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Spectrum-Energy Efficiency of Wireless Networks

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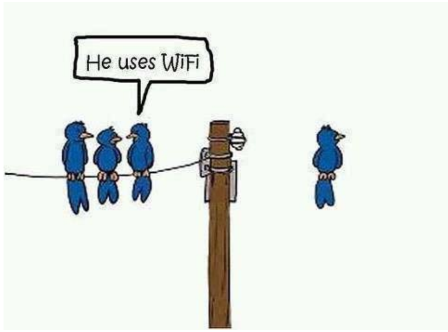


The secret to humor is surprise@Facebook
https://www.facebook.com/TSTHIS/photos_stream

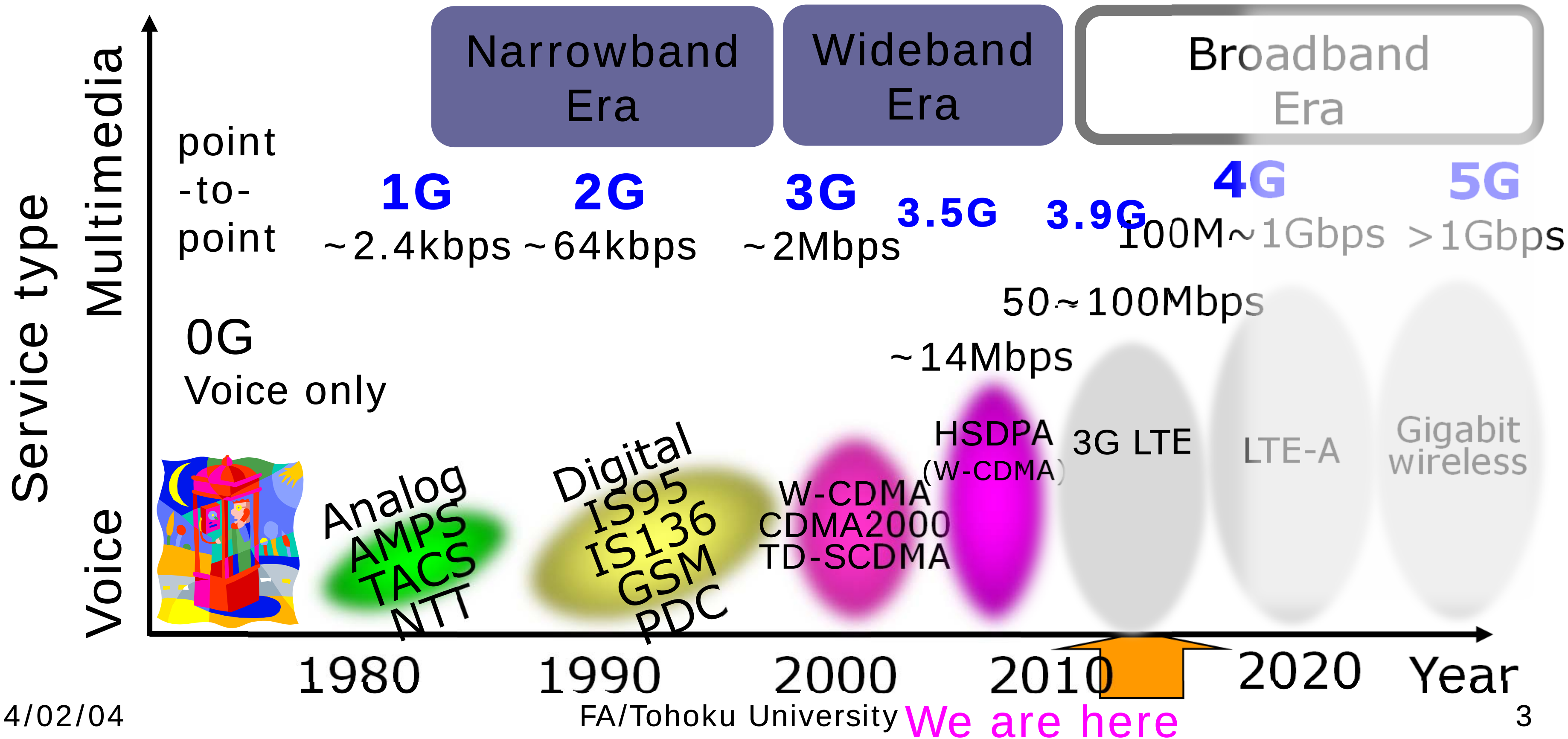
OUTLINE

- Wireless Evolution
- Challenges for 5G Wireless
- Toward Green Wireless
- Concluding Remarks

Wireless Evolution

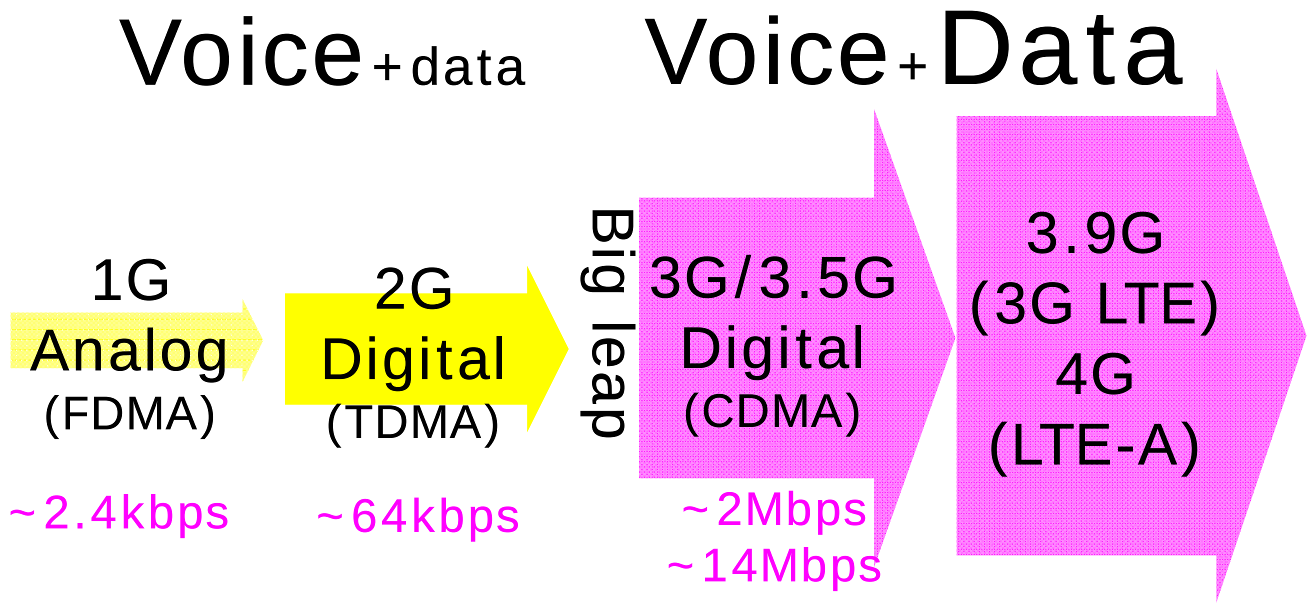
Wireless Has Been Continuously Evolving

- 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).



Wireless Has Been Continuously Evolving

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



Improved frequency utilization

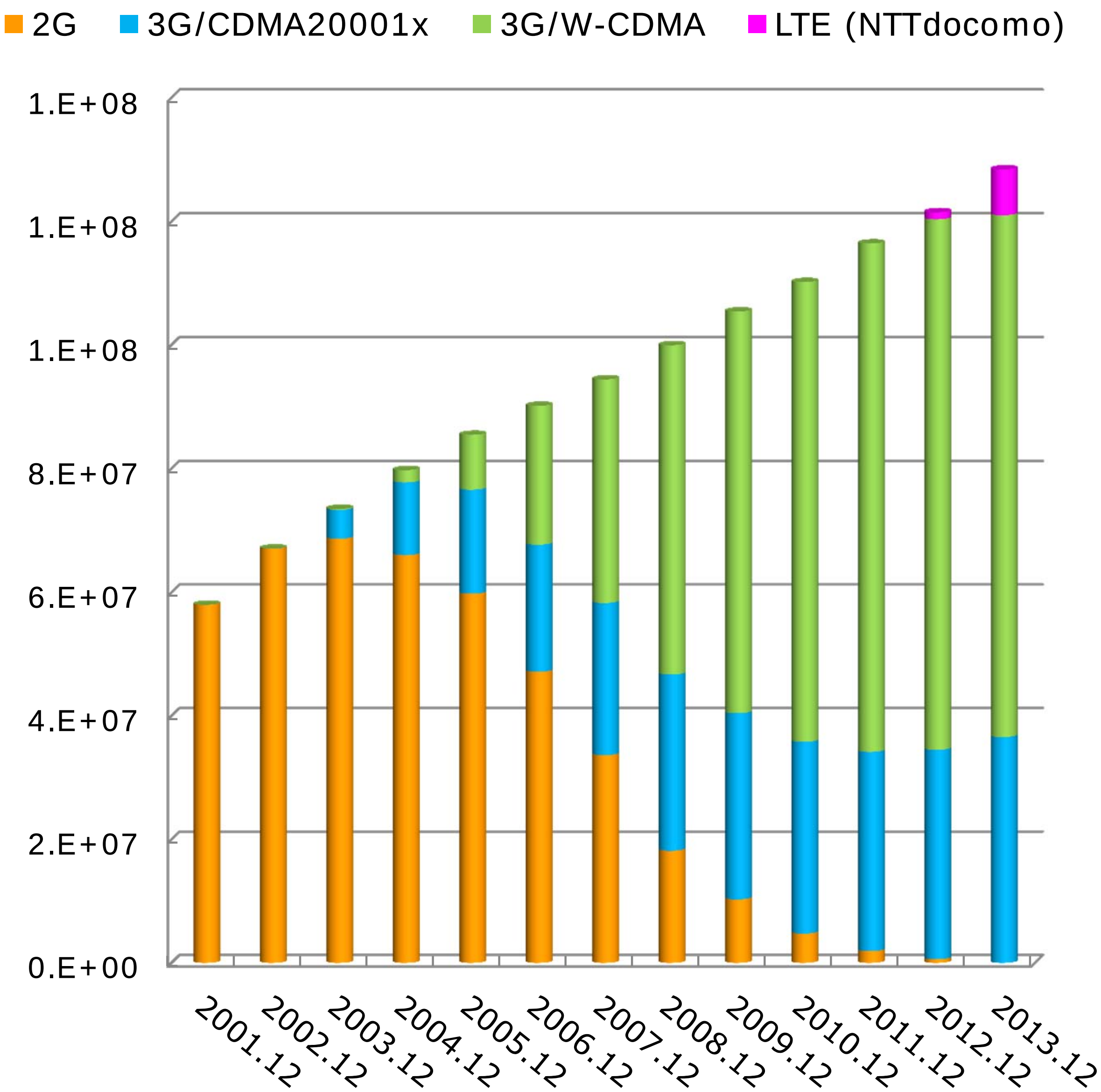
3.5G (HSPA,5MHz)		3.9G (LTE,~20MHz)		4G (LTE-A, ~100MHz)	
Up	Down	Up	Down	Up	Down
14.4 Mbps	14.4 Mbps	75 Mbps	300 Mbps	15bps /Hz	30bps /Hz

Narrowband → Broadband

Increased no. of voice-band channels → Increased peak rate (increased throughput)

On-going Shift To LTE (Japan)

