Introduction to 5G

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Slides and Audio/Video recordings of this class lecture are available at:

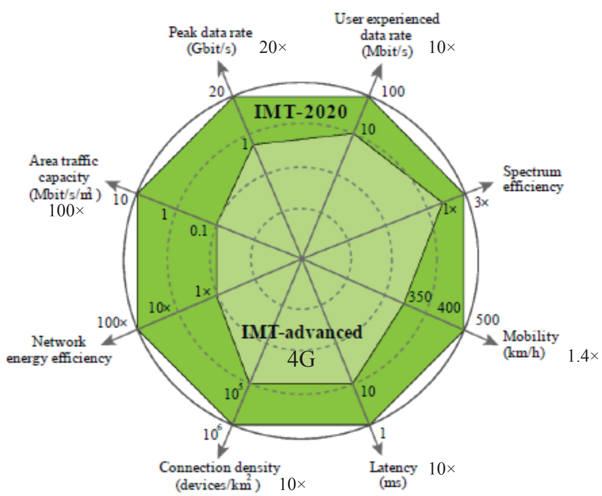
http://www.cse.wustl.edu/~jain/cse574-16/

Overview

1. What: 5G Definition
2. How:
   1. New Radio Multiplexing Technologies
   2. New Efficient Spectrum Usage Techniques
   3. New Energy Saving Mechanisms
   4. CapEx/OpEx Reduction Techniques
   5. New Spectrum
   6. Application Specific Improvements

Note: This is the 4th module in a series of lectures on 2G/3G, LTE, LTE-Advanced, and 5G

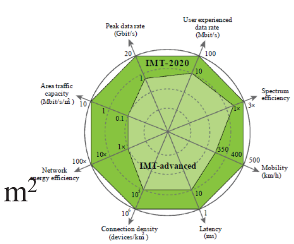
5G Definition



Ref: ITU-R Recommendation M.2083-0, "IMT Vision – Framework and overall objectives of the future development of IMT for 2020 and beyond," Sep. 2015, 21 pp., https://www.itu.int/dms_pubrec/itu-r/rec/m/R-REC-M.2083-0-201509-I!!PDF-E.pdf

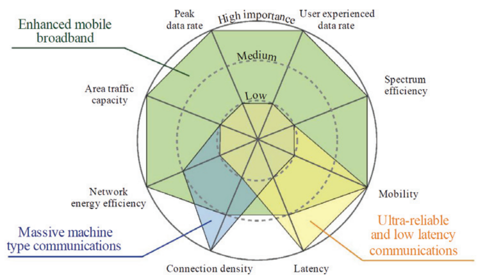
5G Definition (Cont)

1. Peak Data Rate: max rate per user under ideal conditions. 10 Gbps for mobiles, 20 Gbps under certain conditions.
2. User experienced Data Rate: Rate across the coverage area per user. 100 Mbps in urban/suburban areas. 1 Gbps hotspot.
3. Latency: Radio contribution to latency between send and receive
4. Mobility: Max speed at which seamless handover and QoS is guaranteed
5. Connection Density: Devices per km^2
6. Energy Efficiency: Network bits/Joule, User bits/Joule
7. Spectrum Efficiency: Throughput per Hz per cell
8. Area Traffic Capacity: Throughput per m^2



Importance

- Three Key Application Areas:
  - Enhanced Mobile Broadband
  - Ultra-Reliable and Low Latency: Real-time, safety
  - Massive Machine Type Communications



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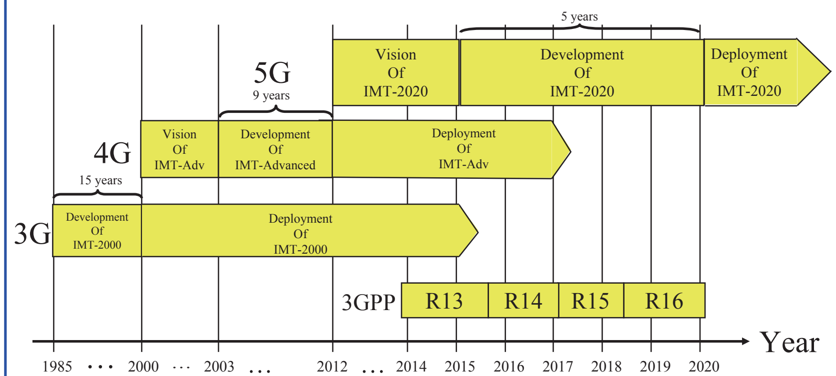
Timeline

- 3G: IMT-2000 started in 1985, first release in 2000
- 4G: IMT-Advanced, vision in 2003, First release in 2012
- 5G: IMT-2020, vision in 2015, first release in 2020



Ref: ITU-R, "Workplan, timeline, process and deliverables for the future development of IMT," 4pp.,

How?

