18-452/18-750
Wireless Networks and Applications
Lecture 15: LTE

Peter Steenkiste

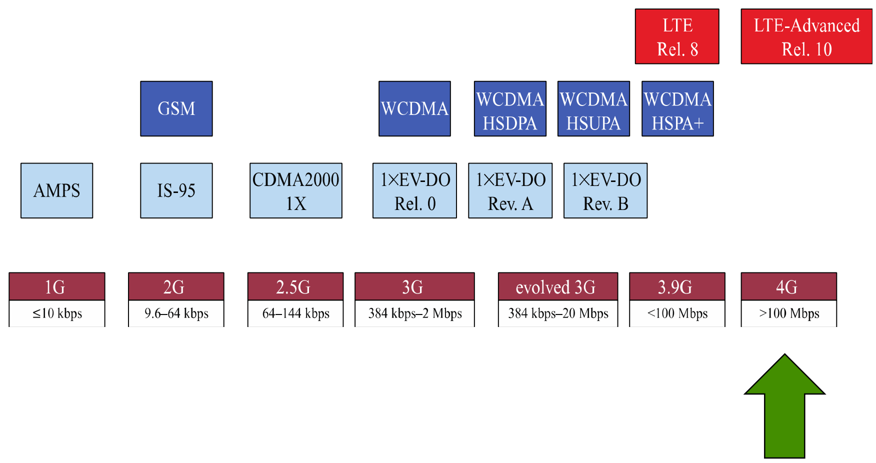
Spring Semester 2024

http://www.cs.cmu.edu/~prs/wirelessS24/

Announcements

- **Please sign up for a P2 meeting**
  - » See piazza post
  - » If you don't have a team, please send me mail asap
- **Survey teams and choices of topics are due this Friday**
  - » 2 person teams!
  - » First come first serve in terms of topics

Evolution of Cellular Wireless Systems



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Overview LTE

- Motivation
- Architecture
- Resource management
- LTE protocols
- Radio access network
  - » OFDM refresher
- LTE advanced

Some slides based on material from
"Wireless Communication Networks and Systems"

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Purpose, Motivation, and Approach to 4G

- Defined by ITU directives for International Mobile Telecommunications Advanced (IMT-Advanced)
- All-IP packet switched network
- Ultra-mobile broadband access
- Peak data rates
  - » Up to 100 Mbps for high-mobility mobile access
  - » Up to 1 Gbps for low-mobility access
- Dynamically share and use network resources
- Smooth handovers across heterogeneous networks
  - » 2G and 3G networks, small cells such as picocells, femtocells, and relays, and WLANs
- High quality of service for multimedia applications

High Level Features

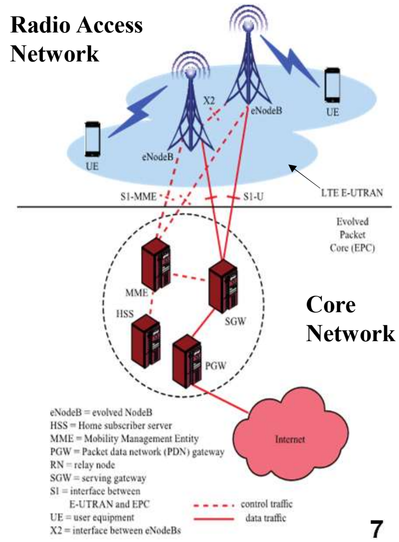
- No support for circuit-switched voice
  - » Instead providing Voice over LTE (VoLTE)
- Replace spread spectrum/CDMA with OFDM

Technology	1G	2G	2.5G	3G	4G
Design began	1970	1980	1985	1990	2000
Implementation	1984	1991	1999	2002	2012
Services	Analog voice	Digital voice	Higher capacity packetized data	Higher capacity, broadband	Completely IP based
Data rate	1.9. kbps	14.4 kbps	384 kbps	2 Mbps	200 Mbps
Multiplexing	FDMA	TDMA, CDMA	TDMA, CDMA	CDMA	OFDMA, SC-FDMA
Core network	PSTN	PSTN	PSTN, packet network	Packet network	IP backbone