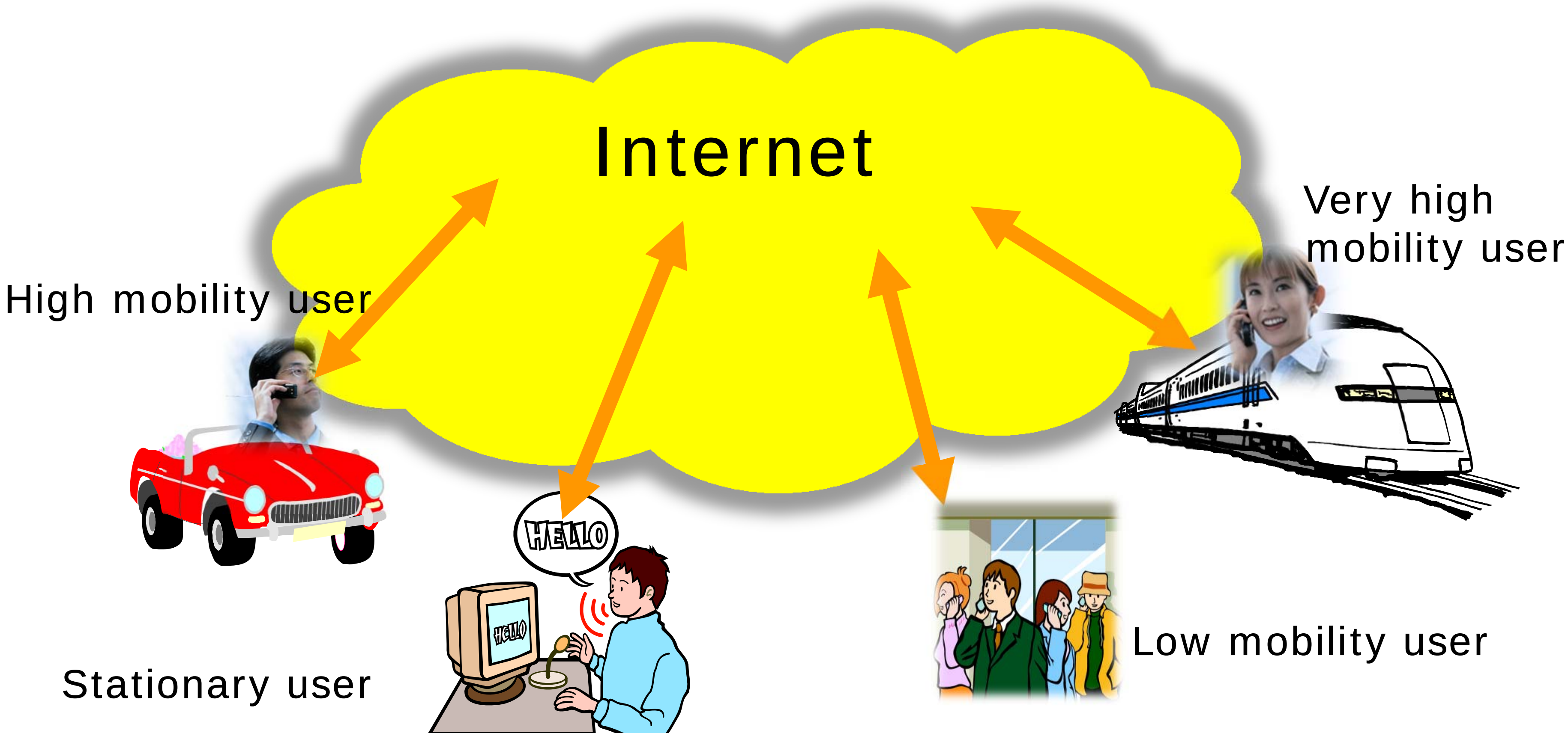
- Total no. of cellular subscribers@end of Dec. 2013(TCA)
  - 135,832,000 (penetration: 106.5%)
- 2G has disappeared
- 3G dominates the Japanese market
- LTE is rapidly spreading



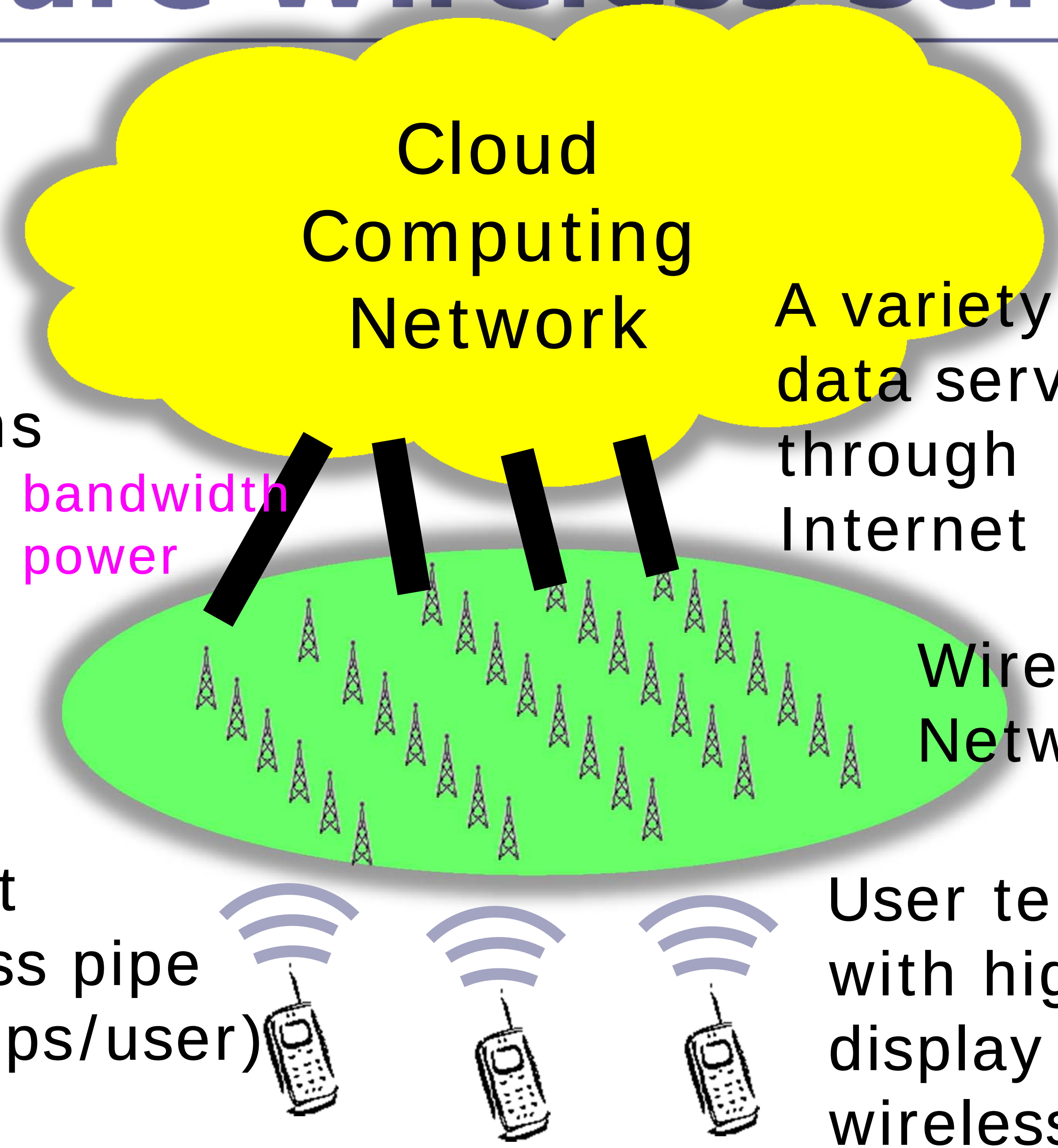
*Japanese population estimate@1 Aug. 2012:127.48M

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



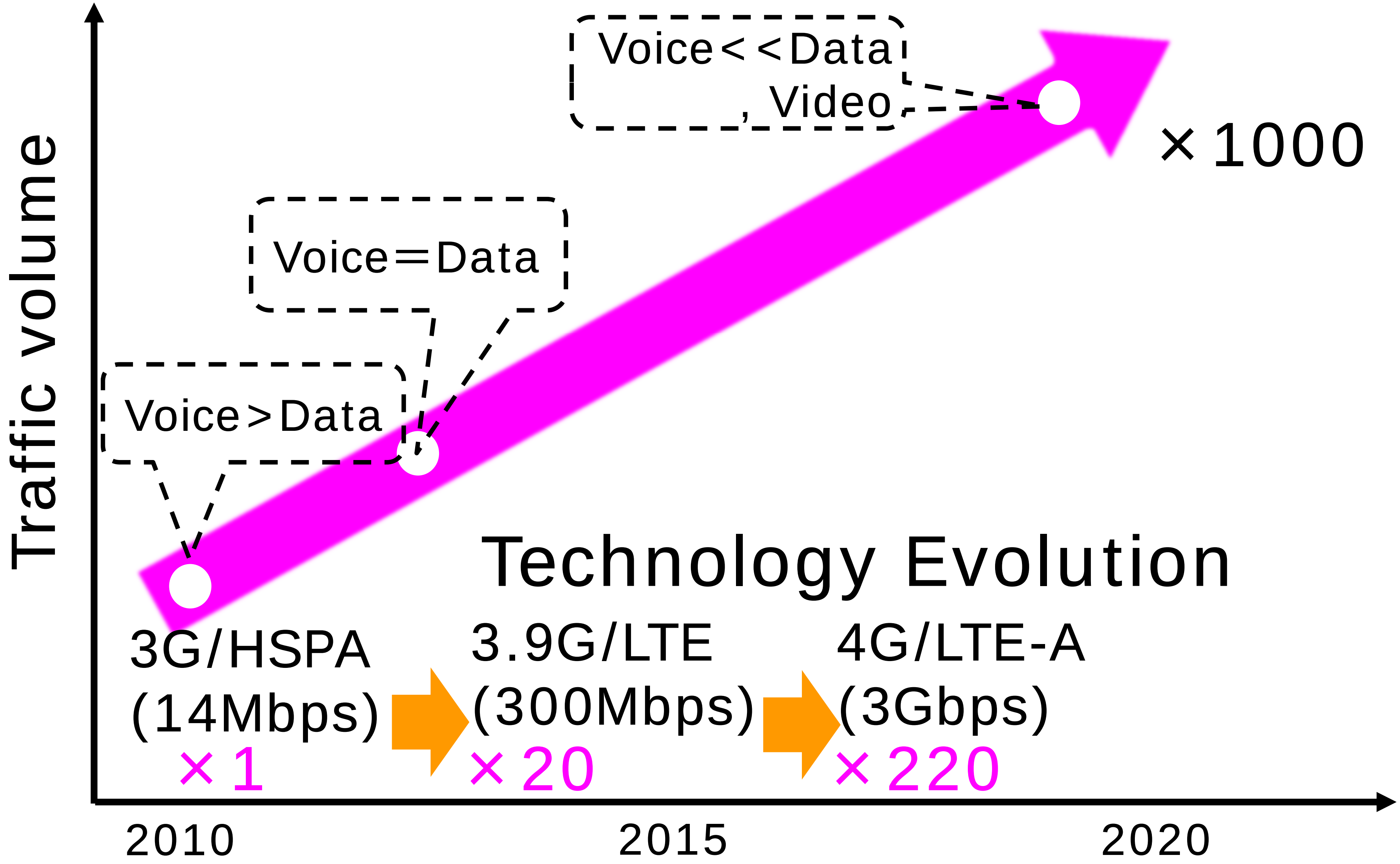
Future Wireless Services



Problems

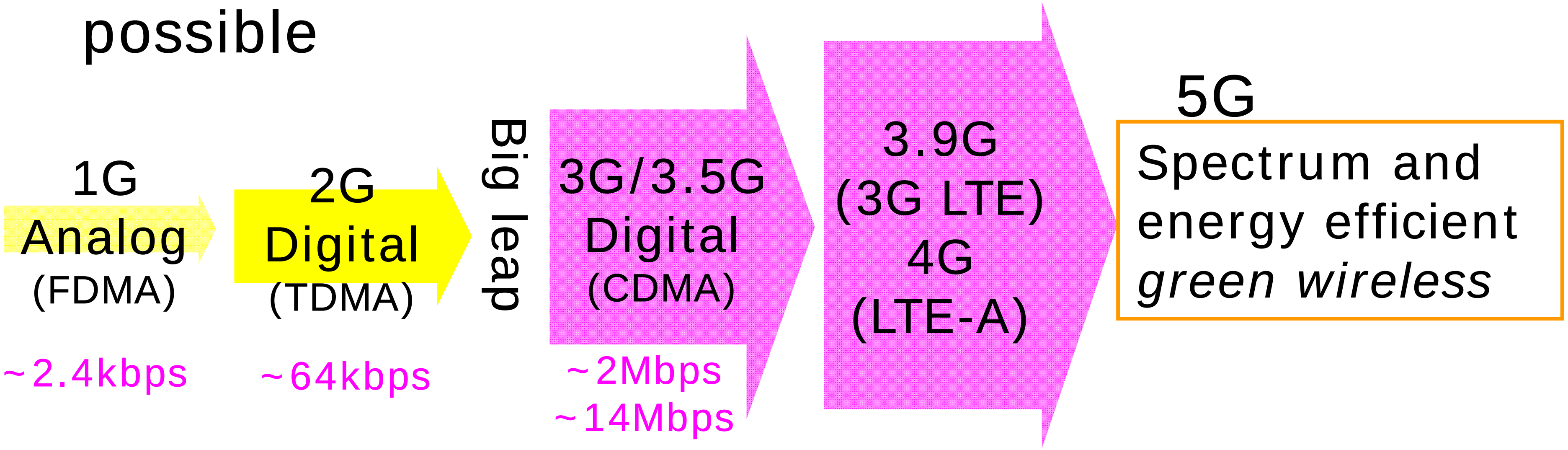
- Limited bandwidth
- Limited power

Explosive Growth of Mobile Traffic (x1,000 in 10 years)



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



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Up	Down	Up	Down	Up	Down
14.4 Mbps	14.4 Mbps	75 Mbps	300 Mbps	15bps/ Hz	30bps/ Hz

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/km^2
- 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/km^2) 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

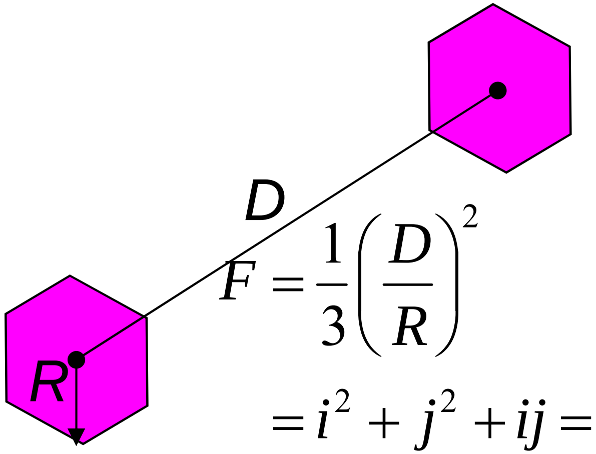
Cellular Spectrum Efficency

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

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

Spectrum efficiency (bps/Hz)

