Introduction to LTE

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Audio/Video recordings of this class lecture are available at:
http://www.cse.wustl.edu/~jain/cse574-16/

1. LTE: Key Features
2. OFDMA and SC-FDMA
3. Evolved Packet Core (EPC)
4. LTE Frame Structure
5. Resource Allocation

LTE: Key Features

Long Term Evolution. 3GPP Release 8, 2009.

1. **3.9G** (Pre-4G) cellular technology
   Sold as 4G by some providers.
   4G=International Mobile Telecommunication (IMT) Advanced Requirements in ITU M.2134-2008
2. **Many different bands**: 700/1500/1700/**2100**/2600 MHz
3. **Flexible Bandwidth**: 1.4/3/5/10/15/20 MHz
4. Frequency Division Duplexing (FDD) and Time Division Duplexing (TDD)
   ⇒ Both *paired* and *unpaired* spectrum
5. 4x4 MIMO, Multi-user collaborative MIMO
6. Beamforming in the downlink

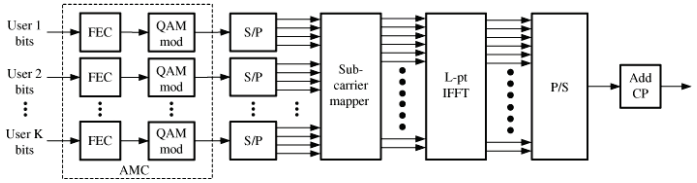
Ref: A. Ghosh, J. Zhang, J. G. Andrews, R. Muhamed, "Fundamentals of LTE," Prentice Hall, 2010, ISBN: 0137033117, 464 pp. Safari book.

LTE: Key Features (Cont)

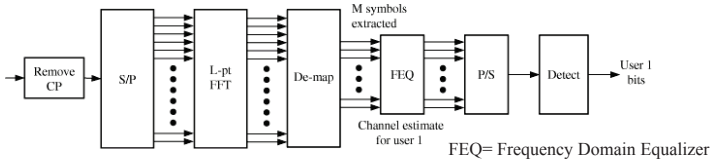
8. Data Rate: 326 Mbps/down 86 Mbps up (4x4 MIMO 20 MHz)
9. Modulation: OFDM with QPSK, 16 QAM, 64 QAM
10. **OFDMA** downlink,
    Single Carrier Frequency Division Multiple Access (**SC-FDMA**) uplink
11. **Hybrid ARQ** Transmission
12. Short **Frame Sizes** of 10ms and 1ms ⇒ faster feedback and better efficiency at high speed
13. **Persistent scheduling** to reduce control channel overhead for low bit rate voice transmission.
14. **IP based** flat network architecture

OFDMA Downlink

- Transmitter at Base Station: IFFT converts frequency to time



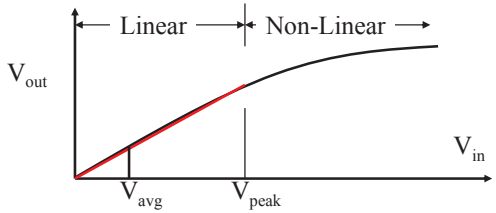
- Receiver at User Terminal: FFT converts time to frequency



Ref: A. Ghosh, J. Zhang, J. G. Andrews, R. Muhamed, "Fundamentals of LTE," Prentice Hall, 2010, ISBN: 0137033117, 464 pp. Safari book.

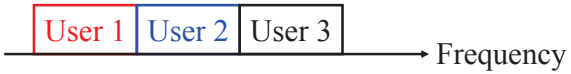
Peak-to-Average Power Ratio (PAPR)

- OFDM
  - ⇒ Each carrier modulated according to specific channel condition
  - ⇒ High variation of power levels
  - ⇒ Higher Peak-to-Average Power Ratio (PAPR)
  - ⇒ Higher cost of amplifiers
- Amplifiers are linear only over a restricted region
  - ⇒ Costly amplifier or reduce average signal power significantly
  - ⇒ Can afford such amplifiers in Base stations but not in mobiles



SC-FDMA

- Single-Carrier Frequency Division Multiple Access
- Each user gets a contiguous part of the channel

