

Internet of Things (IoT) Definitions and Walkthrough

The OSI Model and TCP/IP Protocol Suite

Outline

- THE OSI MODEL
- LAYERS IN THE OSI MODEL
- TCP/IP PROTOCOL SUITE
- ADDRESSING

THE Open-Source Interconnect MODEL

OSI Model

7

Application

6

Presentation

5

Session

4

Transport

3

Network

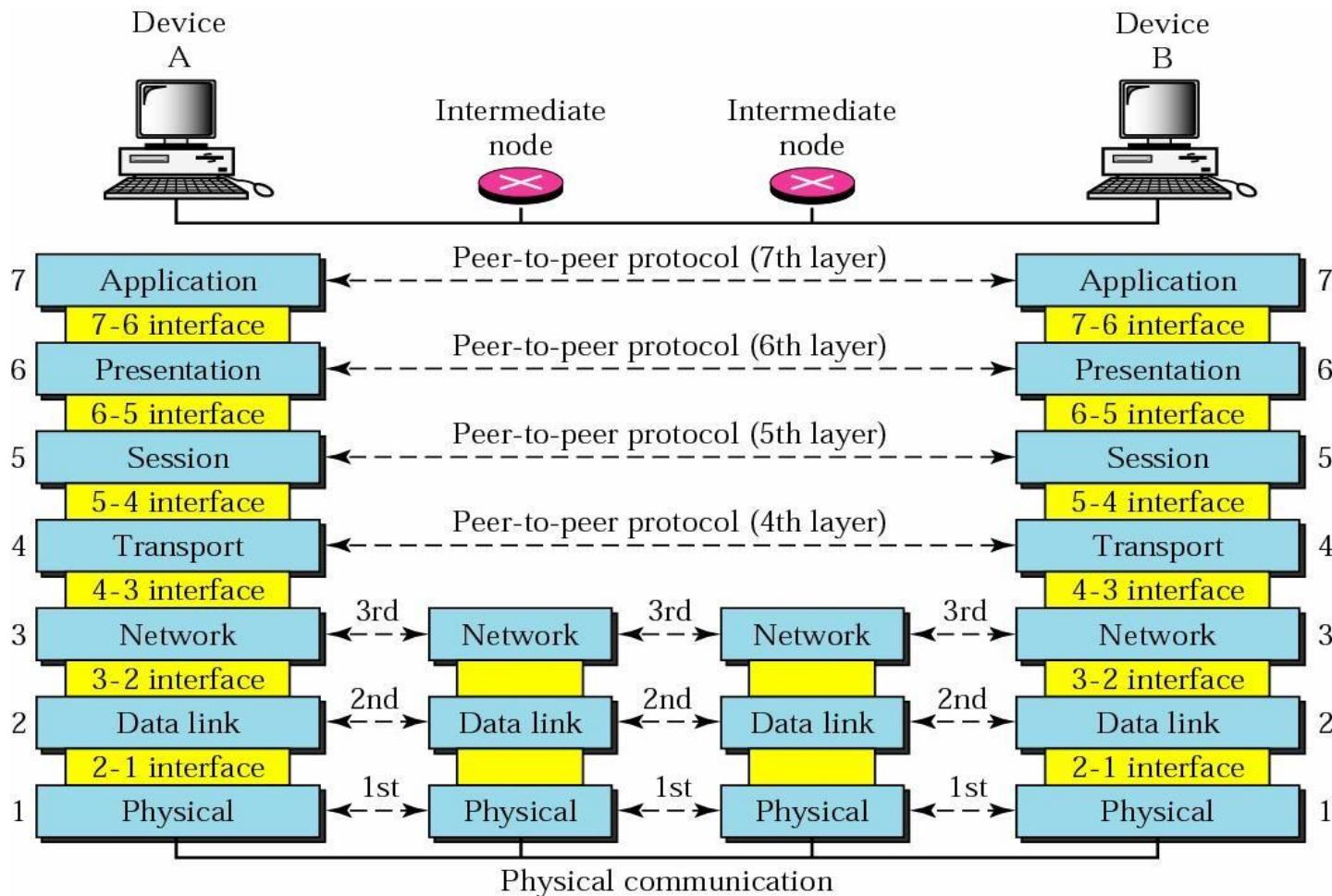
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Data link

1

Physical

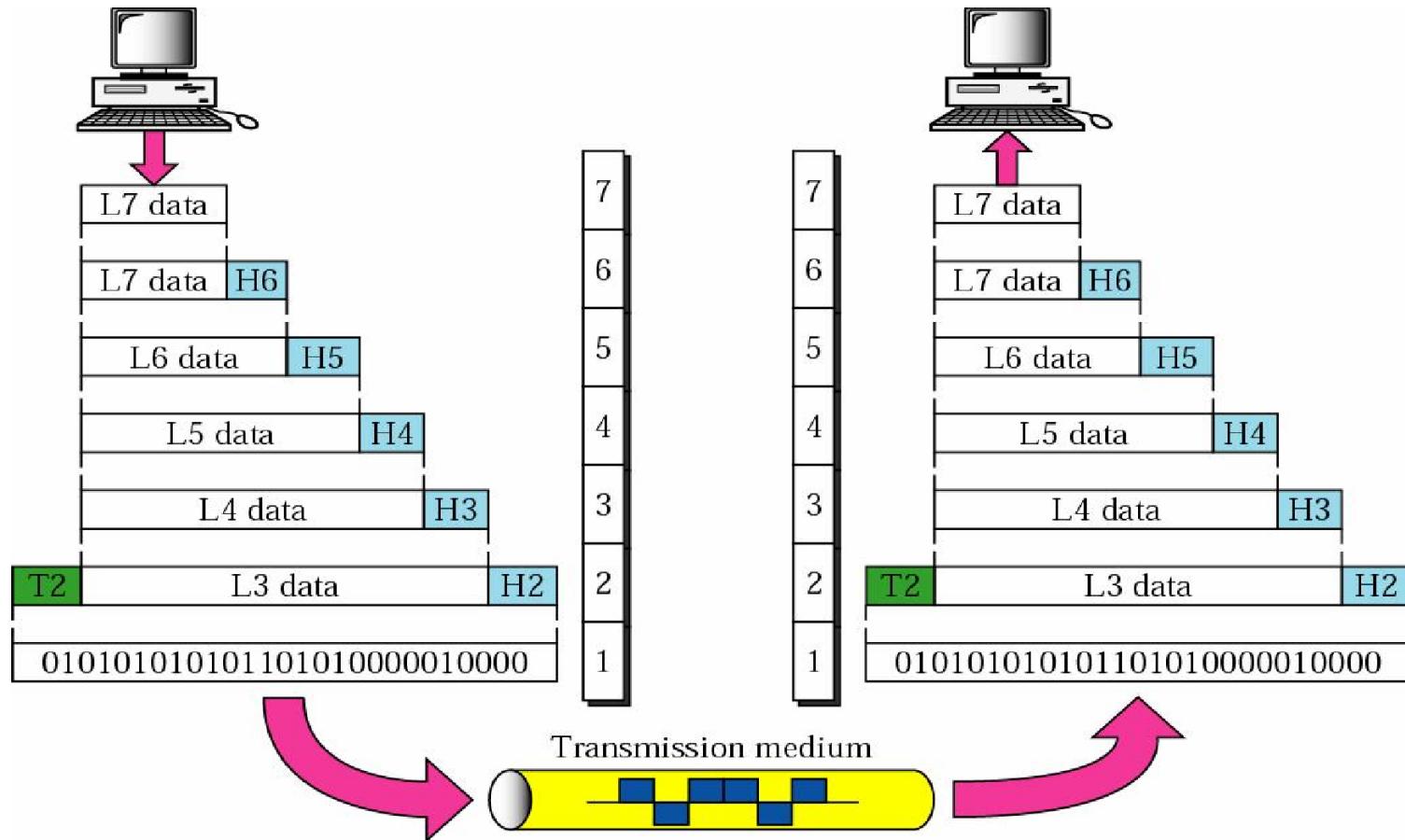
OSI Layers



Peer-to-Peer Processes

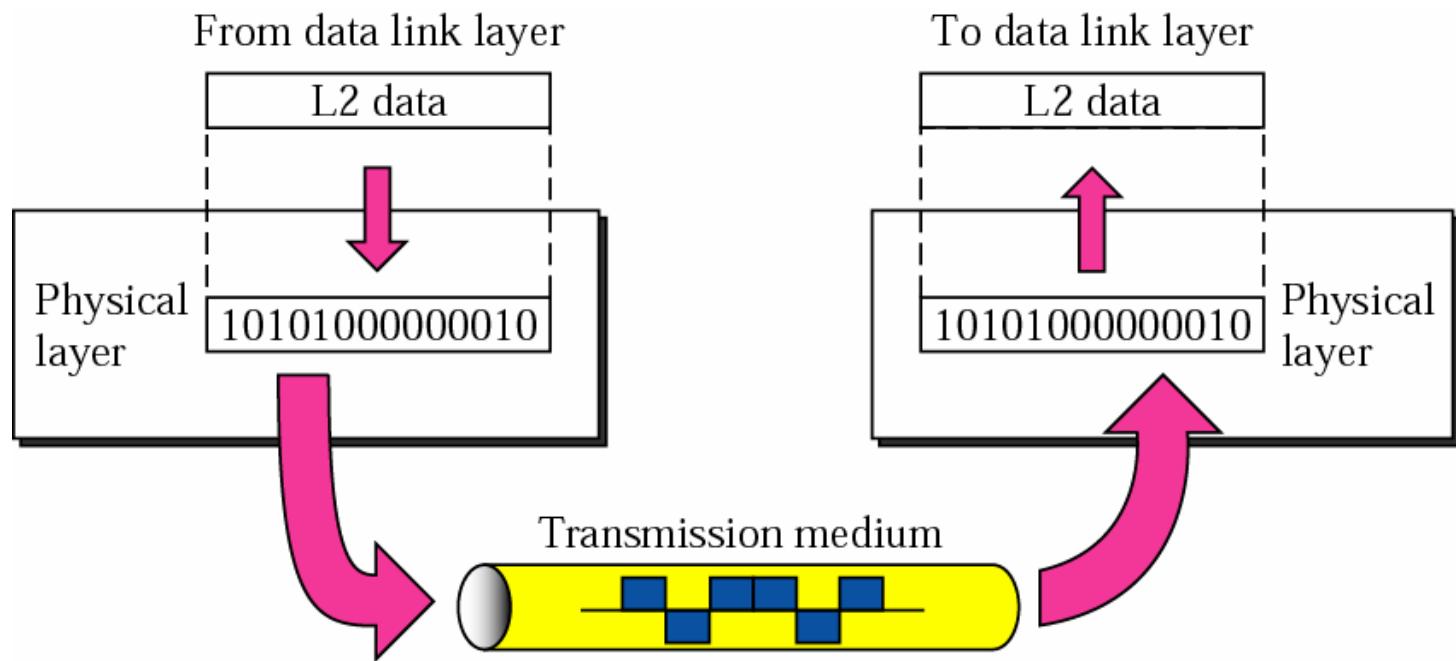
- The processes on each machine that communicate at a given layer are called ***peer-to-peer processes***
- Each layer in the sending device added its own information to the message it receives from the layer just above it
- At the receiving machine, the message is unwrapped layer by layer

An Exchange Using the OSI Model



LAYERS IN THE OSI MODEL

Physical Layer



Physical Layer

- Physical characteristics of interface and media
 - The type of transmission media
- Representation of bits
 - Define the type of **encoding** (how 0s and 1s are changed to signals)
- Data rate
 - The number of bits sent each second
- Synchronization of bits
 - The sender and receiver must not only use the same bit rate but must also be synchronized at the bit level

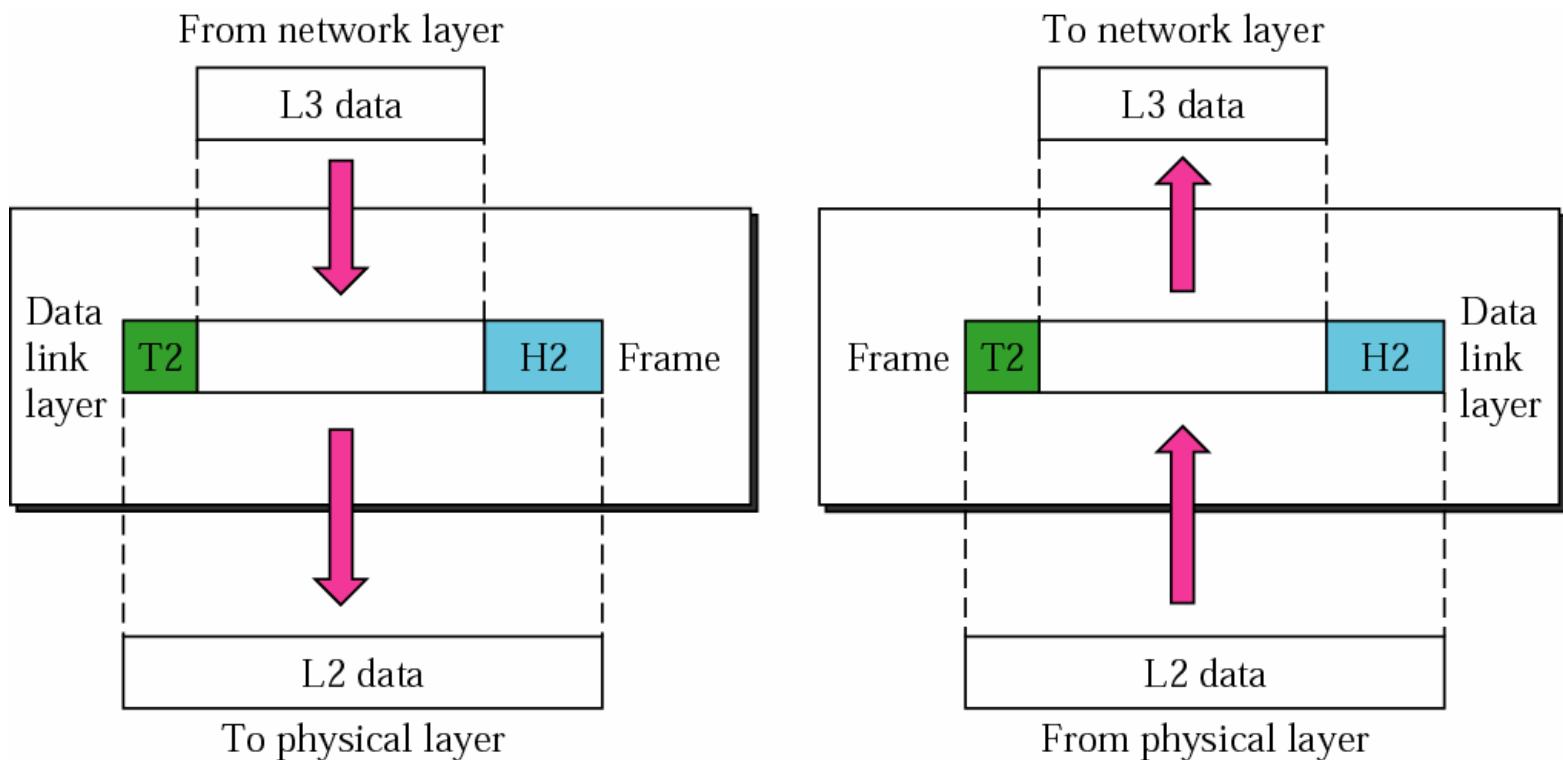
Physical Layer (Cont.)

- Line configuration
 - Point-to-point configuration
 - Multipoint configuration
- Physical topology
 - Define how devices are connected to make a network
 - For example, mesh, star, ring, or bus topology
- Transmission mode
 - Define the direction of transmission between two devices
 - Half-duplex mode
 - two devices can send and receive but not at the same time
 - Full-duplex mode
 - Two devices can send and receive at the same time

Data Link Layer

- Transform the physical layer to a reliable link
- Make the physical layer appear error free to the upper layer

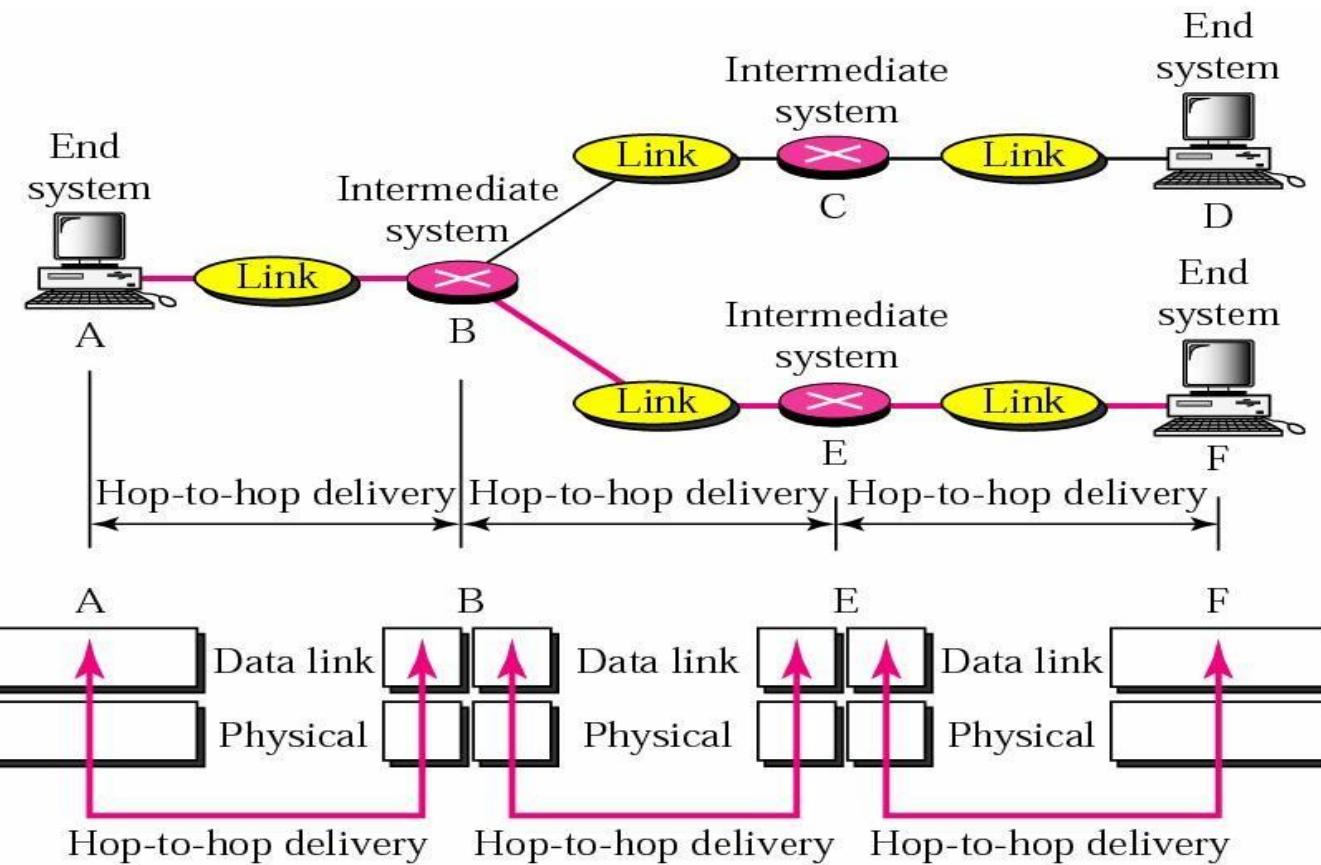
Data Link Layer



Data Link Layer

- **Framing**
 - Divide the stream of bits into frames
- **Physical addressing**
 - only one hop
- **Flow control**
- **Error control**
 - Detect and retransmit damaged or lost frames
 - Prevent duplication of frames

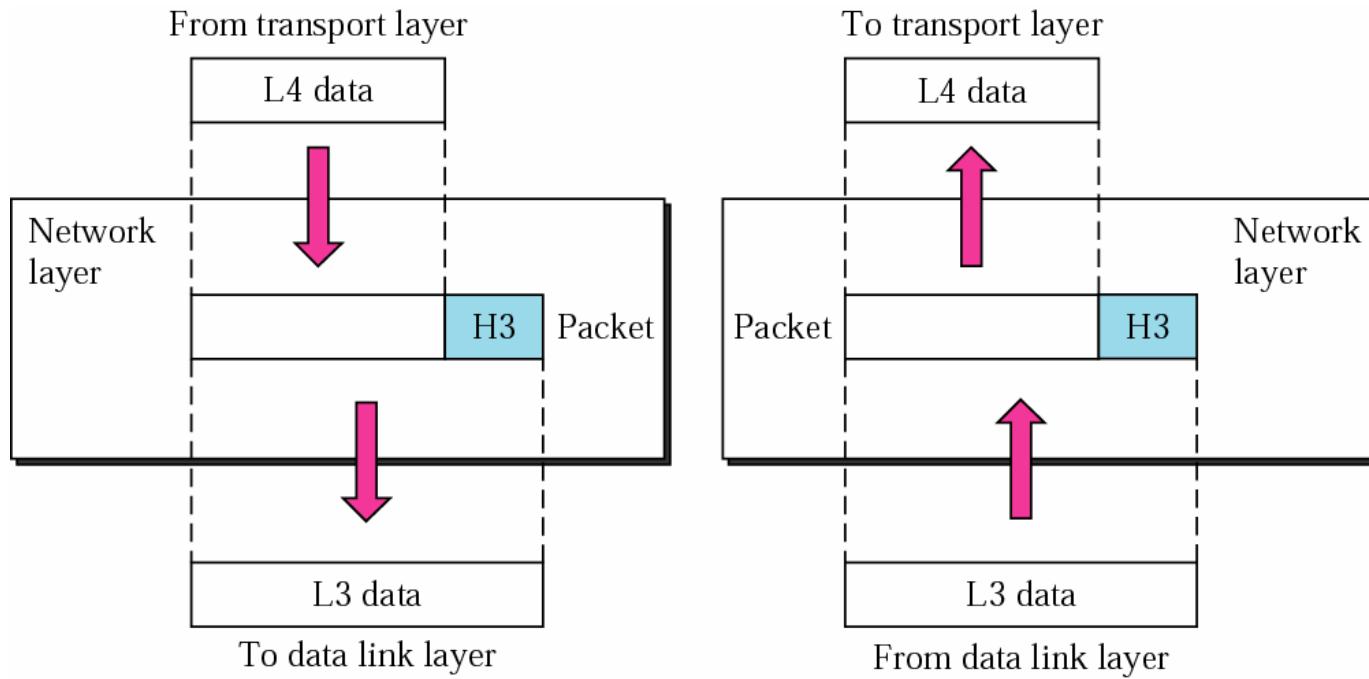
Node-to-Node (Hop-to-Hop) Delivery



Network Layer

- Be responsible for the source-to-destination delivery of a packet possibly across multiple networks (links)
 - Data link layer take care of the delivery of the packet between two systems on the same network (links)
 - Network layer ensures the delivery of a packet from its point of origin to its final destination

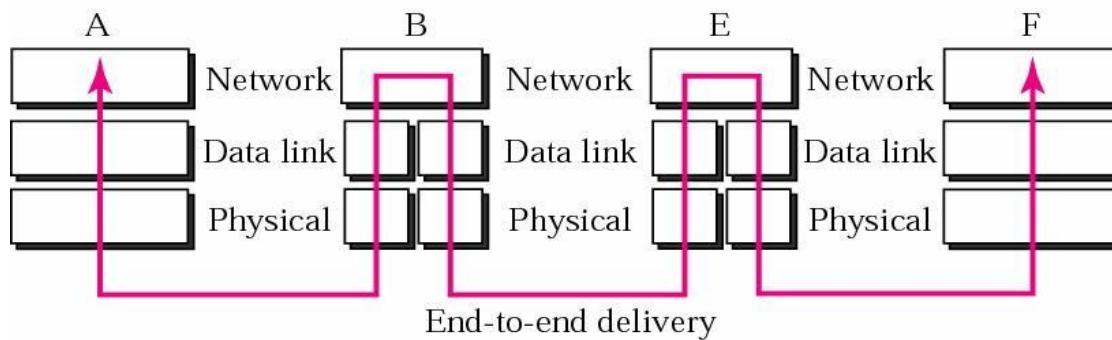
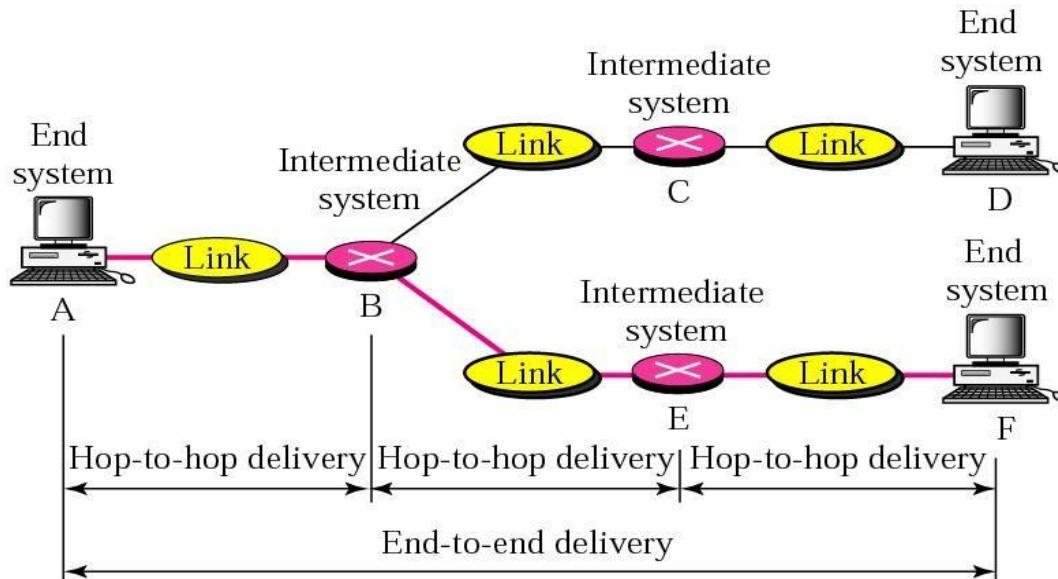
Network Layer



Network Layer

- Logical addressing
 - Physical addressing in the data link layer handles the addressing problem locally
 - If a packet pass the network boundary
 - We need another addressing system to distinguish the source and destination systems
- Routing

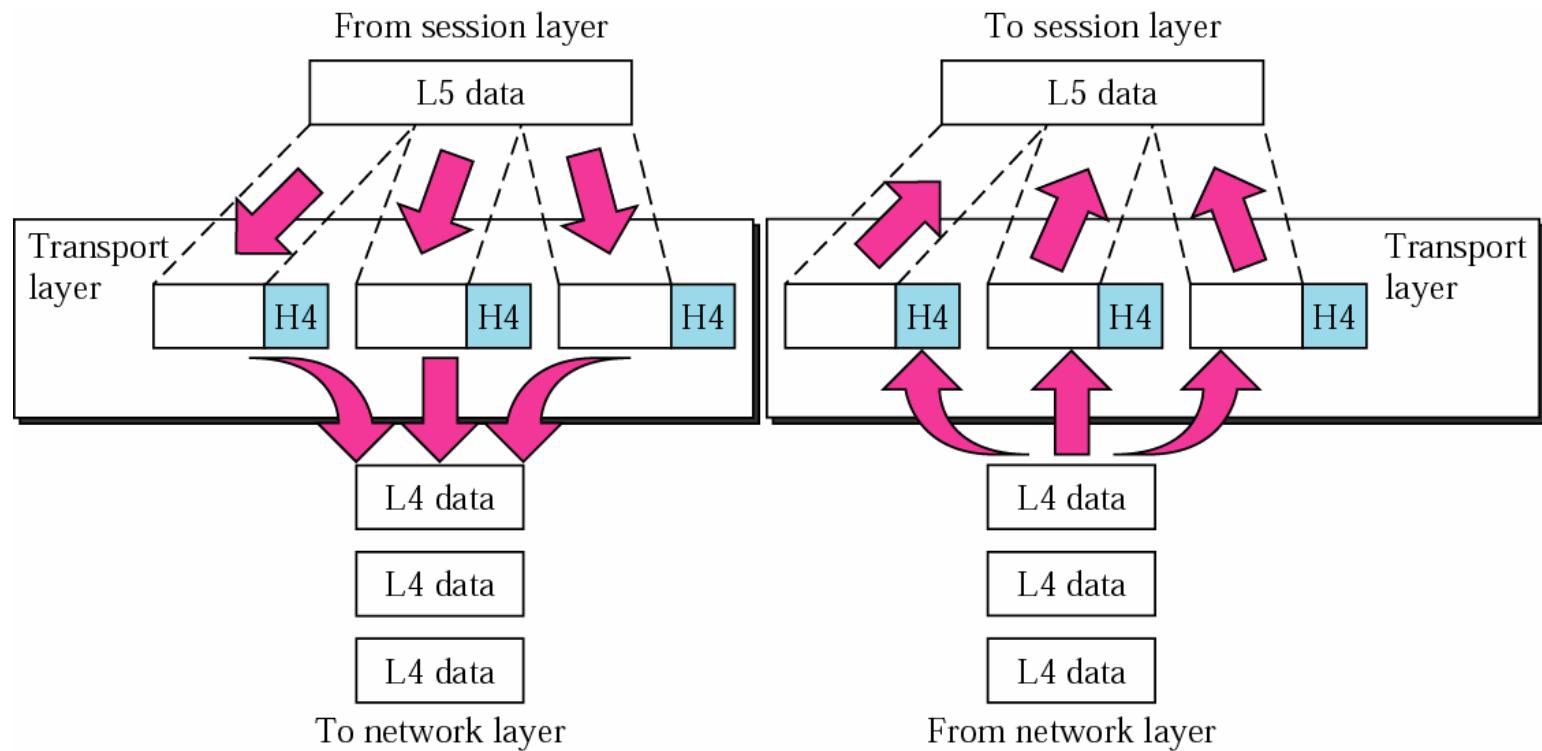
End-to-End Delivery by the Network Layer



Transport Layer

- Be responsible for source-to-destination (end- to-end) delivery of the entire message
 - Network layer only oversees the end-to-end delivery of individual packets
- Oversee both error control and flow control at the source-to-destination level

Transport Layer



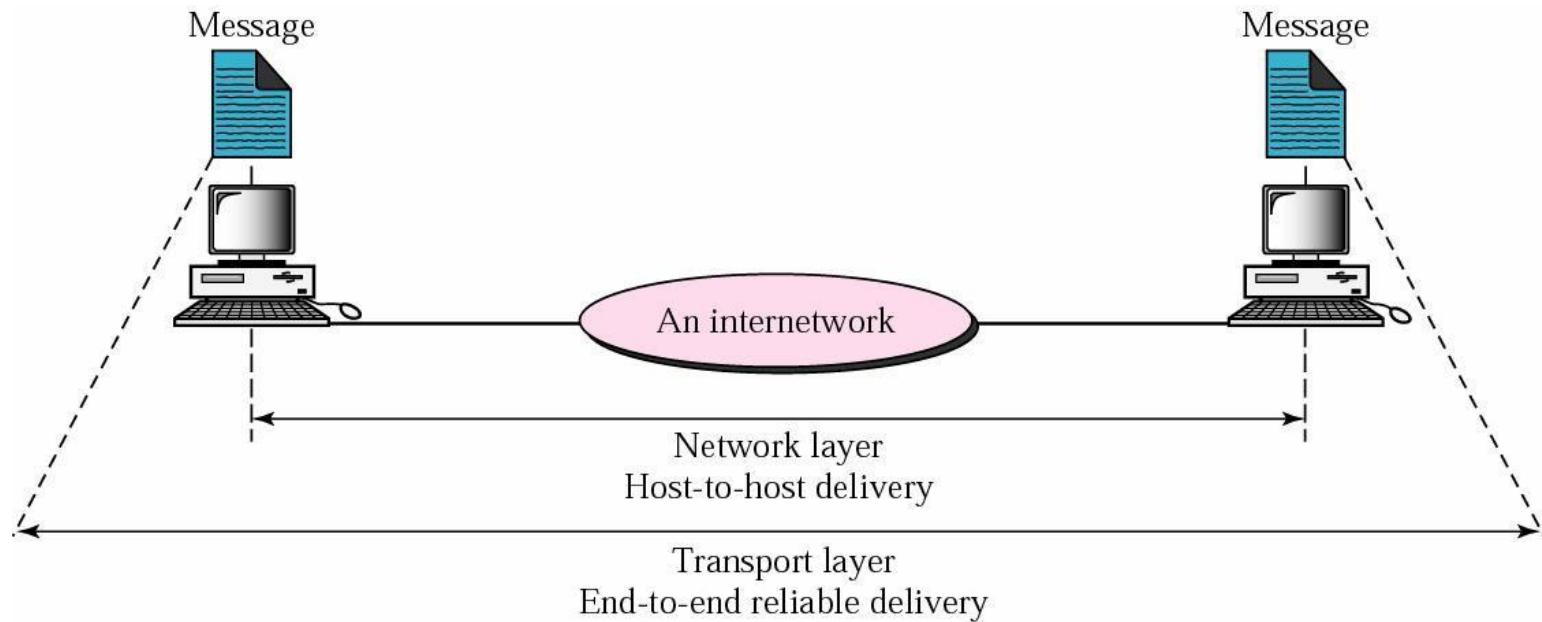
Transport Layer

- Service-point addressing
 - Service-point address: port address
 - The network layer gets each packet to the correct computer
 - The transport layer gets the entire message to the correct process on that computer
- Segmentation and reassembly

Transport Layer (Cont.)