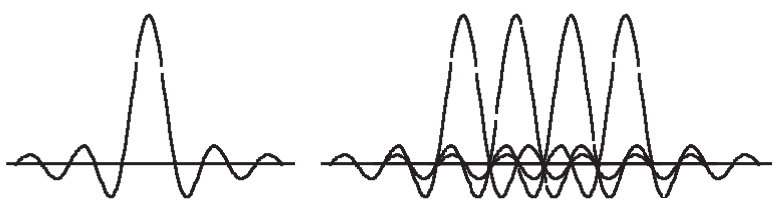
1. New Radio Multiplexing Technologies
2. New Efficient Spectrum Usage Techniques
3. New Energy Saving Mechanisms
4. CapEx/OpEx Reduction Techniques
5. New Spectrum
6. Application Specific Improvements

New Radio Multiplexing Technologies

1. Spectrum Filtered OFDM (f-OFDM)
2. Filtered Bank Multicarrier (FBMC)
3. Non-Orthogonal Multiple Access (NOMA)
4. Pattern Division Multiple Access (PDMA)
5. Low Density Spreading (LDS)
6. Sparse Code Multiple Access (SCMA)
7. Interleave-Division Multiple Access (IDMA)

Problems with OFDM

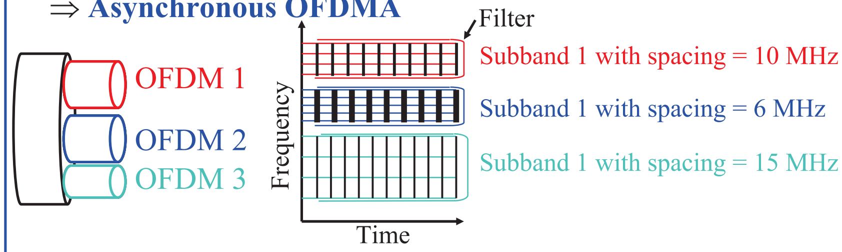
- Spectrum overflow ⇒ Need **guard bands**
- Entire band should use the **same subcarrier** spacing
- Entire time should use the **same symbol size** and cyclic prefix
- All users should strictly **time synchronize** in the uplink



Ref: P. Zhu, "5G Enabling Technologies," PIMRC, Sep 2014, 20 slides, http://www.ieee-pimrc.org/2014/2014-09-03%205G%20Enabling%20Technologies%20PMIRC%20Huawei_Final.pdf

Spectrum Filtered OFDM (f-OFDM)

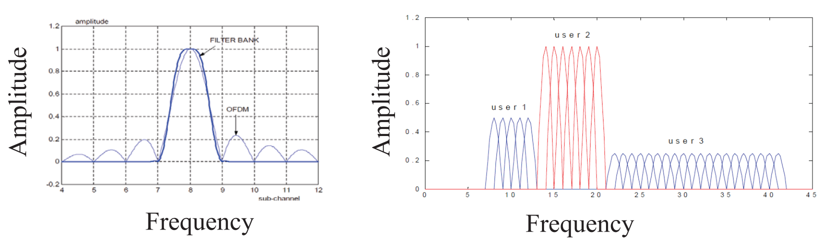
- Band divided into multiple subbands
- Each subband may use different OFDM parameters optimized for the application: Frequency spacing, cyclic prefix, …
- Each subband spectrum is **filtered** to avoid inter-subband interference ⇒ Spectrum filtered
- Different users (subbands) do not need to be time synchronized ⇒ **Asynchronous OFDMA**



Ref: P. Zhu, "5G Enabling Technologies," PIMRC, Sep 2014, 20 slides, http://www.ieee-pimrc.org/2014/2014-09-03%205G%20Enabling%20Technologies%20PMIRC%20Huawei_Final.pdf

Filtered Bank Multicarrier (FBMC)

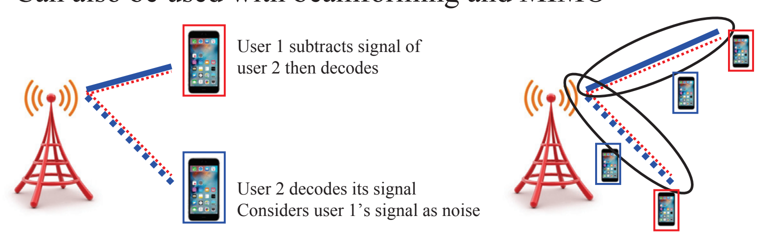
- A filter is used to remove the subcarrier overflow
- No side lobes ⇒ No cyclic prefix needed ⇒ More bits/Hz
- Different users can have different subbands with different parameters



Ref: M. Bellanger, "FBMC physical layer – principle," June 2011, 13 slides, http://www.cept.org/Documents/se-43/500/SE43(11)Info06_FBMC-physical-layer-principle

Non-Orthogonal Multiple Access (NOMA)

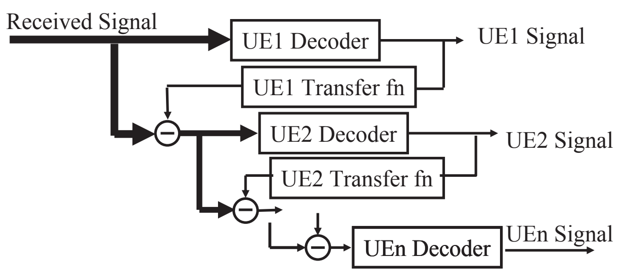
- Users are distinguished by power levels
- Users with poor channel condition get higher power
- Users with higher power decode their signal treating others as noise
- Users with lower power subtract the higher powered signals before decoding
- Can also be used with beamforming and MIMO



Ref: G. Ding, et al, "Application of Non-orthogonal Multiple Access in LTE and 5G Networks," https://pdfs.semanticscholar.org/a404/21a9762db528bfe848166765fee43e740c94.pdf

Pattern Division Multiple Access (PDMA)

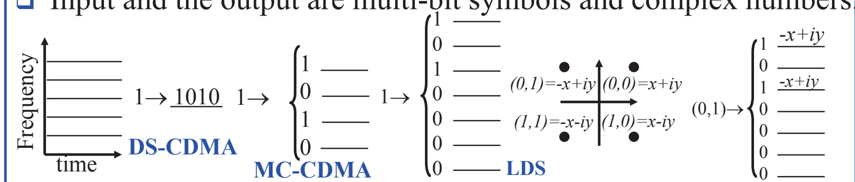
- A variation of NOMA
- The users detect the signal with highest signal, subtract its waveform ⇒ Successive Interference Cancellation (SIC)
- Can increase spectral efficiency by a factor between 1 and 2.



