Next Generation Wireless Technology

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- Wireless Evolution
- Multi-carrier vs Single-carrier
- New Approach In Mobile Networks
Wireless Evolution

- From 2G to 3G
- Then into 4G

Wireless Evolution

- Everyone wants to communicate instantly with anyone, any time, from anywhere
  - Arrival of ubiquitous society: communication is available everywhere
  - This is only possible by wireless. Wireless is indispensable in our forthcoming ubiquitous society
- Every 10 years, a new wireless technology has come up and changed our society
- 1980’s: from “point-to-point” to “anytime, anywhere” communication
  - 1G systems (analog)
- 1990’s: from voice to “data”
  - 2G systems (digital)
  - Access to the Internet
- 2000’s: “wideband data”
  - 3G systems and then 3.5G systems (high speed packet)
- 2010’s: “broadband, ubiquitous”
  - 4G systems
  - Roaming across heterogeneous networks
Wireless Evolution

- Cellular systems have evolved from narrowband to wideband wireless networks
- Now on the way to broadband wireless networks

<table>
<thead>
<tr>
<th>Service Type</th>
<th>Multimedia</th>
</tr>
</thead>
<tbody>
<tr>
<td>0G Voice only</td>
<td>Voice point-to-point</td>
</tr>
<tr>
<td>1G ~2.4kbps</td>
<td>Narrowband Era</td>
</tr>
<tr>
<td>2G ~64kbps</td>
<td>Wideband Era</td>
</tr>
<tr>
<td>3G ~2Mbps</td>
<td>Broadband Era</td>
</tr>
<tr>
<td>4G 100M~1Gbps</td>
<td>Broadband wireless</td>
</tr>
</tbody>
</table>

Voice

- 1980 AMPS
- 1990 Digital IS95
- 2000 HSDPA
- 2010 HSDPA

We are here

50~100Mbps

~14Mbps

~2Mbps

~64kbps

~2.4kbps

50~100Mbps

~2Mbps

~64kbps

~2.4kbps
3G Systems Using W-CDMA

- Data transfer rates in 2G systems are too slow for retrieving rich information distributed in the Internet.
- 3G cellular systems are designed to offer cellular users a significantly higher data-rate services using wideband DS-CDMA technology (5MHz bandwidth).
  - Indoor: 2Mbps
  - Pedestrian: 384kbps
  - Vehicular: 144kbps

2GHz band

Indoors ~2Mbps

Pedestrian ~384kbps

Mobile ~144kbps

IMT2000 Network

3.5G and 3.9G Systems

- 3G systems will continue to evolve to meet the demands of (internet-related) broadband wireless services and substantially strengthen its downlink data rate capability
  - High-speed downlink packet access (HSDPA), called 3.5G systems of ~14Mbps/5MHz, started in Japan in 2006
  - Even 3.5G of 14Mbps data rate capability will sooner or later become insufficient
  - A 3.9G close to 4G will appear to provide broadband services of 50~100Mbps/20MHz using the 3G bands

- 4G systems are expected to provide much faster services of a peak data rate of 100M~1Gbps

- ITU allocated the spectrum for 4G systems in Dec. 2007
  - 450~470MHz/790~806MHz/2.3~2.4GHz/3.4G~3.6GHz
  - 4G development will start soon
  - 4G systems will appear in around 2015
Shift From Single-Carrier Only to Multi-Carrier/Single-Carrier

- In 3.9G, wireless downlink access will be based on multi-carrier technique including OFDMA, while uplink access based on single-carrier technique with FDE.

**Frequency-domain Signal Processing**

- **FDMA**
  - Frequency: f1, f2, f3
  - Time: TDMA

- **OFDMA, SC-FDMA**
  - Frequency: f1, f2, f3
  - Time: CDMA

- **3G**
  - Frequency: #1, #2, #3
  - Time: Spreading code #1

- **4G**
  - Frequency: ?
  - Code-domain: ?