- Connection control
 - Connectionless
 - Connection-oriented
- Flow control
 - End to end flow control
 - The flow control, however, at the data link layer is across a single link
- Error control
 - End to end error control that makes sure that the entire message arrives without error (damage, loss, or duplication)

Reliable End-to-End Delivery of a Message

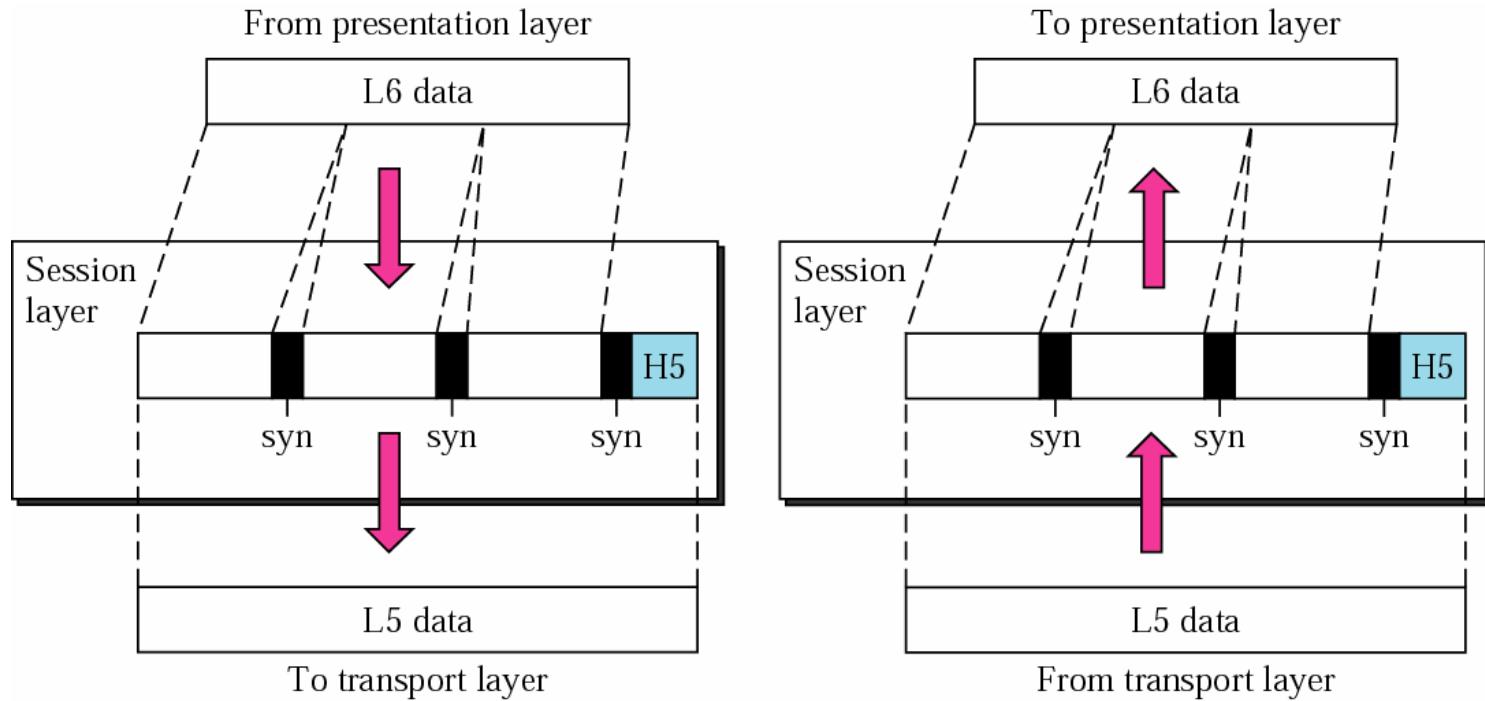


end-to-end delivery by the transport layer

Session Layer

- Session layer is the network dialog controller
 - It establishes, maintains, and synchronizes the interaction between communication systems

Session Layer



Session Layer

- Dialog control

- Allow two systems to enter a dialog
- Allow the communication between two processes in
 - Half-duplex
 - Full-duplex

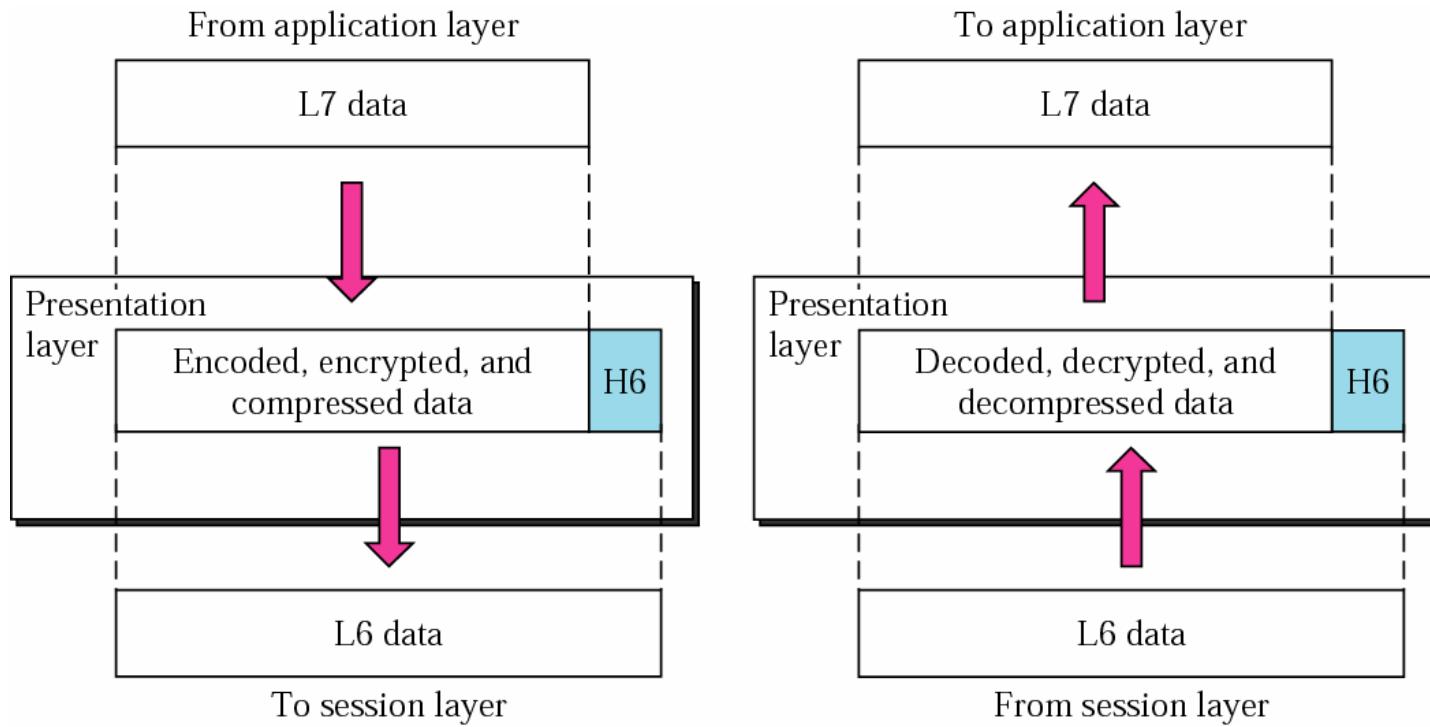
- Synchronization

- Allow a process to add checkpoints (synchronization points) into a stream of data

Presentation Layer

- Be concerned with the syntax and semantics of the information exchanged between two systems

Presentation Layer



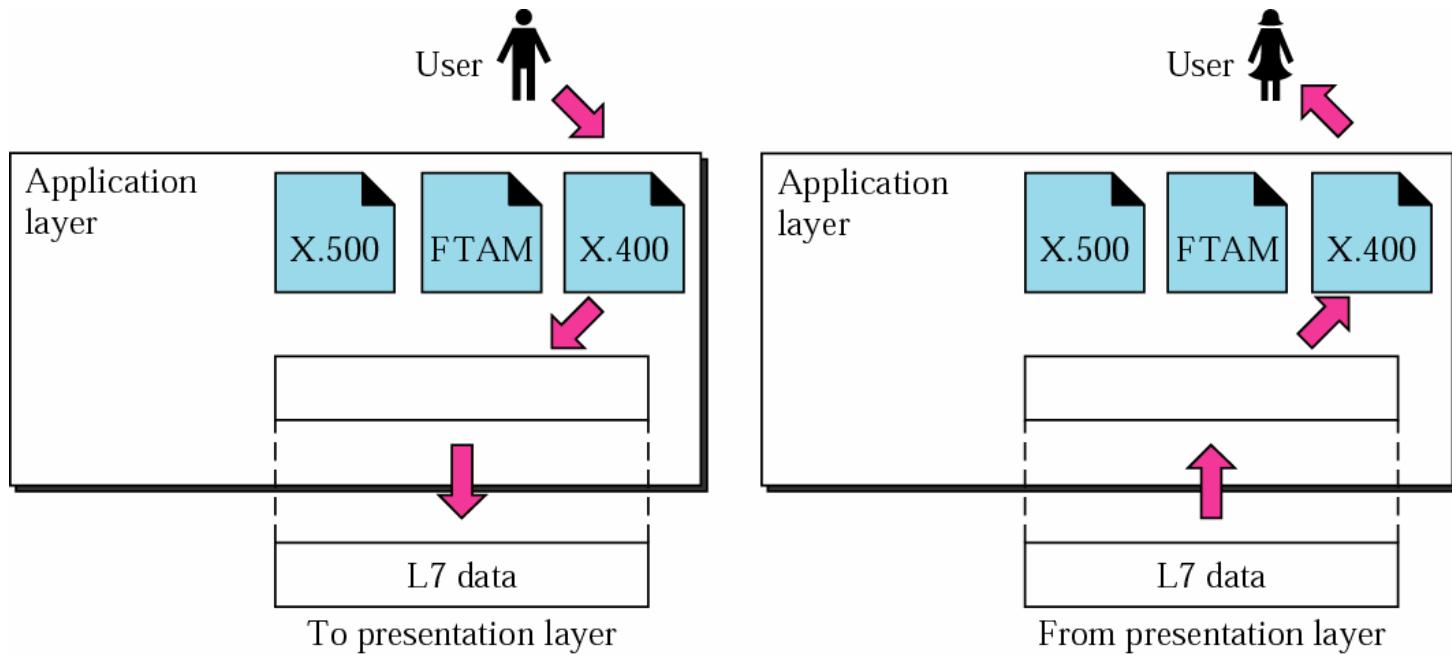
Presentation Layer

- Translation
 - Different computers use different encoding systems
 - The presentation layer is responsible for interoperability between these different encoding methods
- Encryption
- Compression

Application Layer

- The application layer enables the user, whether human or software, to access the network

Application Layer



Application Layer

- Specific services provided by the application layer
 - Network virtual terminal
 - File transfer, access, and management (FTAM)
 - Mail services
 - Directory services

Summary of Layers

OSI (Open Source Interconnection) Model

Layers	Purpose / Function	Protocol Used	Fundamental Data Type
7. Application	User Application Layer: browser, ftp, app, etc. (remote file access, resource sharing, LDAP, SNMP)	SMTP FTP	Data
6. Presentation	Syntax Layer: encrypt, compress (optional) (data encrypt/decrypt, codec, translation)	JPEG, ASCII, ROT13	Data
5. Session Layer	Synchronization & Logical Port Routing (session establishment, start & terminate, security, logging, name recognition)	RPC, NFS, NetBIOS	Data
4. Transport Layer	TCP: Host to Host & Flow Control (end to end connections & reliability, message segmentation, acknowledgment, session multiplexing)	TCP / UDP	TCP: Segments UDP: Datagrams
3. Network Layer	Packets: IP Address (path determination, logical addressing, routing, traffic control, frame segmentation, subnet management)	IP, IPX, ICMP	Packets
2. Data Link Layer	Data Frames: MAC address, packet (physical addressing, Media Access Control, LLC, frame error checking, sequencing and reordering)	PPP/SLIP	Frames
1. Physical Layer	Physical Device: Cables, fibers, RF spectrum (data encoding, media attachment, baseband/broadband, signaling, binary transmission)	Coax, fiber, wireless	Bits / Signals

TCP/IP PROTOCOL SUITE

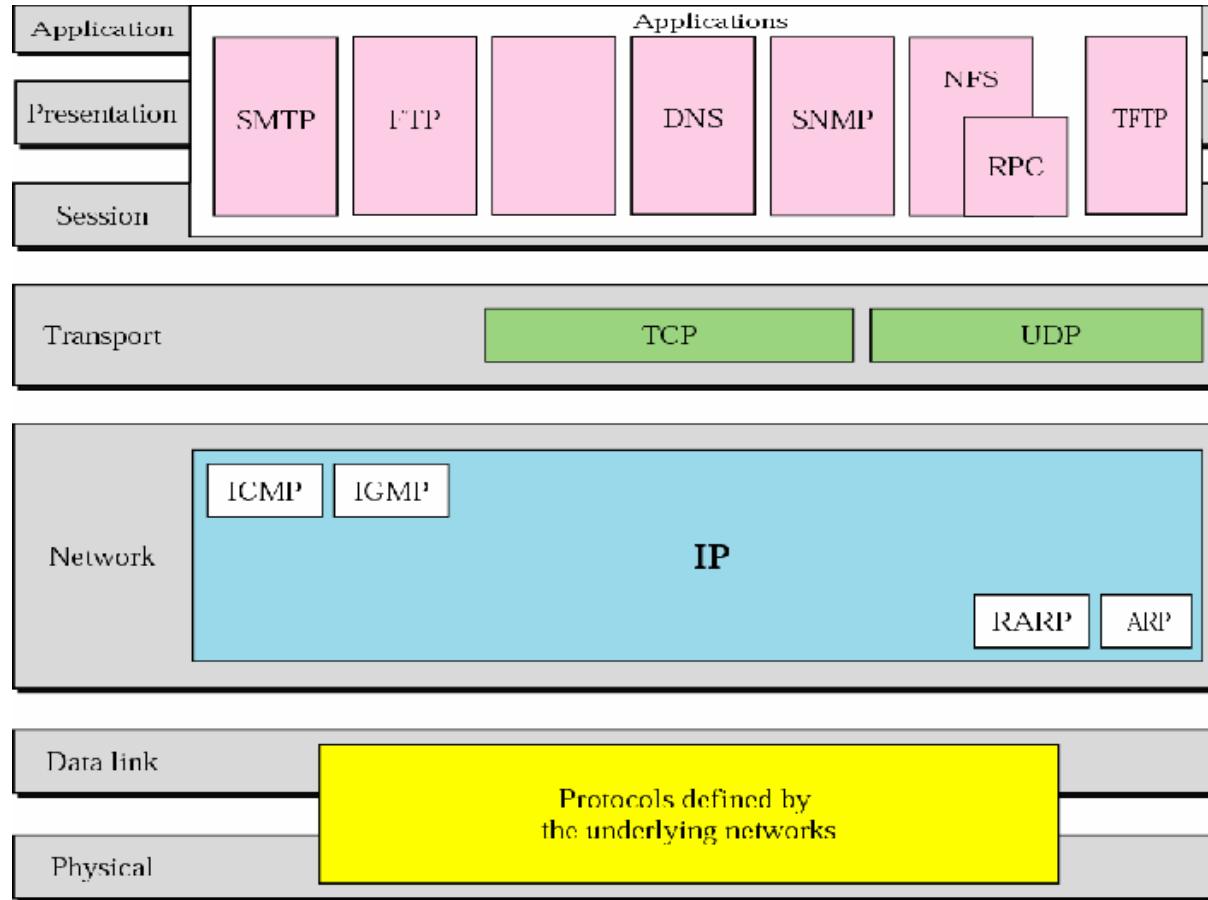
TCP/IP Protocol Suite

- TCP/IP protocol suite was developed prior to the OSI model and is made of five layers
 - Physical, data link, network, transport, and application layers
- The first four layers correspond to the first four layer of the OSI model

TCP/IP Protocol Suite

- The three topmost layers of the OSI model are represented in TCP by a single layer called the *application layer*

TCP/IP and OSI Model



Physical and Data Link Layers

- TCP/IP does not define any specific protocol
- TCP/IP supports all of the standard and proprietary protocols

Network Layer

- Internetworking Protocols (IP)
- Four supporting protocols
 - ARP
 - RARP
 - ICMP
 - IGMP

Internetworking Protocol (IP)

- The packets in IP are called *datagrams*
- Unreliable and connectionless datagram protocol
- Best-effort delivery services
 - Provide no error checking or tracking

Address Resolution Protocol (ARP)

- Associate an IP address with the physical address
 - Data in LAN are transmitted by the physical address

Reverse Address Resolution Protocol (RARP)

- Discover a host's internet address via its physical address
- Used when
 - A computer is first connected to the network
 - When a diskless computer is booted

Internet Control Message Protocol (ICMP)

- A mechanism used to send notification of datagram problems back to the sender
- ICMP sends query and error reporting messages

Internet Group Message Protocol (IGMP)

- Facilitate the simultaneous transmission of a message to a group of recipients

Transport Layer

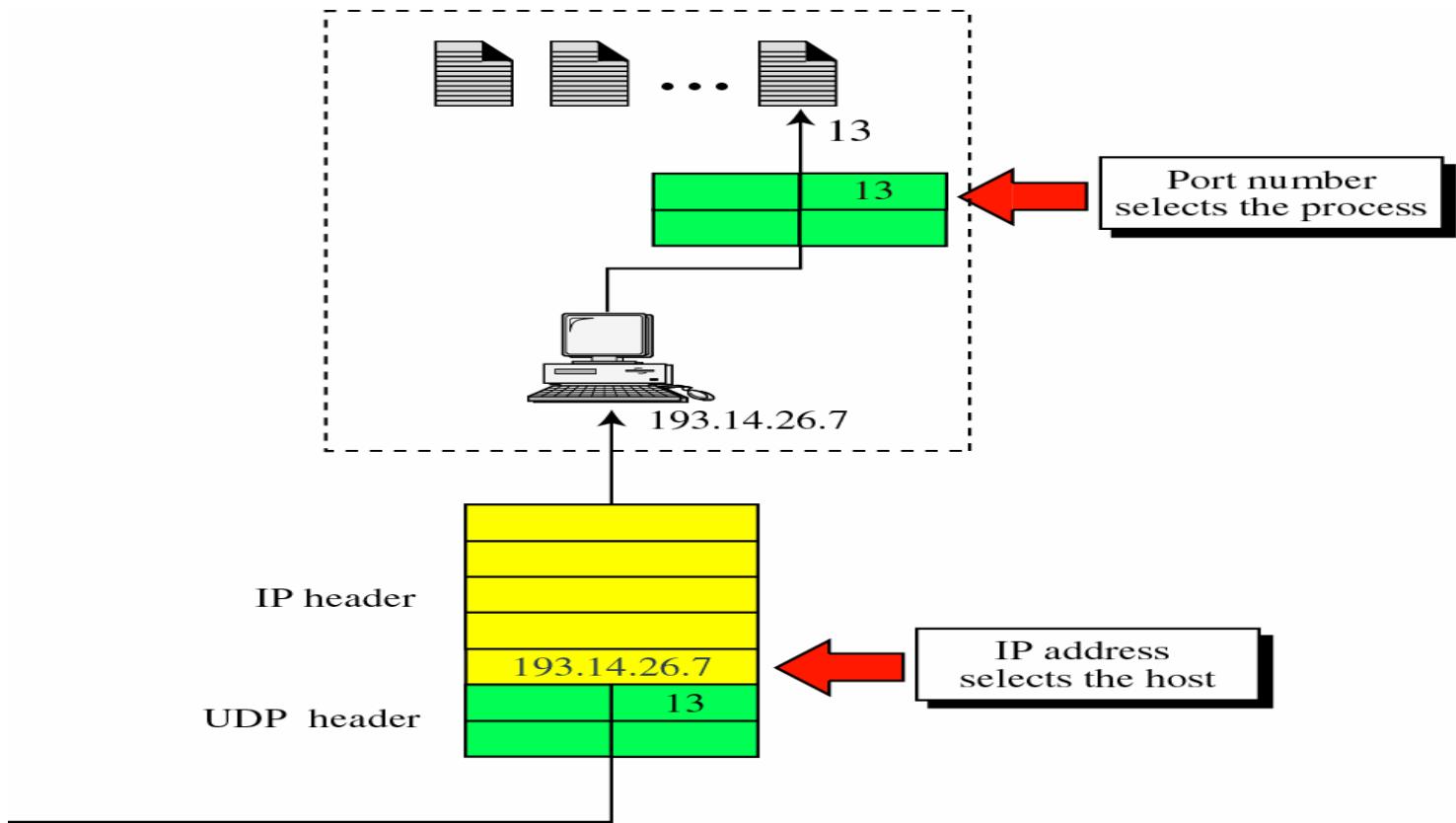
- TCP/UDP
 - A process-to-process protocol
- IP
 - A host-to-host protocol

User Datagram Protocol (UDP)

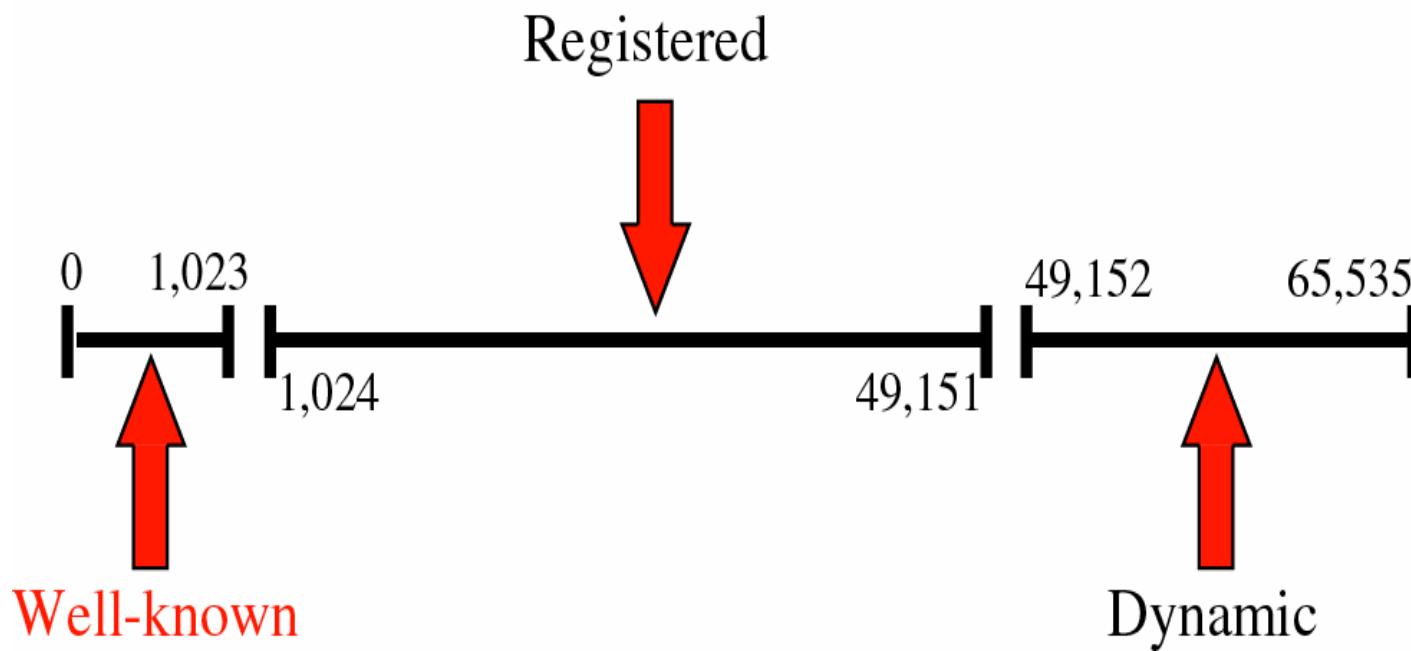
User Datagram Protocol (UDP)

- Add only
 - Port numbers
 - Checksum error control
 - length

IP Addresses Versus Port Numbers



IANA Ranges



Well-Known Ports for UDP

Port	Protocol	Description
7	Echo	Echoes a received datagram back to the sender
9	Discard	Discards any datagram that is received
11	Users	Active users
13	Daytime	Return the data and the time
17	Quote	Returns a quote of a day
19	Chargen	Return a string of characters
53	Nameserver	Domain Name Service
67	Bootps	Server port to download bootstrap information
68	Bootpc	Client port to download bootstrap information

Socket Addresses

- UDP needs two identifiers
 - The IP address
 - The port number
- Socket address
 - The combination of an IP address and a port number

Socket Addresses

IP address

200.23.56.8



Port number

69



200.23.56.8

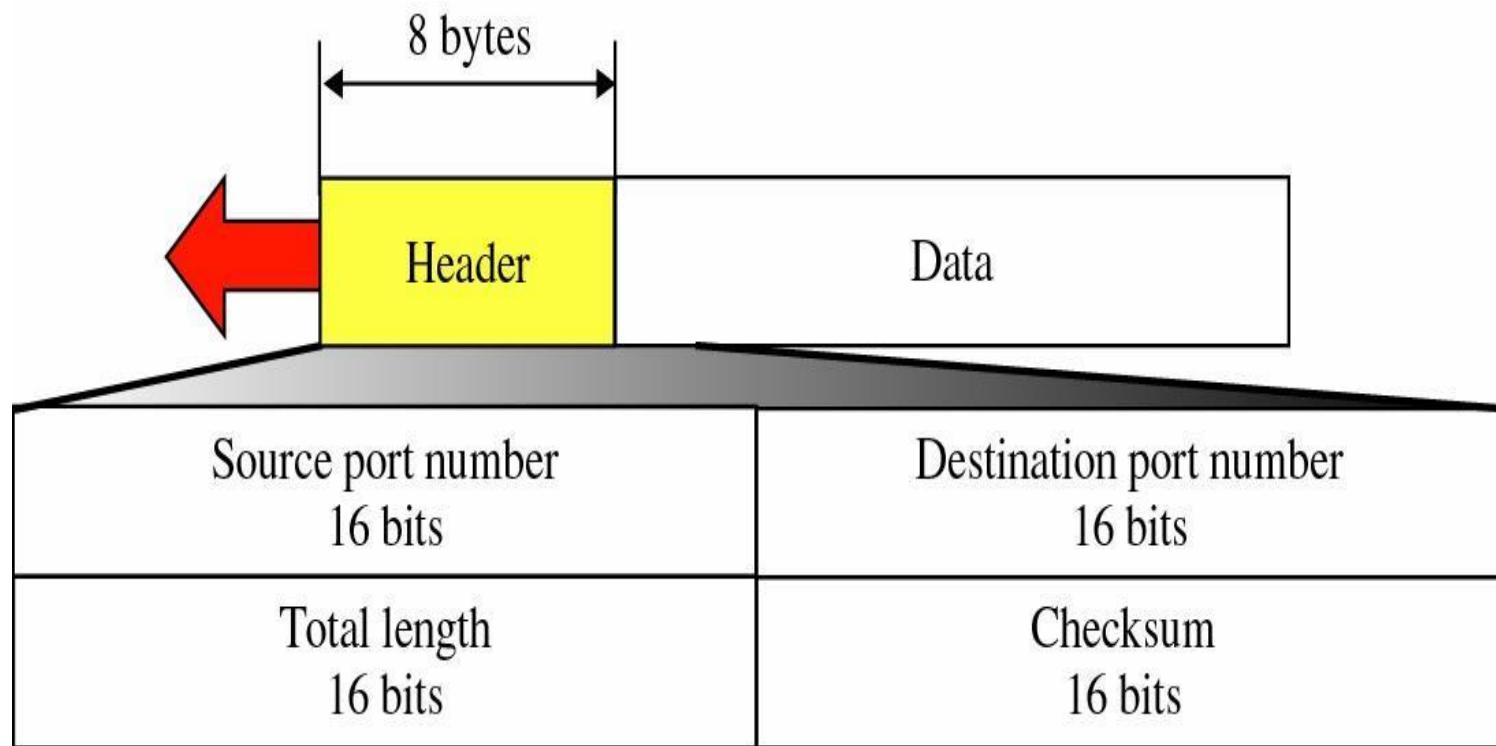
69

Socket address

User Datagram

- UDP packets: called *user datagrams*
 - Have a fixed-size header of 8 bytes
- The fields are
 - Source port number: 16-bits: 0~65535
 - Usually chosen by the UDP software
 - Destination port number: 16-bits: 0~65535
 - Length: 16 bits:
 - Total length (*header plus data*) of the user datagram
 - Minimum length must be 8 bytes (contains only header)
 - Checksum: 16 bits
 - Detect errors over the entire user datagram (*header plus data*)

User Datagram Format



UDP Operation

- Connectionless Services
- Flow and Error Control
- Encapsulation and Decapsulation
- Queuing

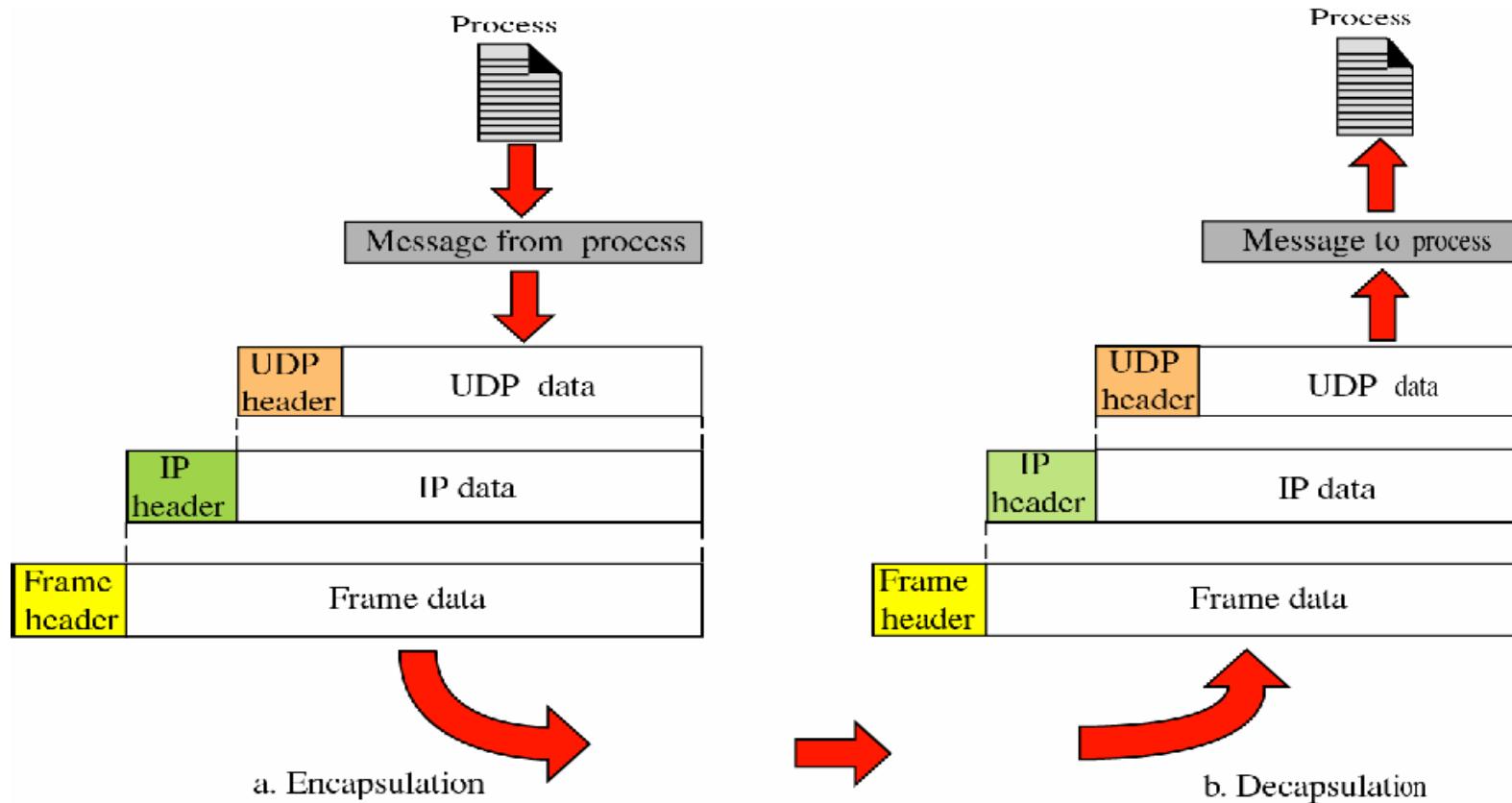
Connectionless Services

- Each user datagram is an independent datagram
 - Even coming from the same source process
- The user datagram is not numbered
- No connection establishment and no connection termination