Ref: J. Zeng, et al, "Pattern Division Multiple Access (PDMA) for Cellular Future Radio Access," Intl Conf on Wireless Comm & Signal Proc (WCSP), Oct. 2015, 5 pp., http://ieeexplore.ieee.org/xpl/login.jsp?tp=&arnumber=7341229

Low Density Spreading (LDS)

- **Direct Sequence-CDMA**: Symbols are *spread* in time. Multiple users spread over at same time and frequency.
- **Multi-carrier CDMA**: Symbols are *spread* in frequency. Multiple users spread over same subcarriers at same time.
- **LDS**: Multi-carrier CDMA in which symbols are spread over large vectors most of whose elements are zero (sparse).
  - At each subcarriers, the number of interferers is small
  - Codes can even be randomly chosen
- Input and the output are multi-bit symbols and complex numbers.



Ref: M. AL-imari, et al., "Low Density Spreading Multiple Access," J. Inform Tech Software Eng, Vol 2, Issue 4, 2012, http://epubs.surrey.ac.uk/788182/1/Ready%20to%20Upload.pdf

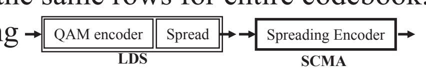
Sparse Code Multiple Access (SCMA)

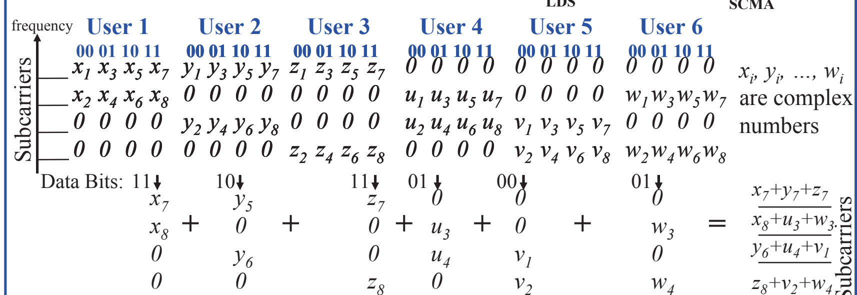
- In stead of repeating the same symbol on different subcarriers (as in LDS), optimally coded symbols on different subcarriers.
- Symbols are mapped to higher-dimensional complex symbols and then mapped to subcarriers
  - K dimensions are spread over K subcarriers
- Codes are <u>non</u>-orthogonal ⇒ More code books and users can be supported than if limited to orthogonal
- Sparse ⇒ A lot of zeros in the code book ⇒ Easier to decode
  - All codes in one codebook have zeros in the same location
  - Each code book has K dimension of which N are zero. Total ${}^{K}C_{N} = \binom{K}{N}$ codebooks.
- Good for unscheduled random access without polling and grant scheduling ⇒ Good for IoT
- SCMA combines spreading and coding

Ref: P. Zhu, "5G Enabling Technologies," PIMRC, Sep 2014, 20 slides, http://www.ieee-pimrc.org/2014/2014-09-03%205G%20Enabling%20Technologies%20PMIRC%20Huawei_Final.pdf

SCMA Example

- 2-bit symbols to <u>4</u>-dimensional symbols with <u>2</u> zeros: K=4, N=2
- Number of possible mappings ${}^{4}C_{2} = \binom{4}{2}$= 6 codebooks
- Six users can be supported over 4 subcarriers
- Each codebook has 2 zeros in the same rows for entire codebook.
- Combines spreading and coding





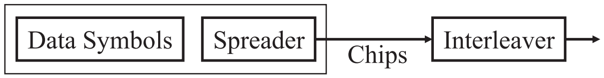
Ref: K. Au, et al, "Uplink Contention Based SCMA for 5G Radio Access," http://arxiv.org/vc/arxiv/papers/1407/1407.5495v1.pdf

Interleave-Division Multiple Access (IDMA)

- **Interleaving**: Rearranging symbols according to a specified pattern ⇒ Reduces correlation between successive symbols

  [0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 0, 1]× [2, 4, 3,1]→[1, 3, 2, 0, 5, 7, 6, 4, 9, 1, 0, 8]
- **DS-CDMA**: Symbols are interleaved then spread in to chips

- **IDMA**: Symbols spread and then interleaved.



  - Different users have different interleaving pattern
  - Low-Rate Spreading ~ DS-CDMA without spreading ⇒ High spectral efficiency

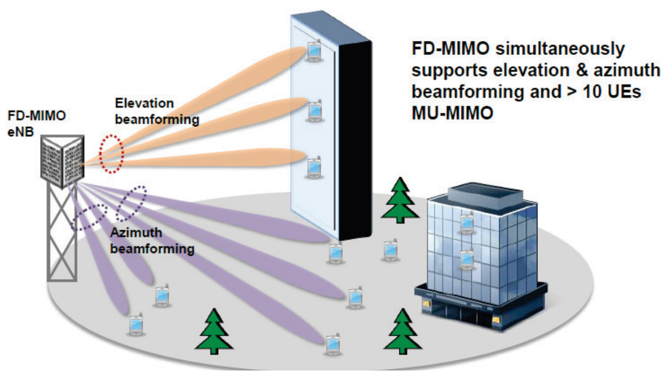
Ref: J. C. Fricke, et al, "An Interleave-Division Multiple Access Based System Proposal for the 4G Uplink," IST Summit, 2005, 5 pp., http://www.agilon.de/Dr__Hendrik_Schoneich/Publications/Fricke_IST_Summit_2005.pdf