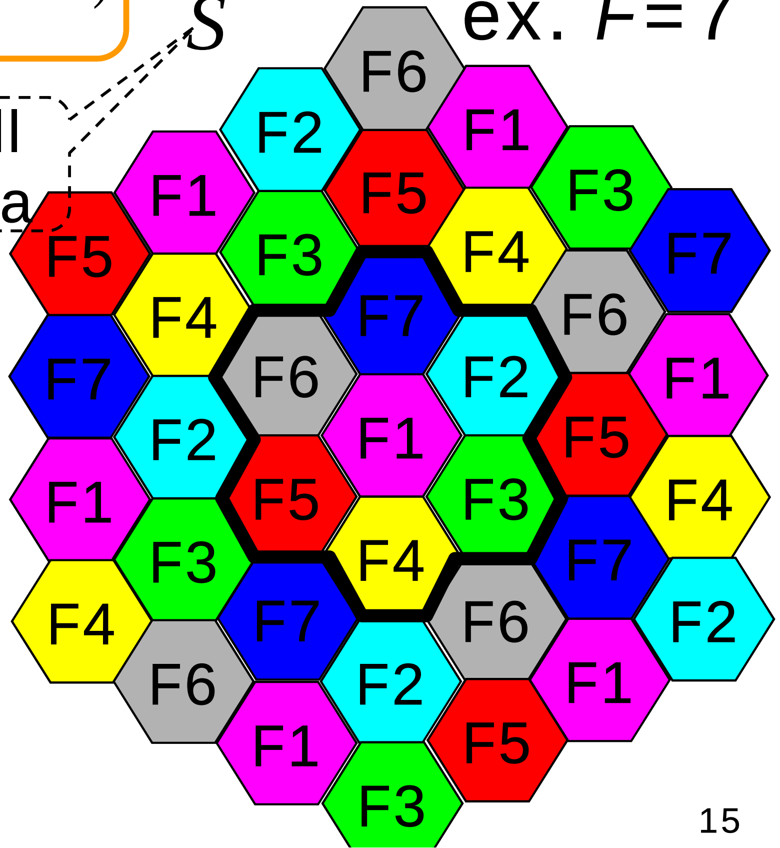
Cell area



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

$$= i^2 + j^2 + ij = 1,3,4,7,9\cdots$$

ex. F=7



- Peak data rate per BS

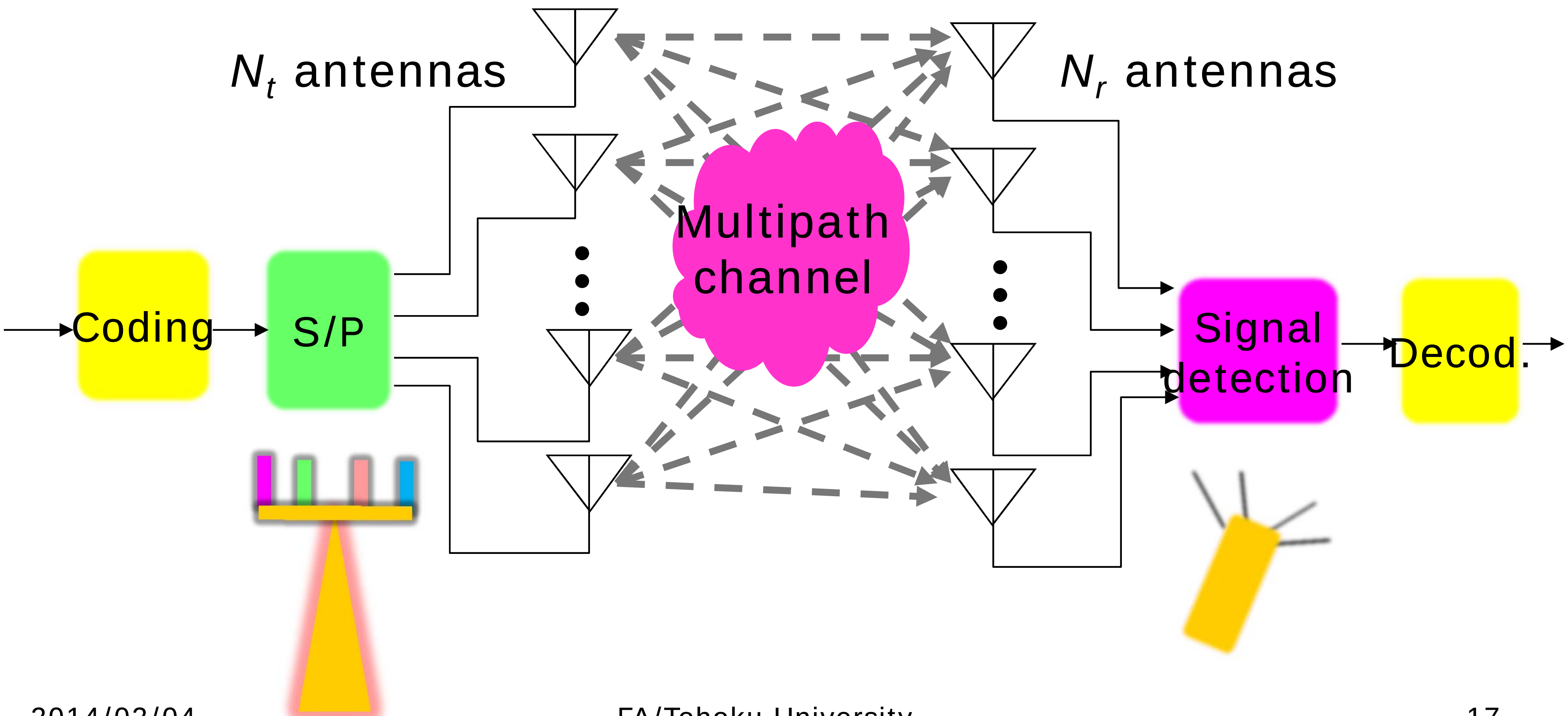
$$\text{Total bandwidth } B(\text{Hz}) \times \eta_{\text{se}}(bps/Hz \cdot km^2) \times \text{Cell area } S(\text{km}^2)$$

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

N_t and N_r are numbers of transmit and receive antennas, respectively

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

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

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

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

However, MIMO Cannot Solve Energy Issue

- Transmit power is another important issue

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

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Received SINR

<u>Transmit SINR</u>

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

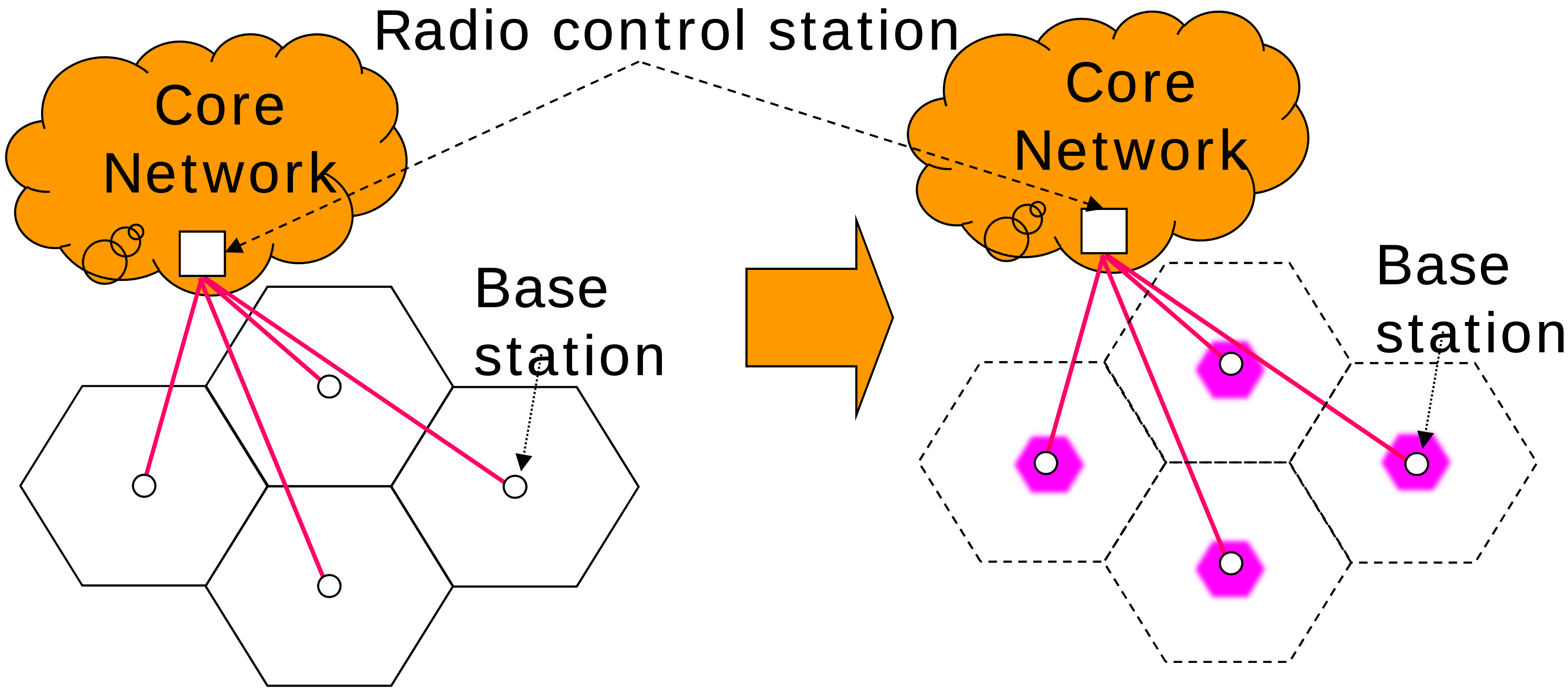
where d_{bs-mt} is the distance between BS and MT, α is the path loss exponent and χ is the shadowing loss in dB.