2008/04/29
FA/Tohoku University
Wireless Access of 3.9G (LTE)

- Different multi-access techniques between downlink and uplink (this is the first time in its history)
  - Downlink: OFDMA, ~100Mbps
  - Uplink: SC-FDMA, ~50Mbps
- Scheduling for packet access
  - Multiuser diversity in wireless channel
  - Hybrid ARQ using incremental redundancy (IR) strategy
  - Non real time services

<table>
<thead>
<tr>
<th></th>
<th>Downlink</th>
<th>Uplink</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth(MHz)</td>
<td>1.4/3/5/10/15/20</td>
<td></td>
</tr>
<tr>
<td>IFFT/FFT block size</td>
<td>128/256/512/1024/1536/2048</td>
<td></td>
</tr>
<tr>
<td>Multi-access</td>
<td>OFDMA</td>
<td>SC-FDMA</td>
</tr>
<tr>
<td>Scheduling</td>
<td>Multi-user diversity gain</td>
<td></td>
</tr>
<tr>
<td>ARQ</td>
<td>Turbo-coded IR-HARQ</td>
<td></td>
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</tbody>
</table>
**Downlink OFDMA**

- Resource allocation: one or more resource blocks of 1msec and 12 subcarriers (180kHz) each are allocated according to each user’s channel condition (scheduling) to obtain multiuser diversity gain.
- Proportional fairness (PF)* scheduling can maximize the throughput while keeping fairness among users.

A User B 1ms

Freq.

B

B

m

User A

BS

User B

12 subcarriers (180kHz)

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Uplink SC-FDMA

- For uplink, peak to average power ratio (PAPR) is a big factor to decide the access technique
- To reduce the peak transmit power of mobile power amplifiers, SC-FDMA with FDE is a good choice
  - Block transmission is used. Each block is transformed by DFT into frequency-domain signal which is then mapped onto broad bandwidth in such a way that users’ spectra are not overlapped.
  - To reduce PAPR of SC-FDMA signal, equidistance spectrum mapping is used
Two types of equidistance spectrum mapping
- Localized FDMA
- Distributed FDMA

Advantage of localized FDMA
- Multi-user diversity gain, similar to downlink OFDMA, can be obtained
- According to each user’s channel condition, one or more resource blocks of 1msec and 12 subcarriers (180kHz) each is allocated

![Diagram showing Localized and Distributed FDMA](image)
Technical Issues for 4G

- For a peak data rate of \(~1\text{Gbps/}100\text{MHz}\), there are two important technical issues to address

- Channel problem
  - Wireless channel is extremely frequency-selective and produces strong inter-symbol interference (ISI). Some advanced equalization technique is necessary
  - A very high frequency-efficient transmission technique is necessary to achieve the cellular frequency efficiency of more than \(10\text{bps/Hz/BS}\)

- Power problem
  - For a very high rate transmission, a huge transmit power is required if the same communication range in distance as in the present cellular systems is kept
  - To keep the transmit power the same as in the present systems, fundamental change is necessary in wireless access network architecture
Channel & Power Problems

- There will be two important technical issues which should be solved before 4G systems will appear
- Channel problem is a consequence of the presence of multipaths having different time delays
- Power problem is a consequence of high data rates
Channel Problem

- In terrestrial wireless communications, the transmitted signal is reflected or diffracted by large buildings between transmitter and receiver, creating propagation paths having different time delays.

- For 1Gbps transmission, 1bit time length is equivalent to the distance of 0.3 m. So, many distinct multipaths exist, thereby extremely enhancing the channel frequency-selectivity.
For broadband data transmission, the transfer function of wireless channel is not constant and varies over the signal bandwidth.

Challenge is to transmit data at high speed (close to 1 Gbps) with high quality over such a severe frequency-selective channel.

$L=16$

Uniform power delay profile
$l$-th path time delay $= 100/ + [-50,50]$ns
Multi-carrier vs Single-carrier

- In 3G systems, DS-CDMA (or single-carrier CDMA) is adopted for both uplink and downlink since it is a very flexible multi-access technique.

- Which will be an optimal wireless access technique in a severe frequency-selective channel, single-carrier CDMA or multicarrier CDMA or OFDMA for 4G systems?

MC vs SC

- CDMA can overcome the channel frequency-selectivity and even improve the transmission performance, yet retaining multi-access capability.
  - DS-CDMA: Time-domain spreading
  - MC-CDMA: Frequency-domain spreading
- DS-CDMA: single-carrier/time-domain spreading

- MC-CDMA: multi-carrier/frequency-domain spreading
Rake Receiver for DS

- Receivers of present 3G systems use time-domain rake combining, which is a channel matched filter.
- Rake combining can improve the BER performance if the channel frequency-selectivity is not too strong (or the number $L$ of resolvable paths is not too large).