New Efficient Spectrum Usage Techniques

1. 3D Beamforming and Massive MIMO
2. FDD-TDD Carrier Integration
3. Distributed Antenna Systems (DAS)
4. Simultaneous Transmission and Reception
5. Dynamic TDD
6. License Assisted Access (LAA)
7. Multimode Base Stations
8. Intelligent Multi-Mode RAT Selection
9. Higher order modulations in small cells

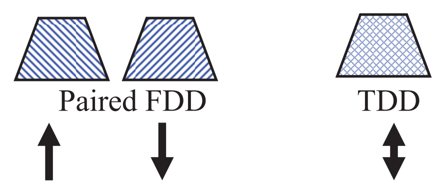
3D Beamforming

- Aka 3D-MIMO or Full-dimension MIMO (**FD-MIMO**)
- Infinite Antennas = **Massive MIMO**



Ref: G. Xu, et al, "Full-Dimension MIMO: Status and Challenges in Design and Implementation," May 2014, http://www.ieee-ctw.org/2014/slides/session3/CTW_2014_Samsung_FD-MIMO.pdf

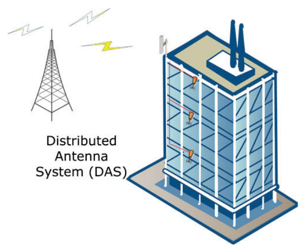
FDD-TDD Carrier Integration



- Can aggregate Down FDD band with TDD in downlink
- Aggregate Up FDD band with TDD in uplink
- Use only FDD in Primary Cell and TDD in Small Cell or vice versa
- Generally FDD bands are lower frequency ⇒ Used for primary
- In future, 32 carriers could be aggregated

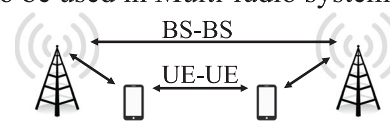
Distributed Antenna Systems (DAS)

- Multiple antennas connected via cable
- Used for indoor coverage
- Need multiple cables for MIMO
- Some times the RF signal is converted to digital and transmitted over fiber optic cables and converted back to RF ⇒ Active DAS



Simultaneous Transmission and Reception

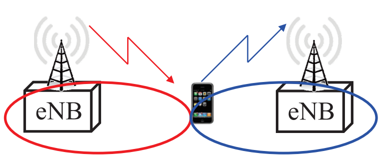
- Also known as "**Full Duplex**" on the same frequency ⇒ Doubles the throughput, reduces end-to-end latency, allows transmitters to monitor the channel
- Difficult because transmitted signal too strong and interferes with reception ⇒ FDD (Large gap between transmit and receive frequencies) or TDD (Half-Duplex)
- Solution: **Self-Interference cancellation (SIC)** in analog and digital domain
- Similar techniques can be used to overcome BS-BS or UE-UE interference
- SIC can also be used in Multi-radio systems (WiFi and Bluetooth)



Ref: W. Afifi and M. Krunz, "Adaptive Transmission-Reception-Sensing Strategy for Cognitive Radios with Full-duplex Capabilities," April 2010, 12 pp., http://www2.engr.arizona.edu/~wessamafifi/DySPAN14.pdf

Dynamic TDD

- Time Division Duplexing (TDD) allows varying uplink to downlink ratio
- All cells in an area must synchronize their UL/DL subframes pattern, otherwise mobile's transmission get interference from neighboring BS
- LTE allows 7 variations of UL/DL subframe patterns. S=Switchover time from D to U



TDD Conf	TTI index									
	0	1	2	3	4	5	6	7	8	9
0	D	S	U	U	U	D	S	U	U	U
1	D	S	U	U	D	D	S	U	U	D
2	D	S	U	D	D	D	S	U	D	D
3	D	S	U	U	U	D	D	D	D	D
4	D	S	U	U	D	D	D	D	D	D
5	D	S	U	D	D	D	D	D	D	D
6	D	S	U	U	U	D	S	U	U	D

Ref: V. Pauli, Y. Li, E. Seidel, "Dynamic TDD for LTE-A and 5G," Nomor Research GmbH, Sep 2015, 8 pp., http://nashville.dyndns.org:823/YourFreeLibrary/_lte/LTE%20advanced/WhitePaperNomor_LTE-A_5G-eIMTA_2015-09.pdf

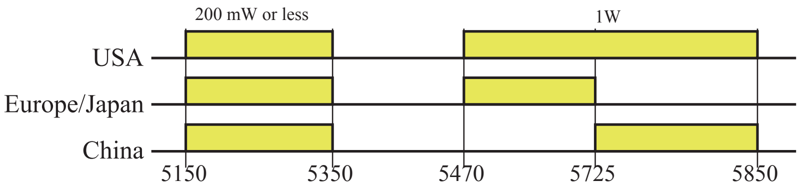
Dynamic TDD (Cont)

- Too many U's or D's in a row delay acks/nacks and affect the usefulness of HARQ.
- Release 12 added flexible "F" subframes that can be declared as S, D, or U ⇒ Can change every 10 ms.
- **Enhanced Interference Mitigation and Traffic Adaptation (eIMTA):** Cells can change UL/DL pattern as needed. Mobiles asked to transmit at higher power if needed.
- This will be further enhanced for 5G