Distance between BS and MT

Energy Issue

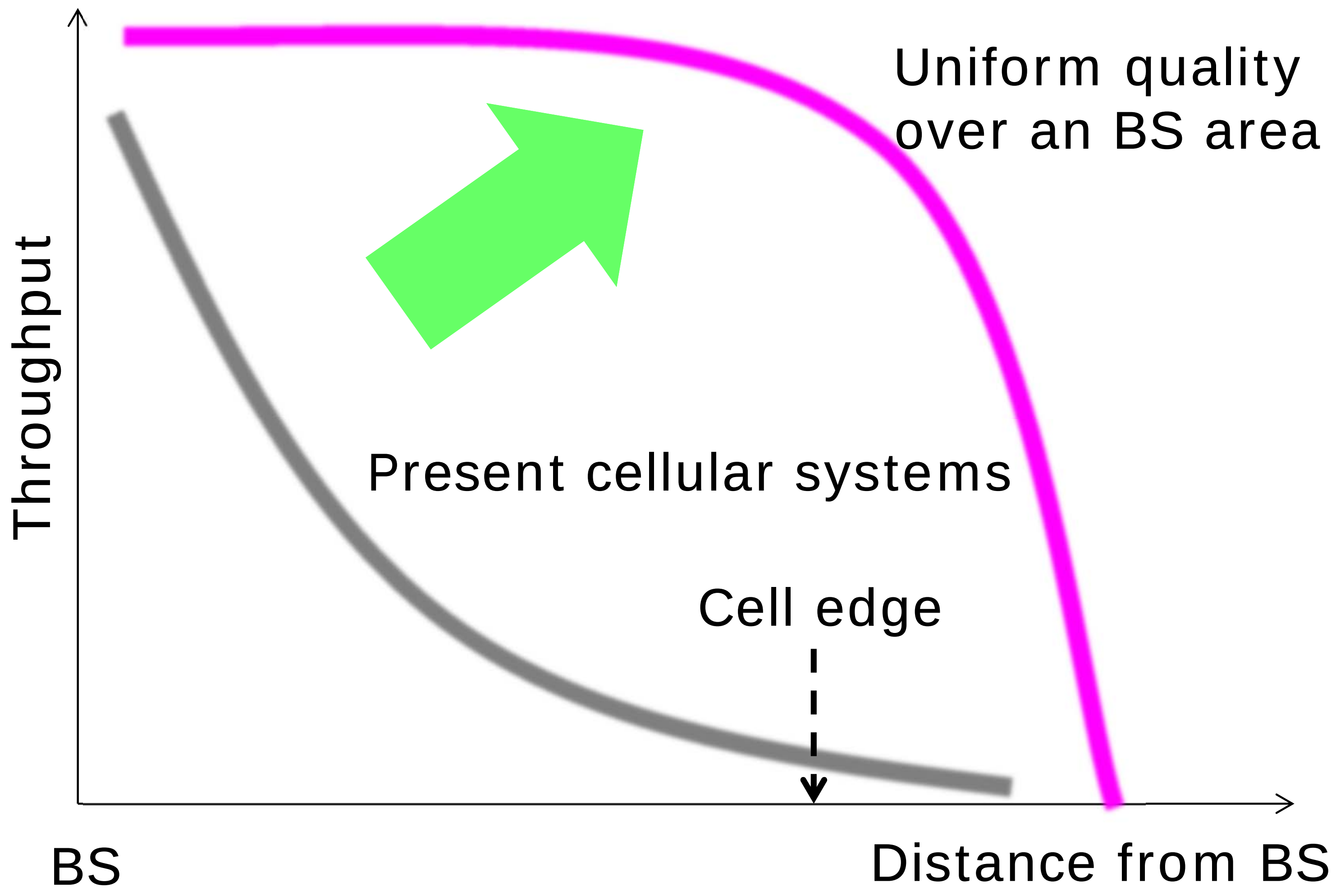
Communication Range Shrinks

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



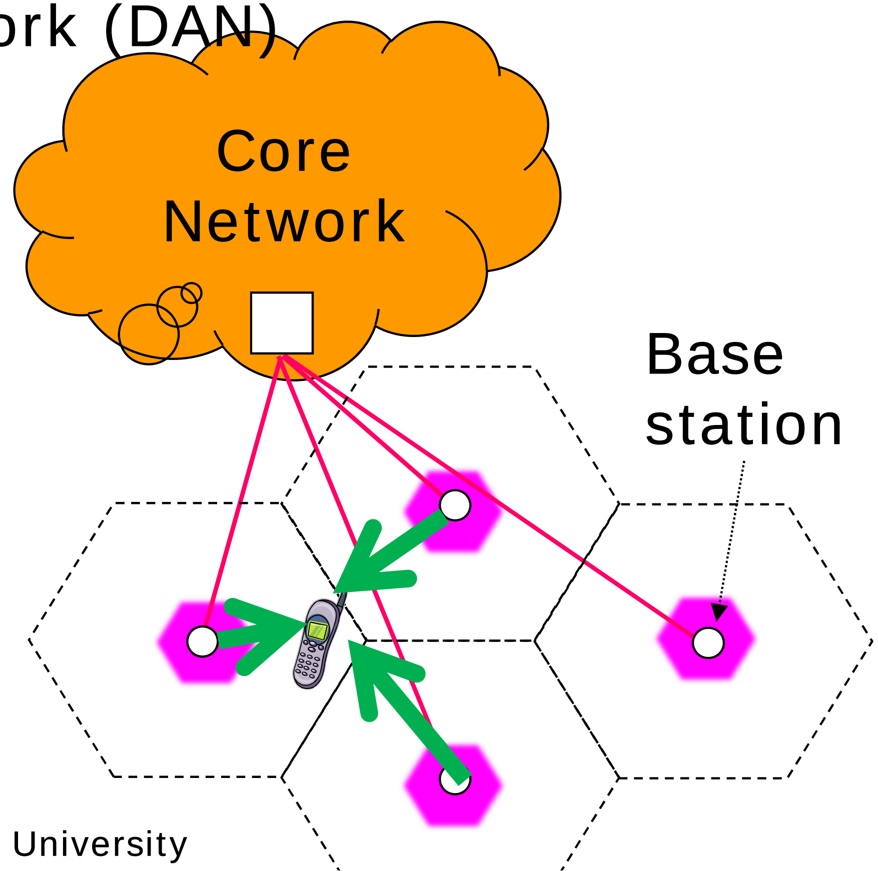
Uniform Quality Is The Target

- Uniform quality over an BS area



Coordinated Multi-point Transmission (CoMP)

- 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?

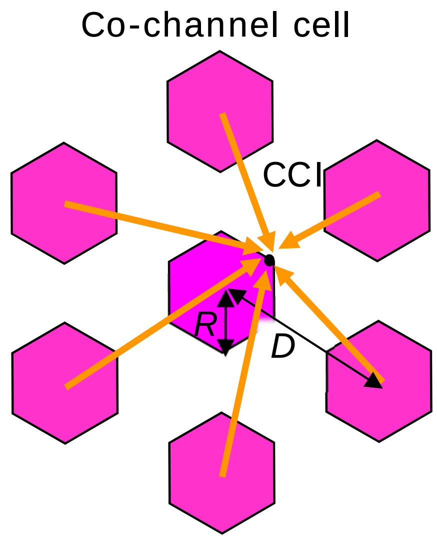
SE and EE Formulation

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

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

where

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



Simplified CCI model

SE and EE Formulation

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

$$\begin{cases} \eta_{se}(\text{bps/Hz}\cdot\text{km}^2) = \left[\dfrac{1}{F}\times\log_2\left(1+\dfrac{1}{\Gamma_{tpc}^{-1}+\left(A^{-1}\beta\right)6\left(\sqrt{3F}-1\right)^{-\alpha}}\right)\right]\times\dfrac{1}{(3\sqrt{3}/2)R^2} \\ \eta_{ee}(\text{b/J}) = \left[\left(\beta\Gamma_{tpc}\right)^{-1}\times\log_2\left(1+\dfrac{1}{\Gamma_{tpc}^{-1}+\left(A^{-1}\beta\right)6\left(\sqrt{3F}-1\right)^{-\alpha}}\right)\right]\times\dfrac{A\cdot T\cdot R^{-\alpha}}{N_0} \end{cases}$$

with

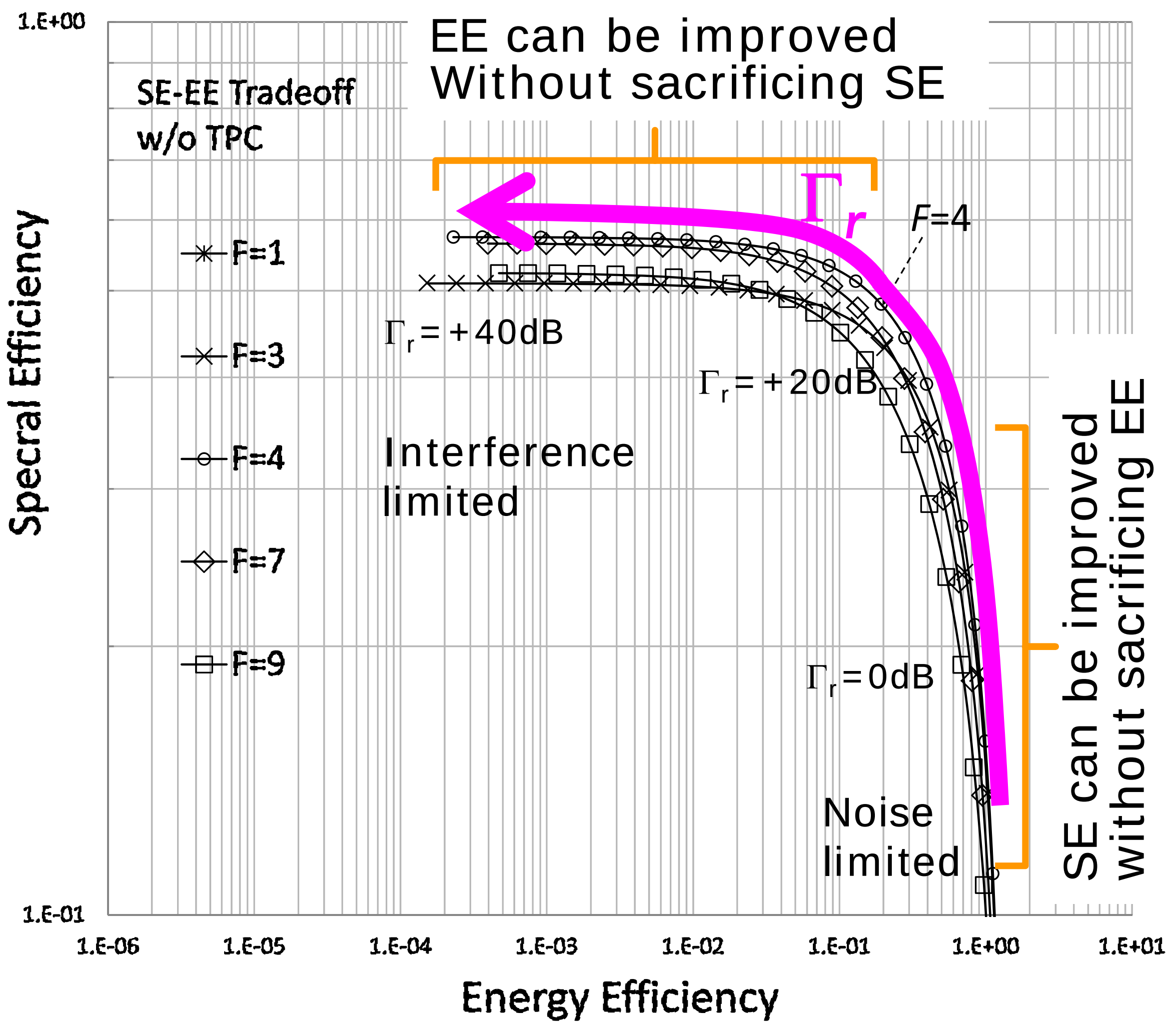
$$\beta = \exp\left(\frac{\sigma^2}{2}\left(\frac{\ln 2}{10}\right)^2\right)\times\frac{L}{M\cdot L-1},$$

where

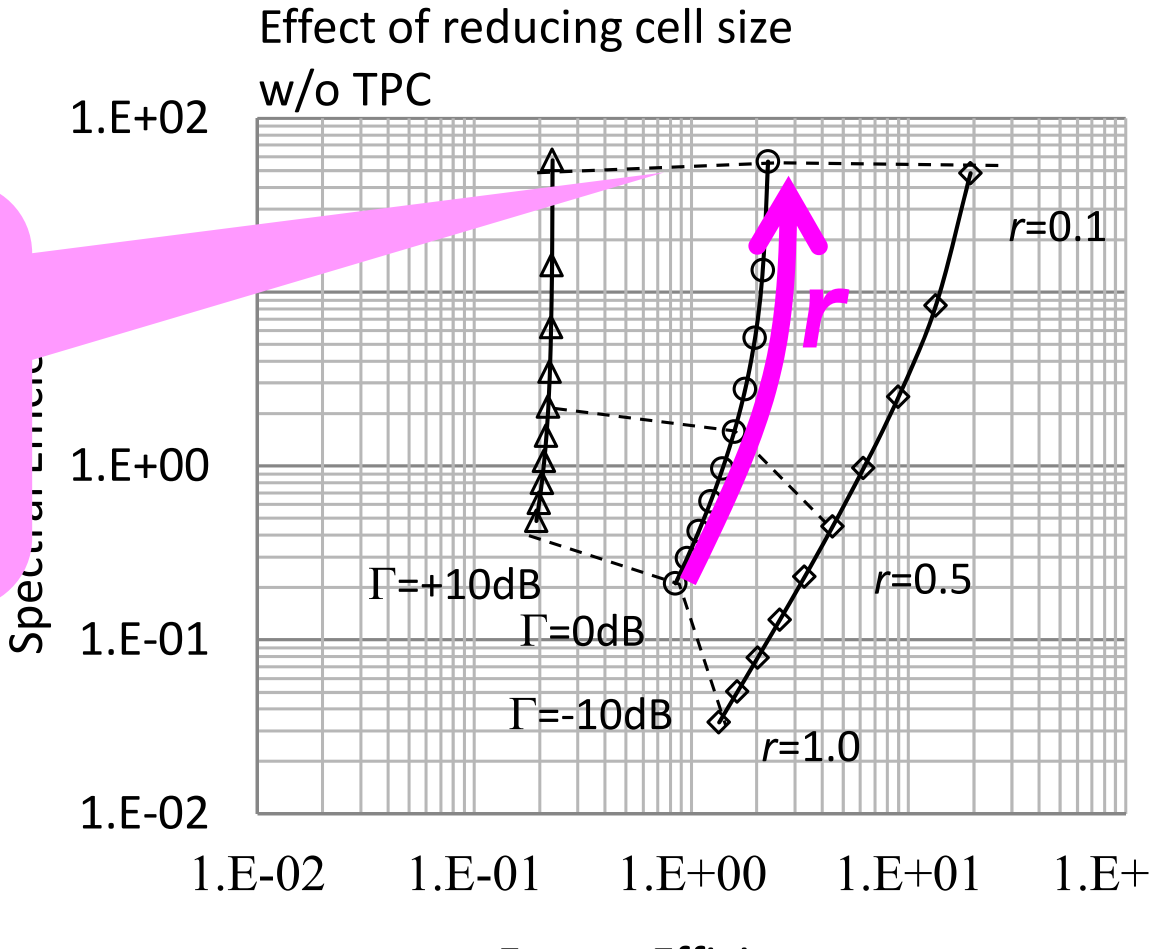
$$\begin{cases} \Gamma_{tpc}:\text{SNR}-\text{based TPC target } E_s/N_0,\ \sigma:\text{shadowing loss standard deviation} \\ A:\text{constant represnenting antenna gains and feeder loss, etc} \\ F:\text{cluster size for frequency reuse},\ M:\text{no. of receive diversity antennas} \\ L:\text{no. of propagation paths (frequency - selective channel)} \end{cases}$$

