    - But, more importantly
    - Frequency reuse to increase bps/Hz/BS or bps/Hz/km²

- **Energy issue**
  - Single-carrier waveform with reduced peak power
  - But, this is not enough

- **Doubly-selective channel issue**
  - Frequency-selective channel: frequency-domain equalization (FDE)
  - Time-selective channel: Higher frequency band will be used → Quite high tracking ability against high Doppler shifts is necessary
Challenges For 5G Wireless

- Spectrum Issue
- Energy Issue
- Channel Issue
Spectrum Issue
Limited Spectrum

- LTE-advanced (4G) networks are expected to provide broadband packet data services of up to 1Gbps. However, available bandwidth is limited.
  - In December 2007, ITU allocated 3.4~3.6GHz band for 4G services. Only 200MHz is available for global use.
  - This must be shared by at least 2 operators and by the up/down links.
  - 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 with least transmit power is demanded.
Frequency Reuse

- Because of limited available bandwidth, the same frequency must be reused
  - From the spectrum efficiency (bps/Hz/km²) point of view, the same frequency needs to be reused at locations as close as possible
  - Co-channel interference is a limiting factor on frequency efficiency
- Co-channel interference management becomes a crucial issue to realize spectrum efficient broadband networks
Cellular Spectrum Efficiency

- Reuse of the same frequency causes serious CCI problem
- Cellular spectrum efficiency definition

\[ \eta_{se}(\text{bps/Hz} \cdot \text{km}^2) = \frac{1}{F} \times \log_2 (1 + SINR) \times \frac{1}{S} \]

Spectrum efficiency (bps/Hz)

\[ F = \frac{1}{3} \left( \frac{D}{R} \right)^2 \]

\[ = i^2 + j^2 + ij = 1, 3, 4, 7, 9, \ldots \]
Peak data rate per BS

$$\text{Total bandwidth } B(\text{Hz}) \times \eta_{se} (bps / Hz \cdot km^2) \times \text{Cell area } S(\text{km}^2)$$

However, the available bandwidth $B$ may be around 100MHz only

How to improve SE?
- MIMO may be a savior
MIMO May Be A Savior

- Independent data streams are transmitted simultaneously from transmit antennas using the same carrier frequency.
- Spatial multiplexing is to increase achievable data rate with the limited bandwidth, i.e., the channel capacity in bps/Hz.
MIMO can improve SE in linear proportion to the number of antennas

\[ \eta_{se} \leq \frac{1}{F} \times \min \{N_t, N_r\} \log_2 \left( 1 + \frac{\Lambda}{N_t \min \{N_t, N_r\}} \sum_{n_r=0}^{N_r-1} \sum_{n_t=0}^{N_t-1} |h_{n_r,n_t}|^2 \right) \times \frac{1}{S} \]

\[ \rightarrow \frac{1}{F} \times \min \{N_t, N_r\} \log_2 \left( 1 + \Lambda \frac{N_r}{\min \{N_t, N_r\}} \right) \times \frac{1}{S} \text{ if } N_t, N_r \gg 1 \]

Problem is how to implement many antennas in a hand portable unit?

\(N_t\) and \(N_r\) are numbers of transmit and receive antennas, respectively
Wearable Antenna

- How to implement many antennas in a hand portable unit?
- Wearable antenna on your head?

No space available at a small hand portable unit

Wearable antenna
However, MIMO Cannot Solve Energy Issue

Transmit power is another important issue

\[
\eta_{se} \leq \frac{1}{F} \times \min\{N_t, N_r\} \log_2 \left(1 + \frac{\Lambda}{N_t} \frac{1}{\min\{N_t, N_r\}} \sum_{n_r=0}^{N_r} \sum_{n_t=0}^{N_t-1} |h_{n_r, n_t}|^2 \right) \times \frac{1}{S}
\]

\[
\rightarrow \frac{1}{F} \times \min\{N_t, N_r\} \log_2 \left(1 + \frac{\Lambda}{\min\{N_t, N_r\}} \right) \times \frac{1}{S} \text{ if } N_t, N_r >> 1
\]

Transmit SINR

\[
\Lambda_t = \Lambda \times d_{bs\rightarrow mt}^\alpha \times 10^{-\chi/10},
\]

where \(d_{bs\rightarrow mt}\) is the distance between BS and MT, \(\alpha\) is the path loss exponent and \(\chi\) is the shadowing loss in dB.
Energy Issue
Communication Range Shrinks

- For broadband communications, communication range shrinks significantly because of the transmit power limitation.
- Fundamental change is necessary in wireless access network.
Uniform Quality Is The Target