TTI index									
0	1	2	3	4	5	6	7	8	9
D	S	U	F	F	D	S/D	F	F	F

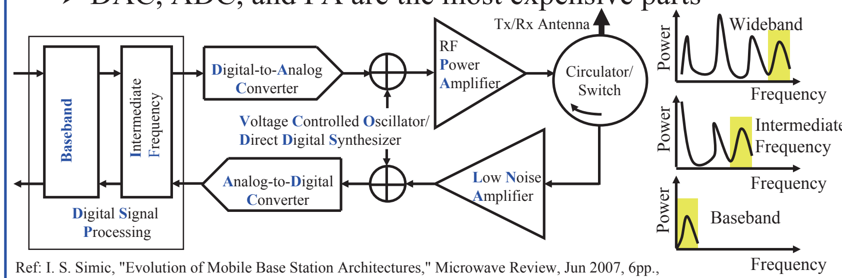
License Assisted Access (LAA)

- A.k.a. unlicensed LTE (LTE-U). Release 13.
- 5 GHz band for public hot-spots and in-building
- Different rules and bands in different countries, e.g.,
  - Avoid if a radar is operating
  - Can't block 20 MHz if using only 180 kHz
  - Transmit only if free. Recheck after maximum occupancy time ⇒ Can not transmit continuously as in standard LTE
- End-to-End LTE ⇒ Better integration than with WiFi
- May use as a downlink-only carrier aggregation



Multimode Base Stations

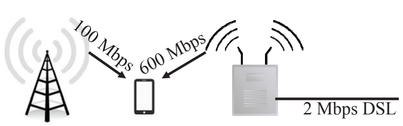
- 2G/3G/4G/WiFi/WiMAX, multi-band, multi-frequency, multiple modulation formats, multiple air interfaces
- Need "Software Define Radios (SDRs)"
  - Analog signal is sampled at a very high rate and processed using digital signal processing (DSP)
  - DAC, ADC, and PA are the most expensive parts



Ref: I. S. Simic, "Evolution of Mobile Base Station Architectures," Microwave Review, Jun 2007, 6pp., http://www.mtt-serbia.org.rs/microwave_review/pdf/Vol13No1-07-ISimic.pdf

Intelligent Multi-Mode RAT Selection

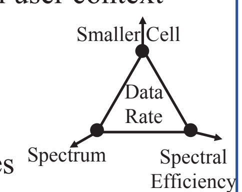
- Selecting between LTE, WiFi, 3G, …
- Can not just select
  - Highest speed
  - Highest signal power
  - Cheapest
- Correct choice also depends upon the type of traffic: voice vs. data ⇒ Network assisted selection



Ref: 4G Americas, "Integration of Cellular and WiFi Networks," Sep 2013, 65 pp., http://www.4gamericas.org/files/3114/0622/2546/Integration_of_Cellular_and_WiFi_Networks_White_Paper-_9.25.13.pdf

Hyper-Dense Small Cells

- Used in extremely busy areas. Sports arena, Malls, Metro trains ⇒ Heterogeneous and Small Cell Network (HetSNets)
- Self-Organizing: Neighbor discovery, parameter setting,
- Backhaul Flexibility: DSL, HomePlug, Wireless, …
- Mobility-Management:
  - Frequent Handovers Mitigation: Ping-pong. Network assisted as in intelligent multi-mode RAT selection
  - Forward Handover: Small cell can prefetch user context from the Serving cell
- Load balancing between small cells and with macro cell
- Multi-RAT Management: 2G/3G/4G/WiFi
- Privately Owned: Security and Incentive issues



Ref: I. Hwang, B. Song, and S. S. Soliman, "A Holistic View on Hyper-Dense Heterogeneous and Small Cell Networks," IEEE Communications Magazine, Jun 2013, pp. 20-27, http://blog.sciencenet.cn/home.php?mod=attachment&id=62246

New Energy Saving Mechanisms

1. Discontinuous Transmission (DTX)
2. Antenna Muting
3. Cell on/off switching
4. Power Save Mode for IoT

Discontinuous Transmission (DTX)

- Do not transmit during silence ⇒ Resources can be reused by others
- Was difficult to do in static allocation like GSM
- Already part of LTE

Antenna Muting

- Base stations have multiple antenna for MIMO
- Antenna Muting: Turn off some antenna at low load
- Advantage: Energy savings
- Problem: Number of antenna is assumed fixed and each antenna has its own pilot signals
  - Space-Frequency Block Code (SFBC) is used to transmit different frequency components from different antenna
  - ⇒ Throughput reduces
- Studies have shown significant energy savings with acceptable loss in throughput at low load.
- In 5G number of Antenna will become dynamic

Ref: P. Skillermark and P. Frenger, "Enhancing Energy Efficiency in LTE with Antenna Muting," 75th Vehicular Technology Conf. (VTC Spring), Yokohama, 2012, pp. 1-5, https://pdfs.semanticscholar.org/29ec/17e00ccae04ae34b74f9e6e62c1e2c42d789.pdf

Cell On/Off Switching

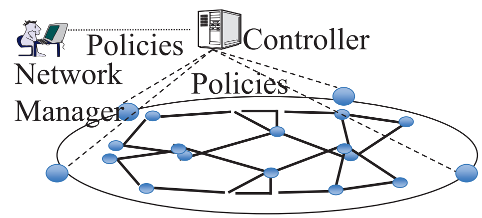
- Under low load a cell or small cell can be turned off
- Off cells broadcast "Discovery reference signals (DRS)" periodically so that they can be turned on if necessary
- Takes a few hundred ms
- Used for energy consumption during nights

CapEx/OpEx Reduction Techniques

1. Software Defined Networking (SDN)
2. Network Function Virtualization (NFV)
3. Mobile Edge Computing (MEC)
4. Cloud Radio Access Network (C-RAN)

Software Defined Networking (SDN)