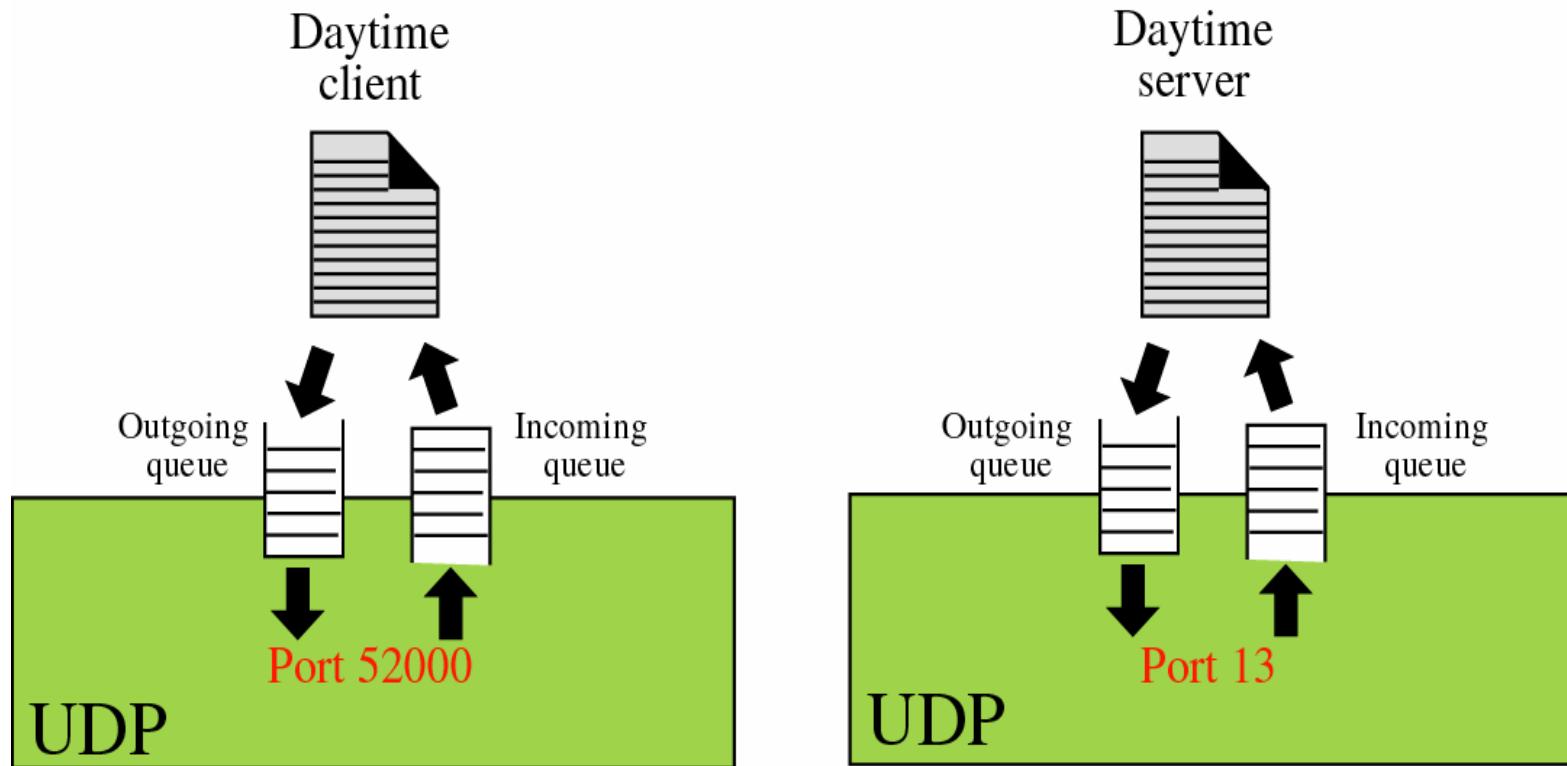
Flow and Error Control

- No flow control
 - The receiver may overflow with incoming messages
- No error control except for the checksum
 - The sender does not know if a message has been lost or duplicated

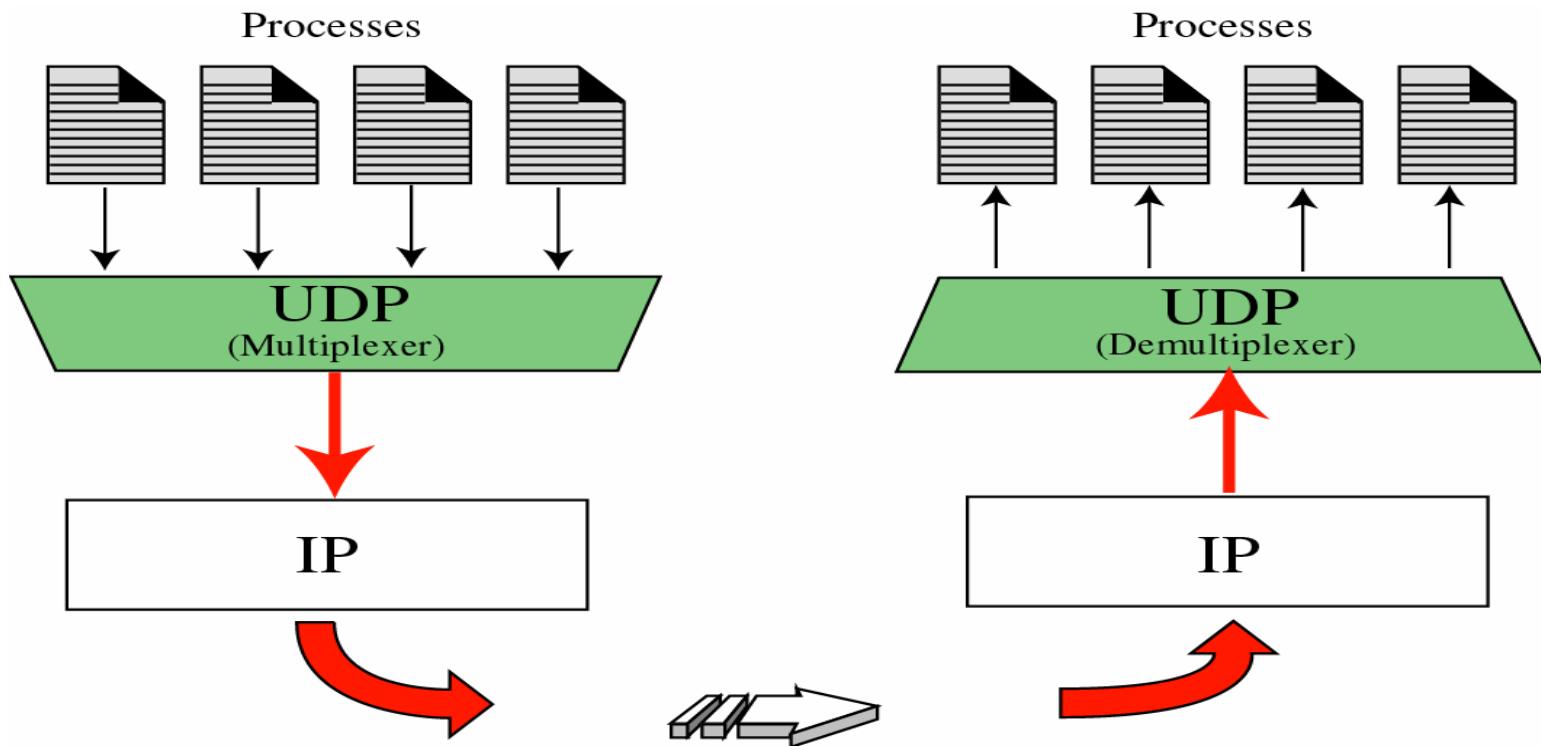
Encapsulation and Decapsulation



Queues in UDP



Multiplexing and Demultiplexing



Uses of UDP

- For a process that require simple request-response communication with little concern for flow and error control
- For a process with internal flow and error-control
 - TFTP (Trivial File Transfer Protocol)
- For multicasting and broadcasting
 - Embedded in UDP but not in the TCP software
- For some management processes
- For some route updating protocol
 - RIP (Routing Information Protocol)

Transmission Control Protocol (TCP)

Introduction

□ TCP

- Like UDP, TCP provides process-to-process communication using Port numbers
- A connection-oriented protocol
 - Create a virtual connection between two TCPs to send data
- Add flow and error-control mechanisms at the transport layer
 - For flow control: TCP uses a *sliding window protocol*
 - For error control: TCP uses the *acknowledge packet*, *time-out*, and *retransmission* mechanisms

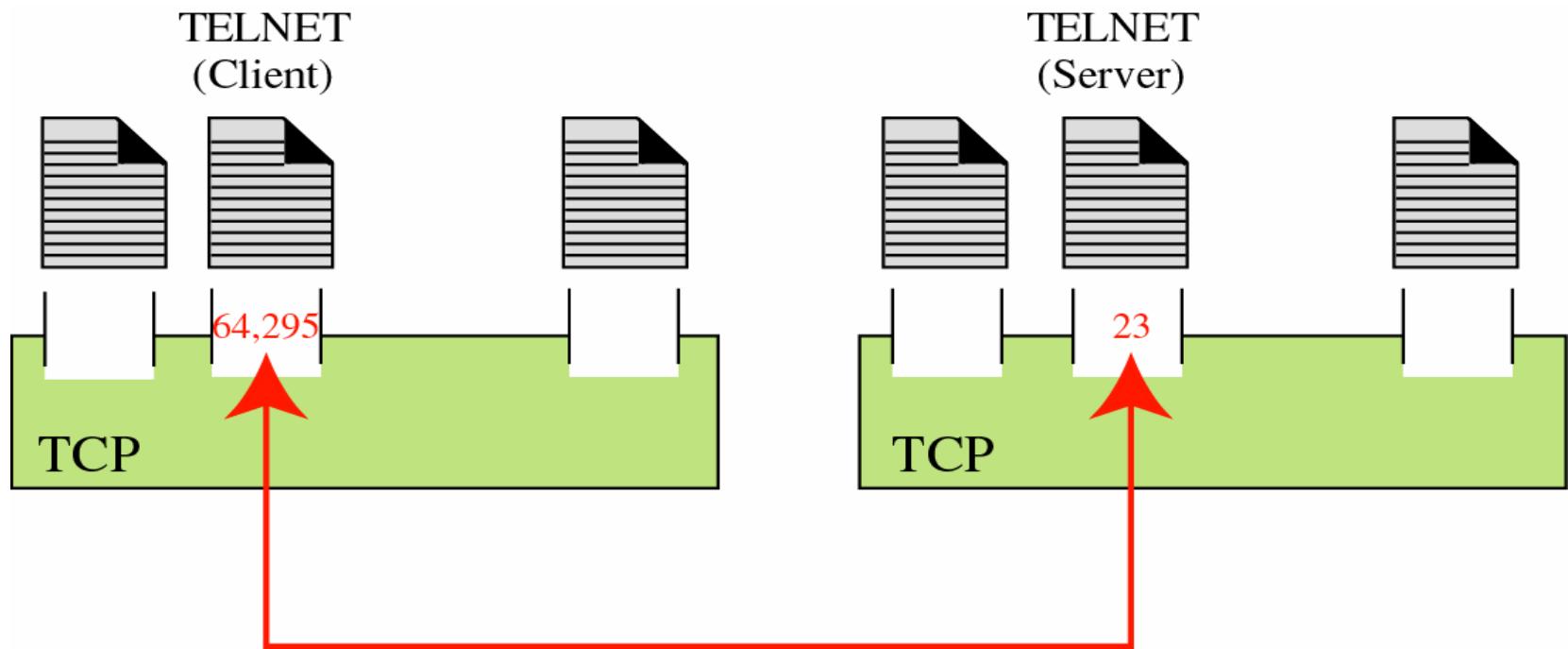
TCP Services

- TCP provides services to the processes at the application layer
 - Process-to-Process Communication
 - Stream Delivery Service
 - Full-Duplex Service
 - Connection-Oriented Service
 - Reliable Service

Port Number

- Client's port number
 - Chosen randomly by the TCP software running on the local host
 - Called *ephemeral(temporary) port number*
- Server's port number
 - Define itself with a port number
 - Called *well-known port numbers*

Port Numbers



Well-Know Ports Used by TCP

Port	Protocol	Description
7	Echo	Echoes a received datagram back to the sender
9	Discard	Discards any datagram that is received
11	Users	Active users
13	Daytimes	Return the data and the time
17	Quote	Return a quote of the day
19	Chargen	Return a string of characters
20	FTP, Data	File Transfer Protocol (data connection)
21	FTP, Data	File Transfer Protocol (control connection)



Example 1

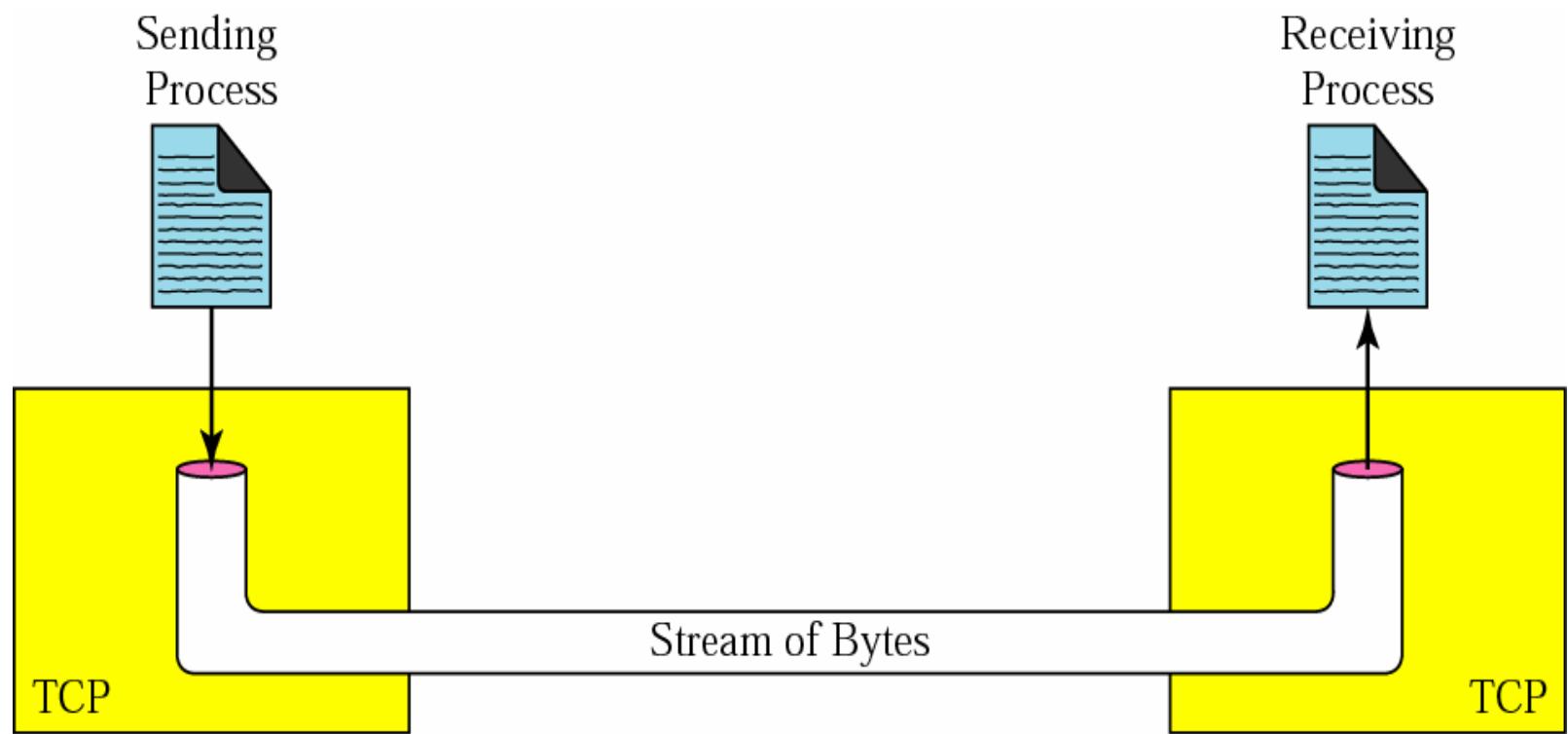
In UNIX, the well-known ports are stored in a file called /etc/services. Each line in this file gives the name of the server and the well-known port number. We can use the grep utility to extract the line corresponding to the desired application. The following shows the ports for FTP.

```
$ grep ftp /etc/services  
ftp-data      20/tcp  
ftp-control   21/tcp
```

Stream Delivery Service

- UDP treats each chunk independently
 - No any connection between the chunks
- In contrast, TCP allow the data be delivered/received as a stream of bytes

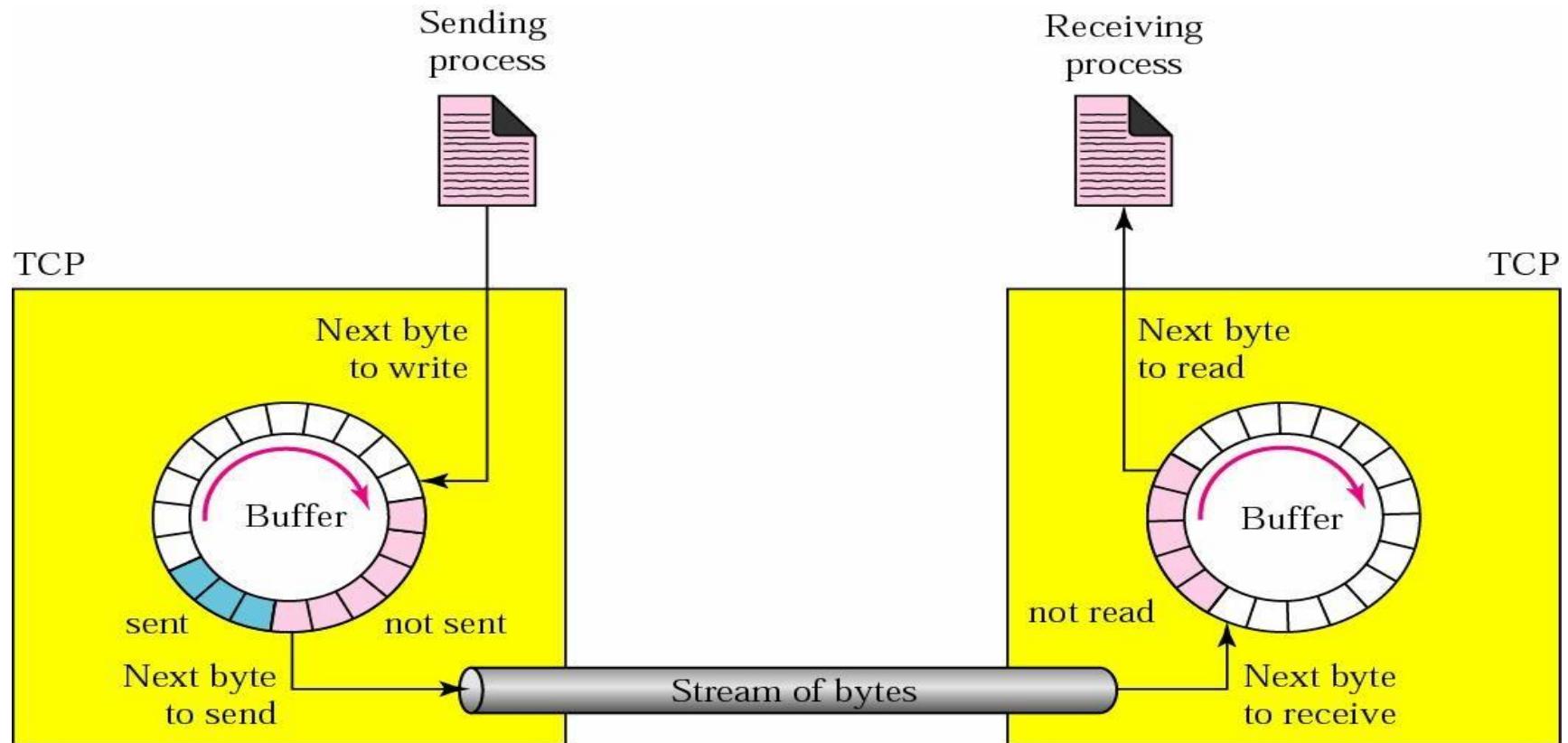
Stream Delivery



Stream Delivery Service (Cont.)

- However, the sending and receiving speed may not be the same
 - TCP needs buffers for storage
- Two buffers in TCP
 - Sending buffer and receiving buffer, one for each connection
 - Also used in flow- and error-control mechanisms

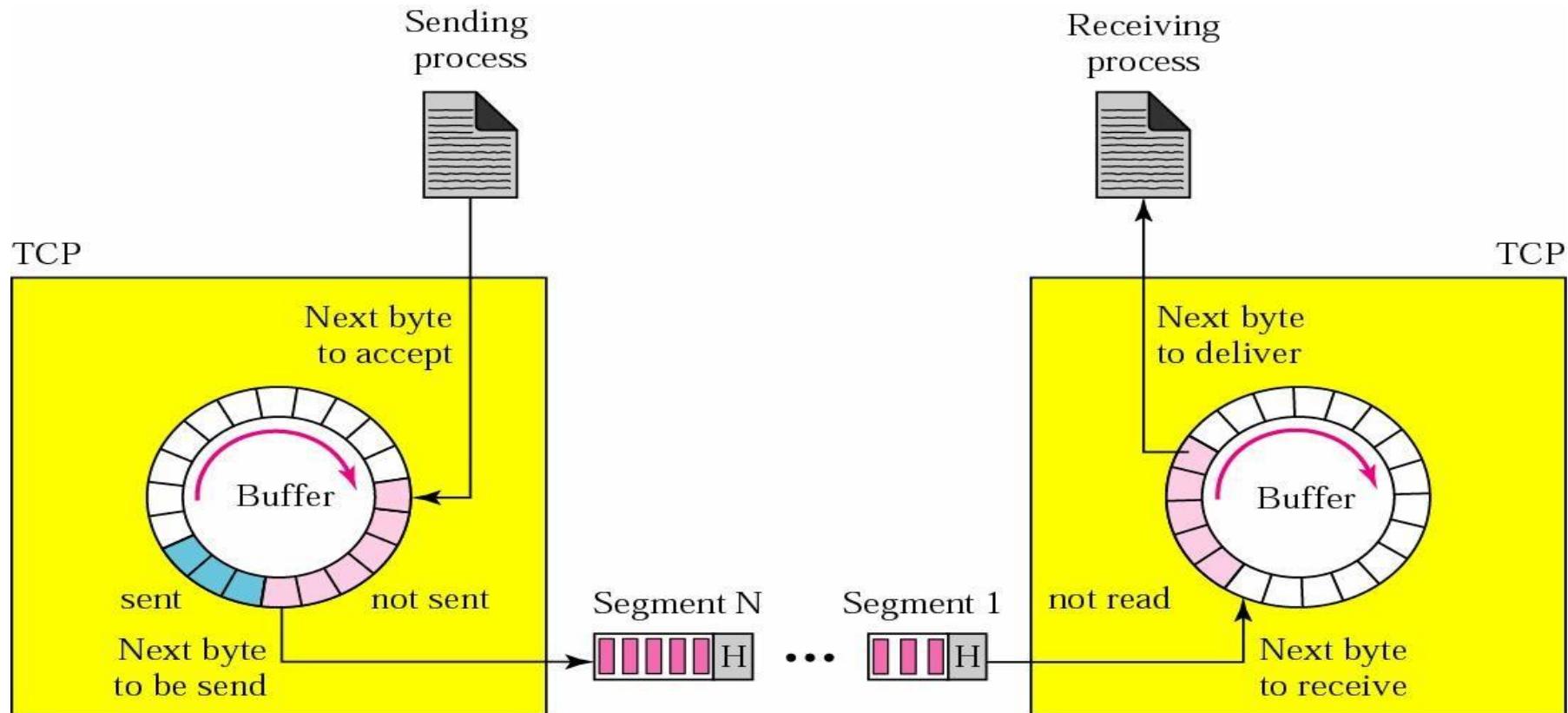
Sending and Receiving Buffers



Segments

- TCP groups a number of bytes together into a packet called a *segment*
 - A TCP packet is called a **segment**
 - TCP adds a header to each segment
 - Then, the segments are encapsulated in an IP datagram

TCP Segments



Full-Duplex Communication

- TCP offers full-duplex service
 - Data can flow in both directions at the same time
 - Each TCP has a sending and receiving buffer and segments are sent in both direction

Connection-Oriented Service

- TCP is a connection-oriented protocol
 - However, the connection is virtual, not a physical connection
 - Each TCP segment may use a different path to reach the destination

Reliable Service

- TCP uses an *acknowledge mechanism* to check the safe and sound arrival of data

Numbering Bytes

- Although TCP uses segments for transmission and reception
 - There is no field for a segment number in the segment header, i.e., TCP header
- TCP uses *sequence number* and *acknowledgement number* to keep track of the segment being transmitted or received
 - Notably, these two fields refer to the *byte number*, not the *segment number*

Byte Numbers

- TCP numbers all data bytes that are transmitted in a connection
- The numbering does not necessarily start from 0
 - *It starts randomly*
 - Between 0 and $2^{32} - 1$ for the number of the first byte
 - Byte numbering is used for *flow* and *error* control

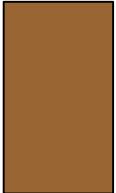
***The bytes of data being transferred
in each connection are numbered by
TCP.***

***The numbering starts with
a randomly generated number.***

Sequence Number

- TCP assigns a sequence number to each segment that is being sent
- The sequence number for each segment is *the number of the first byte* carried in that segment

***The value of the sequence number field
in a segment defines the number
of the first data byte
contained in that segment.***



Example 2

Suppose a TCP connection is transferring a file of 5000 bytes. The first byte is numbered 10001.

What are the sequence numbers for each segment if data is sent in five segments, each carrying 1000 bytes?

Solution

- *The following shows the sequence number for each segment:*

Segment 1 ➔ Sequence Number: 10,001 (range: 10,001 to 11,000)

Segment 2 ➔ Sequence Number: 11,001 (range: 11,001 to 12,000)

Segment 3 ➔ Sequence Number: 12,001 (range: 12,001 to 13,000)

Segment 4 ➔ Sequence Number: 13,001 (range: 13,001 to 14,000)

Segment 5 ➔ Sequence Number: 14,001 (range: 14,001 to 15,000)

Example

- Imagine a TCP connection is transferring a file of 6000 bytes.
 - The first byte is numbered 10010
- What are the sequence numbers for each segment if data is sent in five segments with
 - The first four segments carrying 1,000 bytes
 - The last segment carrying 2,000 bytes?

Solution

The following shows the sequence number for each segment:

Segment 1 → 10,010 (10,010 to 11,009)

Segment 2 → 11,010 (11,010 to 12,009)

Segment 3 → 12,010 (12,010 to 13,009)

Segment 4 → 13,010 (13,010 to 14,009)

Segment 5 → 14,010 (14,010 to 16,009)

Acknowledgment Number

- Communication in TCP is full duplex
 - Both parties can send and receive data at the same time in a connection
- Each party numbers the bytes, usually with a different starting byte number
 - *Sequence number*: the number of the first byte carried by the segment
 - *Acknowledgment number*: the number of the next byte that *the party expects to receive*

Acknowledgment Number (Cont.)

- Acknowledgment number is *cumulative*
- For example, if a party uses 5,643 as an acknowledgment number
 - It has received all bytes from the beginning up to 5,642
 - Note that, *this does not mean that the party has received 5642 bytes*
 - The first byte number does not have to start from 0

The value of the acknowledgment field in a segment defines the number of the next byte a party expects to receives.

The acknowledgment number is cumulative.

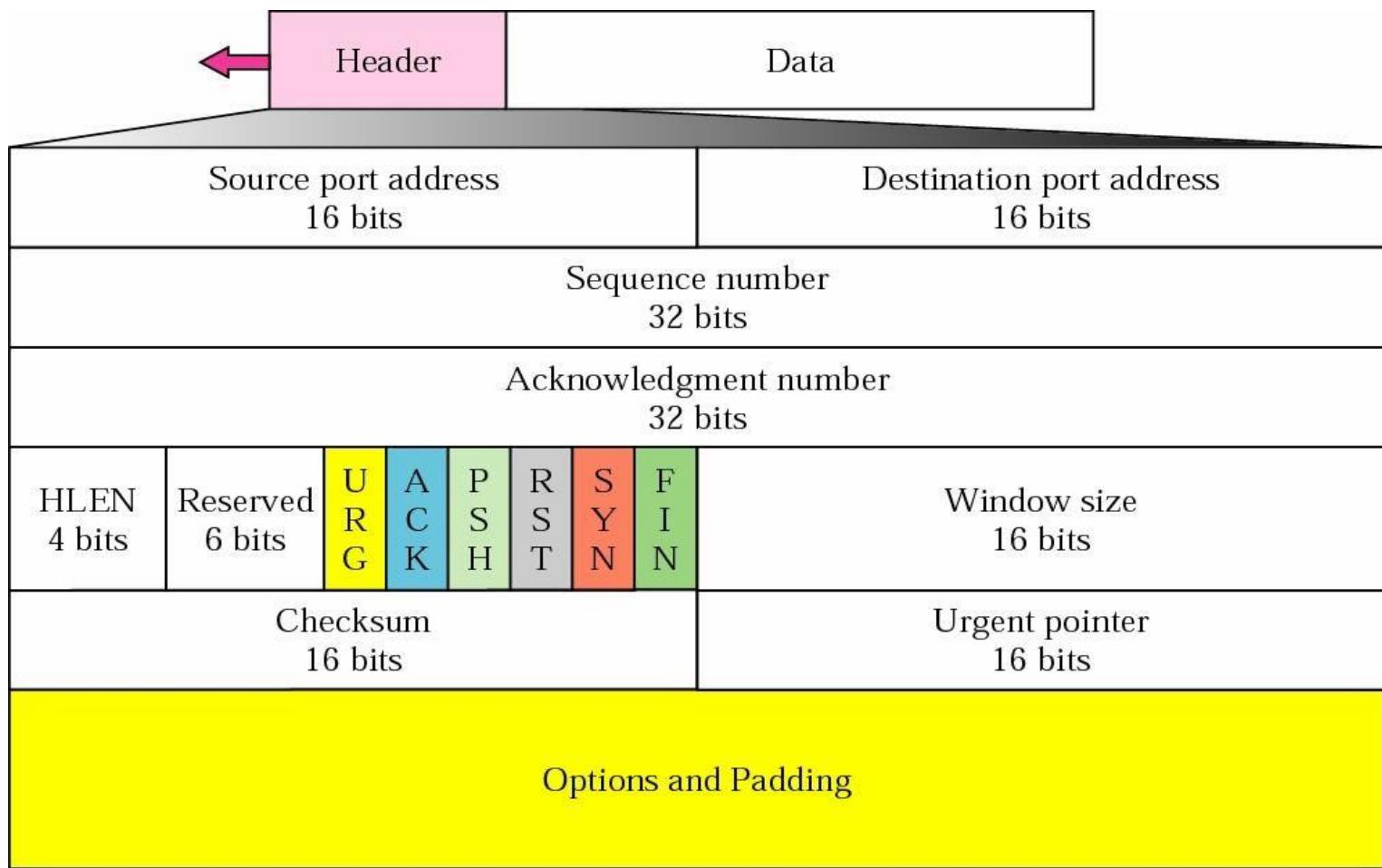
Flow Control

- The receiver controls how much data are to be sent by the sender
 - Prevent the receiver from being overwhelmed with data
- The numbering system allow TCP to use a ***byte-oriented flow control***

Error Control

- TCP implements an error control mechanism
 - To provide reliable service
 - Also byte-oriented

TCP Segment Format



The McGraw-Hill Companies, Inc., 2000

TCP Segment Format

- Source port address: 16-bit
- Destination port address: 16-bit
- Sequence number: 32-bit
 - The first byte number in this segment
 - In connection establishment, each party randomly generate an ***initial sequence number (ISN)***
 - Usually different in each direction
- Acknowledgment number: 32-bit
 - The byte number that the receiver expects
 - If received byte number x , ack. number is $x+1$
 - ***Acknowledgment and data can be piggybacked together***

TCP Segment Format (Cont.)

- Header length: 4-bit
 - The number of *4-byte words* in the TCP header
 - Value of this field is between 5 and 15
 - TCP header is between 20-60 bytes
- Reserved: 6-bit
 - Reserved for future use
- Control: 6-bits

Control Field

URG: Urgent pointer is valid

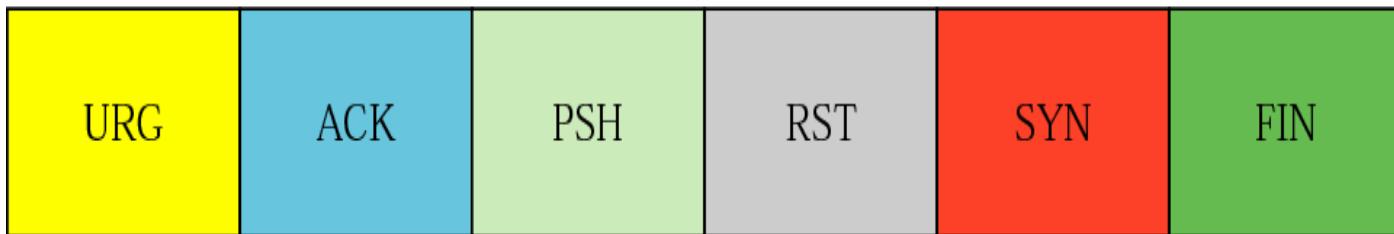
ACK: Acknowledgment is valid

PSH: Request for push

RST: Reset the connection

SYN: Synchronize sequence numbers

FIN: Terminate the connection



TCP Segment Format (Cont.)