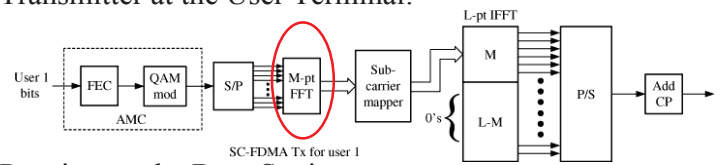


- Uses single carrier modulation and adds a cyclic prefix
- Single carrier ⇒ Not much variation in amplitude
  ⇒ Lower PAPR
- Better for uplink because slight mis-synchronization among users does not affect the decoding significantly
- With OFDMA each user's subcarriers are spread all over the band and may affect other users subcarriers all over the band

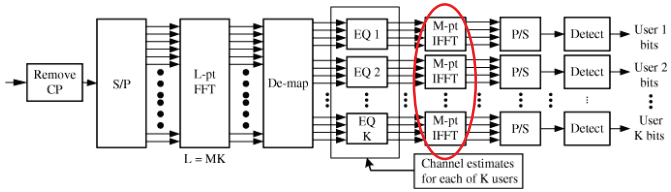
Ref: A. Ghosh, J. Zhang, J. G. Andrews, R. Muhamed, "Fundamentals of LTE," Prentice Hall, 2010, ISBN: 0137033117, 464 pp.

SC-FDMA (Cont)

- In practice, SC-FDMA is implemented as if the user is allocated a contiguous subset of subcarriers
- Transmitter at the User Terminal:



- Receiver at the Base Station:

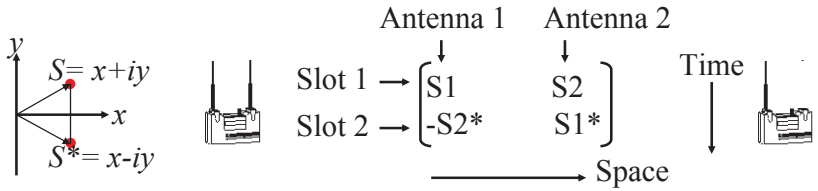


- SC-FDMA = Discrete Fourier Transform *Pre-coded* OFDMA

Ref: A. Ghosh, J. Zhang, J. G. Andrews, R. Muhamed, "Fundamentals of LTE," Prentice Hall, 2010, ISBN: 0137033117, 464 pp.

Space Time Block Codes (STBC)

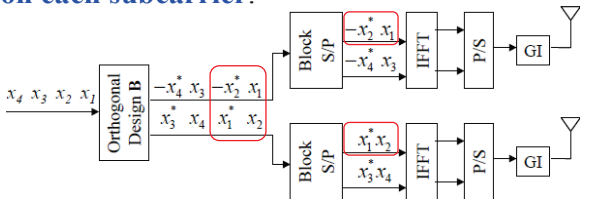
- Invented 1998 by Vahid Tarokh.
- Transmit multiple redundant copies from multiple antennas
- Precisely coordinate distribution of symbols in space and time.
- Receiver combines multiple copies of the received signals optimally to overcome multipath.
- Example: Two antennas: Two symbols in two slots ⇒ Rate 1



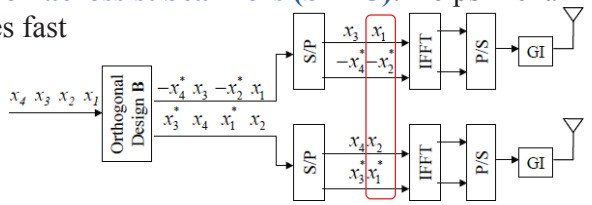
S1* is complex conjugate of S1 ⇒ columns are orthogonal

Space-Frequency Block Codes

- STBC on OFDM (Multi-carrier): Two alternatives
- **STBC on each subcarrier**:



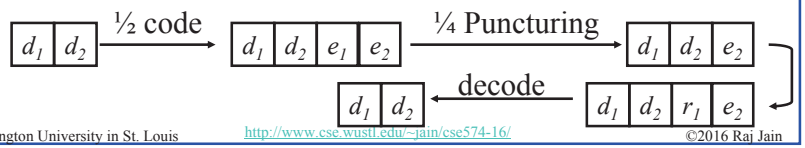
- **STBC on across subcarriers (SFBC)**: Helps if channel changes fast



Ref: G. Bauch, "Space-Time Block Codes Versus Space-Frequency Block Codes," IEEE VTC, Apr 2003, http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.2.1724&rep=rep1&type=pdf