- Uniform quality over an BS area

Graph showing throughput vs distance from BS, with a green arrow pointing to the curve for uniform quality over an BS area and a black arrow indicating the cell edge.
In LTE-A, the coordinated multi-point transmission (CoMP) will be introduced:
- Improved SINR (increased capacity) with limited transmit power for a user near the cell edge
- This is the first step towards the realization of distributed antenna network (DAN)
Green Wireless

- Until LTE, much effort has been paid to improving the SE
- Recently, strong attention has been paid not only to SE but also to EE
  - Future broadband wireless networks require significant improvement of both SE and EE
- How to simultaneously improve SE and EE?
SE and EE Formulation

- Spectrum and energy efficiencies (worst case) of cellular network w/o TPC

\[
\begin{align*}
\eta_{se} (\text{bps/Hz} \cdot \text{km}^2) &= \left[ \frac{1}{F} \times \log_2 \left( 1 + \frac{1}{\Gamma_r^{-1} + 6(\sqrt{3F} - 1)^{-\alpha}} \right) \right] \times \frac{1}{(3\sqrt{3}/2)R^2} \\
\eta_{ee} (b/J) &= \left[ \Gamma_r^{-1} \times \log_2 \left( 1 + \frac{1}{\Gamma_r^{-1} + 6(\sqrt{3F} - 1)^{-\alpha}} \right) \right] \times \frac{A \cdot T \cdot R^{-\alpha}}{N_0}
\end{align*}
\]

where

\[
\begin{align*}
\Gamma_r : \text{received SNR at cell edge given by } (A \cdot P_t \cdot T / N_0) \times R^{-\alpha} \\
A : \text{constant representing antenna gains and feeder loss, etc} \\
P_t : \text{transmit power per subcarrier} \\
T : \text{block length (1/T represents the subcarrier separation)} \\
R : \text{cell radius, } F : \text{cluster size for frequency reuse}
\end{align*}
\]
SE and EE Formulation

- Spectrum and energy efficiencies of cellular network \( w/ \) SNR-based TPC

\[
\eta_{se}(\text{bps/Hz} \cdot \text{km}^2) = \frac{1}{F} \times \log_2 \left(1 + \frac{1}{\Gamma_{tpc}^{-1} + (A^{-1}\beta)6(\sqrt{3F} - 1)^{-\alpha}}\right) \times \frac{1}{(3\sqrt{3}/2)R^2}
\]

\[
\eta_{ee}(b/J) = \left(\beta \Gamma_{tpc}\right)^{-1} \times \log_2 \left(1 + \frac{1}{\Gamma_{tpc}^{-1} + (A^{-1}\beta)6(\sqrt{3F} - 1)^{-\alpha}}\right) \times \frac{A \cdot T \cdot R^{-\alpha}}{N_0}
\]

with

\[
\beta = \exp\left(\frac{\sigma^2}{2} \cdot \left(\frac{\ln 2}{10}\right)^2\right) \times \frac{L}{M \cdot L - 1},
\]

where

- \( \Gamma_{tpc} \): SNR – based TPC target \( E_s/N_0 \), \( \sigma \): shadowing loss standard deviation
- \( A \): constant representing antenna gains and feeder loss, etc
- \( F \): cluster size for frequency reuse, \( M \): no. of receive diversity antennas
- \( L \): no. of propagation paths (frequency-selective channel)
SE-EE Tradeoff w/o TPC

- Cluster size $F=4$ seems to be the best

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

EE can be improved Without sacrificing SE

<table>
<thead>
<tr>
<th>$F$</th>
<th>SE-EE Tradeoff w/o TPC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$\Gamma_r=+40$dB</td>
</tr>
<tr>
<td>3</td>
<td>$\Gamma_r=+20$dB</td>
</tr>
<tr>
<td>4</td>
<td>Interference limited</td>
</tr>
<tr>
<td>7</td>
<td>$\Gamma_r=0$dB</td>
</tr>
<tr>
<td>9</td>
<td>Noise limited</td>
</tr>
</tbody>
</table>

SE can be improved without sacrificing EE

Energy Efficiency vs. Spectral Efficiency
Reducing the cell size (small-cell) is quite effective to improve both SE and EE

- Reducing the cell size by a factor of 10 leads to about 100 times improvement of SE
- With small cell size (i.e., $r=0.1R$), the EE can be improved without degrading the SE by reducing the transmit power
SE-EE Tradeoff w/ TPC

- TPC can improve the EE tradeoff significantly
- The best cluster size is still $F=4$
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
  - Reducing the cell radius by a factor of 30 (1,000m → 30m)
    - X1,000 capacity increase
    - Reduced transmit power by a factor of 150,000

- Small-cell network
  - Single-user access for increasing the bandwidth/user and hence, user data rate
  - Millimeter wave bands can be used
Small-cell Network

- Control traffic for location registration and handover may significantly increase
  - Radio control signaling becomes a heavy burden
Another Important Issue: Doubly-selective Channel

- Simple one-tap frequency-domain equalization (FDE) similar to OFDM
Doubly-selective Channel

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

- The transfer function $H(f, t)$ of broadband channel at time $t$ is not constant and varies over the signal bandwidth.
- This channel is called the frequency-selective channel.
- Advanced equalization technique is necessary.