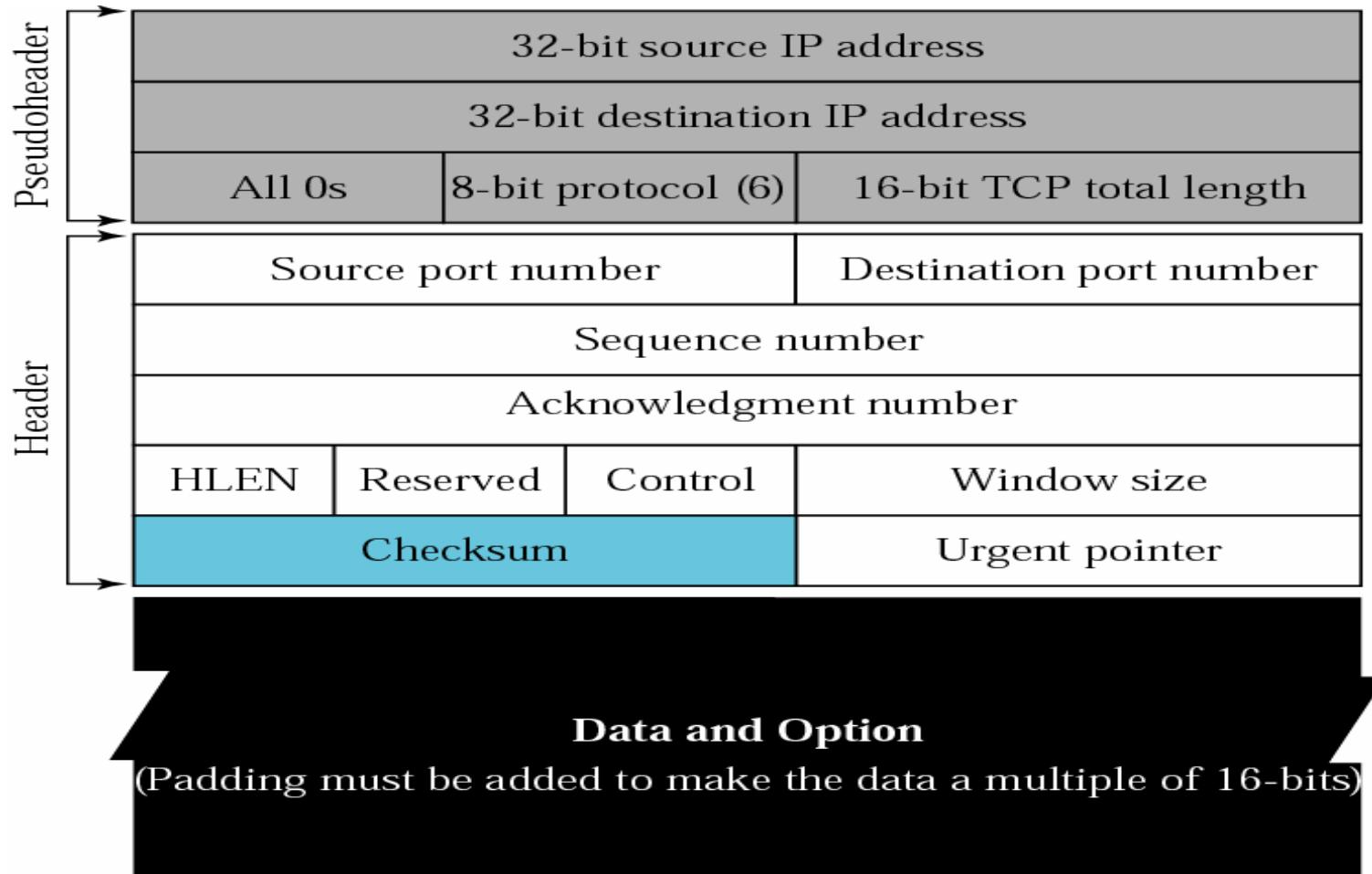
□ Control

- URG: urgent pointer is valid
- ACK: acknowledgment field is valid
- PSH: push the data
- RST: the connection must be reset
- SYN: Synchronization sequence numbers during connection
- FIN: terminate the connection

TCP Segment Format (Cont.)

- Window size: 16-bit
 - Define the size of the receiving window, in bytes
 - Determined by the receiver
 - The maximum window size is $2^{16} = 65535$
- Checksum: 16-bit
 - Follow the same procedure as UDP
 - Checksum for TCP is mandatory (UDP is optional)
- Urgent pointer: 16-bit
 - Valid only if the urgent bit is set
 - Used when the segment contains urgent data
- Options: 0~40 bytes

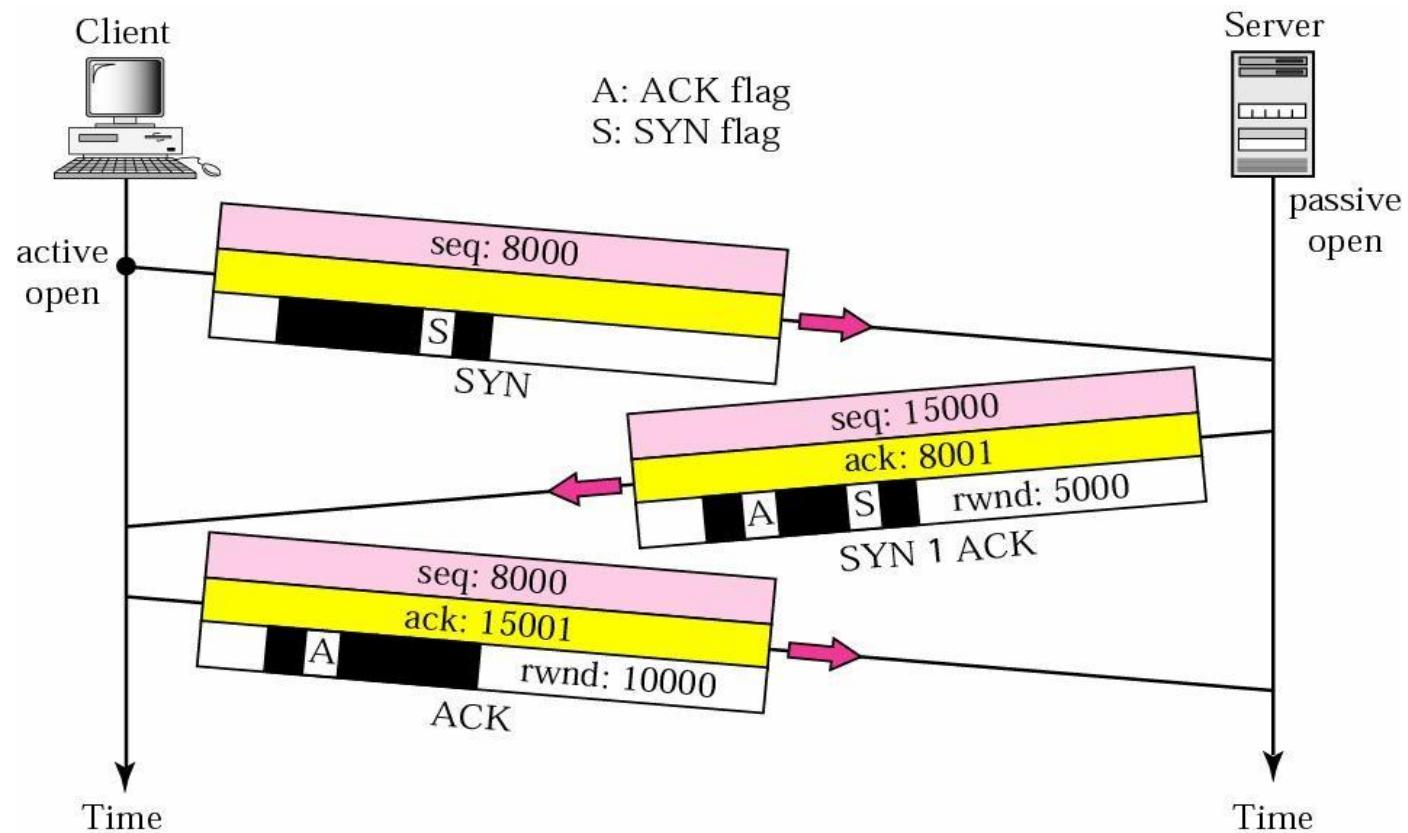
Pseudoheader added to the TCP datagram



A SYN segment cannot carry data, but it consumes one sequence number.

**A SYN + ACK segment cannot carry data,
but does consume one sequence number.**

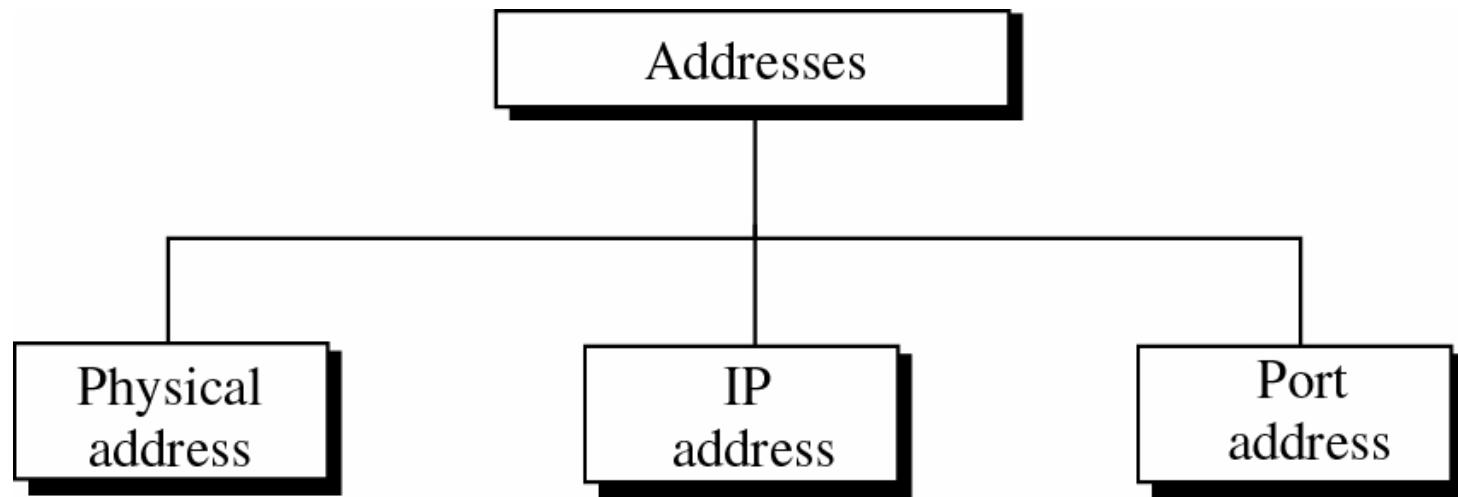
Three-way Handshaking



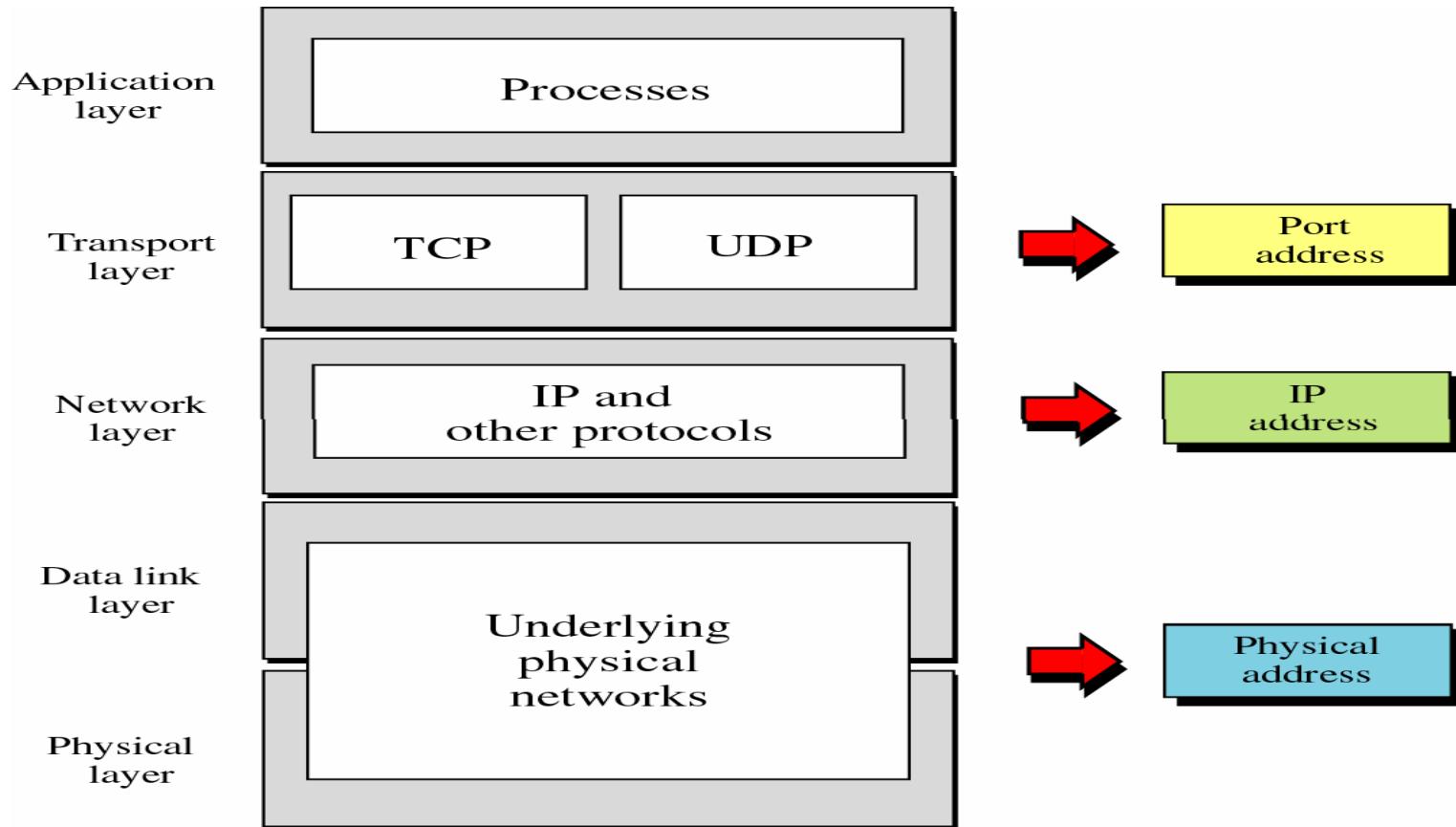
***An ACK segment, if carrying no data,
consumes no sequence number.***

ADDRESSING

Addresses in TCP/IP



Relationship of Layers and Addresses in TCP/IP



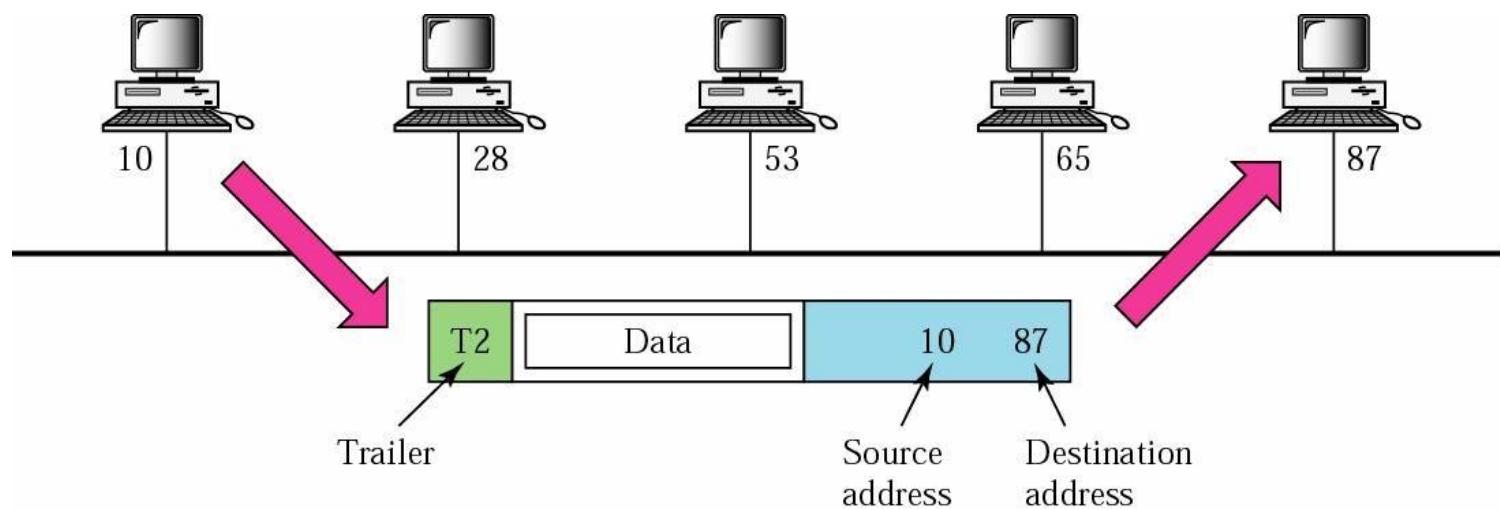
Physical Address

- Also called link address, the address of a node as defined by its LAN or WAN
 - Ethernet: 6 byte
 - LocalTalk: 1 byte
- Physical address can be either
 - Unicast address
 - Multicast address
 - Broadcast address

Example 1

Figure 2.18 shows an example of physical addresses.

Physical Addresses



Example 2

Most local area networks use a 48-bit (6 bytes) physical address written as 12 hexadecimal digits, with every 2 digits separated by a hyphen as shown below:

07-01-02-01-2C-4B

A 6-byte (12 hexadecimal digits) physical address

Internet Address

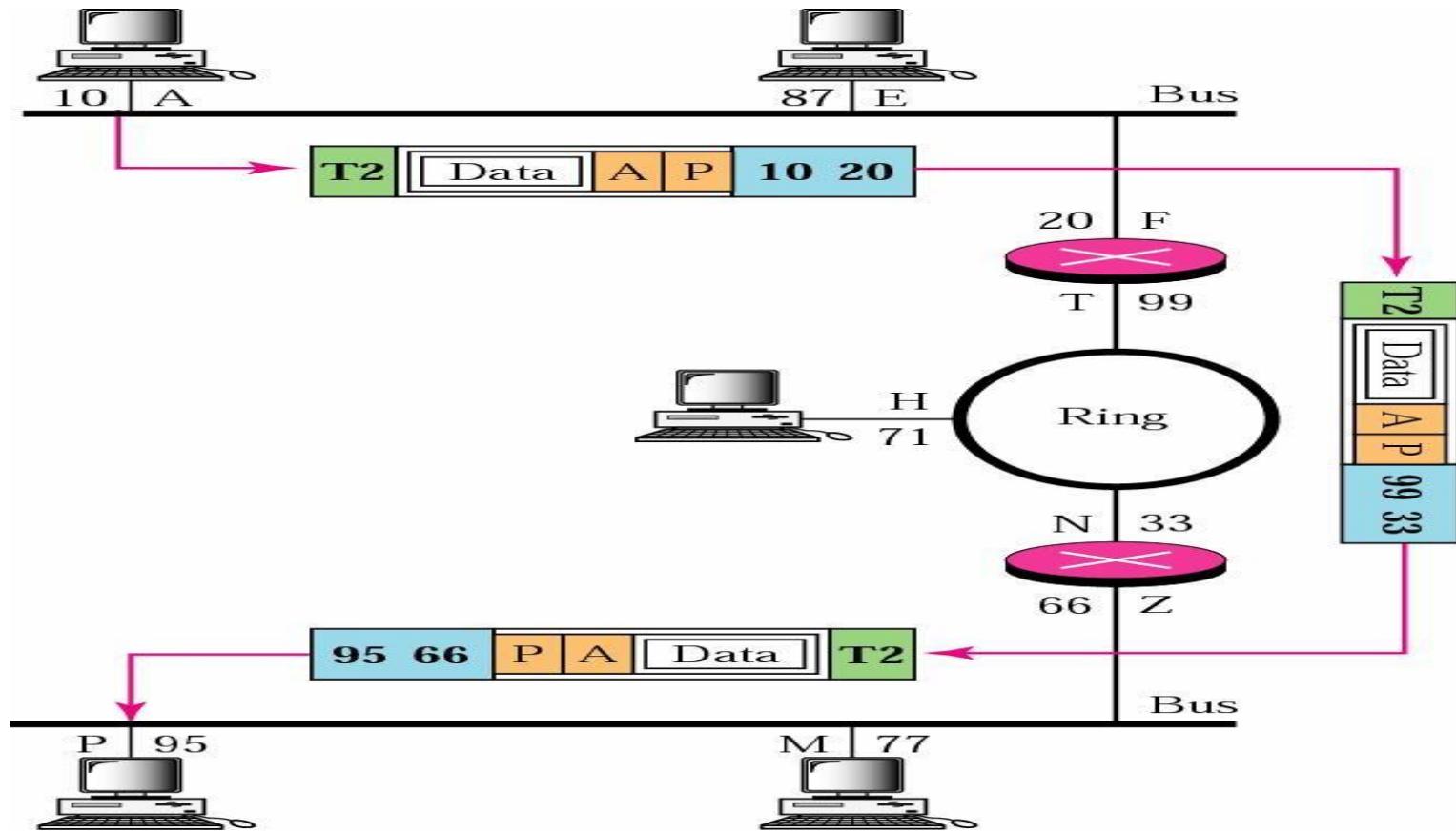
- Provide universal communication services that are independent of underlying physical network
 - Different networks can have different address format
 - A universal addressing system is thus needed
- Internet address can also be either in unicast, multicast and broadcast
- 4 bytes long in IPv4
- 16 bytes long in IPv6

Example 3

Next slide shows an example of Internet addresses.

- Network address A and physical address 10 => send data to => Network address P and physical address 95
- IP address does not change along the trip
- However, physical address changes from network to network

IP Addresses



Example 4

Internet address (in IPv4) is 32 bits in length, normally written as four decimal numbers, with each number representing 1 byte. The numbers are separated by a dot. Below is an example of such an address.

132.24.75.9

Example 5

Internet address (in IPv6) is 128 bits in length
The preferred IPv6 address representation
is: **x:x:x:x:x:x:x** , where each x is the
hexadecimal values of the eight 16-bit pieces
of the address. IPv6 addresses range from

0000:0000:0000:0000:0000:0000:0000:0000

to

ffff:ffff:ffff:ffff:ffff:ffff:ffff:ffff

Port Address

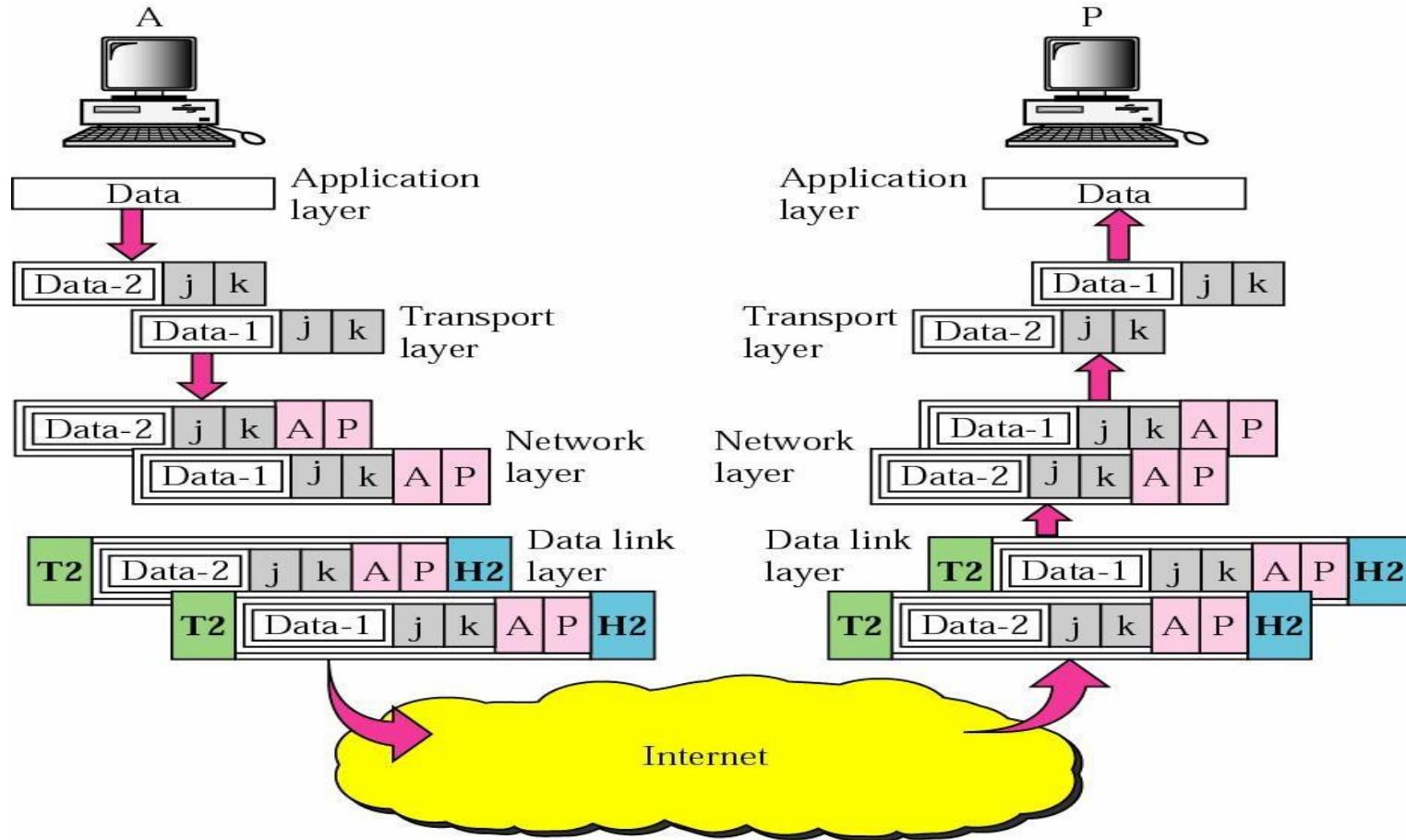
- A label assigns to a process
- 16 bits long

Example 6

Next slide shows an example of transport layer communication.

- Process with port address j send data to another process with port address k

Port Addresses



Example 6

A port address is a 16-bit address represented by one decimal number as shown below.

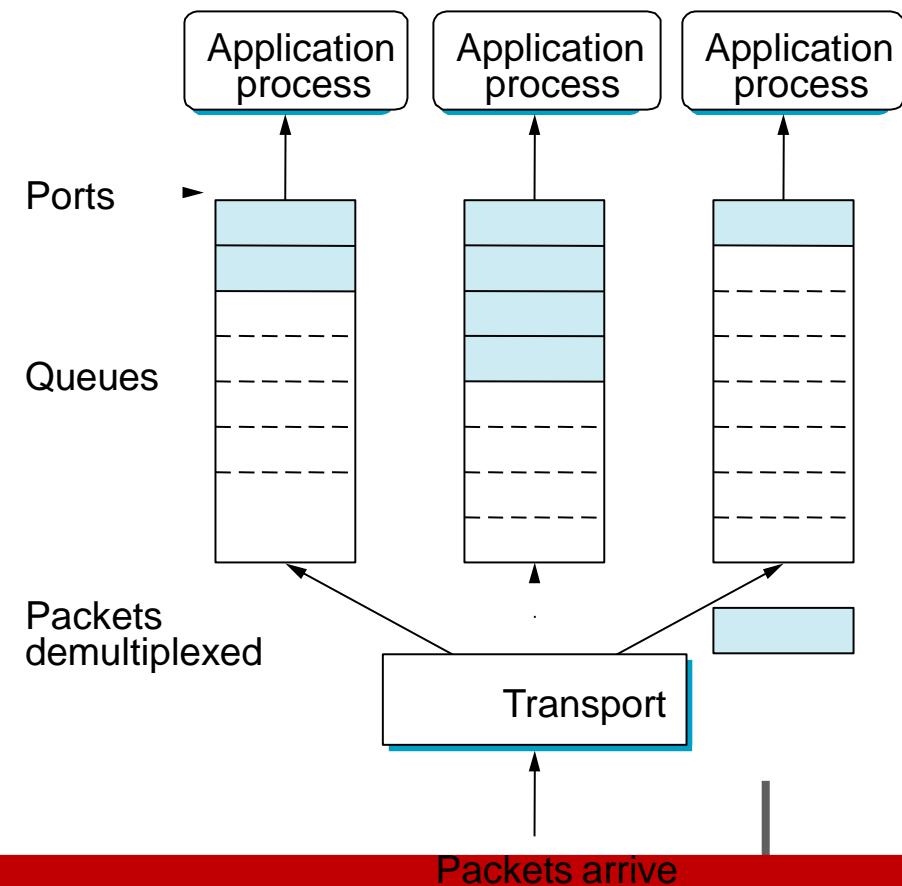
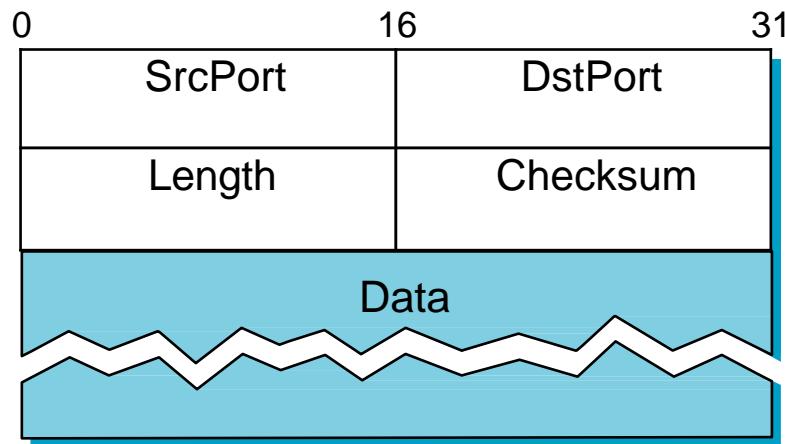
753

A 16-bit port address

Socket Programming

Demultiplexing

- Convert host-to-host packet delivery service into a process-to-process communication channel



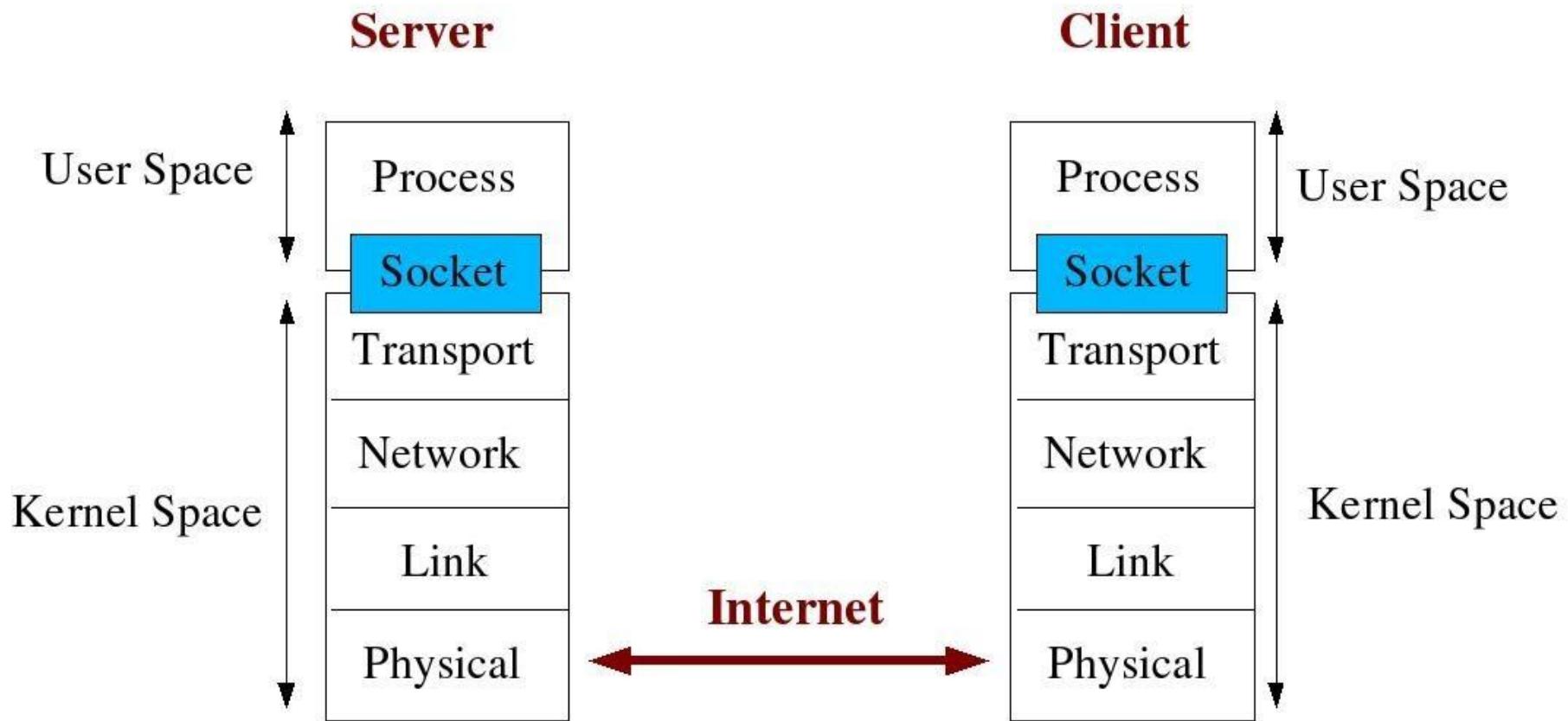
Byte Ordering

- Two types of “Byte ordering”
 - Network Byte Order: High-order byte of the number is stored in memory at the lowest address
 - Host Byte Order: Low-order byte of the number is stored in memory at the lowest address
 - Network stack (TCP/IP) expects Network Byte Order
- Conversions:
 - htons() - Host to Network Short
 - htonl() - Host to Network Long
 - ntohs() - Network to Host Short
 - ntohl() - Network to Host Long

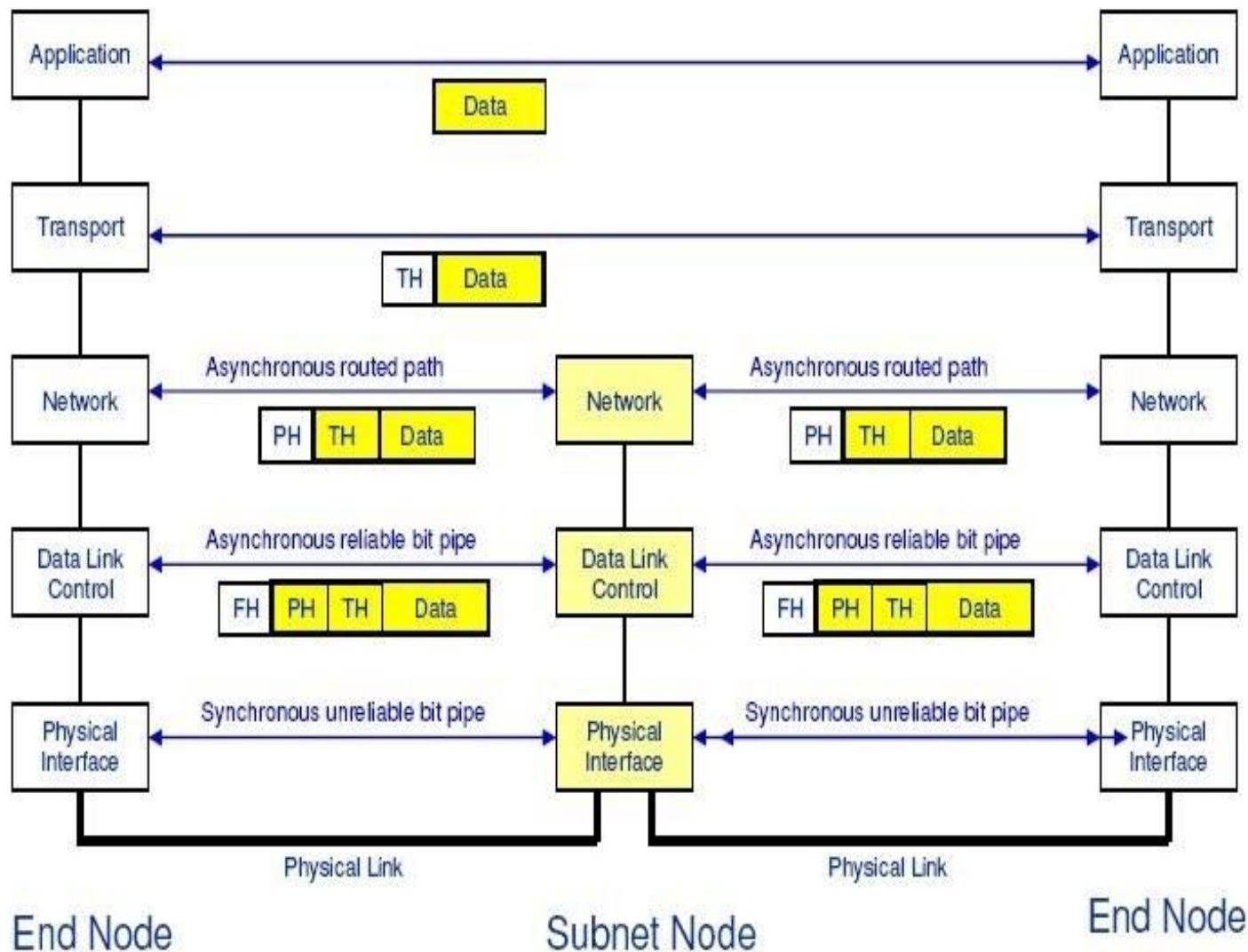
What is a socket?