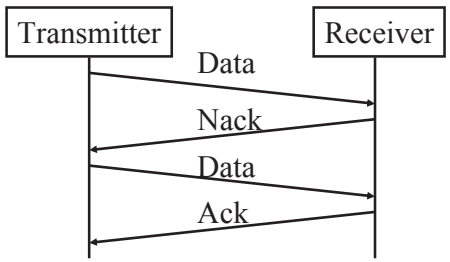
Puncturing

- Use large number of error correcting code (ECC) bits but send only some of them
- Example: 1/2 code = 1 ECC bit/Original bit
- Or 4 bits for each 2-bit symbol
- ¼ puncturing ⇒ Drop every 4th bit ⇒ send 3 bits for each 2-bit symbol = 2/3 code
- Receiver puts random bits in the punctured positions and decodes ⇒ high probability of correct decoding particularly if the SINR is high
- ½ code with 1/4th puncture is not as good as 2/3 code in general but puncturing helps in some situations, such as, H-ARQ



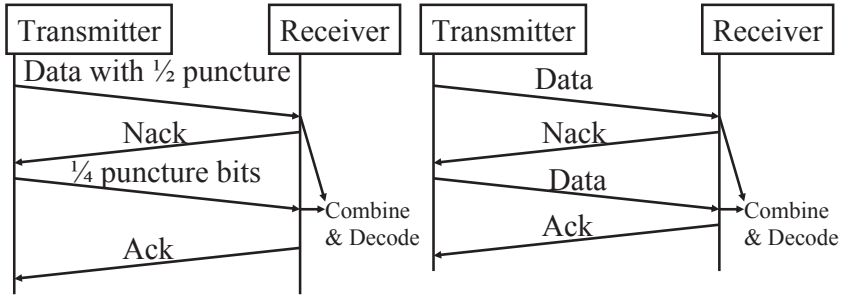
ARQ

- **A**utomatic **R**epeat re**Q**uest (ARQ)
- Retransmit a packet if it is received in error
- Previous (bad) bits are discarded.



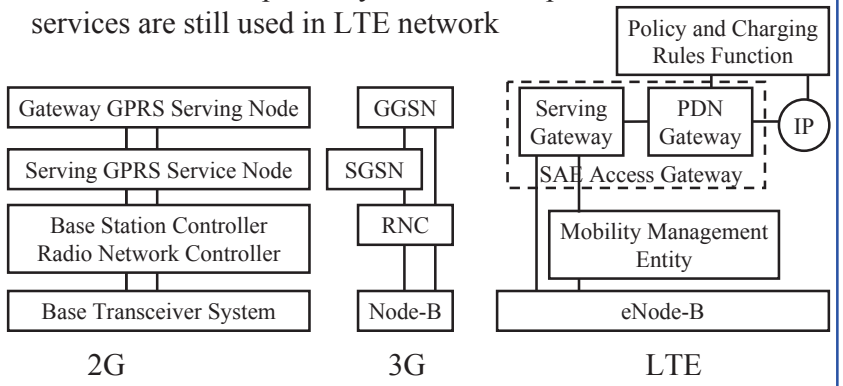
Hybrid ARQ

- PHY and MAC layers work together ⇒ Hybrid
- PHY layer sends some bits first (uses puncturing)
  - Sends additional bits only if necessary.
  - Additional bits are sent until the decoding is successful. (**Incremental Redundancy** or **Type II** H-ARQ)
  - Another alternative is to combine the good bits of multiple transmissions (**Chase Combining** or **Type I** H-ARQ)