PSTN – Public Switched Telephone Network

LTE Architecture

- evolved NodeB (eNodeB)
  - » Most devices connect into the network through the eNodeB
- Evolution of the previous 3GPP NodeB (~2G BTS)
  - » Uses OFDM instead of CDMA
- Has its own control functionality
  - » Dropped the Radio Network Controller (RNC - ~2G BSC)
  - » eNodeB supports radio resource control, admission control, and mobility management (handover)
  - » Tasks were originally the responsibility of the RNC in 2G



Evolved Packet System

- The overall architecture is called the Evolved Packet System (EPS)
- The 3GPP standards divide the network into:
- Radio access network (RAN): cell towers and connections to mobile devices
- Core network (CN): management and connectivity to other networks
- Each can evolve independently
  - » Their evolution is driven by different technologies
  - » Radio technology, optimizing spectrum
  - » Management and control or traffic, servers for management tasks

Evolved Packet System Components

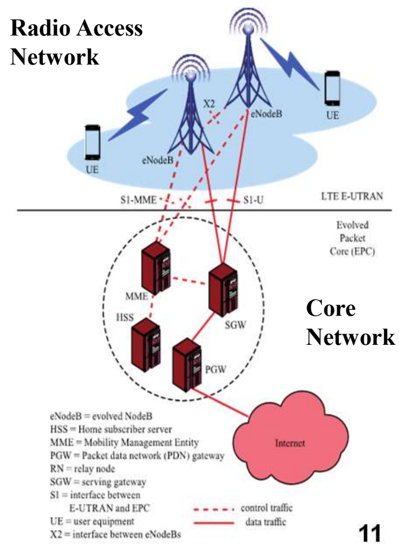
- Long Term Evolution (LTE) is the RAN
  - » RAN: Radio Area Network
  - » Called Evolved UMTS Terrestrial Radio Access (E-UTRA)
  - » Enhancement version of 3GPP's 3G RAN
  - » eNodeB is the only type of node in the E-UTRAN
  - » No Radio Network Controller (RNC)
- Evolved Packet Core (EPC)
  - » Operator or carrier core network – core of the system
- Traditionally circuit switched but now entirely packet switched
  - » Based on IP - Voice supported using voice over IP (VoIP)

Design Principles of the EPS

- Packet-switched transport for traffic belonging to several QoS classes
  - » Voice, streaming, real-time, non-real-time, background
- Comprehensive radio resource management
  - » End-to-end QoS, transport for higher layers
  - » Load sharing/balancing
  - » Policy management across different radio access technologies
- Integration with existing 3GPP 2G and 3G networks
- Scalable spectrum bands from 1.4 MHz to 20 MHz
- Carrier aggregation for spectrum bands up to 100 MHz

Evolved Packet Core Components

- **Mobility Management Entity (MME)**
  - » Supports user equipment context, identity, authentication, and authorization
- **Serving Gateway (SGW)**
  - » Receives and sends packets between the eNodeB and the core network
- **Packet Data Network Gateway (PGW)**
  - » Connects the EPC with external networks
- **Home Subscriber Server (HSS)**
  - » Database of user-related and subscriber-related information
- **Interfaces**
  - » S1 interface between E-UTRAN and EPC
    - – Control and user plane data traffic
  - » X2 interface for eNodeBs to interact with each other
    - – Again for both control purposes and for user plane data traffic



Overview

- **Motivation**
- **Architecture**
- **Resource management**
- **LTE protocols**
- **Radio access network**
  - » OFDM refresher
- **LTE advanced**

LTE Resource Management

- LTE uses *bearers* for quality of service (QoS) control instead of circuits
- EPS bearers
  - » Between entire path between PGW and UE
  - » Maps to specific QoS parameters such as data rate, delay, and packet error rate
- Service Data Flows (SDFs) differentiate traffic flowing between applications on a client and a service
  - » SDFs must be mapped to EPS bearers for QoS treatment
  - » SDFs allow traffic types to be given different treatment
- End-to-end service is not completely controlled by LTE
  - » Control is limited to Radio Access Network and Core Network