(c) Rake receiver

Frequency-domain Equalization for MC

- Frequency-domain equalization (FDE) is used to exploit the frequency selectivity of the channel.
- FDE based on the minimum mean square error (MMSE) criterion can provide the best downlink performance.
- MMSE-weight minimizes the mean square error (MSE) between the transmit subcarrier component and the received distorted component.
DS with Rake vs. MC with FDE

- As the number of resolvable paths increases, the channel frequency-selectivity gets stronger and hence, the achievable BER performance of DS-CDMA with rake combining significantly degrades due to strong IPI
  - Even with $L=2$, a high BER floor appears resulting from IPI if the code-multiplexing order is high
- On the other hand, MC-CDMA with MMSE-FDE provides much better performance
  - Performance improves as $L$ increases

![Graph showing comparison between DS-CDMA and MC-CDMA](image-url)
Application of Frequency-domain Equalization (FDE) to DS-CDMA

- One-tap FDE can replace rake combining to have much improved performance

Frequency-domain Equalization (FDE)

- Coherent Rake combining can be replaced by one-tap FDE
  - Block transmission of $N_c$-chips
  - Insertion of guard interval (GI) at the transmitter
  - FFT/IFFT at the receiver

(a) Transmitter

(b) Receiver

AWGN

Removal of GI

Data modulation

Insertion of GI

Time-domain spreading

Frequency-domain equalization

$w(0)$

$w(k)$

$w(N_c-1)$

Data modulation

Time-domain despreading

$c(t)$

$\text{FFT}$

$\text{IFFT}$

Integrate & dump

$\text{Data de-modulation}$

Received data
Downlink Performance Comparison

- FDE can achieve significantly better performance than rake receiver
- Better BER performance than OFDM even for full code-multiplexing (no. of users, C, is equal to SF=256)
High-speed Packet Access

- Packet services will dominate in 4G systems
- For packet transmissions, some form of error control is necessary to satisfy the quality requirement
- Hybrid ARQ w/incremental redundancy (IR) strategy is a promising technique


Hybrid ARQ (HARQ) with Incremental Redundancy (IR)

- An automatic repeat request (ARQ) combined with the channel coding, called hybrid ARQ (HARQ), is an inevitable technique, since an error-free transmission must be guaranteed for packet data services.
- HARQ combined with FDE is a very promising error control technique for DS- and MC-CDMA.
- HARQ combined with FDE can take advantage of the channel frequency selectivity.

[Diagram showing the process of information, channel encoding, parity encoding, and puncturing for Type II HARQ S-P2.]
ICI cancellation significantly improves the throughput performance.

- Much better throughput than OFDM in a high $E_s/N_0$ region.
- Almost the same throughput as OFDM in a low $E_s/N_0$ region.
MIMO Antenna Technology

- Equivalent to 10bps/Hz/BS when using single-frequency reuse of 100MHz bandwidth
Next generation (4G) wireless systems are expected to provide broadband packet data services of up to around 100M~1Gbps.

However, available bandwidth is limited. Probably, the available bandwidth is less than 100MHz.
- In December 2007, ITU allocated 3.4~3.6GHz band for 4G services.

It is necessary to develop a highly spectrum efficient wireless transmission technology of around 10bps/Hz/BS.

Multiple-input/multiple-output (MIMO) antenna technology will play an important role to realize 4G systems.
How To Achieve 1Gbps?

- 4G target of peak data rate is ~1Gbps, but the available bandwidth may be 100MHz/system in 4G (3.4~3.6GHz band)
- 1Gbps/100MHz/BS = 10bps/Hz/BS
  - If we want to achieve this goal by multi-level modulation, 1024QAM is required
  - However, the achievable BER performance severely degrades
It may be almost impossible to use a higher level modulation such as 1024QAM to achieve 10bps/Hz/BS.