IP-Based Flat Network Architecture

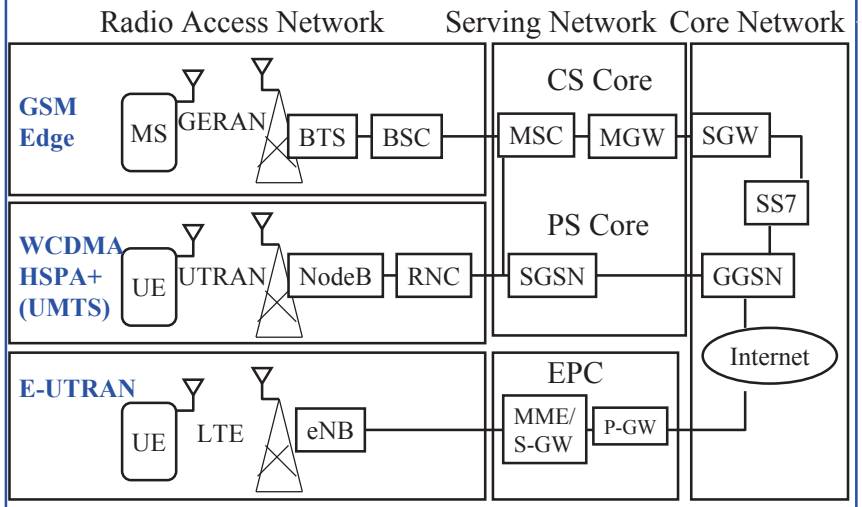
- Flat ⇒ Less hierarchical and fewer nodes
- All services (Voice/multimedia) over IP
- For backward compatibility some non-IP protocols and services are still used in LTE network



Evolved Packet Core (EPC)

- Four new elements:
  1. **Serving Gateway**: Demarcation point between RAN and Core. Serves as mobility anchor when terminals move
  2. **Packet Data network Gateway (PGW)**: Termination of EPC towards Internet or IMS network. IP services, address allocation, deep packet inspection, policy enforcement
  3. **Mobility Management Entity (MME)**: Location tracking, paging, roaming, and handovers. All control plane functions related to subscriber and session management.
  4. **Policy and Charging Rules Function (PCRF)**: Manages QoS

Evolved Packet System (EPS)



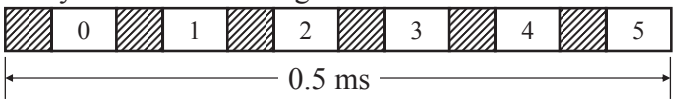
Evolved Packet System (Cont)

- CS = Circuit Switched
- EPC = Evolved Packet Core
- EPS = Evolved Packet System
- GERAN = GSM Enhanced Radio Access Network
- GGSN = Gateway GPRS Support Node
- LTE = Long Term Evolution
- MME = Mobility Management Utility
- MSC = Mobile Switching Center
- P-GW = Packet Gateway
- PS = Packet Switched
- RNC = Radio Network Control
- S-GW = Serving Gateway
- SGSN = Service GPRS Support Node
- SS7 = System 7
- eNB = Evolved NodeB

LTE Frame Structure

- Subframe = 2 slots of 0.5 ms each
- Slot = 6 or 7 symbols of 0.667 ms each
- Normal Cyclic Prefix:5.2 us for 1st symbol, 4.7 us for others

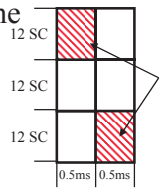
- Extended Cyclic Prefix: for larger networks. 16.7 us



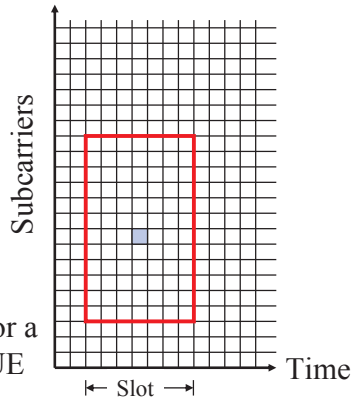
Ref: Rhode and Schwarz, "UMTS Long Term Evolution (LTE) Technology Introduction," http://www.rohde-schwarz.de/file/1MA111_4E_LTE_technology_introduction.pdf

Resource Allocation

- **Time slot:** 0.5 ms
  6 or 7 OFDM symbols
- **Subcarriers:** 15 kHz
- **Physical Resource Block:**
  12 subcarriers (180 kHz)
  over 1 time slot
- **Minimum Allocation**: 2 PRBs per subframe



PRBs for a single UE



Ref: A. Ghosh, J. Zhang, J. G. Andrews, R. Muhamed, "Fundamentals of LTE," Prentice Hall, 2010, ISBN: 0137033117, 464 pp.