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Bearer Management based on QoS Class Identifier (QCI)

QCI	Resource Type	Priority	Packet Delay Budget	Packet Error Loss Rate	Example Services
1	GBR	2	100 ms	10^{-2}	Conversational Voice
2		4	150 ms	10^{-3}	Conversational Video (live streaming)
3		3	50 ms	10^{-3}	Real Time Gaming
4		5	300 ms	10^{-6}	Non-Conversational Video (buffered streaming)
5	Non-GBR	1	100 ms	10^{-6}	IMS Signalling
6		6	300 ms	10^{-6}	Video (buffered streaming) TCP-based (e.g., www, e-mail, chat, ftp, p2p file sharing, progressive video, etc.)
7		7	100 ms	10^{-3}	Voice, Video (live streaming) Interactive Gaming
8		8	300 ms	10^{-6}	Video (buffered streaming) TCP-based (e.g., www, e-mail, chat, ftp, p2p file sharing, progressive video, etc.)
9*		9			

* QCI value typicaly used for the default bearer

Guaranteed (minimum) Bit Rate (QCI 1–4)

No Guarantees (QCI 5–9)

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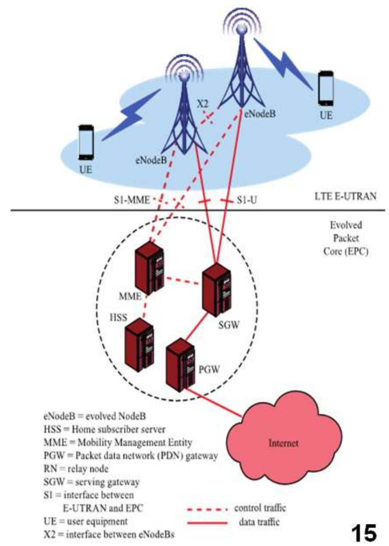
EPC: Mobility Management

- X2 interface used when moving within a RAN coordinated under the same Mobility Management Entity (MME)
- S1 interface used to move to another MME
- *Hard handovers* are used: A UE is connected to only one eNodeB at a time



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EPC: Inter-cell Interference Coordination (ICIC)

- Reduces interference when the same frequency is used in a neighboring cell
- Goal is universal frequency reuse
  - » *N* = 1 in "Cellular principles" lecture
  - » Must avoid interference when mobile devices are near each other at cell edges
  - » Interference randomization, cancellation, coordination, and avoidance are used
- eNodeBs send *indicators*
  - » Relative Narrowband Transmit Power, High Interference, and Overload indicators
- Later releases of LTE have improved interference control
  - » "Cloud RAN": use a cloud to manage interference, spectrum

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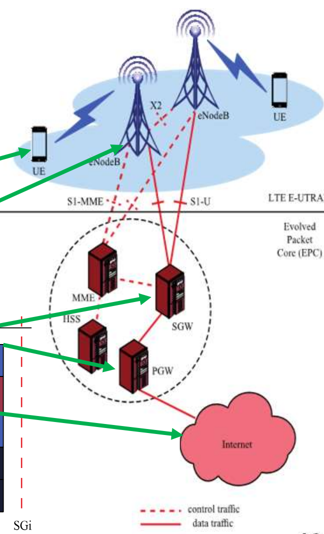
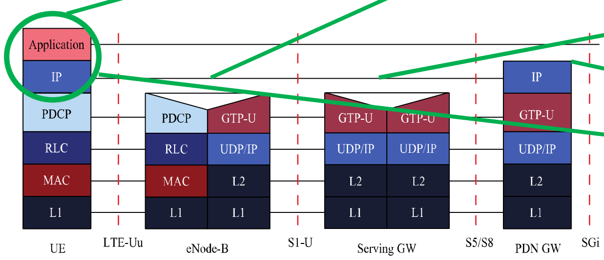
Protocol Layers in Cellular Network

- EPC is an IP network
- Connects mobile devices to Internet via eNoceB
- Mobile link:
  - Radio Link Control
  - Packet Data Convergence Protocol
    - User, control traffic, IP header compression, check sum, ….