MIMO technology can achieve such a high spectrum efficiency by using many antennas at both stations.
Single-Carrier Frequency-domain SDM

- Severe frequency-selective fading
  - So far, frequency nonselective fading channel has been assumed for AAA, STTD, and MIMO. But, for broadband wireless, severe frequency selective fading occurs.
  - They can be combined with DS-CDMA and MC-CDMA with frequency-domain equalization and a much better transmission performance can be achieved due to frequency diversity effect.

- Limitation on no. of antennas
  - Only one or two antennas (probably at most 4 antennas) may be available at a terminal in practice.

- Joint iterative frequency-domain 2D equalization (FDE) and parallel interference cancellation (PIC) for SC transmission
  - The data rate increase without bandwidth expansion is achieved while achieving frequency diversity gain.


Spread MIMO SDM

- Frequency-domain iterative interference cancellation (FDIC) can be introduced to Spread MIMO SDM.
- Joint MMSE frequency-domain equalization (FDE) and parallel interference cancellation (PIC) is repeated for de-multiplexing while achieving frequency-diversity gain.

Multicode DS-CDMA (4,4)MIMO multiplexing with iterative FDIC, $L=16$, $\alpha=0\text{dB}$, $N_c=256$, $N_g=32$, $SF(=C)=1$, QPSK.
Throughput of Spread MIMO SDM

- Close-to-1Gbps (peak) access is required, but the available bandwidth is limited (e.g., 100MHz). MIMO SDM is a promising technique to achieve such a data rate.
- Spread MIMO SDM w/FDIC provides higher throughput than OFDM.

Start


End


A New Approach In Mobile Networks

- Another important technical issue for the realization of high data rate 4G mobile networks is the significant reduction of the transmit power from a mobile terminal (MT)
Transmit Power Problem

- Links for high speed data services are severely power-limited
  - Peak power is in proportion to "transmission rate" x \( f_c^{2.6} \) [Hata-formula] where \( f_c \) is the carrier frequency
  - Let’s consider the peak transmit power for 100Mbps@5GHz at a communication range of 1,000m. We assume the required transmit power for 8kbps@2GHz is 1Watt
  - The required peak transmission power is \( 100\text{Mbps}/8\text{kbps} \times (5\text{GHz}/2\text{GHz})^{2.6} = 135,000 \) times, that is 135kWatt. Obviously, this cannot be allowed
  - To keep the transmission power at 1Watt level, the communication range should be reduced by about 29 times (e.g., 1,000m → 34m cell) if the propagation path loss exponent is 3.5

- Fundamental change is necessary in wireless access network

Multi-hop Virtual Cellular Network (VCN)

- Virtual cellular network (VCN) is suitable for non-real time packet communication
- Virtual cell consisting of many distributed wireless ports
  - One port (central port) acts a gateway to the network
  - Mobile terminal and central port are connected using wireless multi-hop relay technique

(a) Conventional CN

(b) VCN
Multi-hop Route Construction

- Multi-hop routes connecting wireless end-ports (WPs) and central port (CP) are constructed based on the total transmit power minimization criterion
  - The interference to other multi-hop routes can be minimized.
- To avoid excessive transmission delay, the maximum number of hops is limited to $J$
  - An example of constructed routes for $J=4$
Dynamic Channel Allocation

- Channel allocation is an important technical issue to efficiently reuse the limited channel resources.
- In VCN, a distributed dynamic channel allocation (DCA) will be a solution.
- Channel segregation DCA (CS-DCA) is promising.
  - Each WP learns about its favorite channels in a distributed manner without requiring any propagation channel information in advance.

Conclusion

- 4G systems are a broadband packet network which requires Giga-bit wireless technology of 100M~1Gbps capability (=10bps/Hz/BS for a 100MHz system bandwidth)

- Wireless multi-access technique
  - Frequency-domain signal processing plays an important role to achieve the goal
  - Besides OFDMA and SC-FDMA in 3.9G, either DS- or MC-CDMA with FDE can also be a promising candidate for 4G
  - Frequency-domain HARQ and MIMO SDM can be used to take advantage of the channel frequency-selectivity

- Network issue
  - Power problem is an important technical issue in 4G network. Some fundamental change needs to be introduced to the wireless network
  - E.g., multi-hop virtual cellular network, distributed antenna network, MIMO cooperative network, etc.
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