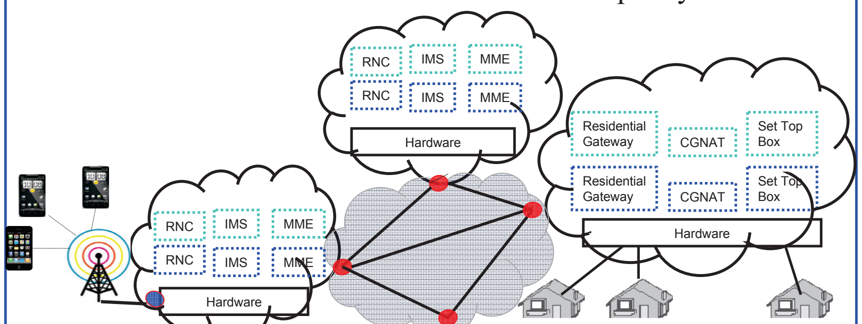
1. **Abstract the Hardware**: No dependence on physical infrastructure. Software API.
2. **Programmable**: Shift away from static manual operation to fully configurable and dynamic
3. **Centralized Control of Policies**: Policy delegation and management



Ref: D. Batista, et al, "Perspectives on software-defined networks: interviews with five leading scientists from the networking community" Journal of Internet Services and Applications 2015, 6:22, http://www.cse.wustl.edu/~jain/papers/jisa15.htm

Network Function Virtualization

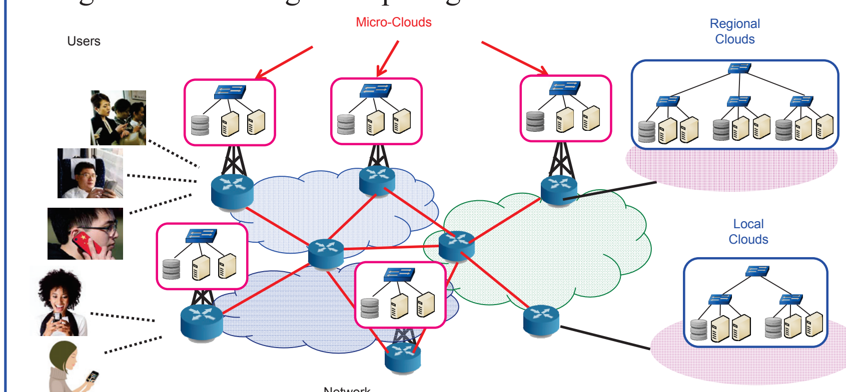
- Standard hardware is fast and cheap ⇒ No specialized hardware
- Implement all functions in software
- Virtualize all functions ⇒ Cloud ⇒ Create capacity on demand



Ref: Raj Jain, "SDN and NFV: Facts, Extensions, and Carrier Opportunities," AT&T Labs SDN Forum Seminar, April 10, 2014, http://www.cse.wustl.edu/~jain/papers/adn_att.htm

Mobile Edge Computing (MEC)

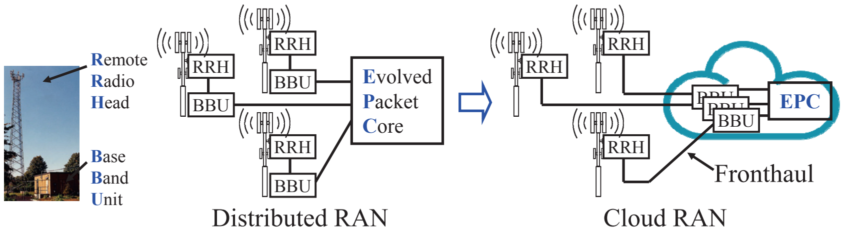
- To service mobile users/IoT, the computation needs to come to edge ⇒ Mobile Edge Computing



Ref: L. Gupta, R. Jain, H. Chan, "Mobile Edge Computing - an important ingredient of 5G Networks," IEEE Softwarization Newsletter, March 2016, http://sdn.ieee.org/newsletter/march-2016/mobile-edge-computing-an-important-ingredient-of-5g-networks

Cloud Radio Access Network (C-RAN)

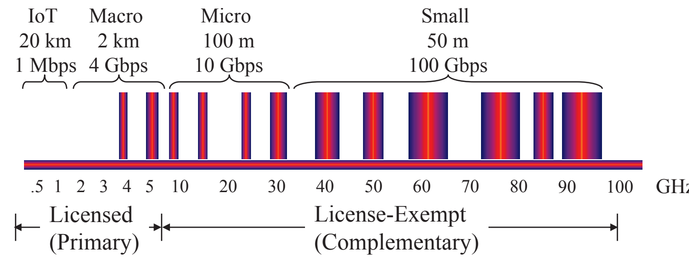
- Centralize baseband processing in a cloud
- Need to carry high-bit rate signal (after A-to-D conversion) from tower to cloud site ~ 10 Gbps
- Optical fiber, 10 Gbps Ethernet, Microwave can be used depending upon the distance ~ 1-20 km of **fronthaul**
- Particularly good for dense small cells. Multi-provider support.