- Socket: An interface between an application process and transport layer
 - The application process can send/receive messages to/from another application process (local or remote) via a socket
- In Unix jargon, a socket is a file descriptor – an integer associated with an open file
- Types of Sockets: **Internet Sockets**, unix sockets, X.25 sockets etc
 - Internet sockets characterized by IP Address (4 bytes), port number (2 bytes)

Socket in TCP/IP Description



Encapsulation



Types of Internet Sockets

- Stream Sockets (SOCK_STREAM)
 - Connection oriented
 - Rely on TCP to provide reliable two-way connected communication
- Datagram Sockets (SOCK_DGRAM)
 - Rely on UDP
 - Connection is unreliable

socket() -- Get the file descriptor

- int socket(int domain, int type, int protocol);
 - domain should be set to AF_INET
 - type can be SOCK_STREAM or SOCK_DGRAM
 - set protocol to 0 to have socket choose the correct protocol based on type
 - socket() returns a socket descriptor for use in later system calls or -1 on error

```
int sockfd;  
sockfd = socket (AF_INET, SOCK_STREAM, 0);
```

Socket Structures

- struct sockaddr: Holds socket address information for many types of sockets

```
struct sockaddr {  
    unsigned short sa_family; //address family AF_xxx  
    unsigned short sa_data[14]; //14 bytes of protocol addr  
}
```

- struct sockaddr_in: A parallel structure that makes it easy to reference elements of the socket address

```
struct sockaddr_in {  
    short int sin_family; // set to AF_INET  
    unsigned short int sin_port; // Port number  
    struct in_addr sin_addr; // Internet address  
    unsigned char sin_zero[8]; //set to all zeros  
}
```

- sin_port and sin_addr must be in **Network Byte Order**

Dealing with IP Addresses

- ```
struct in_addr {
 unsigned long s_addr; // that's a 32bit long, or 4 bytes
};
```
- int inet\_aton(const char \*cp, struct in\_addr \*inp);  

```
struct sockaddr_in my_addr;
my_addr.sin_family = AF_INET;
my_addr.sin_port = htons(MYPORT);
inet_aton("10.0.0.5",&(my_addr.sin_addr));
memset(&(my_addr.sin_zero),'\0',8);
```
- inet\_aton() gives non-zero on success; zero on failure
- To convert binary IP to string: inet\_ntoa()  

```
printf("%s",inet_ntoa(my_addr.sin_addr));
```

## bind() - what port am I on?

- Used to associate a socket with a port on the local machine
  - The port number is used by the kernel to match an incoming packet to a process
- `int bind(int sockfd, struct sockaddr *my_addr, int addrlen)`
  - sockfd is the socket descriptor returned by `socket()`
  - my\_addr is pointer to `struct sockaddr` that contains information about your IP address and port
  - addrlen is set to `sizeof(struct sockaddr)`
  - returns -1 on error
  - `my_addr.sin_port = 0; //choose an unused port at random`
  - `my_addr.sin_addr.s_addr = INADDR_ANY; //use any IP adr`

## Example

```
int sockfd;

struct sockaddr_in my_addr;

sockfd = socket(AF_INET, SOCK_STREAM, 0);
my_addr.sin_family = AF_INET; // host byte order
my_addr.sin_port = htons(MYPORT); // short, network byte
order
my_addr.sin_addr.s_addr = inet_addr("172.28.44.57");
memset(&(my_addr.sin_zero), '\0', 8); // zero the rest of the struct
bind(sockfd, (struct sockaddr *)&my_addr, sizeof(struct
sockaddr));
***** Code needs error checking. Don't forget to do that ***** /
```

## connect() - Hello!

- Connects to a remote host
- `int connect(int sockfd, struct sockaddr *serv_addr, int addrlen)`
  - sockfd is the socket descriptor returned by `socket()`
  - serv\_addr is pointer to `struct sockaddr` that contains information on destination IP address and port
  - addrlen is set to `sizeof(struct sockaddr)`
  - returns -1 on error
- No need to `bind()`, kernel will choose a port

## Example

```
#define DEST_IP "172.28.44.57"
#define DEST_PORT 5000
main(){
 int sockfd;
 struct sockaddr_in dest_addr; // will hold the destination addr
 sockfd = socket(AF_INET, SOCK_STREAM, 0);
 dest_addr.sin_family = AF_INET; // host byte order
 dest_addr.sin_port = htons(DEST_PORT); // network byte
 order
 dest_addr.sin_addr.s_addr = inet_addr(DEST_IP);
 memset(&(dest_addr.sin_zero), '\0', 8); // zero rest of the struct
 connect(sockfd, (struct sockaddr *)&dest_addr, sizeof(struct
 sockaddr));
 **** Don't forget error checking *****/
```

## listen() - Call me please!

- Waits for incoming connections
- int listen(int sockfd, int backlog);
  - sockfd is the socket file descriptor returned by socket()
  - backlog is the number of connections allowed on the incoming queue
  - listen() returns -1 on error
  - Need to call bind() before you can listen()
    - socket()
    - bind()
    - listen()
    - accept()

## accept() - Thank you for calling !

- accept() gets the pending connection on the port you are listen()ing on
- int accept(int sockfd, void \*addr, int \*addrlen);
  - sockfd is the listening socket descriptor
  - information about incoming connection is stored in addr which is a pointer to a local struct sockaddr\_in
  - addrlen is set to sizeof(struct sockaddr\_in)
  - accept returns *a new socket file descriptor* to use for this accepted connection and -1 on error

## Example

```
#include <string.h>
#include <sys/types.h>
#include <sys/socket.h>
#include <netinet/in.h>
#define MYPORT 3490 // the port users will be connecting to
#define BACKLOG 10 // pending connections queue will hold
main(){
 int sockfd, new_fd; // listen on sock_fd, new connection on
new_fd
 struct sockaddr_in my_addr; // my address information
 struct sockaddr_in their_addr; // connector's address information
 int sin_size;
 sockfd = socket(AF_INET, SOCK_STREAM, 0);
```

## Cont...

```
my_addr.sin_family = AF_INET; // host byte order
my_addr.sin_port = htons(MYPORT); // short, network byte
order
my_addr.sin_addr.s_addr = INADDR_ANY; // auto-fill with my IP
memset(&(my_addr.sin_zero), '\0', 8); // zero the rest of the struct
// don't forget your error checking for these calls:
bind(sockfd, (struct sockaddr *)&my_addr, sizeof(struct
sockaddr));
listen(sockfd, BACKLOG);
sin_size = sizeof(struct sockaddr_in);
new_fd = accept(sockfd, (struct sockaddr *)&their_addr,
&sin_size);
```

## send() and recv() - Let's talk!

- The two functions are for communicating over stream sockets or connected datagram sockets.
- `int send(int sockfd, const void *msg, int len, int flags);`
  - sockfd is the socket descriptor you want to send data to (returned by `socket()` or got from `accept()`)
  - msg is a pointer to the data you want to send
  - len is the length of that data in bytes
  - set flags to 0 for now
  - `sent()` returns the number of bytes actually sent (may be less than the number you told it to send) or -1 on error

## send() and recv() - Let's talk!

- `int recv(int sockfd, void *buf, int len, int flags);`
  - sockfd is the socket descriptor to read from
  - buf is the buffer to read the information into
  - len is the maximum length of the buffer
  - set flags to 0 for now
  - recv() returns the number of bytes actually read into the buffer or -1 on error
  - If recv() returns 0, the remote side has closed connection on you

## sendto() and recvfrom() - DGRAM style

- int sendto(int sockfd, const void \*msg, int len, int flags, const struct sockaddr \*to, int tolen);
  - *to* is a pointer to a struct sockaddr which contains the destination IP and port
  - *tolen* is sizeof(struct sockaddr)
- int recvfrom(int sockfd, void \*buf, int len, int flags, struct sockaddr \*from, int \*fromlen);
  - *from* is a pointer to a local struct sockaddr that will be filled with IP address and port of the originating machine
  - *fromlen* will contain length of address stored in *from*

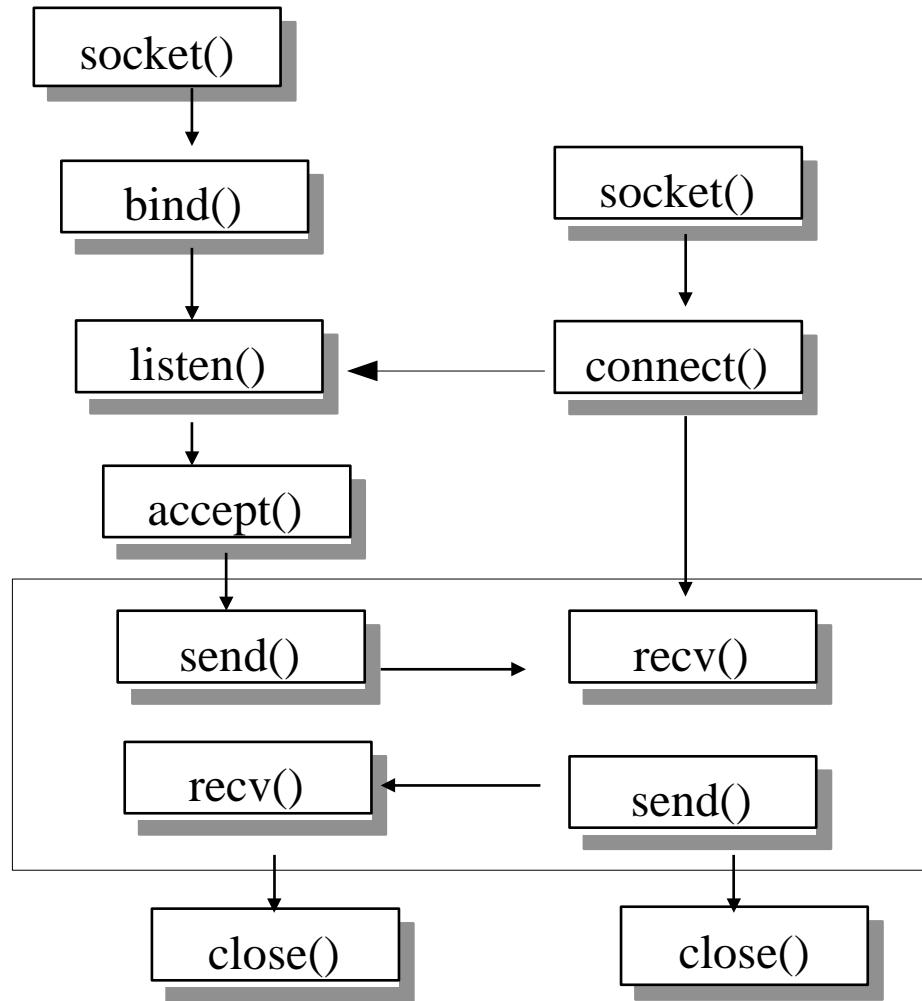
## close() - Bye Bye!

- `int close(int sockfd);`
  - Closes connection corresponding to the socket descriptor and frees the socket descriptor
  - Will prevent any more sends and recvs

# Connection Oriented Protocol

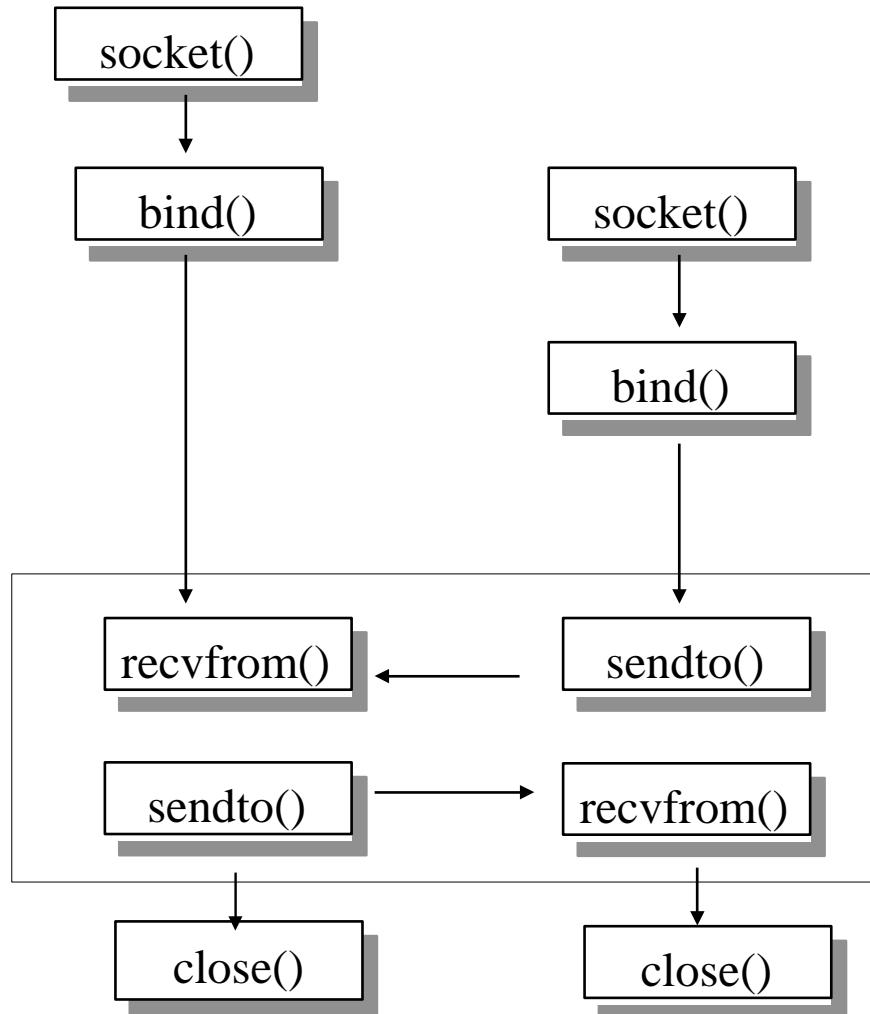
**Server**

**Client**



# Connectionless Protocol

## Server      Client



## Miscellaneous Routines

- `int getpeername(int sockfd, struct sockaddr *addr, int *addrlen);`
  - Will tell who is at the other end of a connected stream socket and store that info in `addr`
- `int gethostname(char *hostname, size_t size);`
  - Will get the name of the computer your program is running on and store that info in `hostname`

## Miscellaneous Routines

- `struct hostent *gethostbyname(const char *name);`

```
struct hostent {
 char *h_name; //official name of host
 char **h_aliases; //alternate names for the host
 int h_addrtype; //usually AF_NET
 int h_length; //length of the address in bytes
 char **h_addr_list; //array of network addresses for the host
}
#define h_addr h_addr_list[0]
```

- 

```
struct hostent *h;
h = gethostbyname("www.cdacacts.in");
printf("Host name : %s \n", h>h_name);
printf("IP Address: %s\n",inet_ntoa(*((struct in_addr *)h>h_addr)));
```

## Summary

- Sockets help application process to communicate with each other using standard Unix file descriptors
- Two types of Internet sockets: SOCK\_STREAM and SOCK\_DGRAM
- Many routines exist to help ease the process of communication

# Syllabus

1. IoT Trends, IoT Architecture, IoT Applications
2. IoT Standards and Protocols
3. Wireless LAN: IEEE 802.11
4. Wireless PAN: IEEE 802.15.1 & 802.15.4, Zigbee
5. Bluetooth, BTLE, LPWAN (LoRa, NB-IoT), 6LowPAN
6. REST, CoAP, MQTT
7. Basics of Cryptography, Overview of IoT and Embedded security
8. Overview of 5G technologies

# IoT Trends, IoT Architecture, IoT Applications

# Internet of Things (IoT)



- The term IoT can most likely be attributed to Kevin Ashton in 1997 with his work at Proctor and Gamble using RFID tags to manage supply chains.
- Then, in 2009: “Conventional diagrams of the Internet include servers and routers and so on, but they leave out the most numerous and important routers of all: people. The problem is, **people have limited time, attention and accuracy** [...] If we had **computers that knew everything** there was to know **about things** [...] we would be able to [...] greatly **reduce waste, loss and cost**. We would know when things needed replacing, repairing or recalling, and whether they were fresh or past their best

# Internet of Things - Scenarios

- Since 1999 the concept evolved far beyond RFID
- **Everything can now be connected to the Internet**
- The term IoT now refers to different scenarios:
  - Wireless Sensor Networks (WSN)
  - Near Field Communications (NFC)
  - Biotechnology and Body Area Networks (BAN)
  - Machine-to-Machine communications (M2M)
  - Personal Area Networks (PAN)
  - ...

# IoT versus machine to machine

## Machine2Machine:

- It is a general concept involving an autonomous device communicating directly to another autonomous device.
- It may very well be the case that an M2M device uses no internet services or topologies for communication.
- This leaves out typical internet appliances used regularly for cloud services and storage.
- An M2M system may communicate over non-IP based channels as well, such as a serial port or custom protocol.

## Internet of Things:

- IoT systems may incorporate some M2M nodes (such as a Bluetooth mesh using non-IP communication), but aggregates data at an edge router or gateway.
- An edge appliance like a gateway or router serves as the entry point onto the internet. Regardless of where the internet *on-ramp* exists, the fact that it has a method of tying into the internet fabric is what defines IoT.

# IoT - How Big?

- Possibly every single device and object will be connected to the Internet
- About 50-100 billions devices in 2020 (data from SAP/Intel and Ericsson)
- IBM Smarter Planet vision:
  - instrumented
  - interconnected
  - intelligent
- Several real world examples: industrial control systems, health monitoring, smart metering, home automation, ...



# Internet of Things - Use Cases

Smart Wearables



Smart Home



Smart City



Smart Agriculture



Connected Car



Health Care



Industry Automation



Smart Energy



# IoT Applications – IIoT, Consumer

**Industrial IoT (IIoT)** is one of the fastest and largest segments in the overall IoT space by the number of connected things and the value those services bring to manufacturing and factory automation.

## Industrial and manufacturing IoT use cases and impact

Following are the industrial and manufacturing IoT use cases and their impact:

- Preventative maintenance on new and pre-existing factory machinery
- Throughput increase through real-time demand
- Energy savings
- Safety systems such as thermal sensing, pressure sensing, and gas leaks
- Factory floor expert systems

## Consumer IoT use cases

The following are some of the consumer IoT use cases:

- **Smart home gadgetry:** Smart irrigation, smart garage doors, smart locks, smart lights, smart thermostats, and smart security.
- **Wearables:** Health and movement trackers, smart clothing/wearables.
- **Pets:** Pet location systems, smart dog doors.

# IoT Applications – Retail

## Retail IoT use cases

Some of the retail IoT use cases are as follows:

- Targeted advertising, such as locating known or potential customers by proximity and providing sales information.
- Beaconing, such as proximity sensing customers, traffic patterns, and inter-arrival times as marketing analytics.
- Asset tracking, such as inventory control, loss control, and supply chain optimizations.
- Cold storage monitoring, such as analyze cold storage of perishable inventory.
- Apply predictive analytics to food supply.
- Insurance tracking of assets.
- Insurance risk measurement of drivers.
- Digital signage within retail, hospitality, or citywide.
- Beaconing systems within entertainment venues, conferences, concerts, amusement parks, and museums.

# IoT Applications – Healthcare, Logistics

## Healthcare IoT use cases

Some of the healthcare IoT use cases are as follows:

- In-home patient care
- Learning models of predictive and preventative healthcare
- Dementia and elderly care and tracking
- Hospital equipment and supply asset tracking
- Pharmaceutical tracking and security
- Remote field medicine
- Drug research
- Patient fall indicators

## Transportation and logistics IoT use cases

Following are some of the transportation and logistics IoT use cases:

- Fleet tracking and location awareness
- Railcar identification and tracking
- Asset and package tracking within fleets
- Preventative maintenance of vehicles on the road

# IoT Applications – Agricultural

## Agricultural and environmental IoT use cases

Some of the agricultural and environmental IoT use cases are as follows:

- Smart irrigation and fertilization techniques to improve yield
- Smart lighting in nesting or poultry farming to improve yield
- Livestock health and asset tracking
- Preventative maintenance on remote farming equipment via manufacturer
- Drones-based land surveys
- Farm-to-market supply chain efficiencies with asset tracking
- Robotic farming
- Volcanic and fault line monitoring for predictive disasters

# IoT Applications – Smart City , military

## Smart city IoT use cases

Some of the smart city IoT use cases are as follows:

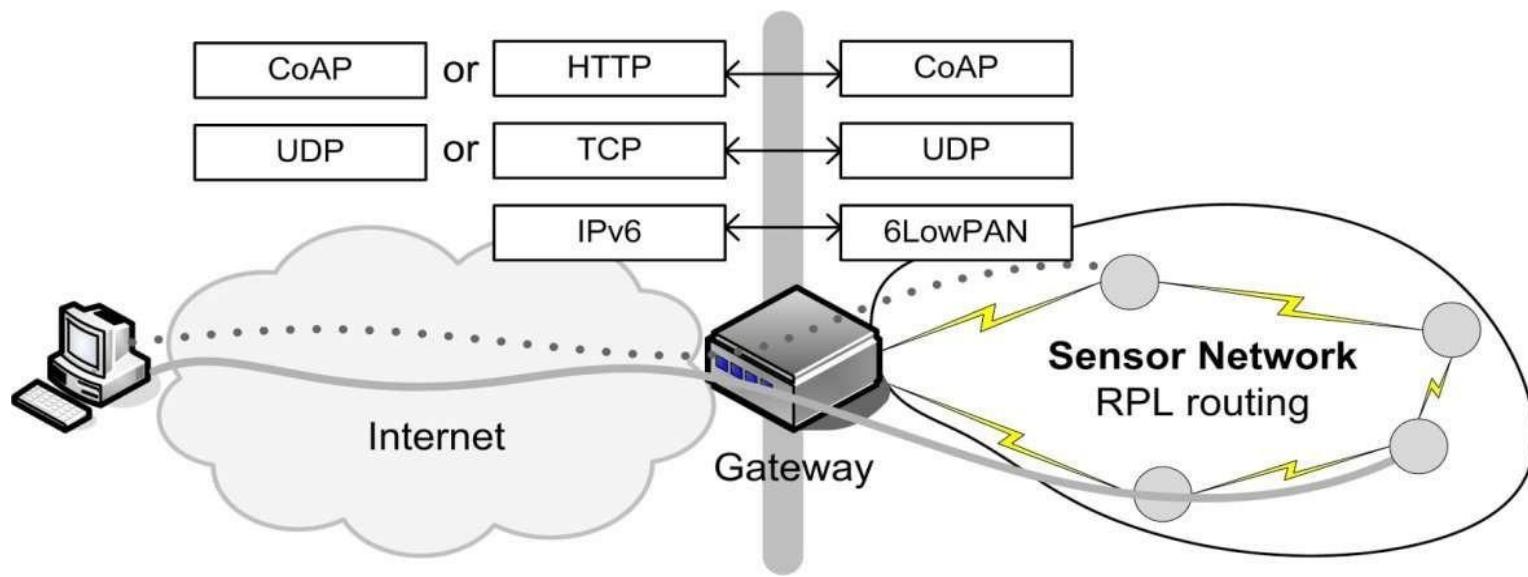
- Pollution control and regulatory analysis through environmental sensing
- Microclimate weather predictions using citywide sensor networks
- Energy efficiency of city lighting on demand
- Smart irrigation of parks and public spaces, depending on weather
- Smart cameras to watch for crime and real-time automated AMBER Alerts
- Smart parking lots

## Government and military IoT use cases

Following are some of the government and military IoT use cases:

- Terror threat analysis through IoT device pattern analysis and beacons
- Swarm sensors through drones
- Sensor bombs deployed on the battlefield to form sensor networks to monitor threats
- Government asset tracking systems
- Real-time military personal tracking and location services
- Synthetic sensors to monitor hostile environments
- Water level monitoring to measure dam and flood containment

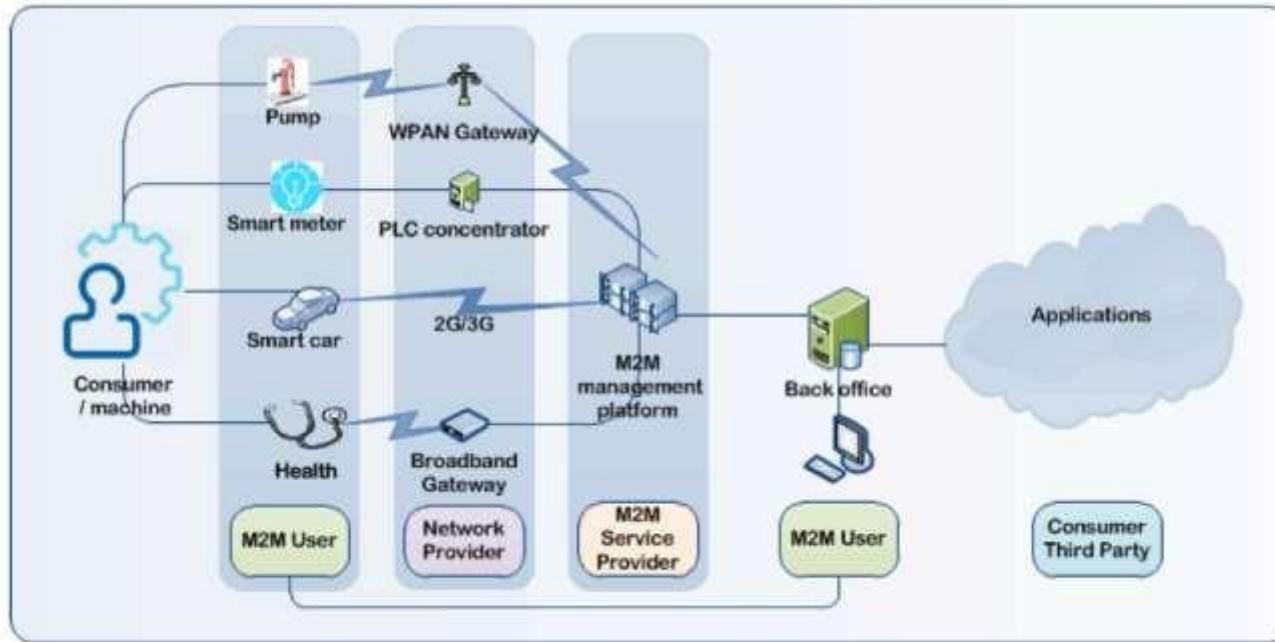
# IoT - the General Idea



- The general idea behind the (commonly accepted) vision of IoT consists in the **extension of Internet protocols to Wireless Sensors Networks (WSNs)**, composed of sensors as well as actuators

# IoT for Manufacturing - Machine to Machine

- The term “Machine to Machine” (**M2M**) describes devices **connected to each other**, by using a variety of fixed/wireless networks and through the Internet to the wider world. They are **active** communication devices



- Note the **wide variety of communication** infrastructures and services and **massive number of nodes**

# IoT - Main Tasks

- **Gather information from things** and send commands to things
  - monitoring: state information
  - control: command enforcement
- **Send information back and forth** remote locations (private/public cloud)
- **Store and aggregate** information
- **Analyze** information to improve system knowledge
- **Take decisions**, in a human-assisted or autonomous manner

# Outline

## 1. Introduction to IoT

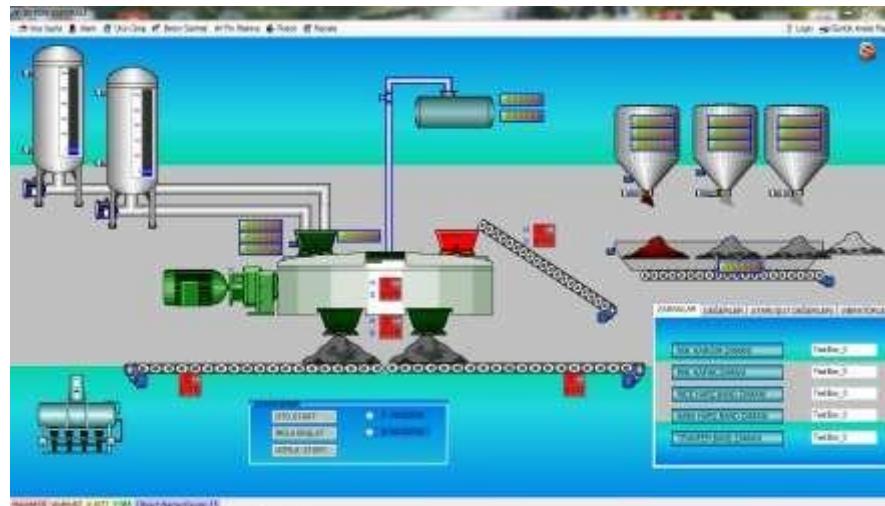
- **definition, enabling technologies and concepts to better understand the general framework of IoT solutions**
- layering architecture, cloud computing vs. fog computing

## 2. Most relevant components of IoT solutions

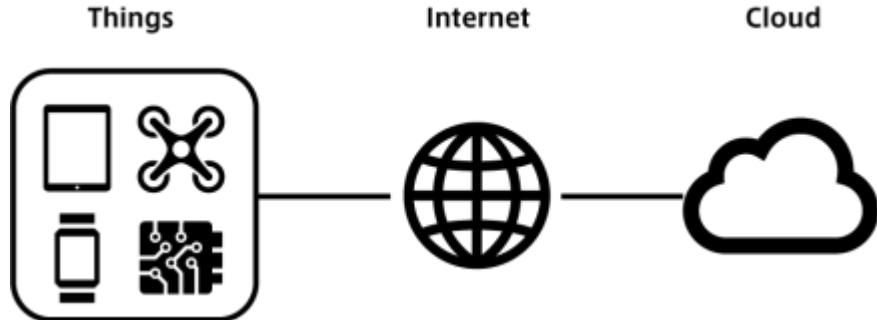
- devices, wireless communication protocols, data exchange protocols, IoT platforms, and data analysis

# SCADA - Supervisory Control And Data Acquisition

- Before IoT, **remote monitoring and control already available for years**
- Central control system with sensors/actuators, controllers, communication equipment, and software
- Issues with SCADA : **Expensive, lack of standard, no interoperability**