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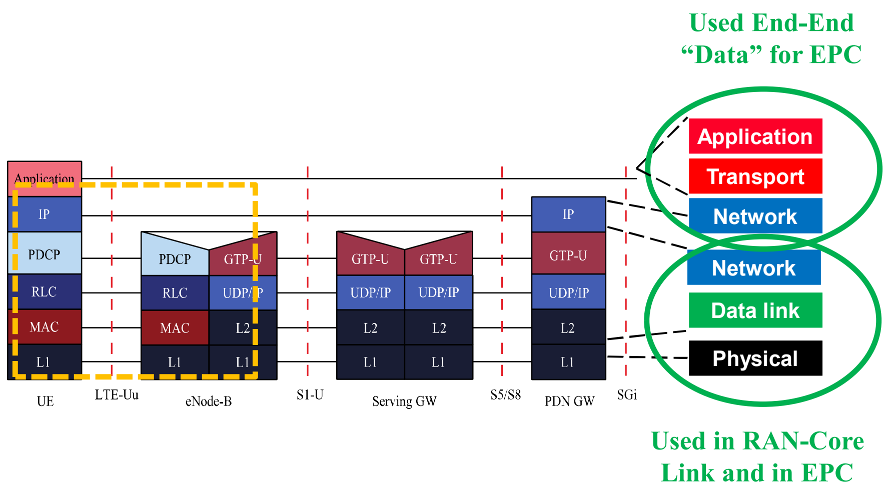
Protocol Layers End-to-End



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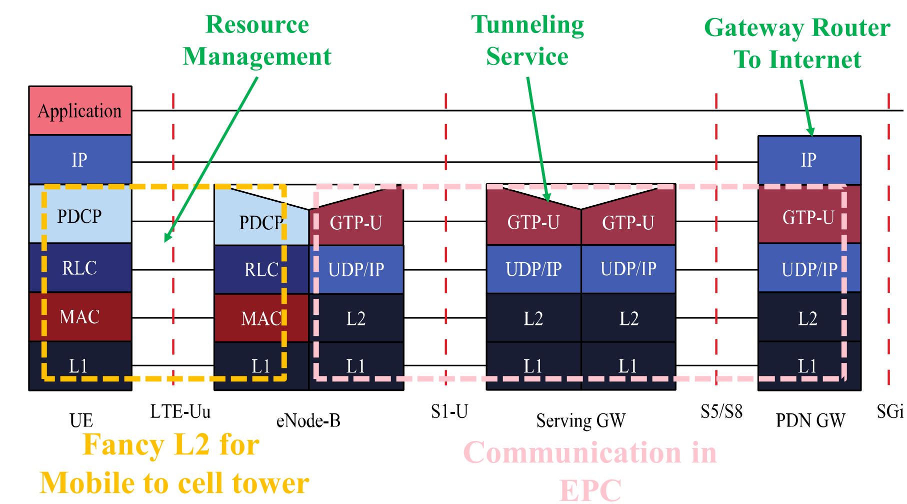
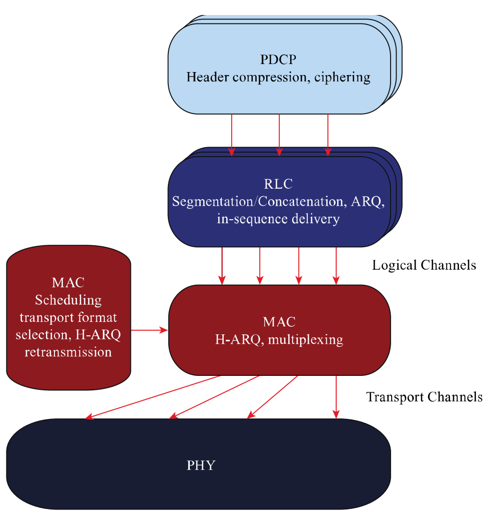
Protocol Layers End-to-End