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

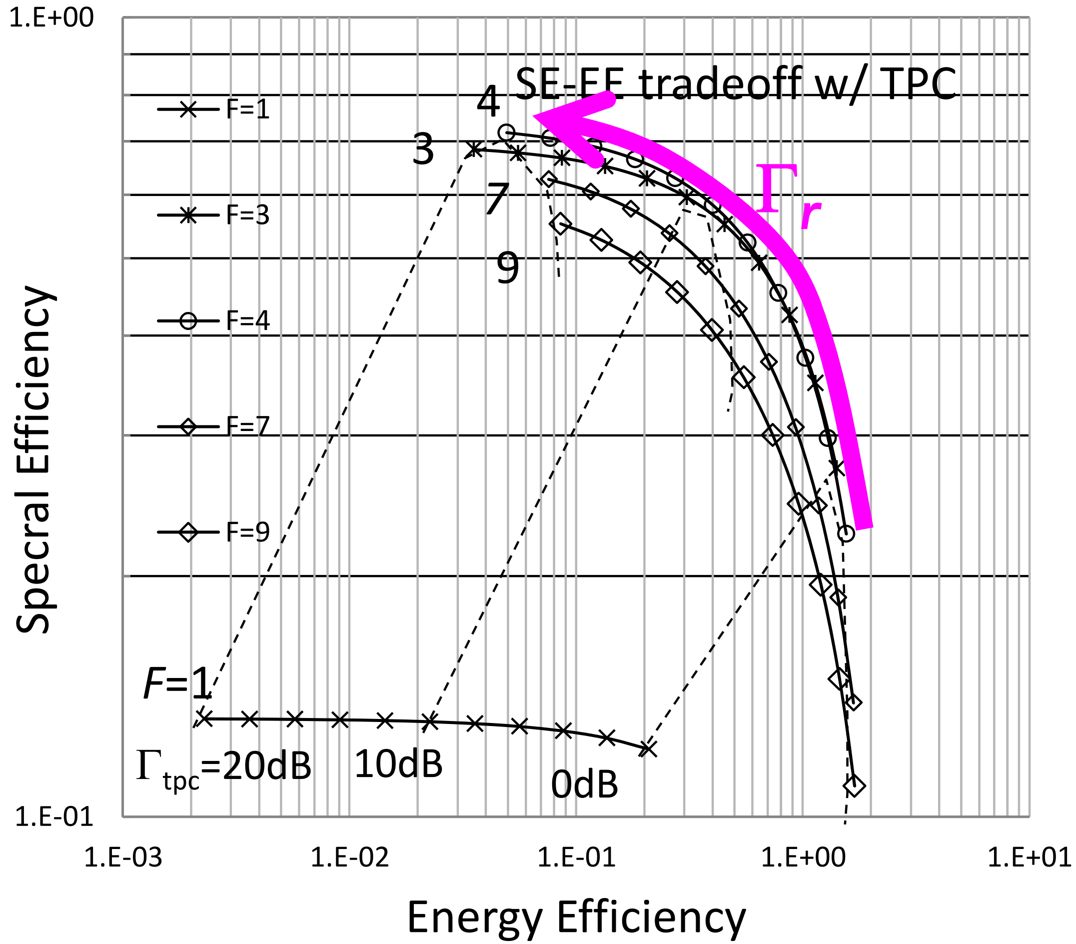


- Reducing the cell size (small-cell) is quite effective to improve both SE and EE
  - Reducing the cell size by a factor of 10 leads to about 100 times improvement of SE
  - With small cell size (i.e., r=0.1R), the EE can be improved without degrading the SE by reducing the transmit power

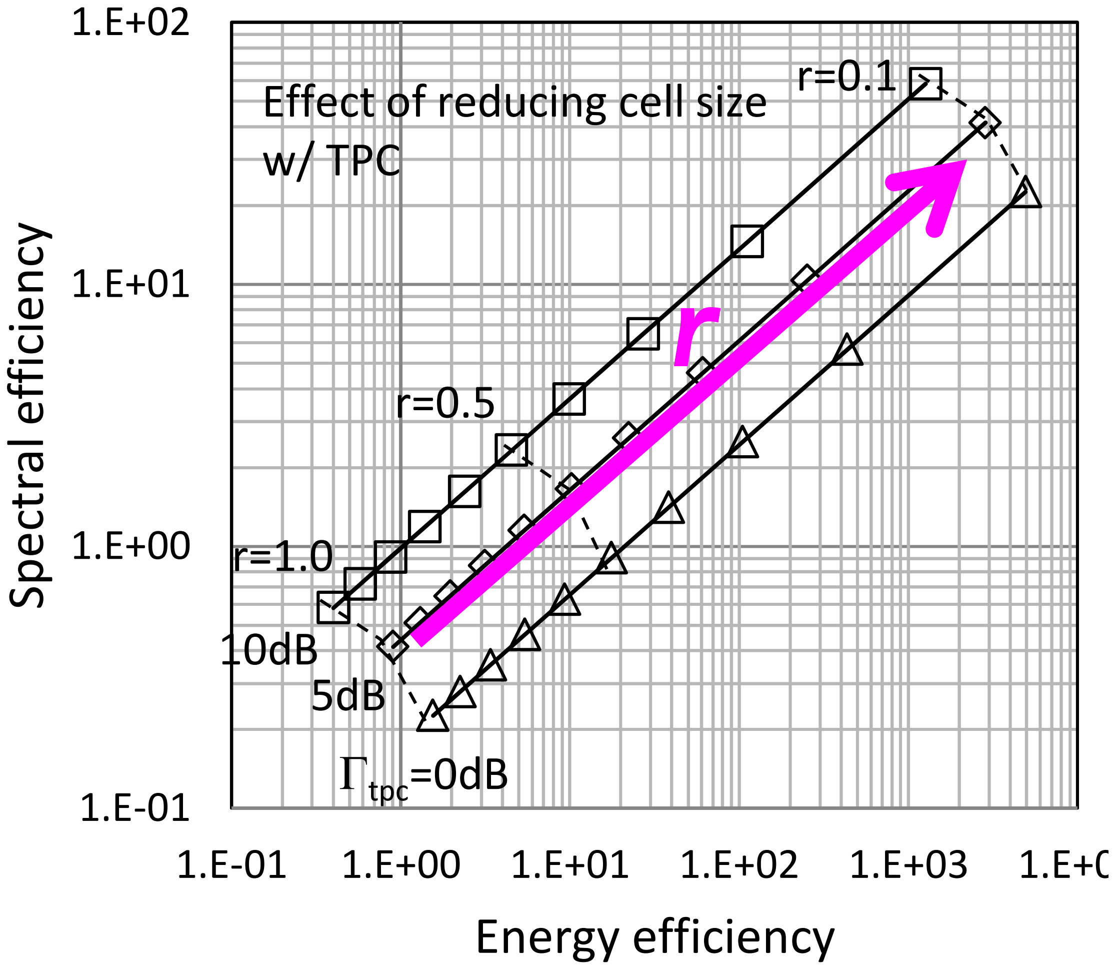


SE-EE Tradeoff w/ TPC

- TPC can improve the EE tradeoff significantly
- The best cluster size is still F=4

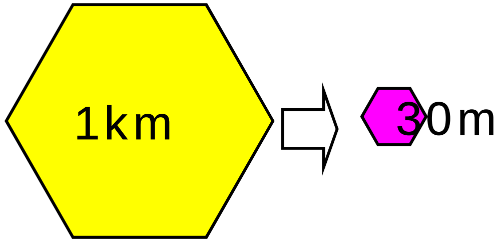


- With TPC, reducing the cell size is quite effective to improve both SE and EE
  - Reducing the cell size by a factor of 10 leads to about x 100 improvement of SE
  - EE improvement is more than SE improvement (x1,000)



Small-cell Network

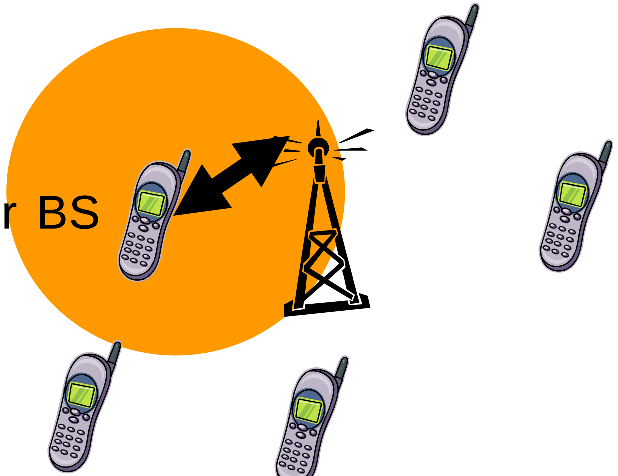
- Simultaneous improvement of SE and EE
  - Reducing the cell radius by a factor of 30 (1,000m → 30m)
    - X1,000 capacity increase
    - Reduced transmit power by a factor of 150,000



x 1,000 capacity increase

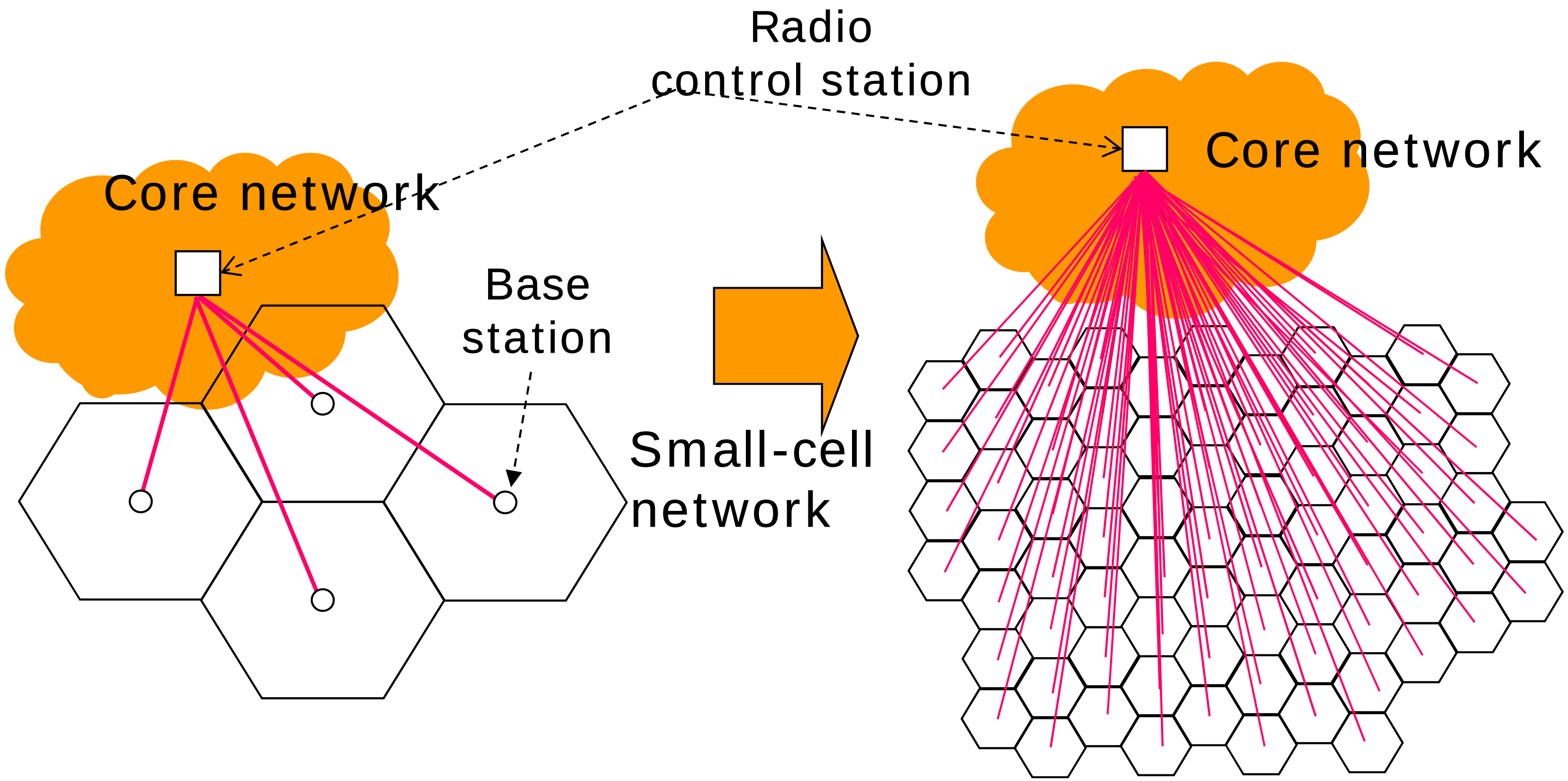
- Small-cell network
  - Single-user access for increasing the bandwidth/user and hence, user data rate
  - Millimeter wave bands can be used

Single user per BS



Small-cell Network

- Control traffic for location registration and handover may significantly increase
  - Radio control signaling becomes a heavy burden