WiMAX vs. LTE

- Similar with very minor differences
- Net Head vs. Bell Head
- Enterprise Networking vs. Carrier Networking
- Academic vs. Telecom
- Intel/Google vs. Ericsson/QUALCOMM
- Both use OFDMA.
  Both are incompatible with 2G and 3G (CDMA) radios.
- Quad-band ⇒ Penta-band

Summary

1. WiMAX and LTE are pre-4G technologies.
2. WiMAX and LTE have numerous **common features**: Many bands, flexible bandwidth, FDD/TDD. MIMO/Beamforming H-ARQ, IP-Based, OFDMA. The key differentiator is SC-FDMA for uplink in LTE to reduce **PAPR**.
3. STBC requires transmitting redundant symbols from multiple antenna. **SFBC** require that these redundant symbols be sent on different subcarriers.
4. **Puncturing** allows some ECC bits to be not transmitting. This is used in **H-ARQ** to send extra bits only if necessary.
5. LTE uses a **super-frame** of 10 subframes of 1 ms each. Each **subframe** has one **slot** for uplink and downlink each.

Reading List

- A. Ghosh, J. Zhang, J. G. Andrews, R. Muhamed, "Fundamentals of LTE," Prentice Hall, 2010, ISBN: 0137033117, 464 pp., Safari Book.
- 3GPP, "LTE," http://www.3gpp.org/technologies/keywords-acronyms/98-lte
- 3GPP, "The Evolved Packet Core," http://www.3gpp.org/technologies/keywords-acronyms/100-the-evolved-packet-core
- Rhode and Schwarz, "UMTS Long Term Evolution (LTE) Technology Introduction," http://www.rohde-schwarz.de/file/1MA111_4E_LTE_technology_introduction.pdf

Wikipedia Links

- https://en.wikipedia.org/wiki/IMT-Advanced
- https://en.wikipedia.org/wiki/4G
- https://en.wikipedia.org/wiki/Radio_Resource_Control
- https://en.wikipedia.org/wiki/Radio_resource_management
- https://en.wikipedia.org/wiki/Single-carrier_FDMA
- https://en.wikipedia.org/wiki/Space%E2%80%93time_block_code
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- https://en.wikipedia.org/wiki/MIMO
- https://en.wikipedia.org/wiki/Multi-user_MIMO
- https://en.wikipedia.org/wiki/Precoding

Wikipedia Links (Cont)

- https://en.wikipedia.org/wiki/Antenna_diversity
- https://en.wikipedia.org/wiki/Many_antennas
- https://en.wikipedia.org/wiki/Multi-user_MIMO
- https://en.wikipedia.org/wiki/Smart_antenna
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- https://en.wikipedia.org/wiki/Radio_Network_Controller
- https://en.wikipedia.org/wiki/Crest_factor
- https://en.wikipedia.org/wiki/PDCP
- https://en.wikipedia.org/wiki/Crest_factor
- https://en.wikipedia.org/wiki/E-UTRA
- https://en.wikipedia.org/wiki/Policy_and_charging_rules_function
- https://en.wikipedia.org/wiki/Puncturing
- https://en.wikipedia.org/wiki/Fading
- https://en.wikipedia.org/wiki/Single-frequency_network
- https://en.wikipedia.org/wiki/Evolved_Packet_System

Wikipedia Links (Cont)

- https://en.wikipedia.org/wiki/Channel_allocation_schemes
- https://en.wikipedia.org/wiki/Hybrid_automatic_repeat_request
- https://en.wikipedia.org/wiki/LTE_timeline
- https://en.wikipedia.org/wiki/Flat_IP
- https://en.wikipedia.org/wiki/E-UTRA
- https://en.wikipedia.org/wiki/Mobility_Management_Entity
- https://en.wikipedia.org/wiki/System_Architecture_Evolution
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- https://en.wikipedia.org/wiki/Signaling_gateway
- https://en.wikipedia.org/wiki/Packet_data_serving_node
- https://en.wikipedia.org/wiki/Automatic_repeat_request
- https://en.wikipedia.org/wiki/Hybrid_automatic_repeat_request
- https://en.wikipedia.org/wiki/Beamforming
- https://en.wikipedia.org/wiki/Multimedia_Broadcast_Multicast_Service
- https://en.wikipedia.org/wiki/Broadcast/Multicast_Control
- https://en.wikipedia.org/wiki/Multicast-broadcast_single-frequency_network

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- https://en.wikipedia.org/wiki/Orthogonal_frequency-division_multiple_access
- https://en.wikipedia.org/wiki/Single-carrier_FDMA
- https://en.wikipedia.org/wiki/4G
- https://en.wikipedia.org/wiki/Orthogonal_frequency-division_multiplexing
- https://en.wikipedia.org/wiki/Orthogonal_frequency-division_multiple_access
- https://en.wikipedia.org/wiki/E-UTRA
- https://en.wikipedia.org/wiki/Cooperative_MIMO
- https://en.wikipedia.org/wiki/Cyclic_prefix