# IoT - Main Goals, in a nutshell...



- IoT can be seen as a novel business approach
  - based on a set of (already available) technology tools
  - exploited in novel (industrial) scenarios
- The Internet (and its standards) exploited to transfer data about things in an **efficient, interoperable, and secure** manner
- Things can be
  - **physical**: Cyber Physical System (CPS) solutions to create a bridge between the physical and digital worlds
  - **digital**: information are already in binary format, but typically not in a standard format
- Gathered data analyzed to acquire a more **in-depth knowledge of physical/digital systems**, typically composed of **geographically distributed** and **heterogeneous** things

# IoT Definition – Small Environment Scenario

- An IoT
  - is a network that
  - connects uniquely identifiable “Things”
  - to the Internet
- The Things
  - have sensing/actuation and
  - potential programmability capabilities
- Through the exploitation of unique identification and sensing
  - information about the Thing can be collected
  - and the state of the Thing can be changed
  - from anywhere, anytime, by anything

# IoT Enabling Technologies

- Reduced **hardware** cost and size
  - from special-purpose to Commercial Off-The-Shelf (COTS)
- Pervasive and cheap **wireless communication**
  - from cables to large-bandwidth and/or wide-coverage wireless communication
- Consolidated and emerging **Web-based communication**
  - from close protocols to open standards, also applied in constrained devices
- **Standards**, to achieve interoperability
  - e.g., communication standards and data representation
- General purpose **horizontal solutions**
  - from SCADA to IoT platforms
- Automatic tools to **infer knowledge**
  - wide application of AI (Artificial Intelligence) techniques

actual game  
changers

# Outline

## 1. Introduction to IoT

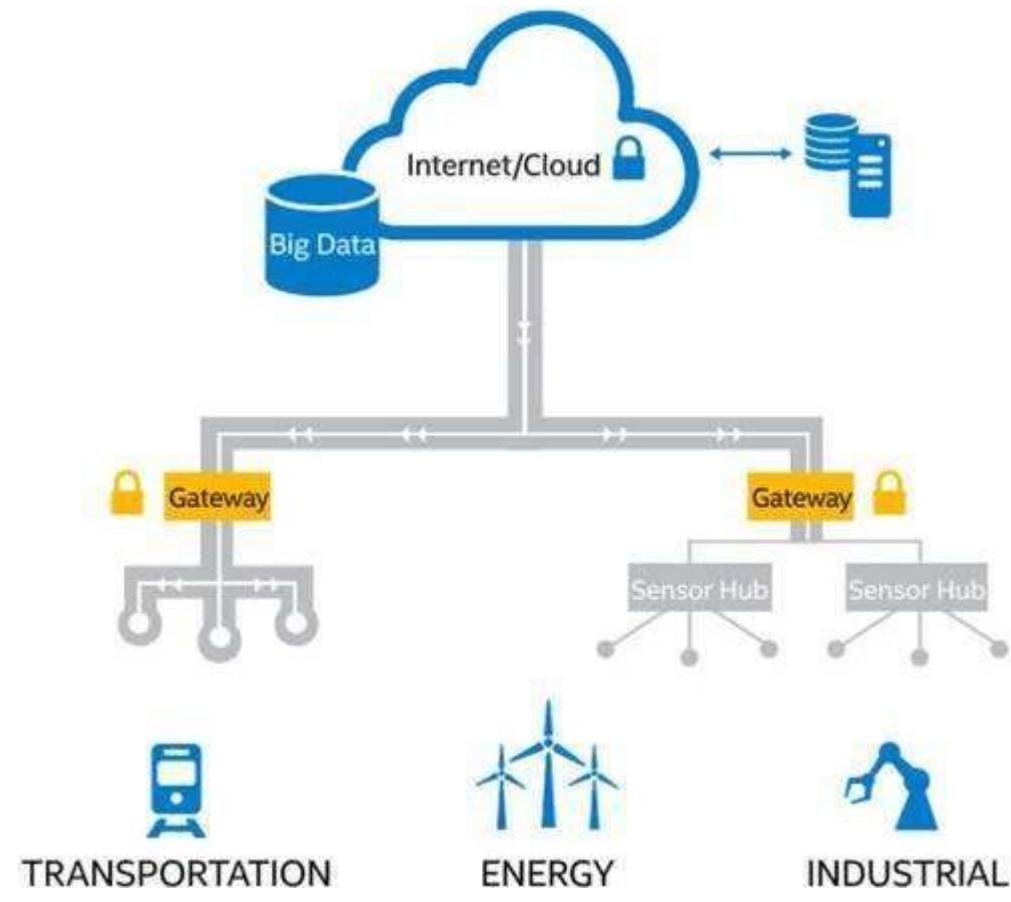
- definition, enabling technologies and concepts to better understand the general framework of IoT solutions
- **layering architecture, cloud computing vs. fog computing**

## 2. Most relevant components of IoT solutions

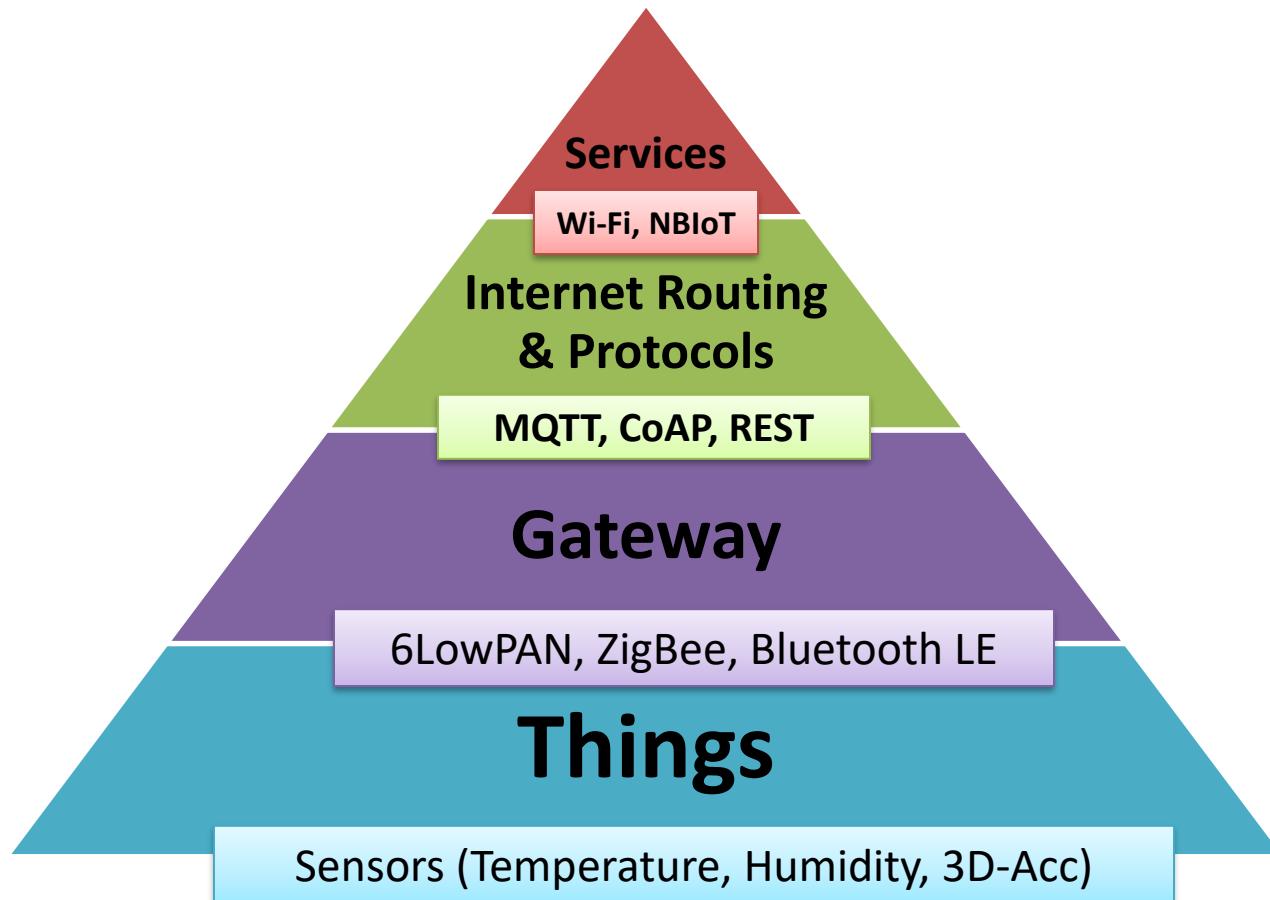
- devices, wireless communication protocols, data exchange protocols

# Typical Cloud-based IoT Architecture

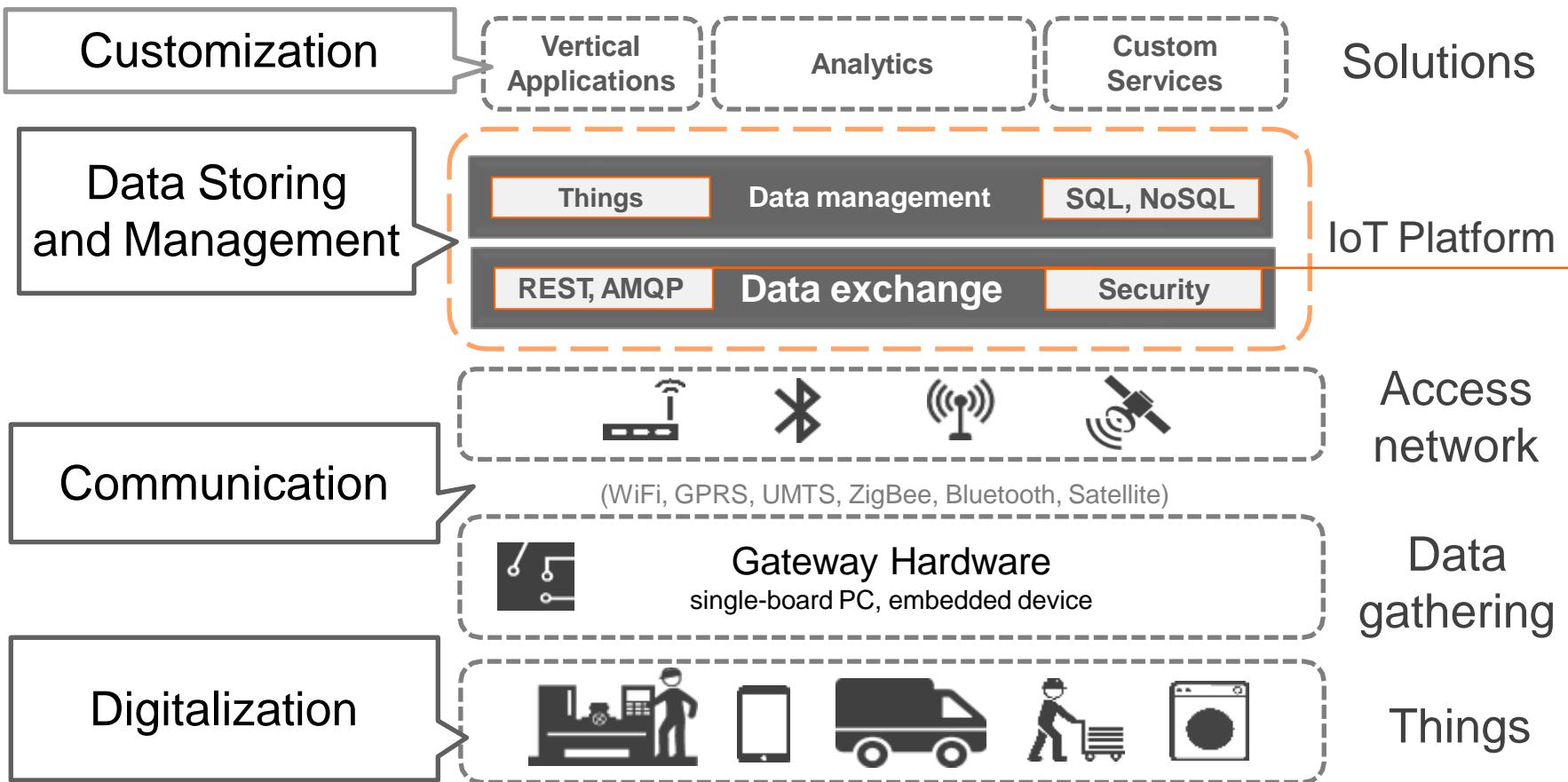
- Several heterogeneous **things**, e.g., sensors and actuators
- Multiple **gateways** geographically close to sensors/actuators
  - directly interact with things
  - dispatch data to/from the Internet
- Server-side remote **applications** stored in the Cloud and managing data



# IoT Architecture



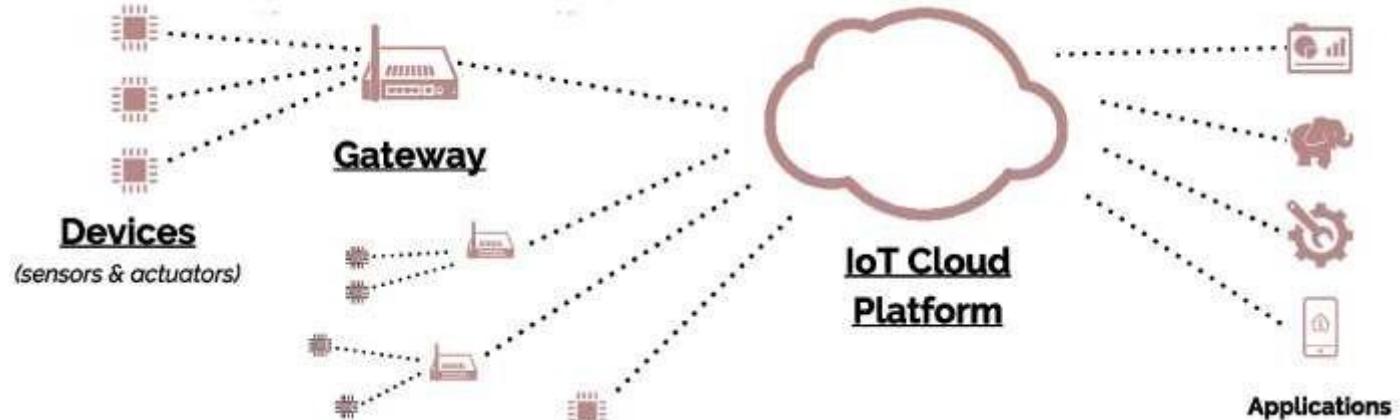
# IoT: One Solution, Many Layers



# Layering to Simplify Complexity

- **Things:** any physical or digital objects that should be monitored or controlled
  - physical objects must be digitalized
  - virtual objects must be standardized
- **Gateway:** close to one or multiple things to interact with them and send data and command back and forth the Internet
- **Communication protocol:** wired/wireless technology to actually send bytes
- **Data exchange protocol:** software protocol to standardize how information are transported (and eventually also represented)
- **IoT Platform:** data storing and management, application of (simple) aggregation/processing functions on data
- **Analytics:** complex analysis on data to infer new knowledge

# Gateway

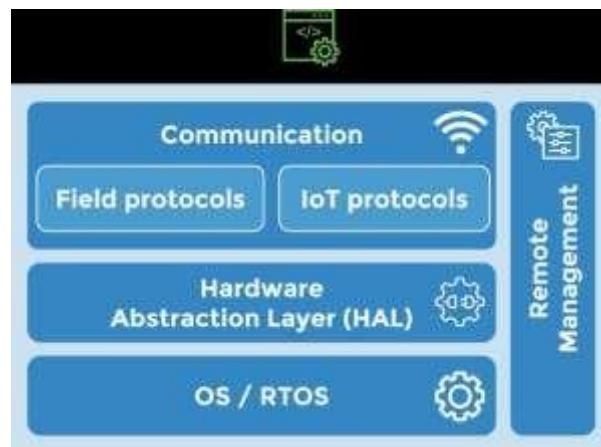


- **Protocol translation** between peripheral trunks of the IoT, eventually provided with lower parts of the communication stacks
- Gateways can also provide: pre-processing, **security**, scalability, service discovery, **geo-localization**, **billing**, etc.
- Pre-processing:
  - data **buffering**: temporarily store data to wait for connectivity or to increase efficiency
  - data **efficiency**: temperature read every 1s, but only per-minute average sent
  - data **aggregation**: water level from different silos, but only the sum is sent
  - data **filtering**: send temperature values only if greater than 25°C

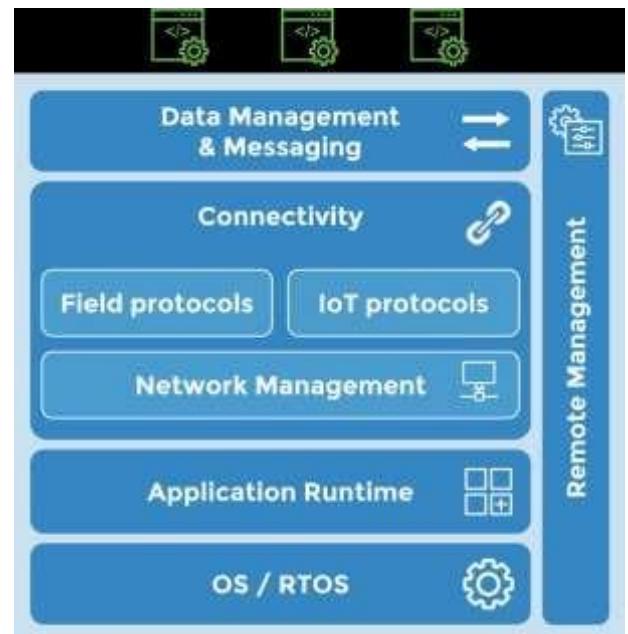
# With/Without Gateway

- If there is no gateway, things have to send/receive data on their own
- In case of constrained devices, reduced set of capabilities, e.g.,
  - no security since cryptography is CPU-intensive
  - no data buffering, filtering aggregation
  - no programmability
  - ...

Stack for constrained devices



Stack for gateways



# Cloud computing: problem space

*"It starts with the premise that the **data services and architecture** should be on **servers**. We call it **cloud computing** – they should be in a ‘cloud’ somewhere. And that if you have the right kind of **browser** or the right kind of access, it doesn't matter whether you have a PC or a Mac or a mobile phone or a BlackBerry or what have you – or new devices still to be developed – you can get access to the cloud..."*

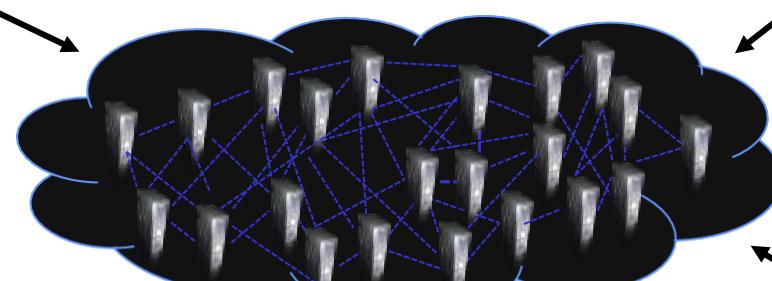
Dr. Eric Schmidt, Google CEO, August 2006



Explosion of data intensive applications on the Internet



Fast growth of connected mobile devices



The Cloud data center



Skyrocketing costs of power, space, maintenance, etc.



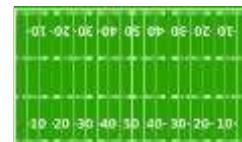
Advances in multi-core computer architecture

# Clouds are Cheaper... and Winning...

- Range in size from “edge” facilities to **megascale**
- **Scale economies**
- Approximate **costs for a small size center** (1K servers) and a **larger**, 50K server center



| Technology     | Cost in small-sized Data Center | Cost in Large Data Center   | Cloud Advantage |
|----------------|---------------------------------|-----------------------------|-----------------|
| Network        | \$95 per Mbps/month             | \$13 per Mbps/month         | 7.1             |
| Storage        | \$2.20 per GB/month             | \$0.40 per GB/month         | 5.7             |
| Administration | ~140 servers/Administrator      | >1000 Servers/Administrator | 7.1             |



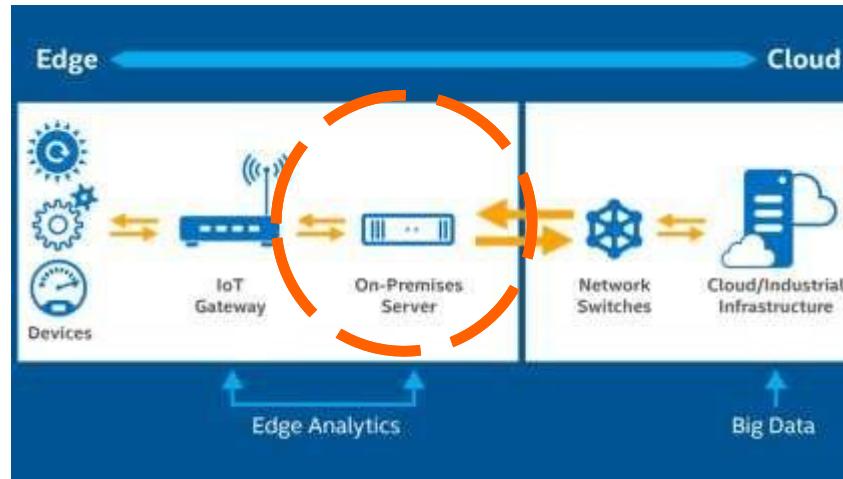
Each data center is  
**11.5 times**  
the size of a football field

# Cloud Computing: a brief introduction

- Primary concepts
  - **IT on demand** pricing
  - best benefits in a **reliable** context
  - pool of **virtualized** computer resources
  - rapid live **providing** while demanding
  - systems on **scaling** architecture
- What is a Cloud
  - one Cloud is capable of providing **IT resources “as a service”**
  - one Cloud is an IT service delivered to users that have:
    - **reduced incremental management costs** when additional IT resources are added
    - services oriented management architecture
    - massive scalability



# Beyond the cloud: From Cloud Computing to Fog/Edge Computing



- First evolution wave: **IoT Cloud Computing** architecture
  - most of the computation on the Cloud
  - **only gateways are deployed close to things**
  - gateways perform **few and simple tasks**
- Second evolution wave: **IoT Fog/Edge Computing** architecture
  - additional **relatively powerful devices**
  - **close to things**, but between gateways and the Cloud
  - **complex analytical tasks** on the client-side, before sending data to the Cloud

# Fog/Edge Computing for IoT

- Cloud models are not designed for the volume, variety, and velocity of data that the IoT generates
- Fog/Edge Computing allows to
  - minimize **latency**
  - conserve network **bandwidth**
  - address **security** concerns in transit and at rest
  - **move data** to the best place for processing
- When to consider Fog/Edge Computing
  - data is collected at the **extreme edge**: vehicles, ships, factory floors, roadways, railways, etc.
  - **thousands or millions of things** across a large geographic area are generating data
  - it is necessary to analyze and **act on data promptly**, in less than a second

# Fog/Edge Computing for IoT use case: Rails



- **Improve passenger safety**
  - analyze and correlate data from cameras on the trains and at stations
  - monitor sensors on wheels and brakes to determine when parts need service before failure causes an accident
- **Prevent cybersecurity attacks**
  - take automated actions such as suspending operations or transferring control to a failover system
- **Alert drivers** to treacherous conditions ahead
  - Fog nodes gather sensor data on tracks and trains to detect unsafe conditions

# Fog/Edge Computing for IoT use case: Manufacturing



- **Increase agility**
  - quickly change production lines and introduce new products
- **Reduce downtime**
  - predictive maintenance to avoid costly equipment downtime
  - Fog/Edge nodes collect machine data and report early signs of problems
- Continually **confirm that safety systems are intact**
  - analyze machine data in real-time
  - promptly shut down compromised equipment automatically, without waiting for a human to respond to an alert

# IoT Standards and Protocols

# Outline

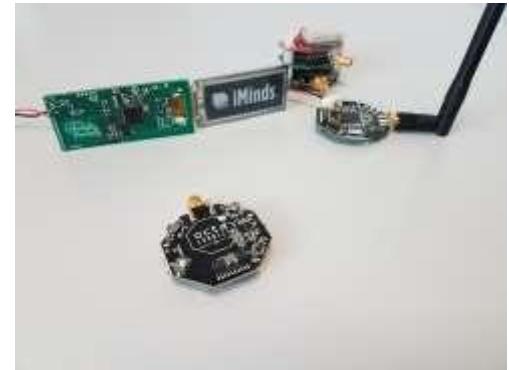
## 1. Introduction to IoT

- definition, enabling technologies and concepts to better understand the general framework of IoT solutions
- layering architecture, cloud computing vs. fog/edge computing

## 2. Most relevant components of IoT solutions

- **devices**, wireless communication protocols, data exchange protocols

# Constrained Devices



- “A node where some of the characteristics that are otherwise pretty much taken for granted for Internet nodes **at the time of writing** are not attainable, [...] due to **cost, size, and energy constraints**”
- Significant constraints on:
  - maximum code complexity (ROM/Flash)
  - size of state and buffers (RAM)
  - available computational power
  - connectivity

# Constrained Networks



- “A network where some of the characteristics pretty much taken for granted with link layers in common use in the Internet **at the time of writing** are not attainable”
- Significant constraints on:
  - low achievable **throughput**
  - high **packet loss**
  - highly **asymmetric links**
  - severe penalties for using **larger packets**
  - limits on **reachability** over time

# Classes of Constrained Nodes

| Name    | Data size (RAM) | Code size (Flash) |
|---------|-----------------|-------------------|
| Class 0 | << 10 KiB       | << 100 KiB        |
| Class 1 | ~ 10 KiB        | ~ 100 KiB         |
| Class 2 | ~ 50 KiB        | ~ 250 KiB         |

- C0 Devices
  - no direct secure Internet connection
  - use larger devices as gateways/proxies
  - preconfigured and rarely reconfigured
- C1 Devices
  - can use environment specific protocols, e.g., CoAP
  - no access to standard Internet protocols, e.g., HTTP, TLS
  - can be integrated into an IP network
- C2 Devices
  - can use most of protocols

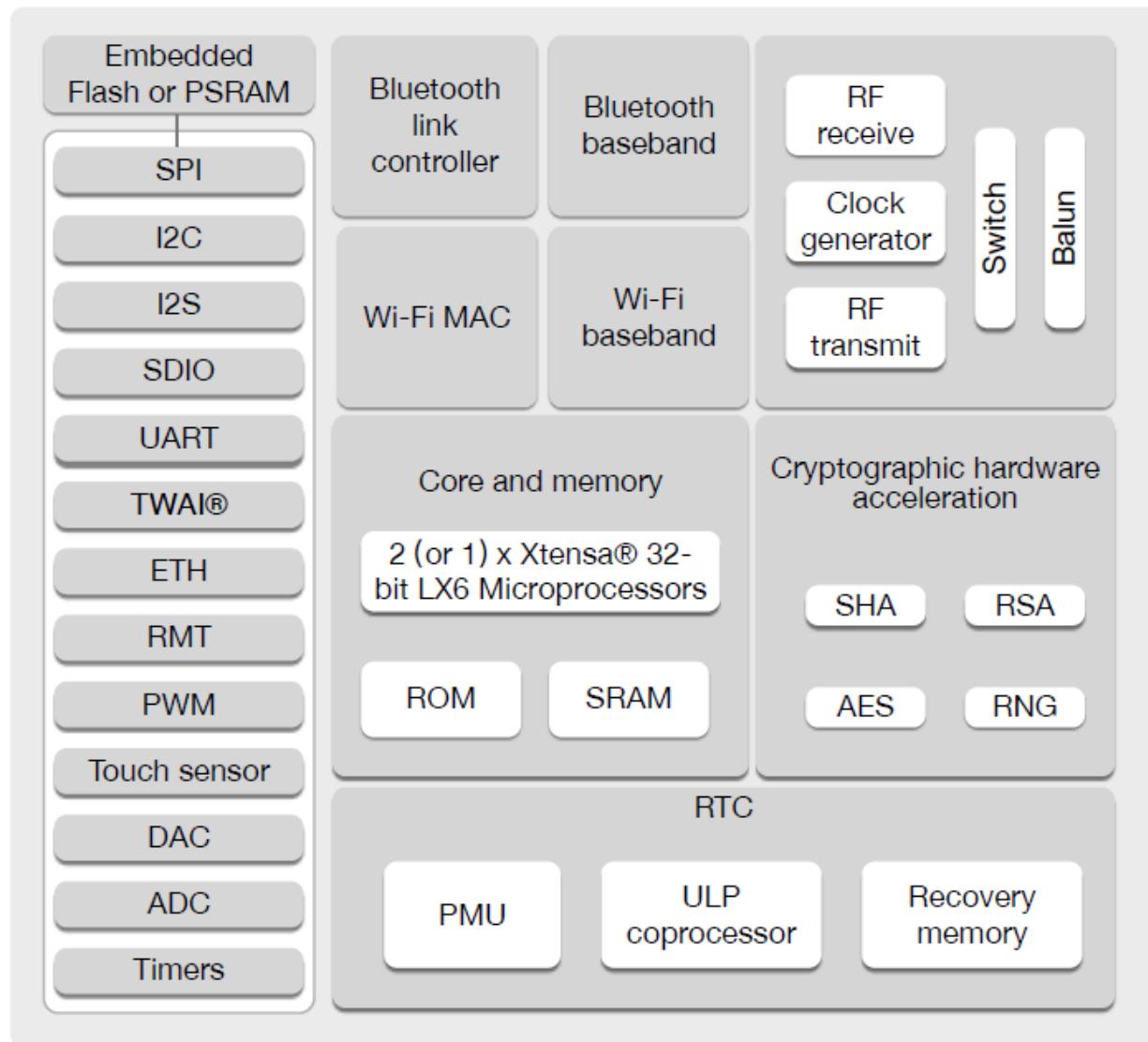
Values in 2014

# IoT Device Example: ESP32

- Ultra Low Power Solution
- Wi-Fi Key Features
  - 802.11 b/g/n
  - 802.11 n (2.4 GHz), up to 150 Mbps
- Bluetooth Key Features
  - Compliant with Bluetooth v4.2 BR/EDR and Bluetooth LE specifications
  - Class-1, class-2 and class-3 transmitter without external power amplifier
  - Bluetooth Piconet and Scatternet
  - Multi-connections in Classic Bluetooth and Bluetooth LE
  - Simultaneous advertising and scanning
- CPU and Memory
  - Xtensa® single-/dual-core 32-bit LX6 microprocessor(s)
  - 4MB of Flash



# ESP32 Block Diagram



# Beyond Class 2: Single Board Computers

- In the last 5/10 years
  - tremendous improvement in CPU/memory capabilities
  - dramatically reduced costs
- Modern Single-Board Computers (SBCs) are very cheap (~100\$) and powerful
  - can host complete operating systems
  - extensions via daughterboards
  - mostly designed to be mains-powered



# Outline

## 1. Introduction to IoT

- definition, enabling technologies and concepts to better understand the general framework of IoT solutions
- layering architecture, cloud computing vs. fog computing

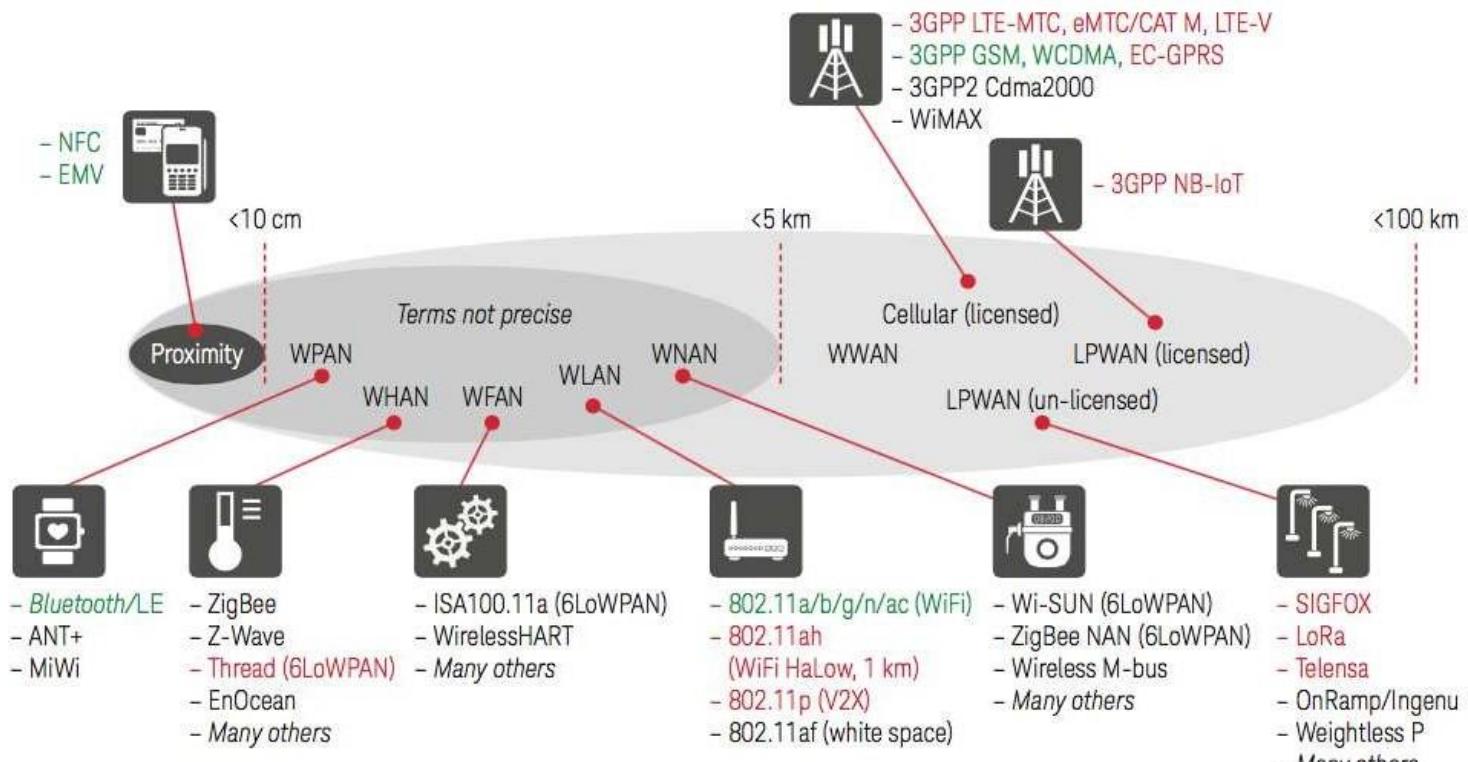
## 2. Most relevant components of IoT solutions