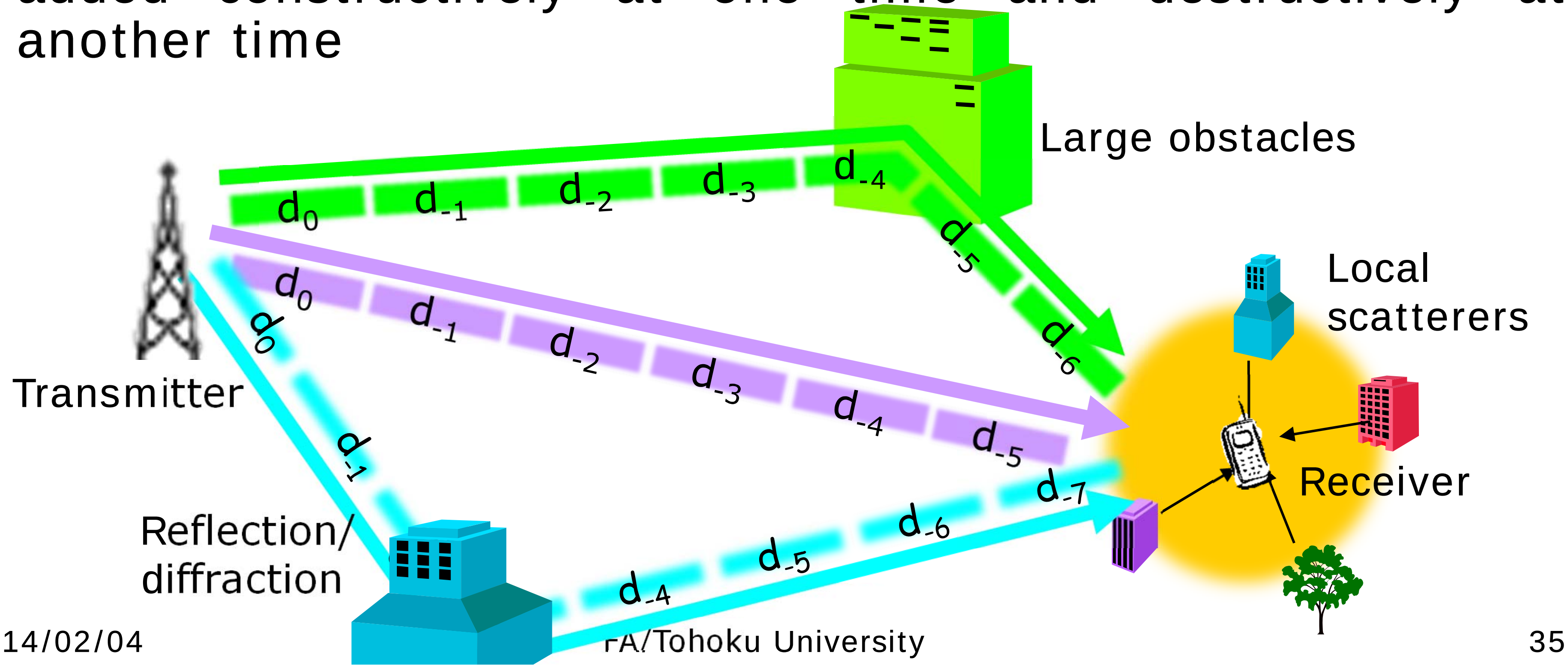


Another Important Issue: Doubly-selective Channel

- 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 (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

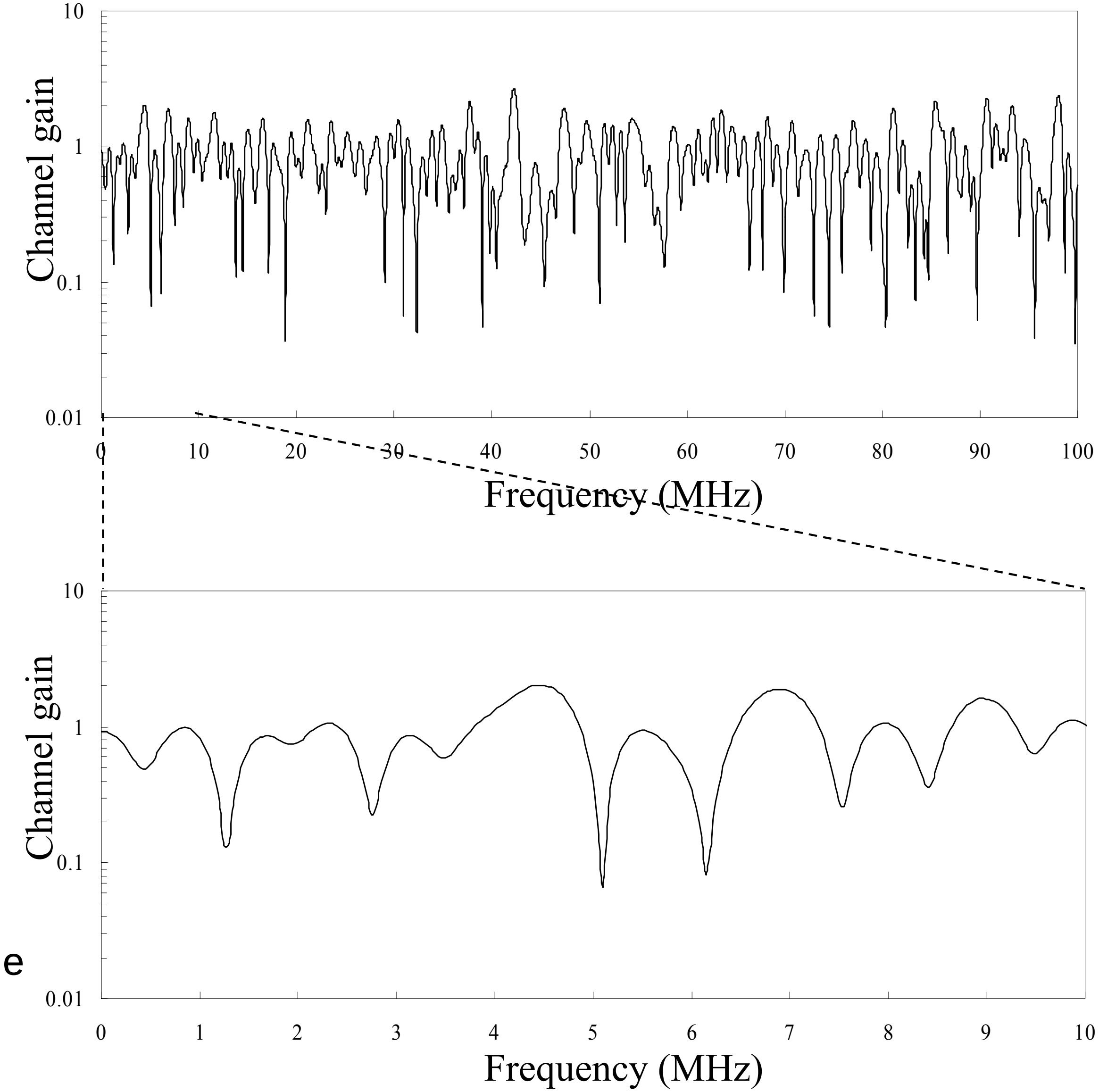


Frequency-selective Channel

- 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

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

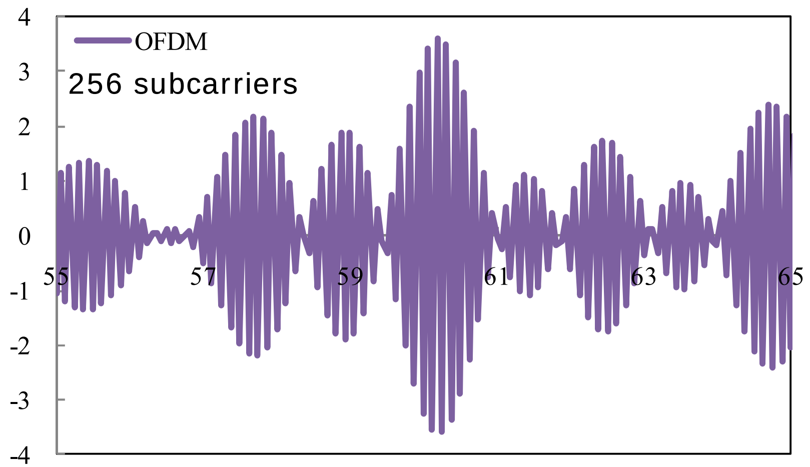
L=16 uniform power delay profile with l-th path time delay =100l + [-50,50)ns



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

OFDM

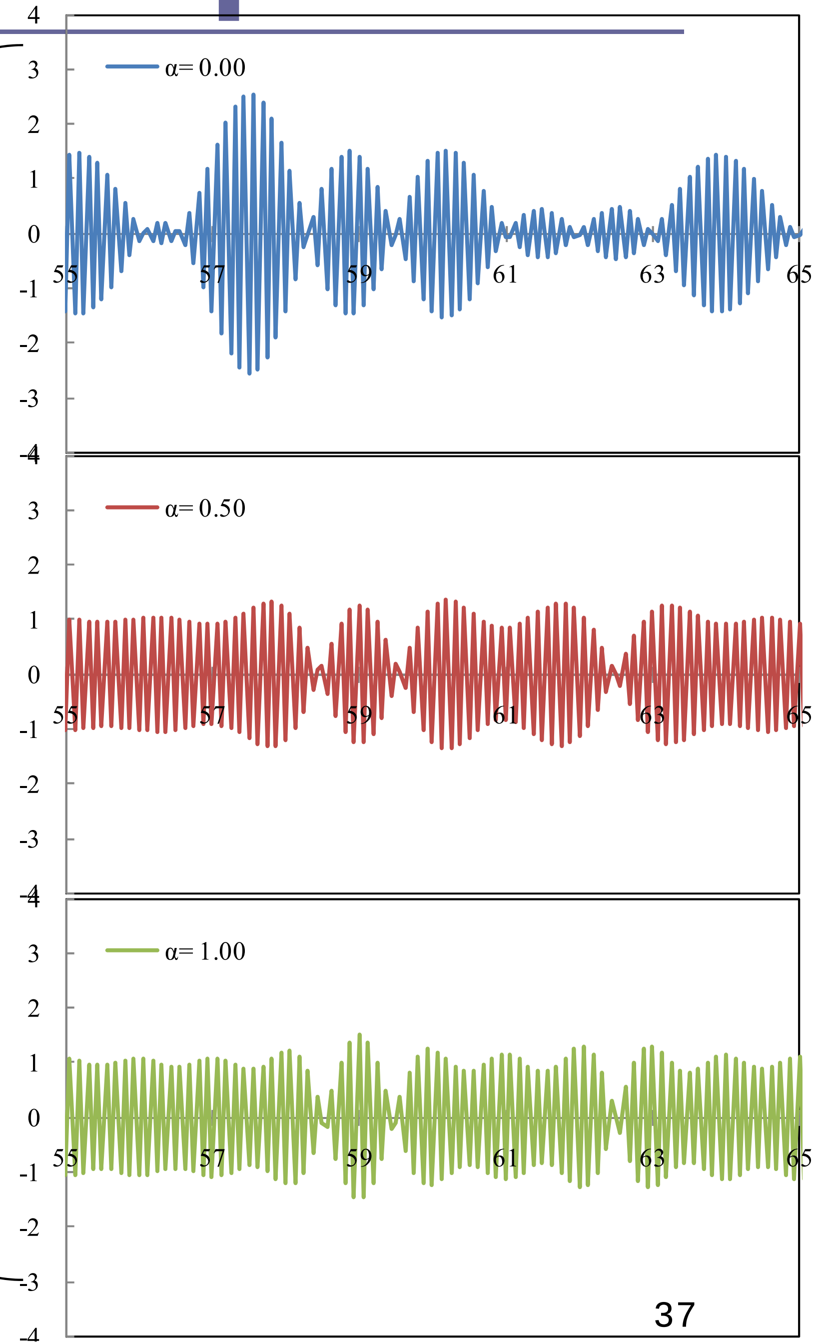


Modulated carrier waveform

$$\mathrm{Re}\left[s(t)\exp(2\pi f_c t)\right]$$

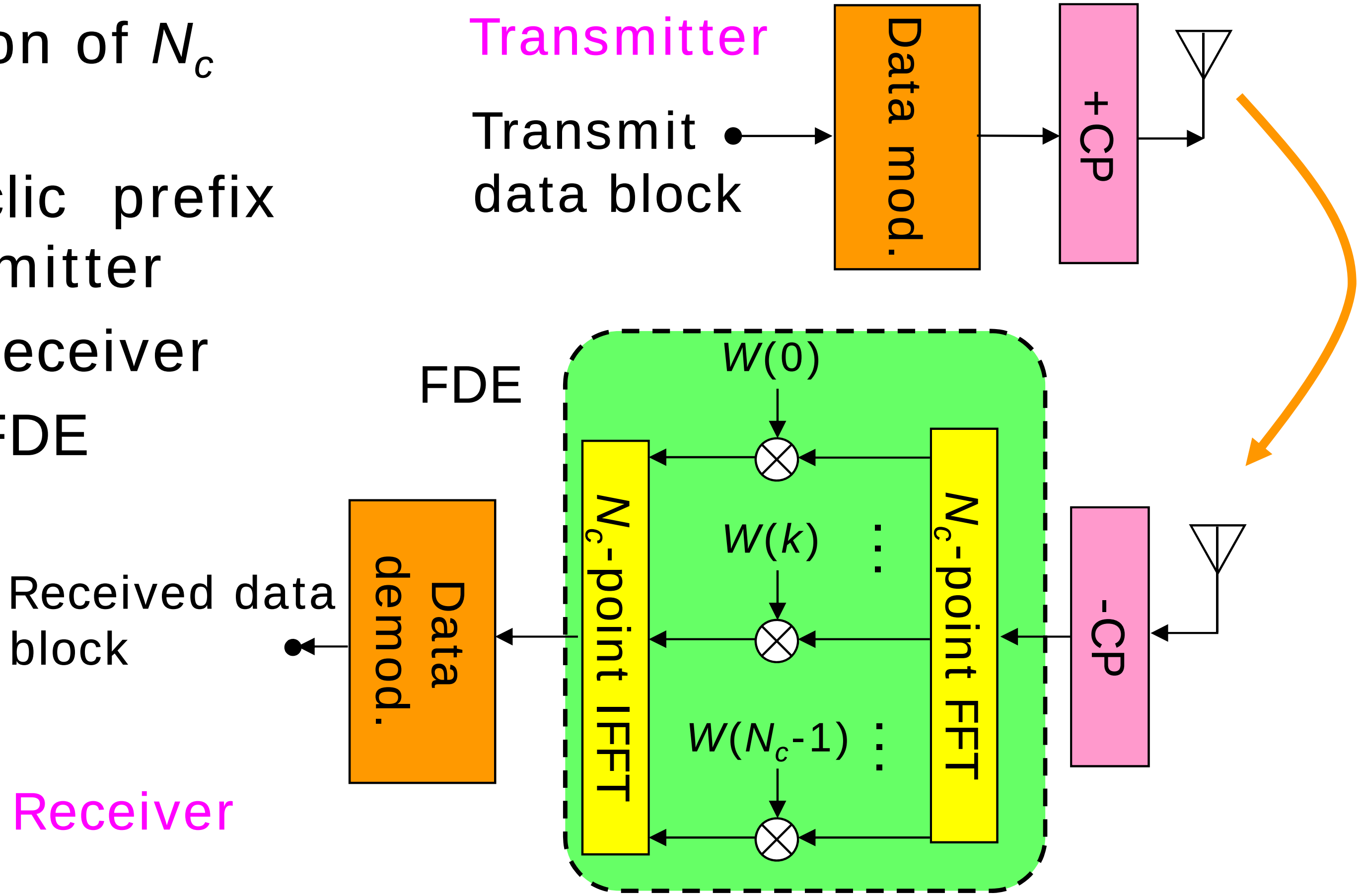
$$= \mathrm{Re}\left[s(t)\right]\cos(2\pi f_c t) - \mathrm{Im}\left[s(t)\right]\sin(2\pi f_c t)$$