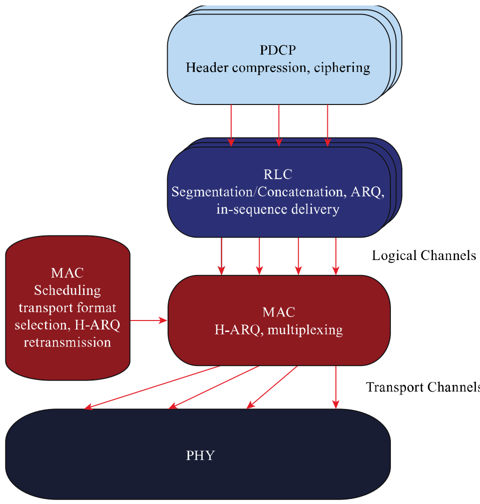


Protocol Layers PDCP and RLC



- **Packet Data Convergence Protocol (PDCP)**
  - » Delivers packets from UE to eNodeB
  - » Involves header compression, ciphering, integrity protection, in-sequence delivery, buffering and forwarding of packets during handover
- **Radio Link Control (RLC)**
  - » Segments or concatenates data units
  - » Performs ARQ
    - – Recover from when MAC layer H-ARQ failures
    - – ARQ: Automatic Repeat Request (retransmission)
    - – H-ARQ: Hybrid ARQ – combines FEC and ARQ

Protocol Layers
MAC and PHY



- Medium Access Control (MAC)
  - Performs H-ARQ: combines FEC and retransmission (ARQ)
  - Prioritizes and decides which UEs and radio bearers will send or receive data on which shared physical resources
  - Decides the transmission format, i.e., the modulation format, code rate, MIMO rank, and power level
- Physical layer actually transmits the data

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LTE Radio Access Network

- LTE uses OFDM and MIMO
- OFDM offers benefits similar to those of CDMA
  - » Good immunity to fading as only a small portion of the energy for any one link is typically lost due to a fade
  - » Fast power control to keep the noise floor as low as possible
- Additional advantages
  - » Highly resistant to fading and inter-symbol interference
  - » Low modulation rates on each of the many sub-carriers
  - » Sophisticated error correction
  - » Scaling rates easier than CDMA
  - » Allows more advanced antenna technologies, like MIMO
- Breaks information into pieces and assigns each one to a specific set of sub-carriers

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Orthogonal Frequency Division Multiple Access (OFDMA)

- Remember Spread Spectrum?
  - » Modulation technique that allows very robust data transfers
- By using different spreading codes/hopping sequences, we can use it as a Multiple Access technique
  - » Multiple senders can transmit simultaneous
  - » Or, a cell tower/base station can communicate with multiple devices simultaneously (upstream+downstream)
- Can we do this for OFDM as well?
- Yes – OFDMA!

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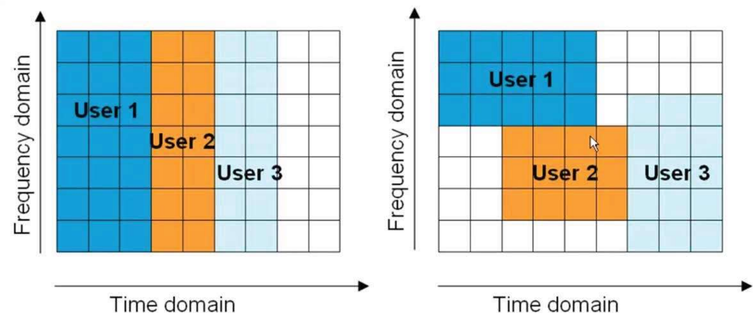
OFDM versus OFDMA



- Traditional OFDM allows channel sharing by users using TDMA
- With OFDMA, users can use subsets of subcarriers in each time slot
- Remember: signals travel everywhere!