Ref: C. I, et al, "Recent Progress on C-RAN Centralization and Cloudification," IEEE Access, Vol. 2, 2014, pp. 1030-1039, http://ieeexplore.ieee.org/iel7/6287639/6514899/06882182.pdf?arnumber=6882182

New Spectrum

- ITU estimates 900-1420 MHz required for 4G/5G by 2020 and 440-540 MHz required for 2G/3G and their enhancements



Ref: P. Zhu, "5G Enabling Technologies," PIMRC, Sep 2014, 20 slides, http://www.ieee-pimrc.org/2014/2014-09-03%205G%20Enabling%20Technologies%20PMIRC%20Huawei_Final.pdf

Ref: ITU-R M.2290-0, "Future Spectrum Requirements estimate for Terrestrial IMT," Dec 2013, http://www.itu.int/dms_pub/itu-r/opb/rep/R-REP-M.2290-2014-PDF-E.pdf

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Above 6 GHz

- Free-space loss increases in proportion to square of frequency and square of distance. 88 dB loss with 30 GHz at 20 m ⇒ 10-100 m cell radius
- Outdoor-to-Indoor: Glass windows add 20-40 dB
- Mobility: Doppler shift is proportional to frequency and velocity. Multipath results in varying Doppler shifts ⇒ Lower mobility
- Wide Channels: Duplex filters cover only 3-4% of center frequency ⇒ Need carrier aggregation.
- Antenna: 8x8 array at 60 GHz is only 2cm x 2cm. A/D and D/A converters per antenna element may be expensive
- 2 Gbps to 1 km is feasible using mm waves

Ref: ITU-R M2376-0, "Technical Feasibility of IMT in bands above 6 GHz," July 2015, http://www.itu.int/dms_pub/itu-r/opb/rep/R-REP-M.2376-2015-PDF-E.pdf

Application Specific Improvements

- Internet of Things
- Video

LTE Applications

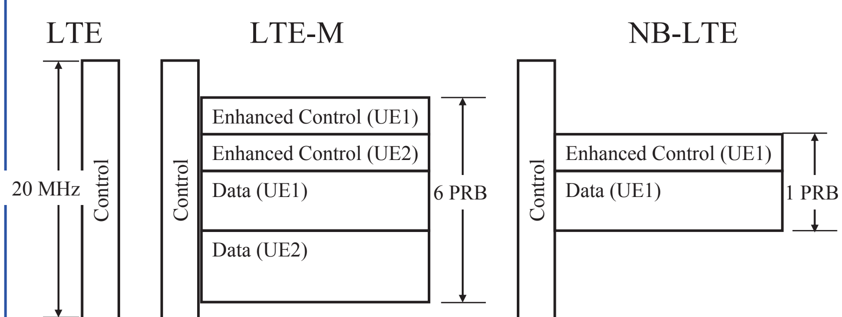
- Machine Type Communication (MTC): M2M or IoT
  - Versus current Human Type Communication (HTC)
  - GSM and HSPA modems for ~$5 are potential choices
  - Extended Coverage GSM (EC-GSM): Half-duplex FDD, Power Saving Mode (Same as LTE), 20 dB enhancements in link budget (total 164 dB) in R13 ⇒ 7x range for low rate
- Device-to-Device (D2D): Proximity services (Nearby search), enable direct device-to-device communication if nearby.
  - Low Latency D2D: Vehicular networking
- Group Communication: Public Safety (Fire, Police), push-to-talk
- Enhanced Multimedia Broadcast Multicast System (eMBMS): Broadcast Services (TV)

Machine Type Communication

- **LTE Low-cast (Category 0) UE**: In Release 12.
  - Single Antenna
  - Reduced peak rate up to 1 Mbps
  - Half-Duplex ⇒ No duplex filter
  - Power saving mode (PSM)
- **MTC LTE (LTE-M) (Category -1)** UE: In Release 13.
  - 1 Mbps using 1.4 MHz = 6 Physical Resource Blocks (PRB)
  - All power on fewer subcarriers
    ⇒ **P**ower **S**pectral **D**ensity (**PSD**) Boosting
    ⇒ 15 dB reduction in link budget by PSD and repetition
    ⇒ Allows UEs in basements and indoors
  - Reduced Tx power to 20 dBm ⇒ integrated amplifier
- **Narrow Band LTE** (**NB-LTE**) introduced Category -2 UE:
  - 128 kbps using 200 kHz band = Single PRB
  - 23 dBm power (required to maintain the link budget)
- Both LTE-M and NB-LTE UEs use single RF chain

Signaling Enhancements for MTC

- **E**nhanced **P**hysical **D**ownlink **C**ontrol **Ch**annel (EPDCCH)
- LTE Cat 0 UE receive signaling in the entire 20 MHz band
- LTE-M UEs receive signaling in their 1.4 MHz band
- For NB-LTE UEs, signaling is part of the assigned PRB

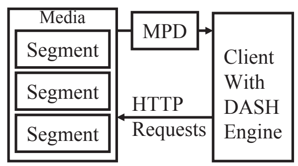


Power Saving Mode (PSM)

- Discontinuous Reception (DRX). Introduced in Release 12
- Allows UE to stay registered while sleeping
- UE's need to monitor resource allocation channel even if it has nothing to send or receive
- Connected mode DRX (cDRX): UE can sleep and periodically wake up to check the control channel
  - Short sleep cycle: 5 to 400 ms
  - Long sleep cycle: 20 ms to 2.5s (if no activity for 4 short cycles)

Dynamic Adaptive Streaming over HTTP (DASH)

- Video is the major component of mobile traffic
  ⇒ DASH provides an efficient method for video streaming
- Standard developed jointly by 3GPP, ISO, Open IPTV Forum
- Standard Web Servers: No changes required to servers, Content Distribution Networks (CDN), or HTTP protocol. HTTP passes easily through firewalls
- Mobile client controls what is downloaded using a "media presentation description (MPD)" file defined by DASH
- MPD contains URLs for segments
- Client requests segments as needed. Allows fast forward, rewind, etc.