- devices, **wireless communication protocols**, data exchange protocols

# Wireless Communication Protocols for the IoT

- The capability of connecting to things in a **seamless, ubiquitous**, and **cheap** manner have pushed the spread of IoT solutions
- IoT wireless communication protocols primarily differs in relation to
  - **coverage range**: from few cm to several km
  - **power consumption**: from few mW to several W
  - **bandwidth**: from few bytes per day to hundreds of MB/s
  - **security**: from plain data to strong encryption
  - **cost**: greatly varying, both for equipment and data transmission

# Several Wireless Communication Protocols



■ : > Billion units/year now  
■ : Emerging

WPAN: Wireless Personal Area Network

WHAN: Wireless Home Area Network

WFAN: Wireless Field (or Factory) Area Network

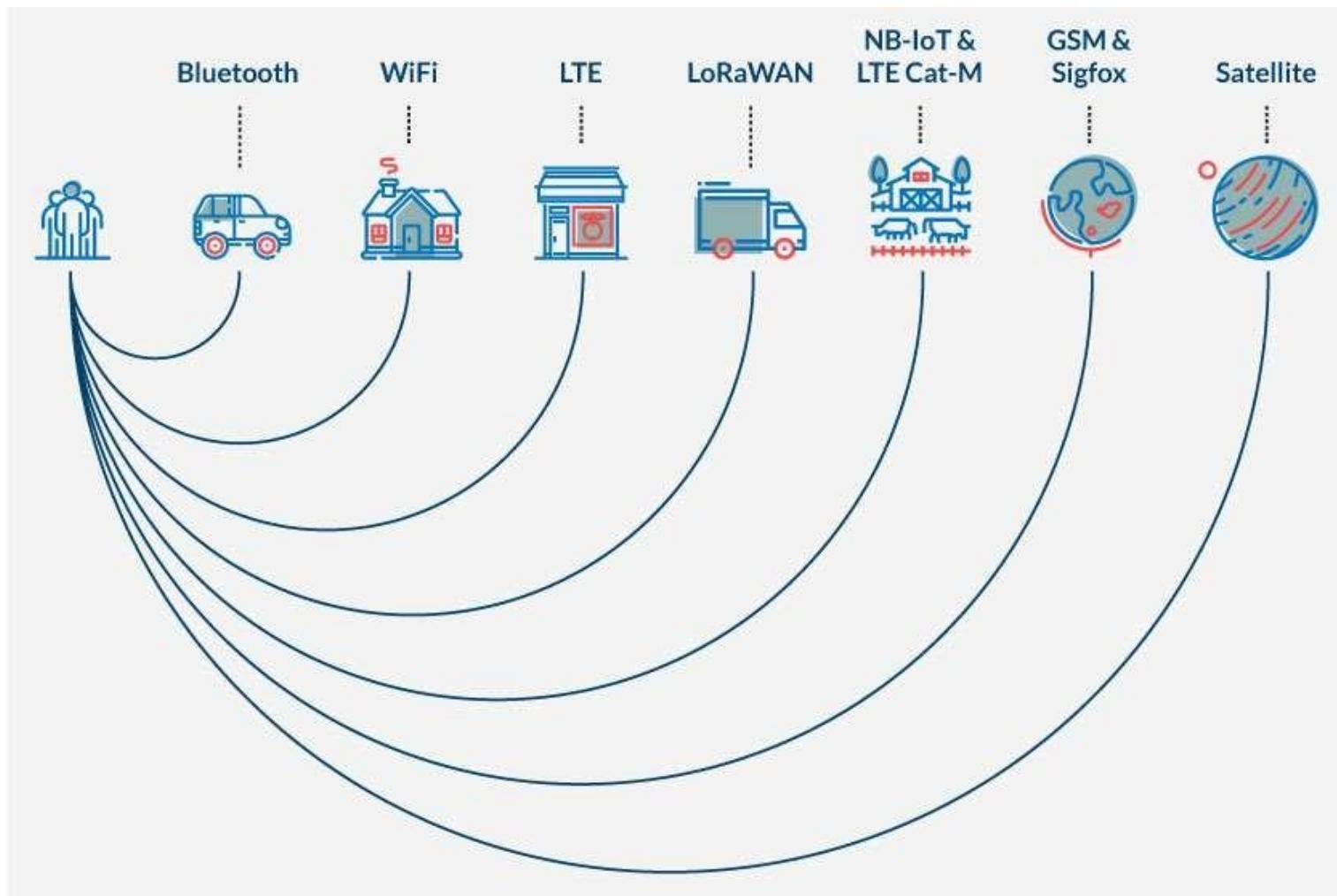
WLAN: Wireless Local Area Network

WNAN: Wireless Neighborhood Area Network

WWAN: Wireless Wide Area Network

LPWAN: Low Power Wide Area Network

# Wireless Protocols per Coverage Range



# Bluetooth



- Bluetooth and BLE are radio protocols for **Personal Area Networks (PAN)**
- Mostly these are on a person's body or in close proximity to them
- Typical range: very short, 20m (or less)
- Max output power: very limited, 0.003 W
- Bandwidth: limited, 0.7–2.1 Mbit/s
- Security: pairing task to exchange encryption keys
- Cost: cheap equipment, no transmission costs
- Good for: devices that stay **in close proximity of each other**, like between a smartphone and a headset, heart rate monitor, bicycle speedometer

# Bluetooth History

| Revision                                                              | Features                                                                                                                                                                                                                    |
|-----------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Bluetooth 1.0 and 1.0B                                                | Basic rate Bluetooth (1 Mbps)<br>Initial version released.                                                                                                                                                                  |
| Bluetooth 1.1                                                         | IEEE 802.15.1-2002 standardized<br>1.0B specification defects resolved<br>Non-encrypted channel support<br><b>Received Signal Strength Indicator (RSSI)</b>                                                                 |
| Bluetooth 1.2                                                         | IEEE 802.15.1-2005<br>Rapid connection and discovery<br><b>Frequency hopping spread spectrum (AFH)</b><br>Host controller interface (three-wire UART)<br>Flow control and retransmission modes                              |
| Bluetooth 2.0<br>(+EDR optional)                                      | <b>Enhanced Data Rate Mode (EDR): 3 Mbps</b>                                                                                                                                                                                |
| Bluetooth 2.1<br>(+EDR optional)                                      | Secure Simple Pairing (SSP) using public key cryptography with four unique authentication methods<br><b>Extended Inquiry Response (EIR)</b> allows for better filtering and reduced power                                   |
| Bluetooth 3.0<br>(+ EDR optional)<br>(+HS optional)                   | L2CAP enhanced retransmission mode (ERTM) for reliable and unreliable connection states<br><b>Alternate MAC/PHY (AMP)</b> 24 Mbps using 802.11 PHY<br>Unicast connectionless data for low latency<br>Enhanced power control |
| Bluetooth 4.0<br>(+ EDR optional)<br>(+HS optional)<br>(+LE optional) | <b>AKA BluetoothSmart</b><br>Introduced Low Energy mode (LE)<br>Introduced ATT and GATT protocols and profiles<br>Dual mode: BR/EDR and LE mode<br>Security manager with AES encryption                                     |
| Bluetooth 4.1                                                         | Mobile wireless service (MWS) coexistence<br>Train nudging (coexistence feature)<br>Interlaced scanning (coexistence feature)<br>Devices support multiple simultaneous roles                                                |
| Bluetooth 4.2                                                         | LE secure connections<br>Link layer privacy<br>IPv6 support profile                                                                                                                                                         |
| Bluetooth 5.0                                                         | Slot availability masks (SAM)<br>2 Mbps PHY and LE<br>LE long range mode<br>LE extended advertising modes<br>Mesh networking                                                                                                |

# Bluetooth 5 communication process and topologies

Bluetooth wireless is comprised of two wireless technology systems: **Basic Rate (BR)** and **Low Energy (LE or BLE)**. Nodes can either be advertisers or scanners by this definition:

- **Advertiser:** Devices transmitting advertiser packets
- **Scanner:** Devices receiving advertiser packets without the intention to connect
- **Initiator:** Devices attempting to form a connection

There are several Bluetooth events that transpire in a Bluetooth WPAN:

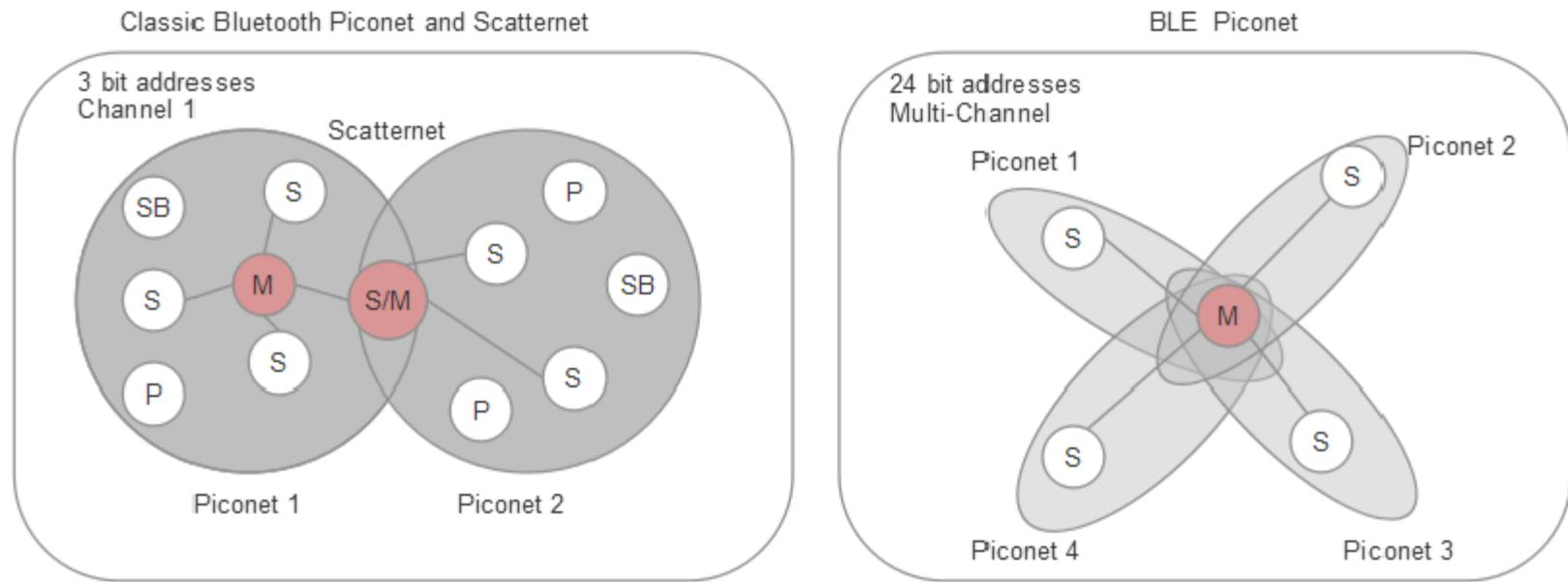
- **Advertising:** Initiated by a device to broadcast to scanning devices to alert them of the presence of a device wishing to either pair or simply relay a message in the advertisement packet.
- **Connecting:** This event is the process of pairing a device and a host.
- **Periodic advertising:** (for Bluetooth 5) allows an advertising device to periodically advertise over the 37 non-primary channels by channel hopping at an interval of 7.5ms to 81.91875s.
- **Extended advertising:** (for Bluetooth 5) allows for extended PDUs to support advertisement chaining and large PDU payloads, possibly as well as new use cases involving audio or other multimedia.

## Overview of operation

During typical operation, a physical radio channel is shared by a group of devices

- Synchronized to a common clock and frequency hopping pattern.
- One device provides the synchronization reference and is known as the master.
- All other devices are known as slaves.
- A group of devices synchronized in this fashion form a **Piconet**.
- This is the basic building block of communication

# Piconet & Scatternet



The difference between classic (BR/EDR) Bluetooth and BLE piconets. In BR/EDR mode up to seven slaves can be associated on a single piconet due to **3-bit addressing**. They all share a common channel between the seven slaves. Other piconets can join the network and form a scatternet only if an associated master on the secondary network is present.

In BLE mode millions of slaves can join in multiple piconets with a single master due to **24-bit addressing**. Each piconet can be on a different channel but only one slave can associate with the master in each piconet. Practically speaking, BLE piconets tend to be much smaller.

## Modes of devices

Devices in a Piconet can be in one of five different modes

- Standby—waiting to join a Piconet
- Inquire—looking for other devices
- Page—master device is asking to connect to specified slave
- Connected—either active slave or master is connected
- Park/Hold—device is part of piconet, but in a low- power state

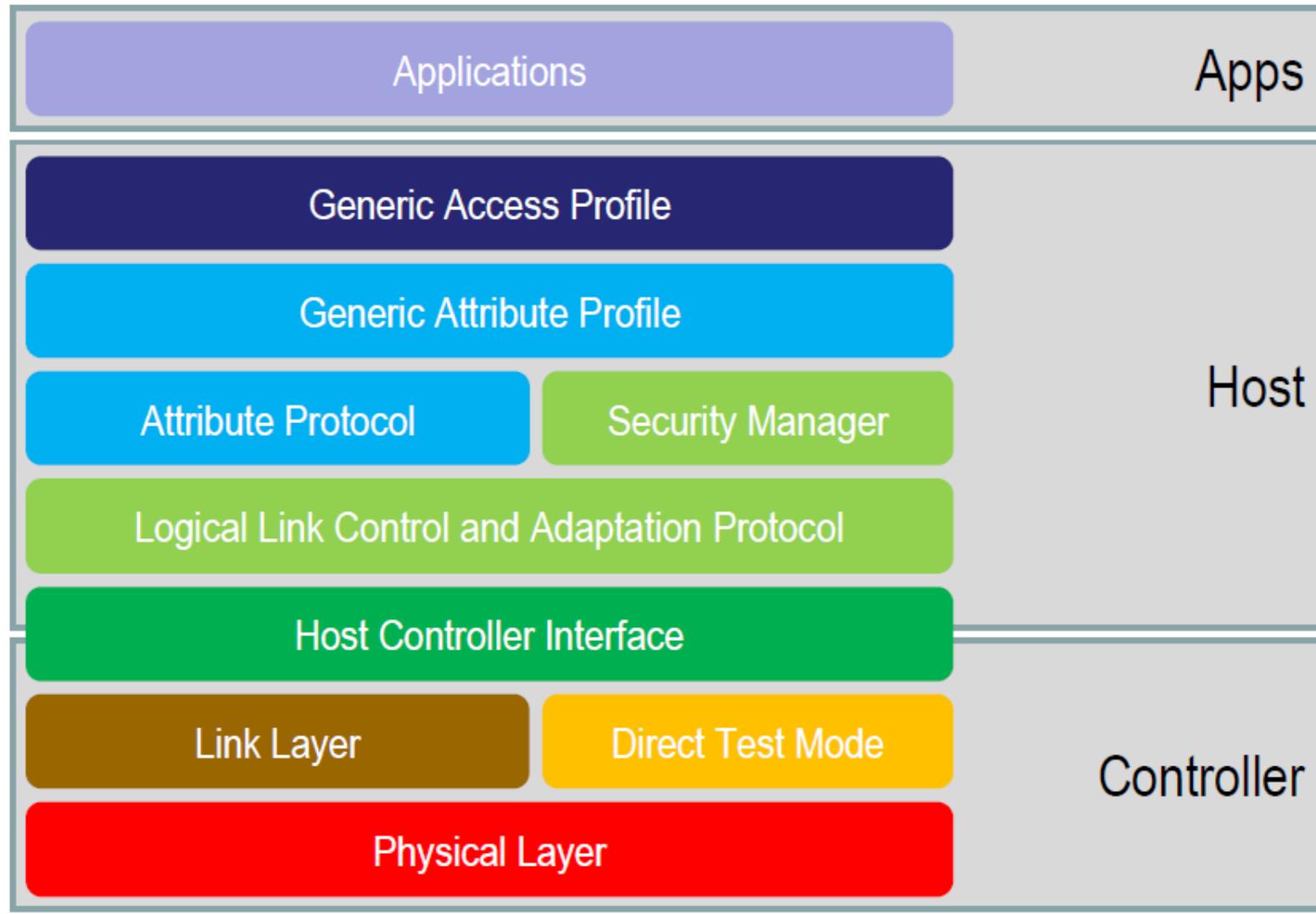
# Device Modes

- **Low Energy (LE) mode:** This uses the 2.4 GHz ISM band and employs FHSS for interference protection. The PHY differs from BR/EDR and AMP radios by modulation, coding, and data rates. LE operates at 1 Msym/s at a bit rate of 1 Mbps. Bluetooth 5 allows for multiple configurable data rates of 125 Kbps, 500 Kbps, 1 Mbps, and 2 Mbps (more on this later).
- **Basic Rate/Enhanced Data Rate mode (BR/EDR):** This uses a different radio than LE and AMP but operates in the ISM 2.4 GHz band. Basic radio operation is rated at 1 Msym/s and supports a bit rate of 1 Mbps. EDR sustains a data rate of 2 or 3 Mbps. This radio uses FHSS for interference protection.

# Bluetooth PHY and Interference

- Bluetooth devices operate in **the 2.4000 to 2.4835 GHz** industrial, scientific, and medical (**ISM**) unlicensed frequency band.
- This unlicensed area is **congested with several other wireless media**, such as **802.11 Wi-Fi**.
- To alleviate interference, Bluetooth supports **frequency-hopping spread spectrum (FHSS)**.
- When having a choice between Bluetooth classic modes of BR/EDR, EDR will have less of a chance of interference and better coexistence with Wi-Fi and other Bluetooth devices since the on-air time is shorter due to its speed.
- **Adaptive Frequency Hopping (AFH)** was introduced in Bluetooth 1.2. AFH uses two types of channels: **used and unused**.
- **Used channels** are in-play as part of the hopping sequence.
- **Unused channels** are replaced in the hopping sequence by used channels when needed in a random replacement method.
- **BR/EDR mode has 79 channels** and **BLE has 40 channels**.
- With 79 channels, BR/EDR mode has less than a 1.5 percent chance of interfering with another channel. This is what allows an office setting to have hundreds of headphones, peripherals, and devices all in the same range contending for frequency space.

# Bluetooth Low Energy Architecture



# BLE Physical Layer

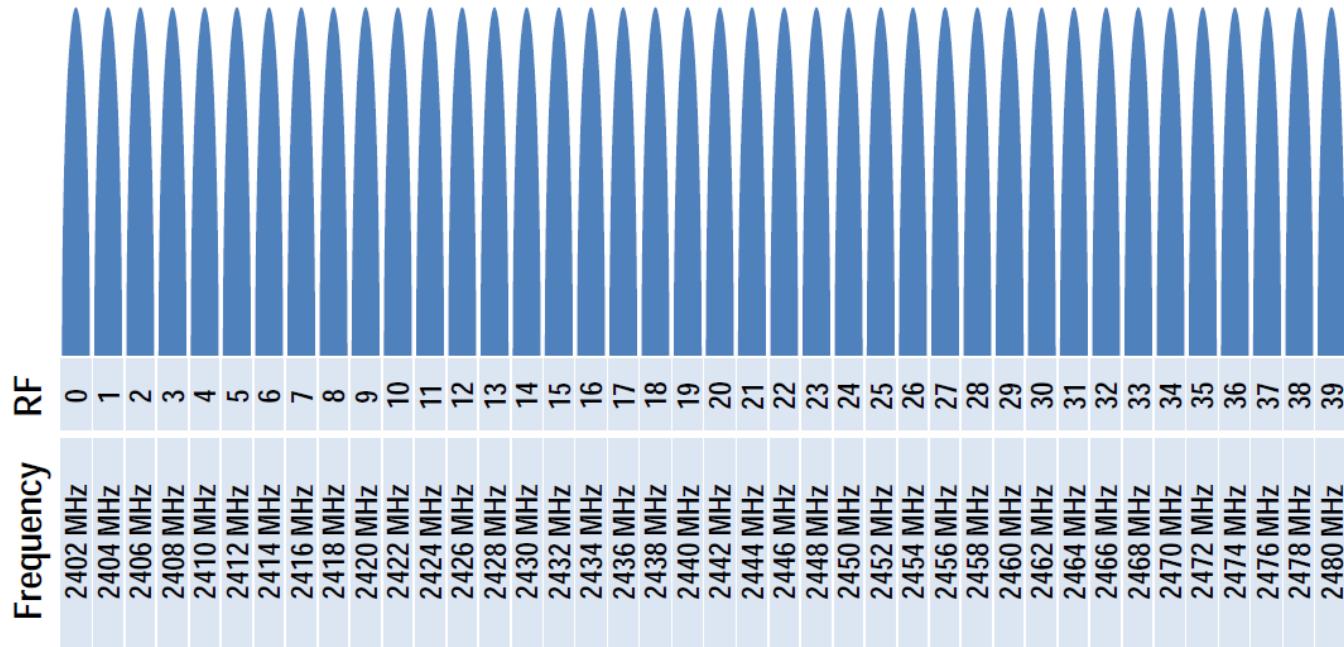
2.4 GHz ISM band

1Mbps GFSK

Larger modulation index than Bluetooth BR (which means better range)