Discussion

- OFDMA allows a base station to transmit data to multiple devices at the same time
  - » Different bit rates can be used for each device
- OFDMA upstream allows multiple devices to the base station at the same time
  - » Requires tight synchronization
- The advantage is that it makes it possible to use the benefit from the high OFDM bandwidth for traffic loads involving smaller transfers
- The cost is that it involves more overhead
  - » The base station and device(s) needs to agree on for each slot what device it is used by

OFDMA:
OFDM with Multiple Access

- LTE downlink uses OFDM with Multiple Access:
- In any time slot, multiple clients receive data on separate groups of subcarriers
  - This is a form of FDMA (similar to 2G/GSM), but using groups of orthogonal subcarriers
- For each group of subcarriers, multiple clients receive data in separate time slots
  - TDMA (also similar to GSM)
  - Multiple low bandwidth users can share subcarriers
- For each client, this enables frequency hopping to mitigate effects of narrowband fading

OFDM disadvantages
SC-FDMA

- As the number of sub-carriers increases, the composite time-domain signal starts to look like Gaussian noise
- This results in a signal with a high peak-to-Average Power ratio (PAPR)
- Avoiding distortion requires increases in cost, size and power consumption
- To avoid this cost on mobile devices, the uplink uses Single-Carrier FDMA
  - Does some preprocessing of the signal to reduce the high PAPR, at the cost of some loss in efficiency
  - Provides better energy and cost efficiency for battery-operated mobiles

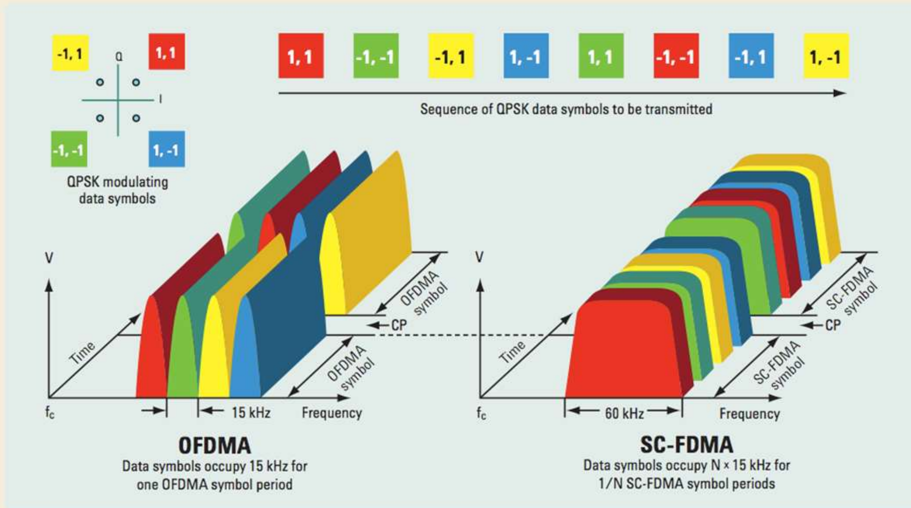


Figure 2. Comparison of how OFDMA and SC-FDMA transmit a sequence of QPSK data symbols

http://cp.literature.agilent.com/litweb/pdf/5989-7898EN.pdf

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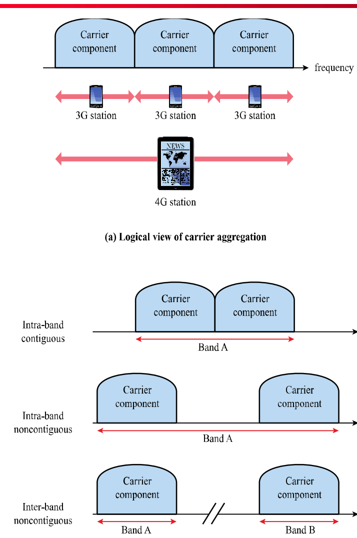
Carrier Aggregation

- **Ultimate goal of LTE-Advanced is 100 MHz bandwidth**
  - » Combine up to 5 "component carriers" (CCs)
  - » Each CC can be 1.4, 3, 5, 10, 15, or 20 MHz
  - » Up to 100 MHz
- **Three approaches to combine CCs**
  - » Intra-band Contiguous: carriers adjacent to each other
  - » Intra-band noncontiguous: Multiple CCs belonging to the same band are used in a noncontiguous manner
  - » Inter-band noncontiguous: Use different bands



(a) Logical view of carrier aggregation

(b) Types of carrier aggregation

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