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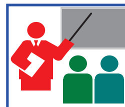

Summary

1. Current IMT Vision document defines 5G in terms of 8 parameters: a peak rate up to 20 Gbps per user, User experienced rate of 100 Mbps, spectral efficiency 3 times of 4G, Mobility support to 500 km/h, a latency of 1 ms, a density of a million connections per m2, energy efficiency 100x of 4G, and traffic capacity of 10 Mbps/m2.
2. New radio multiplexing techniques include f-OFDM, FBMC, NOMA, PDMA, LDS, SCMA, and IDMA
3. New spectrum utilization techniques include 3D Beamforming, Massive MIMO, FDD-TDD Carrier Integration, DAS, Simultaneous Transmission and Reception, Dynamic TDD, LAA, Multimode Base Stations, Intelligent Multi-Mode RAT Selection, and Higher order modulations in small cells
4. New energy savings mechanisms include Discontinuous Transmission (DTX), Antenna Muting, Cell on/off switching, and Power Save Mode for IoT
5. Capex/OpEx reduction techniques include SDN, NFV, MEC, and C-RAN.
6. Application specific improvements include LTE-M, NB-LTE for IoT and DASH for video.
7. New license-exempt spectrum in 6GHz-100 GHz will complement the licensed spectrum.

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- https://en.wikipedia.org/wiki/Software-defined_networking
- https://en.wikipedia.org/wiki/Network_function_virtualization
- https://en.wikipedia.org/wiki/Mobile_edge_computing
- https://en.wikipedia.org/wiki/C-RAN
- https://en.wikipedia.org/wiki/Small_cel l
- https://en.wikipedia.org/wiki/Distributed_antenna_system
- https://en.wikipedia.org/wiki/Dynamic_Adaptive_Streaming_over_HTTP
- https://en.wikipedia.org/wiki/3GPP
- https://en.wikipedia.org/wiki/Beamforming
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Acronyms

- 3GPP 3rd Generation Partnership Project
- ADC Analog-to-Digital Converter
- API Application Programming Interface
- AWGN Additive White Gaussian Noise
- BBU Broadband Unit
- BS Base Station
- CapEx Capital Expenditure
- CDMA Code Division Multiple Access
- CDN Content Distribution Networks
- cDRX Connected mode discontinuous reception
- CGNAT Carrier Grade Network Address Translator
- DAC Digital-to-Analog Converter
- DAS Distributed Antenna Systems
- DASH Dynamic Adaptive Streaming over HTTP
- dB DeciBel
- dBm DeciBel Milliwatt

Acronyms (Cont)

- DL Downlink
- DRS Discovery reference signals
- DRX Discontinuous Reception
- DS-CDMA Direct Sequence Code Division Multiple Access
- DSL Digital Subscriber Line
- DSP Digital signal processing
- DTX Discontinuous Transmission
- eIMTA Enhanced Interference Mitigation and Traffic Adaptation
- eMBMS Enhanced Multimedia Broadcast Multicast System
- eNB Evolved Node-B
- EPC Evolved Packet Core
- EPDCCH Enhanced Physical Downlink Control Channel
- FBMC Filtered Bank Multicarrier
- FD-MIMO Full Dimension MIMO
- FDD Frequency Division Duplexing
- GHz Giga Hertz

Acronyms (Cont)

- GSM Global System for Mobile Telephony
- HARQ Hybrid Automatic Repeat Request
- HetSNets Heterogeneious Small Cell Network
- HSPA High Speed Packet Access
- HTC Human Type Communication
- HTTP Hyper-Text Transfer Protocol
- IDMA Interleave Division Multiple Access
- IEEE Institution of Electrical and Electronic Engineers
- IMS IP Multimedia System
- IMT-2020 5G
- IMT International Mobile Telecommunications
- IoT Internet of Things
- IPTV Internet Protocol Television
- ISO International Standards Organization
- ITU-R International Telecommunications Union- Radio
- ITU International Telecommunications Union

Acronyms (Cont)

- kHz Kilo Hertz
- LAA License Assisted Access
- LDS Low Density Spreading
- LTE-A Long-Term Evolution Advanced
- LTE-M Long-Term Evolution for Machine Type Communication
- LTE-U Long-Term Evolution Unlicensed
- LTE Long-Term Evolution
- MC-CDMA Multi-carrier Code Division Multiple Access
- MEC Mobile Edge Computing
- MHz Mega Hertz
- MIMO Multiple Input Multiple Output
- MME Mobility Management Entity
- MPD Media presentation description
- MTC Machine Type Communication
- mW Milli Watt
- NB-LTE Narroband Long Term Evolution

Acronyms (Cont)

- NFV Network Function Virtualization
- NOMA Non-Orthogonal Multiple Access
- OFDM Orthogonal Frequency Division Multiplexing
- OFDMA Orthogonal Frequency Division Multiple Access
- OpEx Operational Expenditure
- PA Power Amplifier
- PDMA Pattern Division Multiple Access
- PHY Physical Layer
- PRB Physical Resource Blocks
- PSD Power Spectral Density
- PSM Power Saving Mode
- QAM Quadrature Amplitude Monitor
- QoE Quality of Experience
- QoS Quality of Service
- RAN Radio Access Network
- RAT Radio Access Technology

Acronyms (Cont)

- REC Recommendation
- REP Report
- RF Radio Frequency
- RNC Radio Network Controller
- RRH Remote Radio Head
- SCMA Sparse code multiple access
- SDN Software Defined Networking
- SDR Software Defined Radios
- SFBC Space-Frequency Block Code
- SIC Successive Interference Cancellation
- TDD Time Division Duplexing
- TV Television
- UE User Element
- UL Uplink
- URL Uniform Resource Locator
- USA United States of America

Acronyms (Cont)

- VTC Vehicular Technology Conference
- WCSP Wireless Communications and Signal Processing
- WiFi Wireless Fidelity
- WiMAX Worldwide Interoperability for Microwave Access

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