SC



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



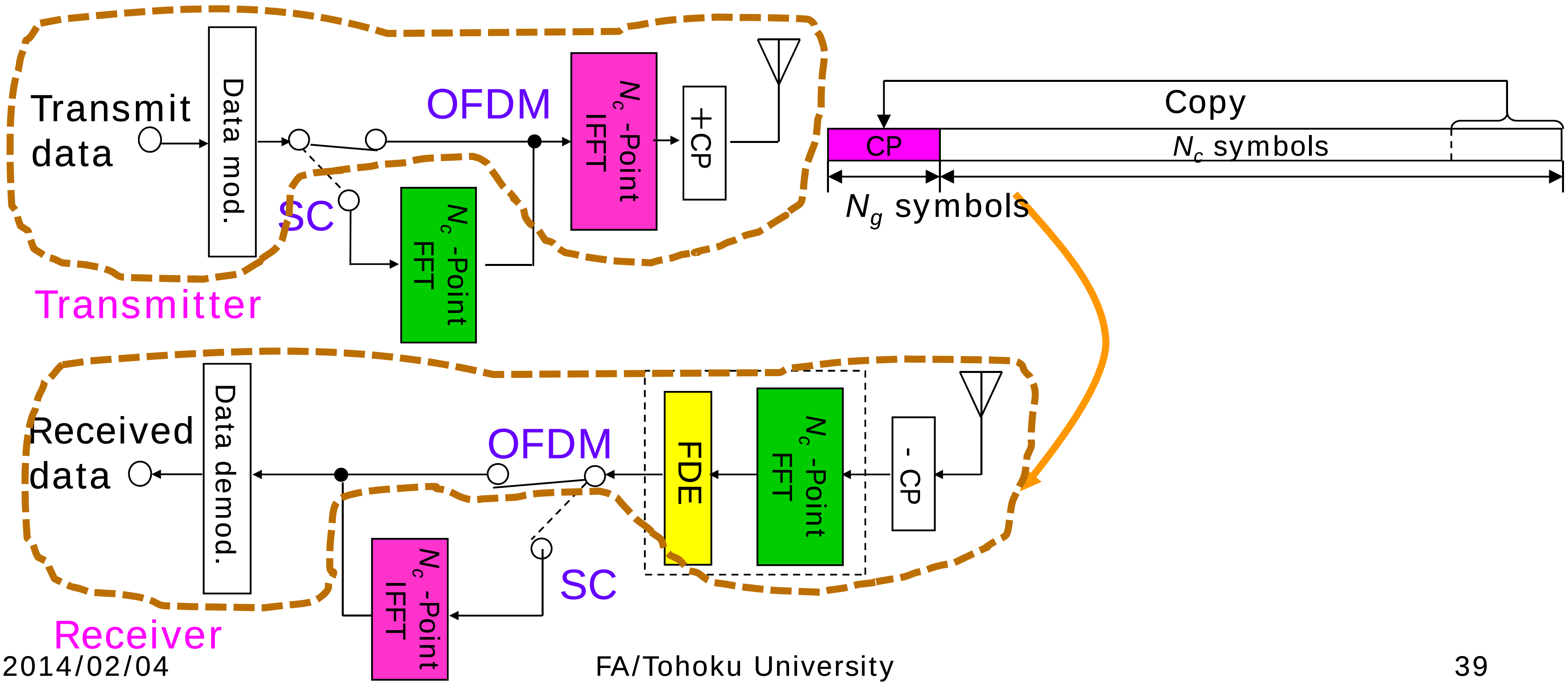
*H. Sari, G. Karam, and I. Jeanclaude, "Transmission Techniques for Digital Terrestrial TV Broadcasting," IEEE Commun. Mag., vol. 33, pp. 100-109, February 1995.

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

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

SC-FDE

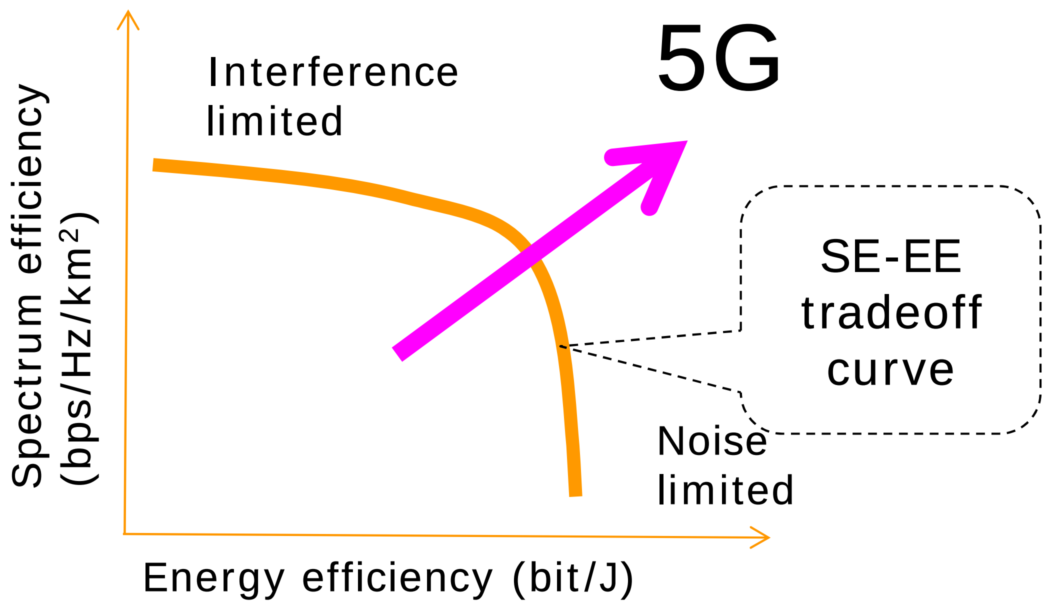
- SC transceivers can be designed based on OFDM
- SC is a family of OFDM
  - FFT at transmitter acts as the precoder of OFDM
  - There may be different precoders which generate many different waveforms between OFDM and SC



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



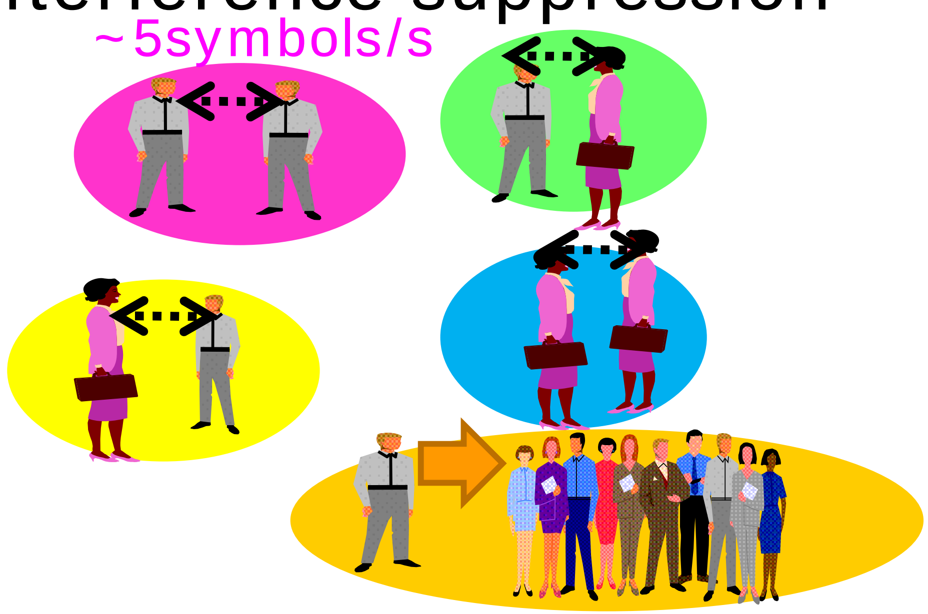
Green Wireless

- 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

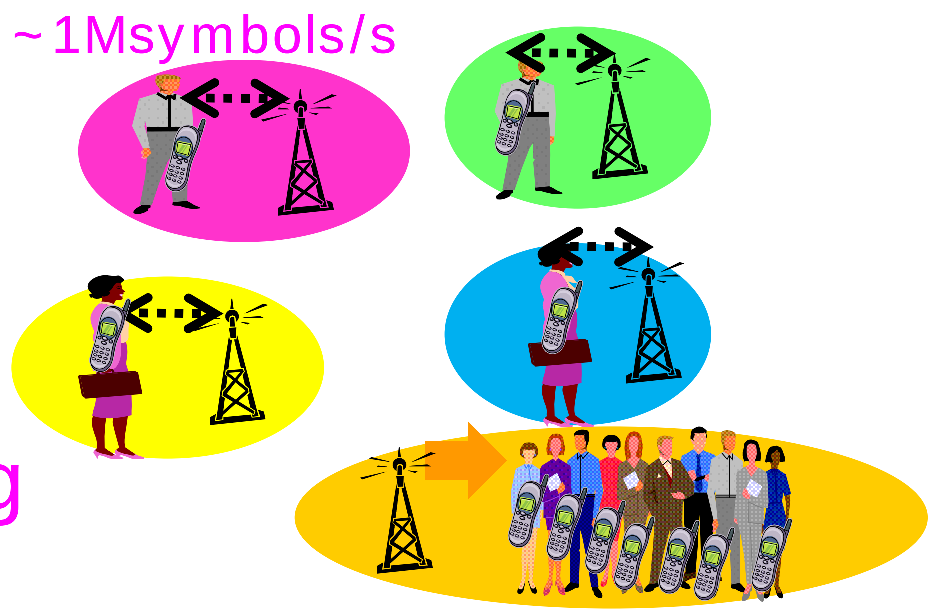
- How can 7 billion people on the globe share the same bandwidth of around 5kHz for voice communication?
  - Super femto-cell structure
    →A few meters coverage
  - Low voice energy and interference suppression
    →Spreading factor (SF)
    =5kHz/5symbols/s
    equivalent to SF=1000

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



No or light coordination among users (SF=~100)

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.