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

$L=16$ uniform power delay profile with $l$-th path time delay $=100/l + [-50, 50)\text{ns}$
Why Single-carrier (SC) Transmission for Uplink?

- Nyquist-filtered SC signal has lower PAPR than OFDM
  - No ISI at the transmitted waveform due to Nyquist filtering
- SC is suitable for the uplink transmission
  - Less expensive power amplifier is required

Modulated carrier waveform

\[ \text{Re}[s(t) \exp(2\pi f_c t)] = \text{Re}[s(t)] \cos(2\pi f_c t) - \text{Im}[s(t)] \sin(2\pi f_c t) \]
SC-FDE

- Block transmission of $N_c$ symbols
- Insertion of cyclic prefix (CP) at the transmitter
- FFT/IFFT at the receiver
- Simple one-tap FDE


2014/02/04 FA/Tohoku University
SC-FDE

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

- Until LTE-A, only a spectrum efficiency has been focused on.
- However, energy efficiency has been 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.
Green Wireless

- High spectrum efficiency
  - Single-cell frequency reuse to boost bps/Hz/km$^2$
- High energy efficiency
  - A few mW for a few 10Mbps
- How to achieve the above?
  - Short range communication is the key
Let’s Learn From Human Being

- How can 7 billion people on the globe share the same bandwidth of around 5kHz for voice communication?
  - Super femto-cell structure → A few meters coverage
  - Low voice energy and interference suppression → Spreading factor (SF) = 5kHz/5symbols/s
    equivalent to SF = 1000

No coordination among people (SF = 1000)
Let’s Learn From Human Being

- Introduction of no or light coordination among users and super femto-cell structure may be able to achieve:
  - 1Msymbols/s/user (SF=\(~100\)) for an 100MHz bandwidth → 4Mbps/user using 16QAM around the world
  - Near 100Msymbols/s/user in an isolated area
Distributed Antenna Network

- Distributed MIMO technology
- Hybrid waveform with reduced peak power (extreme case is the single-carrier waveform)
- Frequency-domain signal processing (equalization)
Distributed Antenna Network

- Distributed antenna network (DAN) is designed to realize a nano-cell network with simultaneously increased spectrum and energy efficiencies.
- Many antennas belonging to a base station (SPC: signal processing center) are distributed around SPC.
- Each distributed antenna forms a cell
- Resource allocation control (frequency, time, power) is carried out by SPC.

Distributed Antenna Network

- Ubiquitous antennas as an entrance to core network

Co-located antennas
- Path loss
- Shadowing loss
- Multipath fading

Multi-access or Multi-user detection

Distributed antennas
- Path loss
- Shadowing loss
- Multipath fading

Single-user access
Short range communication combined with single-user access is the crucial requirement!

Many antennas are spatially distributed around a signal processing center (SPC), which is a gateway to the network:
- Antennas are connected with a SPC by optical links
- With a high probability, some antennas can always be visible from MT
Unlike the traditional cellular network, there is no cell boundary.
DAN Is Not Almighty

- DAN formulate user-centric personal cells
  - Short range communication link with almost single user access
  - Frequency reuse at short distance
- Role of signal processing center (SPC)
  - Density of SPCs is similar to traditional cellular network
  - Wireless signal processing such as space-time coding, equalization, etc
  - Resource allocation (frequency, time, power) to distributed antennas
- Coherent optical SPC-antenna links
  - Wireless and optical convergence on signal processing and communications
- However, traffic density is not uniform and hence, DAN is not almighty
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
Concluding Remarks

- 5G requires energy & spectrum efficient network
- Heterogeneous network is a realistic approach
  - Small-cell network to provide short range communications
    - High speed data services
    - Significantly reduced wireless energy
    - New frequency band e.g., millimeter wave bands
  - Large-cell network is still necessary
    - Call control signaling
    - High mobility users
    - M2M traffic (low data rate but millions of devices)
  - Improved dependability
    - Simultaneous operation of different types of networks

Acknowledgment

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