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- E. Dahlman, et al, "3G Evolution:HSPA and LTE for Mobile Broadband," 2nd Edition, Academic Press, 2008, ISBN:0123745385
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- 3GPP TR 36.913, "Requirements for Further Advancements for E-UTRA," v8.0.1, March 2009.
- S. Sesia, I. Toufik, "LTE – The UMTS Long Term Evolution From Theory to Practice, Second Edition," Wiley , 2011, ISBN: 9780470660256, 792 pp. Safari book.

Acronyms

3GPP	3rd Generation Partnership Project
ARQ	Automatic Repeat Request
BPSK	Binary Phase Shift Keying
BS	Base Station
BSC	Base Station Controller
BTS	Base Transceiver Station
CDMA	Code Division Multiple Access
CFI	Control Format Indicator
CS	Circuit Switched
DCI	Downlink Control Information
DL	Downlink
DVB-H	Digital Video Broadcast handheld
ECC	Error Correcting Code
eNB	Enhanced Node B
eNode-B	Enchanced Node B
EPC	Evolved Packet Core

Acronyms (Cont)

- EPS Evolved Packet System
- FDD Frequency Division Duplexing
- FDMA Frequency Division Multiple Access
- FEQ Frequency Domain Equalizer
- FFT Fast Fourier Transform
- FSTD Frequency-Shift Transmit Diversity
- GERAN GSM/EDGE Radio Access Network
- GGSN Gateway GPRS Support
- GPRS General Packet Radio Service
- GSM Global System for Mobile Communications
- GW Gateway
- HSPA High-Speed Packet Access
- ID Identifier
- IEEE Institution of Electrical and Electronic Engineers
- IETF Internet Engineering Task Force
- IMS Internet Multimedia System
- IMT-Advanced International Mobile Telecommunications Advanced

Acronyms (Cont)

- IP Internet Protocol
- ITU International Telecommunications Union
- kHz Kilo Hertz
- LTE Long Term Evolution
- MAC Message Authentication Code
- MAC Media Access Control
- MBMS Multicast-Broadcast Mobile Services
- MGW Media Gateway
- MHz Mega Hertz
- MIMO Multiple Input Multiple Output
- MME Mobility Management Entity
- MSC Mobile Switching Center
- NACK Negative Acknowledgement
- OFDM Orthogonal Frequency Division Modulation
- OFDMA Orthogonal Frequency Division Multiple Access
- PAPR Peak-to-Average Power Ratio

Acronyms (Cont)

- PCRF Policy and Charging Rules Function
- PDCCH Packet Downlink Control Channel
- PDCP Packet Data Convergence Protocol
- PDFICH Physical Control Format Indicator Channel
- PDN Packet Data Network
- PDU Protocol Data Unit
- PGW Packet Data network Gateway
- PHY Physical Layer
- PS Packet Switched
- QAM Quadrature Amplitude Modulation
- QoS Quality of Service
- QPSK Quadrature Phase Shift Keying
- RAN Radio Access Network
- RLC Radio Link Control
- RNC Radio Network Control
- ROHC Robust Header Compression

Acronyms (Cont)

- RRC Radio Resource Control
- SAE Service Access Gateway
- SC-FDMA Single Carrier Frequency Division Multiple Access
- SC Single Carrier
- SDU Service Data Unit
- SFBC Space Frequency Block Code
- SGSN Service GPRS Support
- SGW Serving Gateay
- SINR Signal to Interference and Noise Ratio
- SISO Single Input Single Output
- SN Sequence Number
- SNR Signal-to-noise ratio
- SO Segment Offset
- SOstart Begining of Segment
- STBC Space Time Block Code
- TD-SCDMA Time Division Synchronous Code Division Multiple Access

Acronyms (Cont)

TDD	Time Division Duplexing
TDMA	Time Division Multiple Access
UE	User Element
UL	Uplink
UMTS	Universal Mobile Telecommunications System
UTRA	UMTS Terrestrial Radio Access
UTRAN	UMTS Terrestrial Radio Access Network
VTC	Vehicular Technology Conference
WCDMA	Wideband Code Division Multiple Access
WiMAX	Worldwide Interoperability for Microwave Access

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