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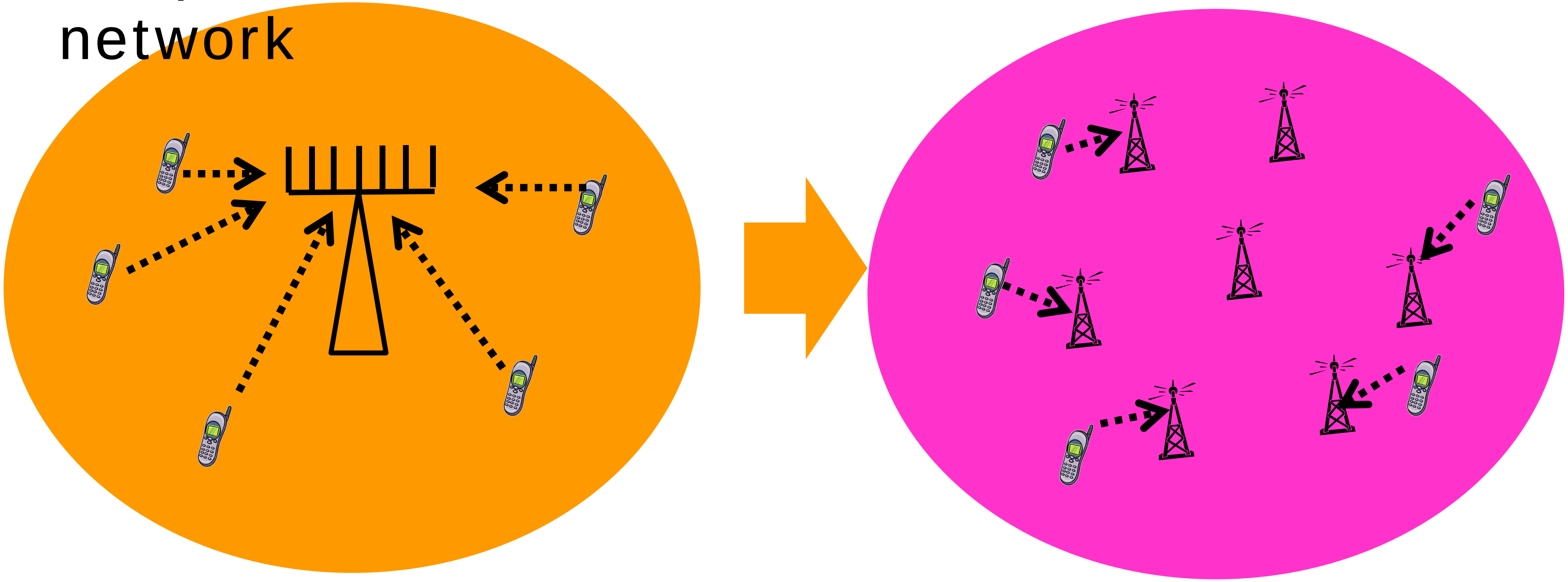
Distributed Antenna Network

- Ubiquitous antennas as an entrance to core network



Co-located antennas

Path loss
Shadowing loss
レ Multipath fading

Multi-access or
Multi-user detection

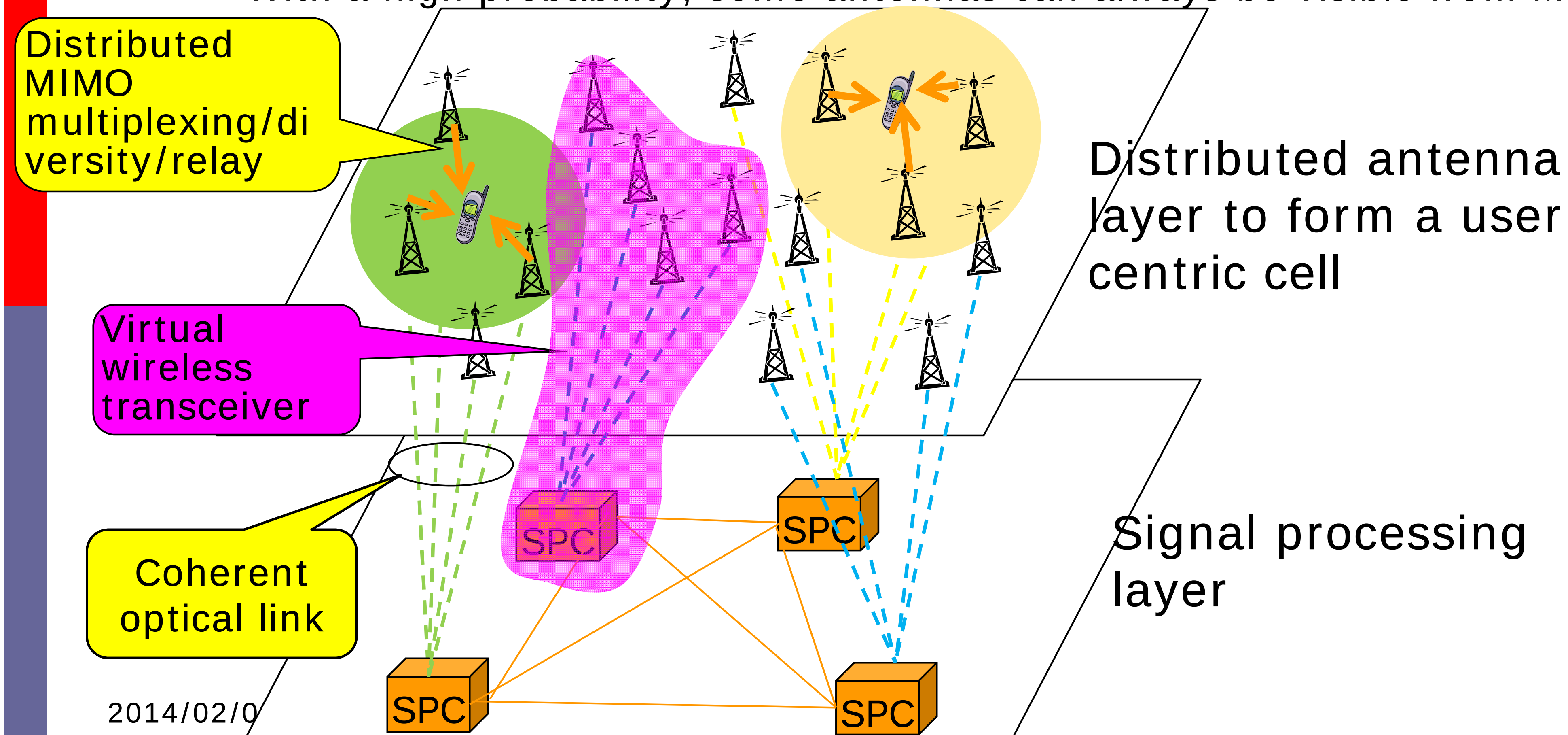
Distributed antennas

レ Path loss
レ Shadowing loss
レ Multipath fading

Single-user access

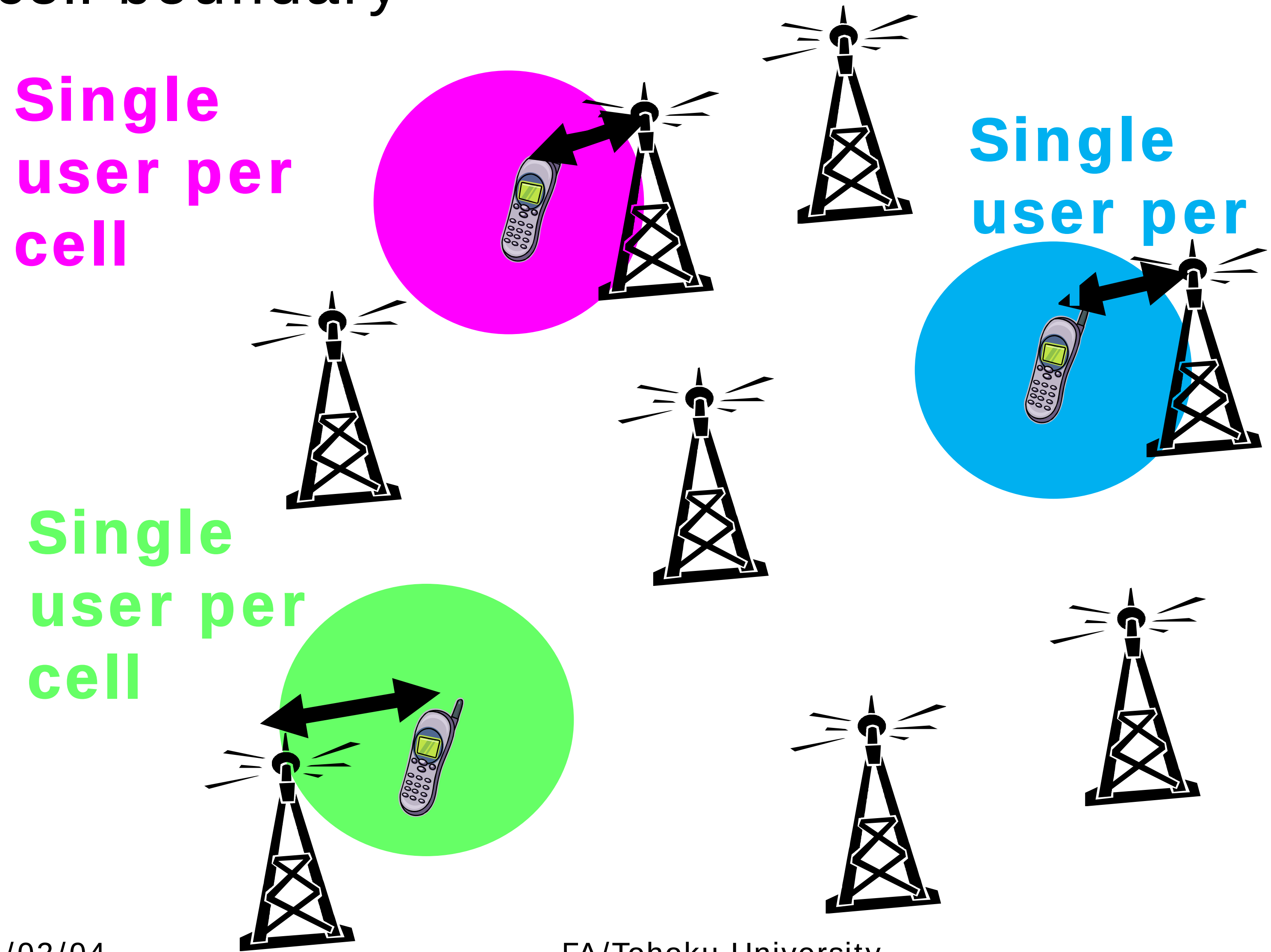
Conceptual Structure of DAN

- 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



User-centric Cell Formulation

- Unlike the traditional cellular network, there is no cell boundary

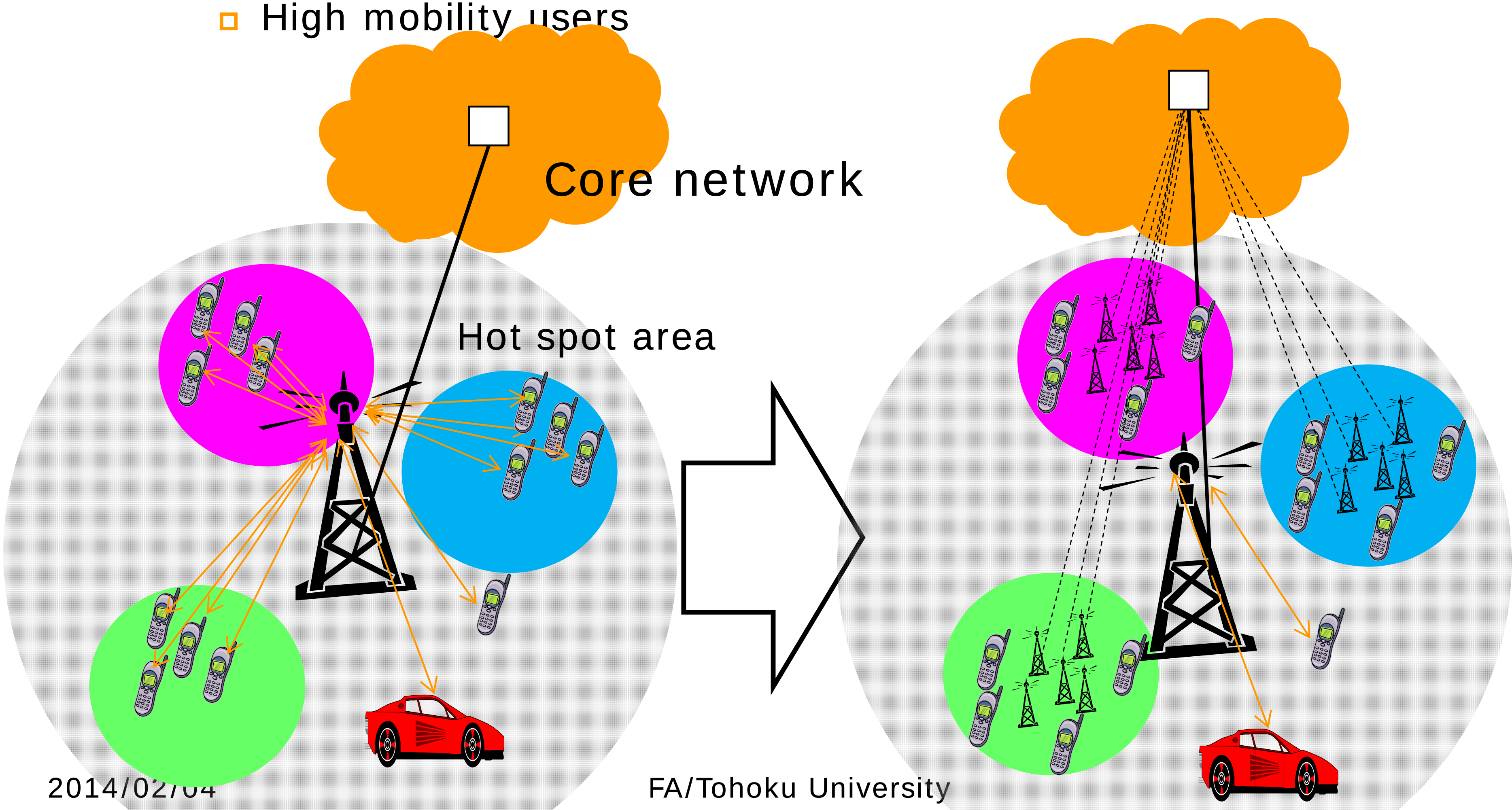


DAN Is Not Almighty

- 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 mbillions of devices)
  - Improved dependability
    - Simultaneous operation of different types of networks

- *Acknowledgment*
  - *Special thanks to members of Wireless Signal Processing & Networking (WSP&N) Lab.*