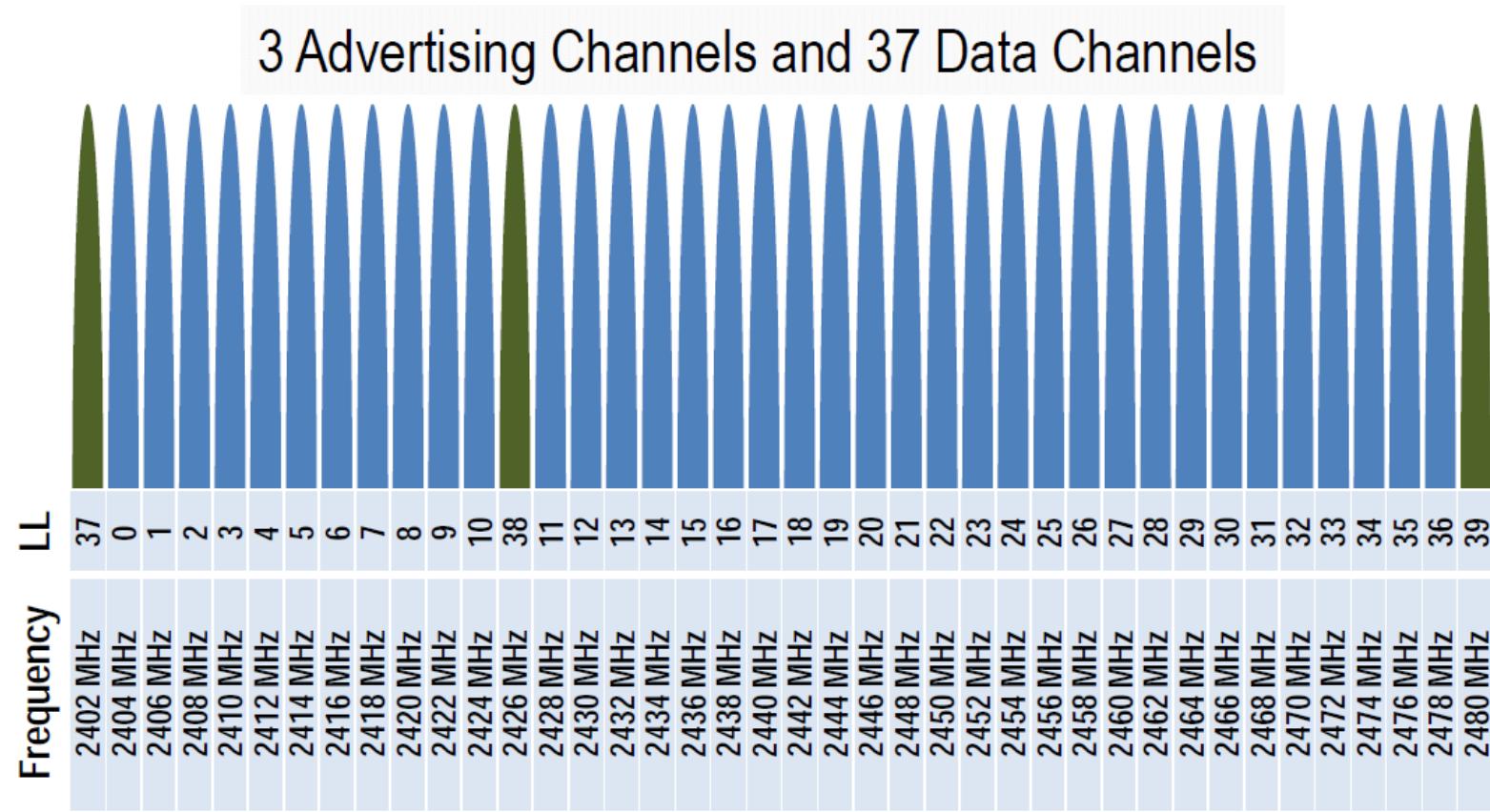
40 Channels on 2 MHz spacing

$$f = 2402 + 2 \cdot k \text{ MHz}$$



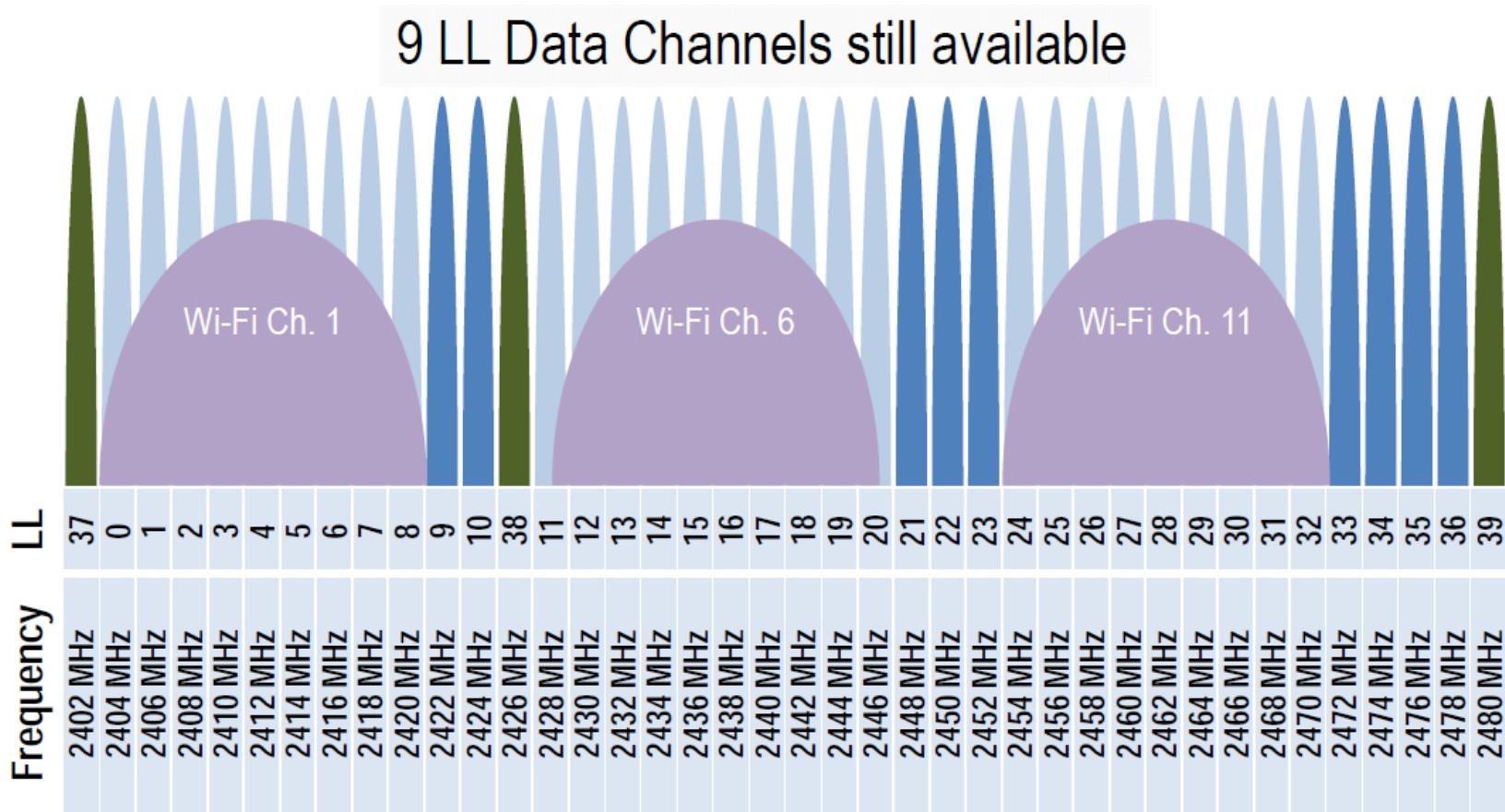
# Physical Channels

Two types of channels



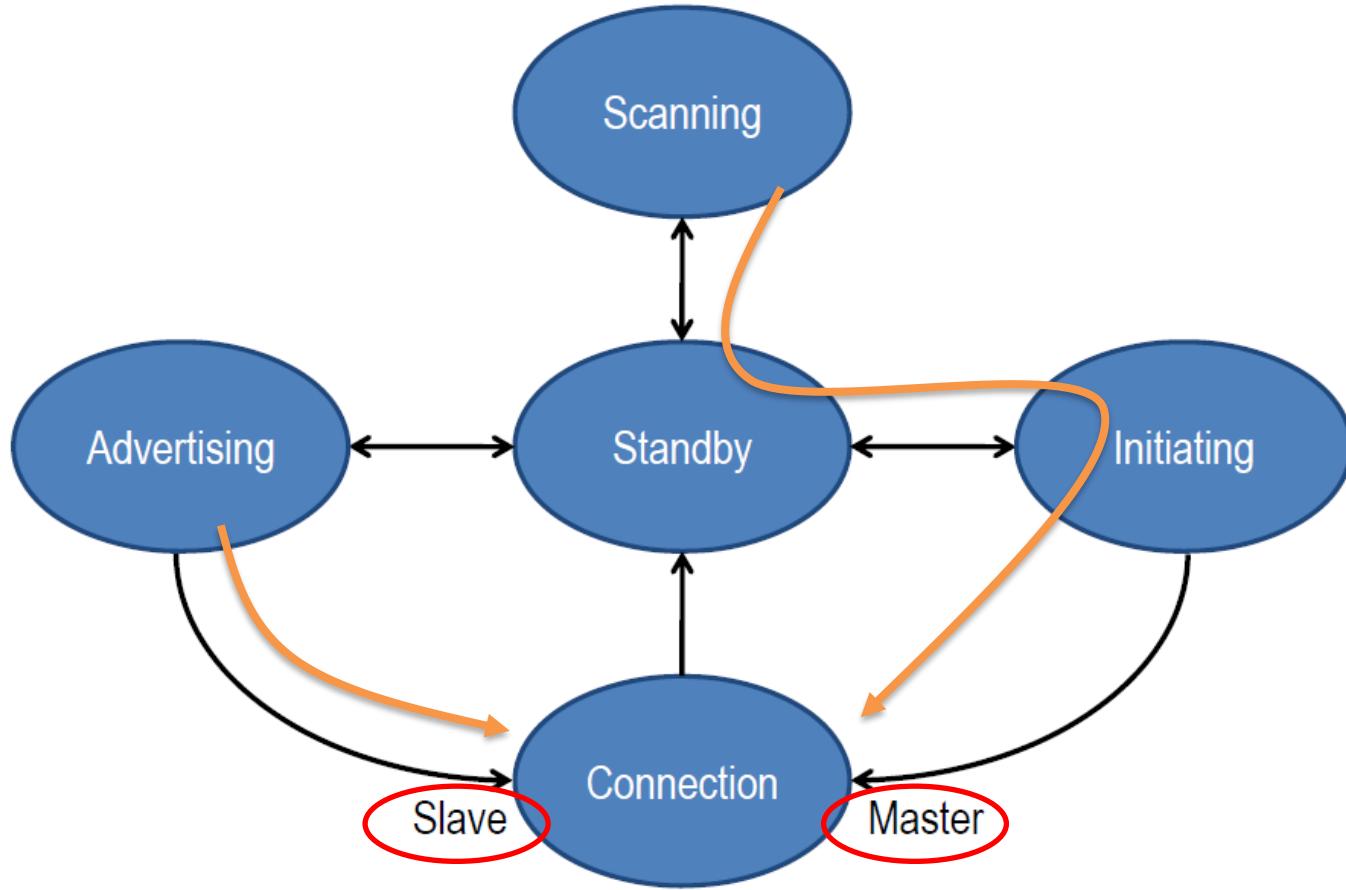
# Physical Channels

Advertising channels avoid 802.11



# Link Layer

## Link Layer state machine

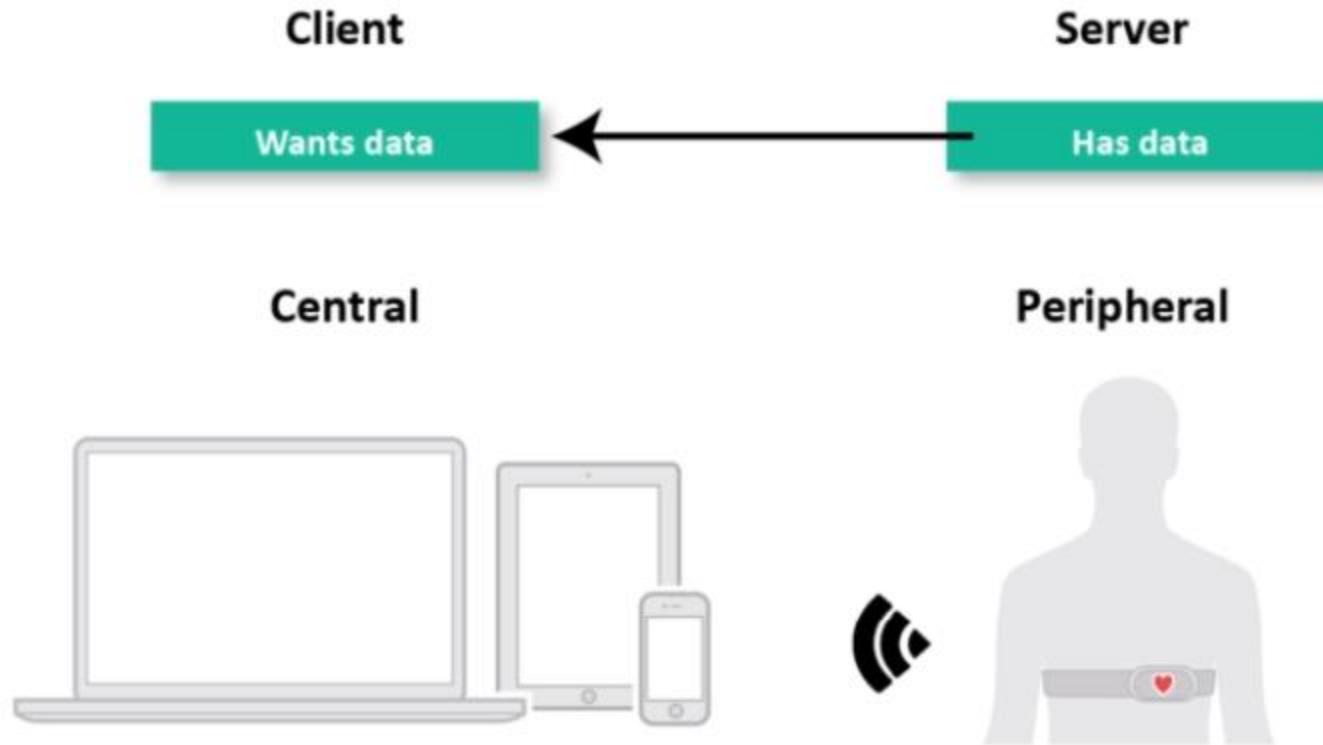


## Device Roles

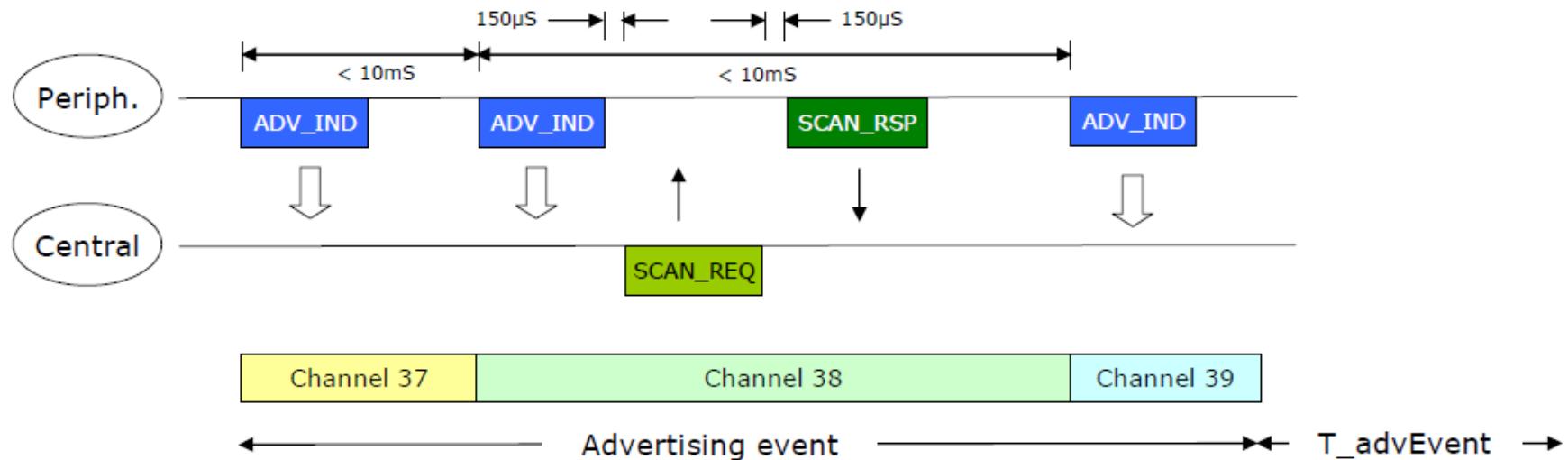
GAP defines various roles for devices, but the two key concepts to keep in mind are **Central** devices and **Peripheral** devices.

- **Peripheral(Mi Band)** devices are small, low power, resource constrained devices that can connect to a much more powerful central device. Peripheral devices are things like a heart rate monitor, a BLE enabled proximity tag, etc.
- **Central(Mobile Phone)** devices are usually the mobile phone or tablet that you connect to with far more processing power and memory.

# Heart Rate Sensor



# Advertising

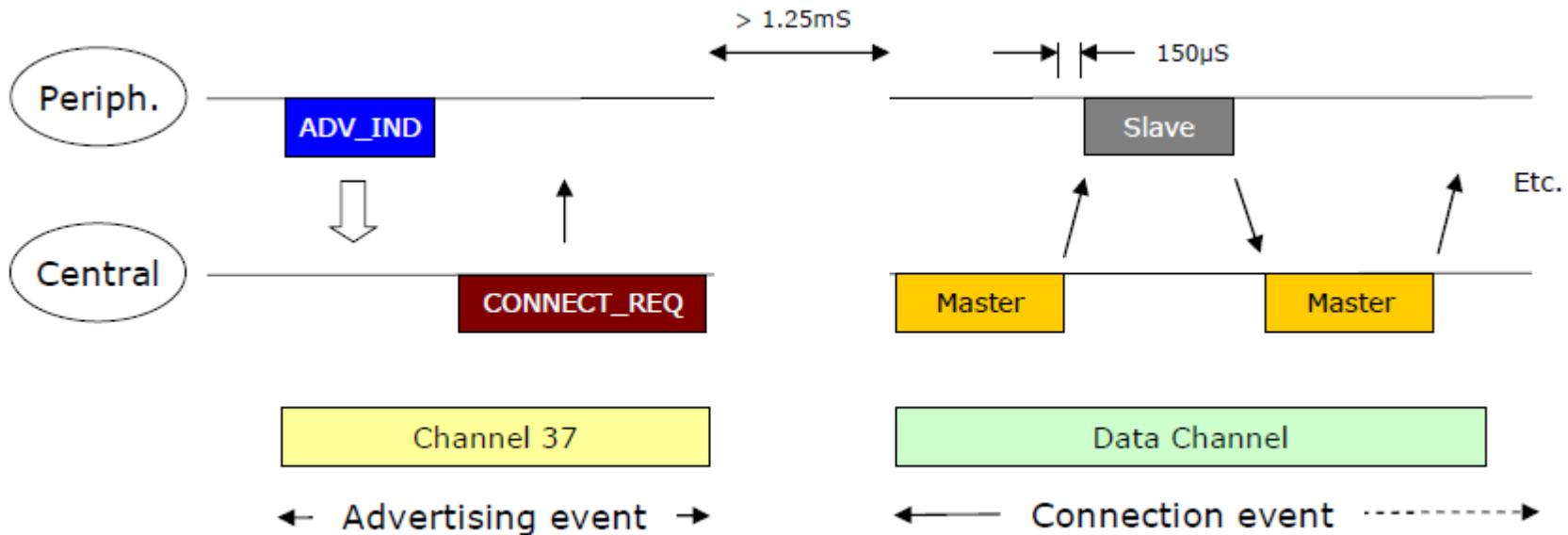


To transmit signed data to a previously bonded device

To advertise their presence to a device wanting to connect

To reconnect asynchronously due to a local event

# Data transactions



Once a connection is made:

Master informs slave of hopping sequence and when to wake

All subsequent transactions are performed in the 37 data channels

Transactions can be encrypted

Both devices can go into deep sleep between transactions

# How low can the energy get?

From the previous slide, calculate energy per transaction

Assume an upper bound of 3ms per minimal transaction

Estimated TX power is 15mW (mostly TX power amp for 65nm chips)

For 1.5v battery, this is 10mA.  $0.015\text{W} * 0.003\text{ sec} = 45\text{ micro Joule}$

How long could a sensor last on a battery?

An example battery: Lenmar WC357, 1.55v, 180mAh, \$2-5

$180\text{mAh}/10\text{mA} = 18\text{Hr} = 64,800\text{ seconds} = 21.6\text{M transactions}$

Suppose this sensor sends a report every minute = 1440/day

For just the BT LE transactions, this is 15,000 days, or > 40 years

This far exceeds the life of the battery and/or the product

This means that battery will cost more than the electronics

This sensor could run on scavenged power, e.g. ambient light



# Basic topology of bluetooth



## 1. Point to Point Topology

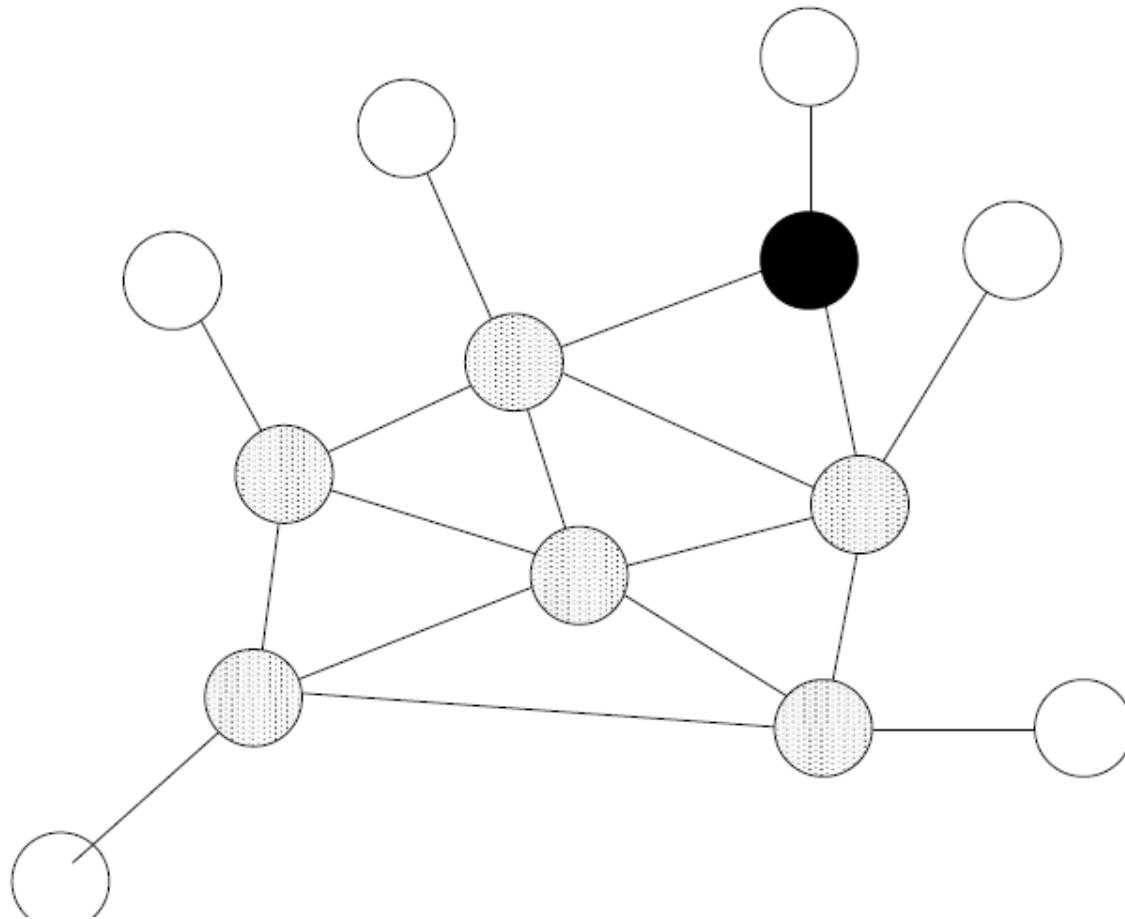
## Point-to-Point

- Point-to-point is a network topology used for establishing one-to-one (1:1) device communications.
- The point-to-point topology available on Bluetooth Basic Rate/Enhanced Data Rate (BR/EDR) is optimized for audio streaming and is ideally suited for a wide range of wireless devices, such as speakers, headsets, and hands-free car kits.
- The point-to-point topology available on Bluetooth Low Energy (LE) is optimized for data transfer and is well suited for connected device products, such as fitness trackers, health monitors, and PC peripherals and accessories.

# Mesh

- Mesh is a network topology used for establishing many-to-many (m:m) device communications.
- The mesh topology available on Bluetooth LE enables the creation of large-scale device networks and is ideally suited for control, monitoring, and automation systems where tens, hundreds, or thousands of devices need to reliably and securely communicate with one another.

# Mesh



# Generic Access Profile

- It controls connections and advertising in Bluetooth.
- GAP is what makes your device visible to the outside world, and determines how two devices can (or can't) interact with each other.

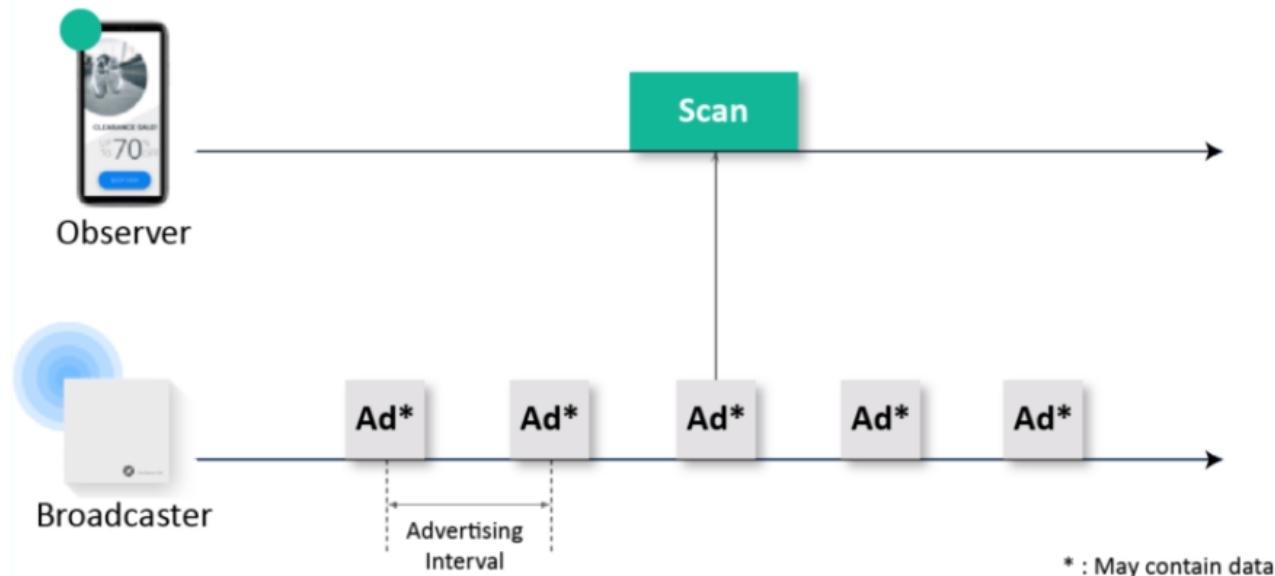


**GAP**

# Advertising Process

While most peripherals advertise themselves so that a connection can be established and GATT services and characteristics can be used (which allows for much more data to be exchanged and in both directions), there are situations where you only want to advertise data.

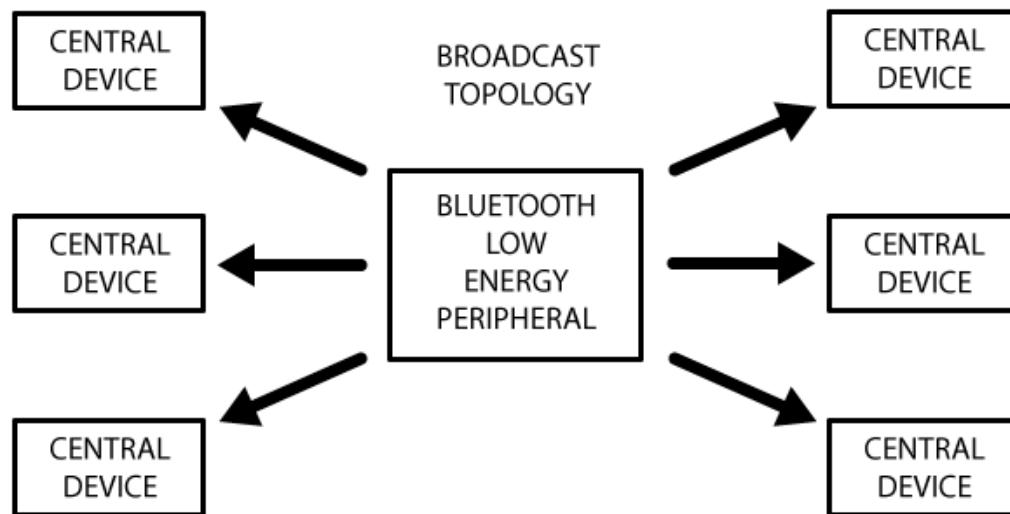
How devices are found in Bluetooth Low Energy communication?



# Broadcast Network Topology

The main use case here is where you want a peripheral to send data to more than one device at a time. This is only possible using the advertising packet since data sent and received in connected mode can only be seen by those two connected devices.

By including a small amount of custom data in the 31 byte advertising or scan response payloads, you can use a low cost Bluetooth Low Energy peripheral to send data one-way to any devices in listening range, as shown in the illustration below. This is known as **Broadcasting** in Bluetooth Low Energy.



# Generic Attribute Profile(GATT)

It defines the way that two Bluetooth Low Energy devices transfer data back and forth using concepts called **Services** and **Characteristics**.

It makes use of a generic data protocol called the **Attribute Protocol (ATT)**, which is used to store Services, Characteristics and related data in a simple lookup table using 16-bit IDs for each entry in the table.

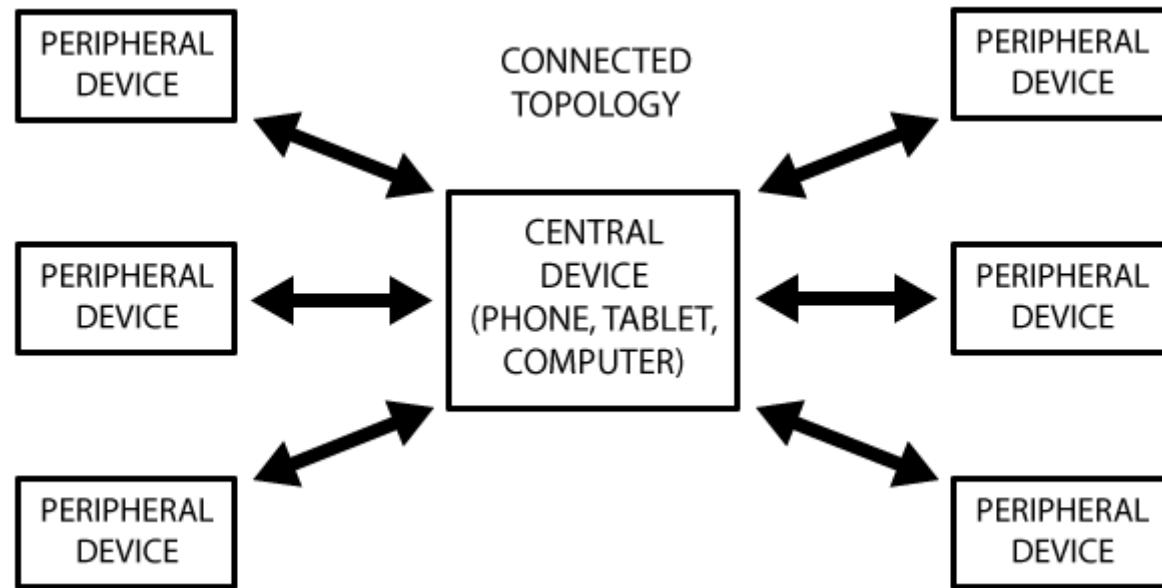


GATT comes into play once a dedicated connection is established between two devices, meaning that you have already gone through the advertising process governed by GAP.

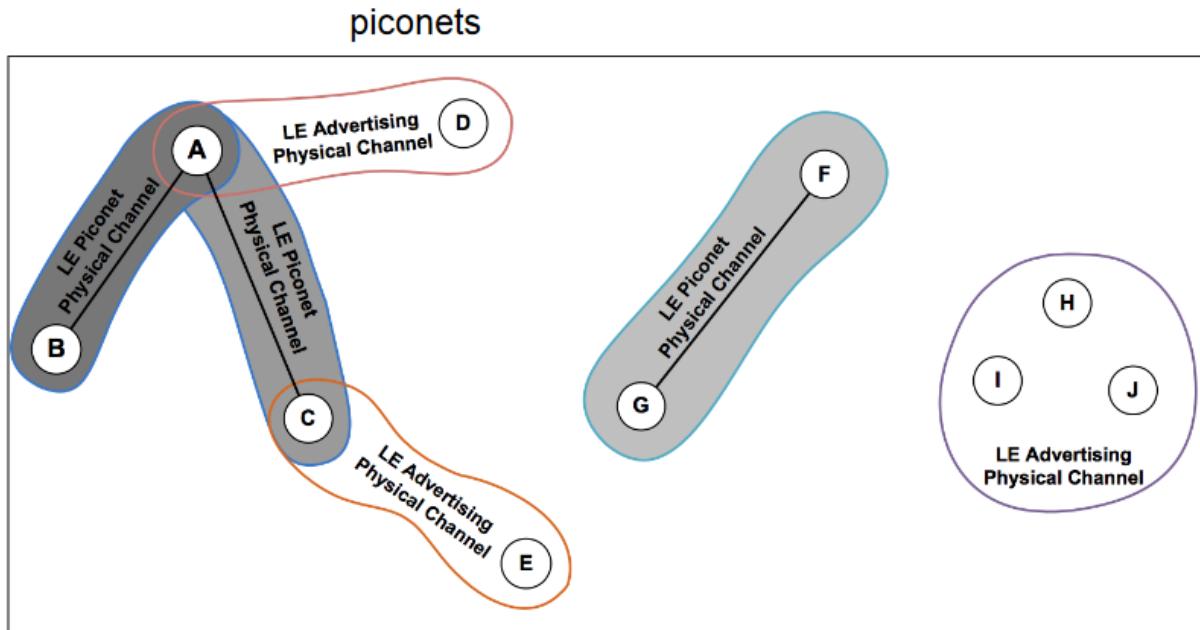
The most important thing to keep in mind with GATT and connections is that *connections* are *exclusive*. What is meant by that is that **a BLE peripheral can only be connected to one central device (a mobile phone, etc.) at a time!** As soon as a peripheral connects to a central device, it will stop advertising itself and other devices will no longer be able to see it or connect to it until the existing connection is broken.

# Connected Network Topology

A peripheral can only be connected to one central device (such as a mobile phone) at a time, but the central device can be connected to multiple peripherals.



# Topology 4.0



Key:

- Lines indicate a connection
- Groups indicate data transmission

Core [5]

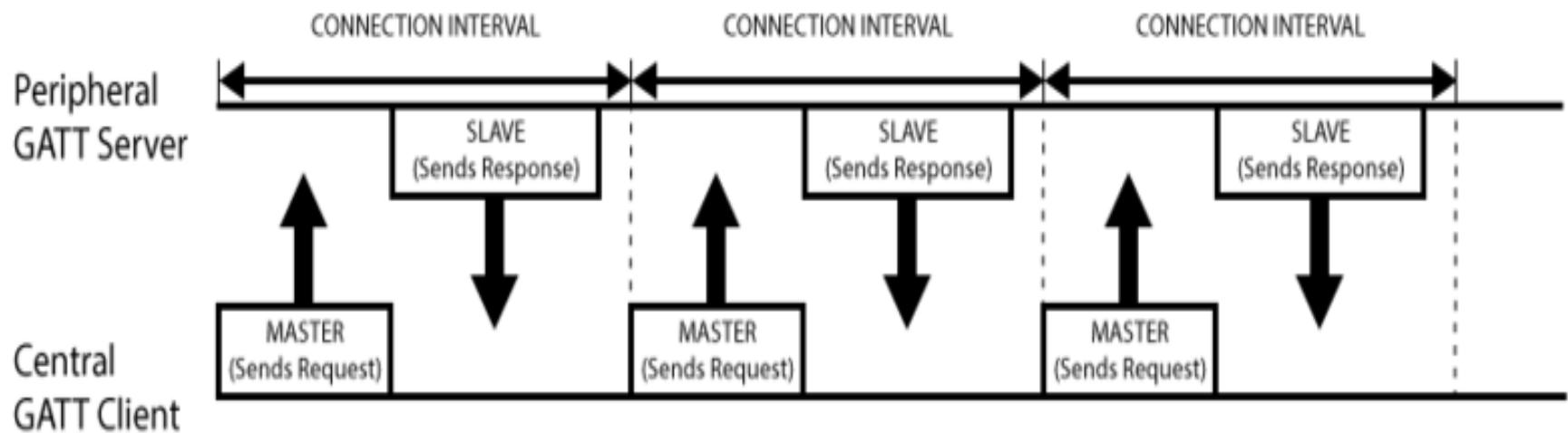
# GATT Transactions

An important concept to understand with GATT is the server/client relationship.

The peripheral is known as the **GATT Server**, which holds the ATT lookup data and service and characteristic definitions, and the **GATT Client** (the phone/tablet), which sends requests to this server.

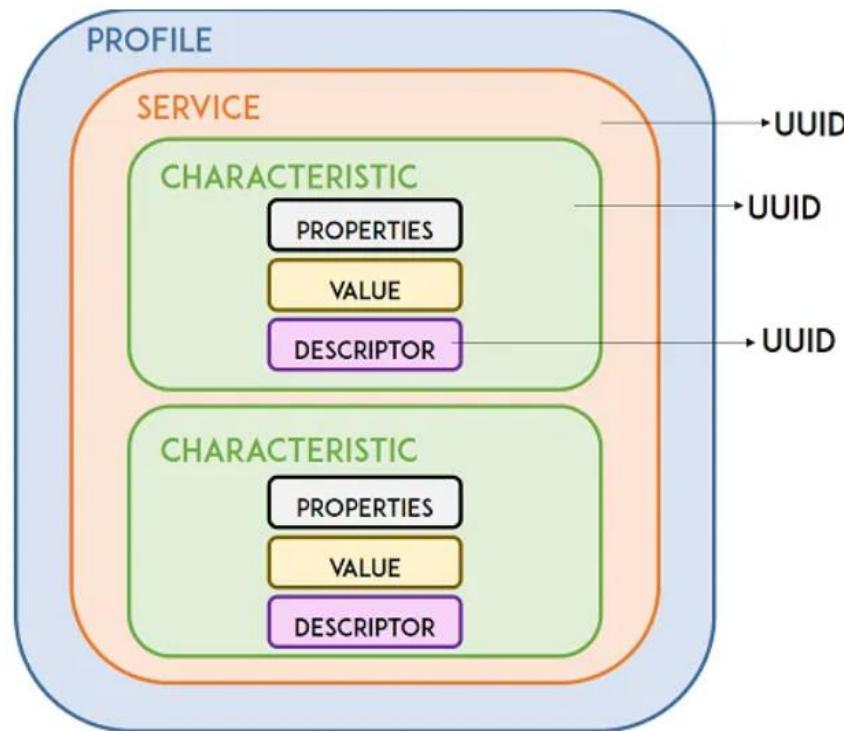
All transactions are started by the master device, the GATT Client, which receives response from the slave device, the GATT Server.

# GATT Transactions Cont.



# Profile, Services and Characteristics

GATT transactions in BLE are based on high-level, nested objects called **Profiles**, **Services** and **Characteristics**, which can be seen in the illustration below:



# Profiles , Services and Characteristics

**Profiles** : It's simple a pre-defined collection of Services that has been compiled by either the Bluetooth SIG or by the peripheral designers. The ***Heart Rate Profile***, for example, combines the Heart Rate Service and the Device Information Service.

**Services** : Services are used to break data up into logic entities, and contain specific chunks of data called characteristics. A service can have one or more characteristics, and each service distinguishes itself from other services by means of a unique numeric ID called a UUID, which can be either 16-bit or 128-bit .

**Characteristics** :The lowest level concept in GATT transactions is the Characteristic, which encapsulates a single data point (though it may contain an array of related data, such as X/Y/Z values from a 3-axis accelerometer, etc.).

# BLE Service

| Name                          | Uniform Type Identifier                             | Assigned Number | Specification |
|-------------------------------|-----------------------------------------------------|-----------------|---------------|
| Generic Access                | org.bluetooth.service.generic_access                | 0x1800          | GSS           |
| Alert Notification Service    | org.bluetooth.service.alert_notification            | 0x1811          | GSS           |
| Automation IO                 | org.bluetooth.service.automation_io                 | 0x1815          | GSS           |
| Battery Service               | org.bluetooth.service.battery_service               | 0x180F          | GSS           |
| Blood Pressure                | org.bluetooth.service.blood_pressure                | 0x1810          | GSS           |
| Body Composition              | org.bluetooth.service.body_composition              | 0x181B          | GSS           |
| Bond Management Service       | org.bluetooth.service.bond_management               | 0x181E          | GSS           |
| Continuous Glucose Monitoring | org.bluetooth.service.continuous_glucose_monitoring | 0x181F          | GSS           |
| Current Time Service          | org.bluetooth.service.current_time                  | 0x1805          | GSS           |
| Cycling Power                 | org.bluetooth.service.cycling_power                 | 0x1818          | GSS           |
| Cycling Speed and Cadence     | org.bluetooth.service.cycling_speed_and_cadence     | 0x1816          | GSS           |
| Device Information            | org.bluetooth.service.device_information            | 0x180A          | GSS           |
| Environmental Sensing         | org.bluetooth.service.environmental_sensing         | 0x181A          | GSS           |
| Fitness Machine               | org.bluetooth.service.fitness_machine               | 0x1826          | GSS           |
| Generic Attribute             | org.bluetooth.service.generic_attribute             | 0x1801          | GSS           |

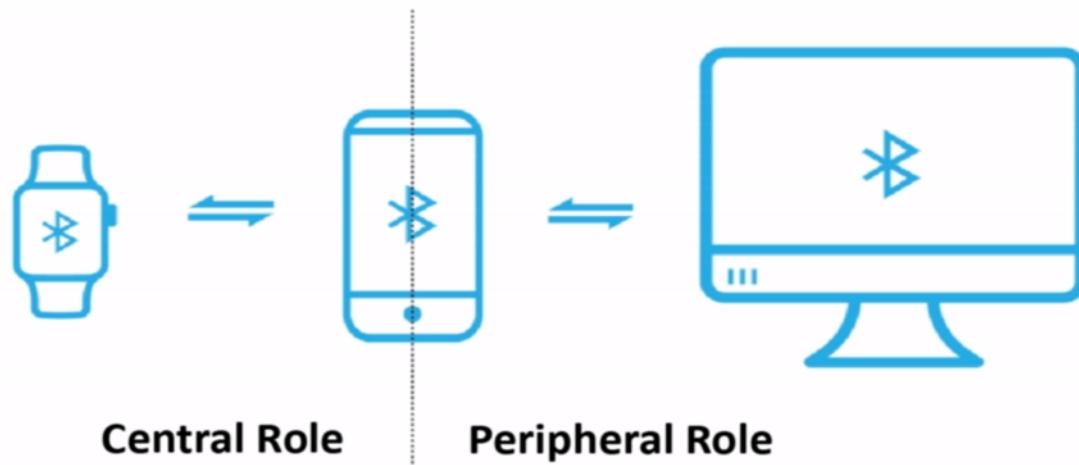
# BLE Characteristic

The properties describe how the characteristic value can be interacted with. Basically, it contains the operations and procedures that can be used with the characteristic:

- Broadcast
- Read
- Write without response
- Write
- Notify
- Indicate
- Authenticated Signed Writes
- Extended Properties

# Features of 4.1 Standard

Device supports multiple simultaneous roles (e.g. Peripheral and Central)!  
Delay tolerant connections!  
Devices can set up dedicated communication channel!  
Low duty directed advertising!  
Coexistence screening!  
Bulk data transfer!



# Wireless LAN: IEEE 802.11

# WiFi - IEEE 802.11



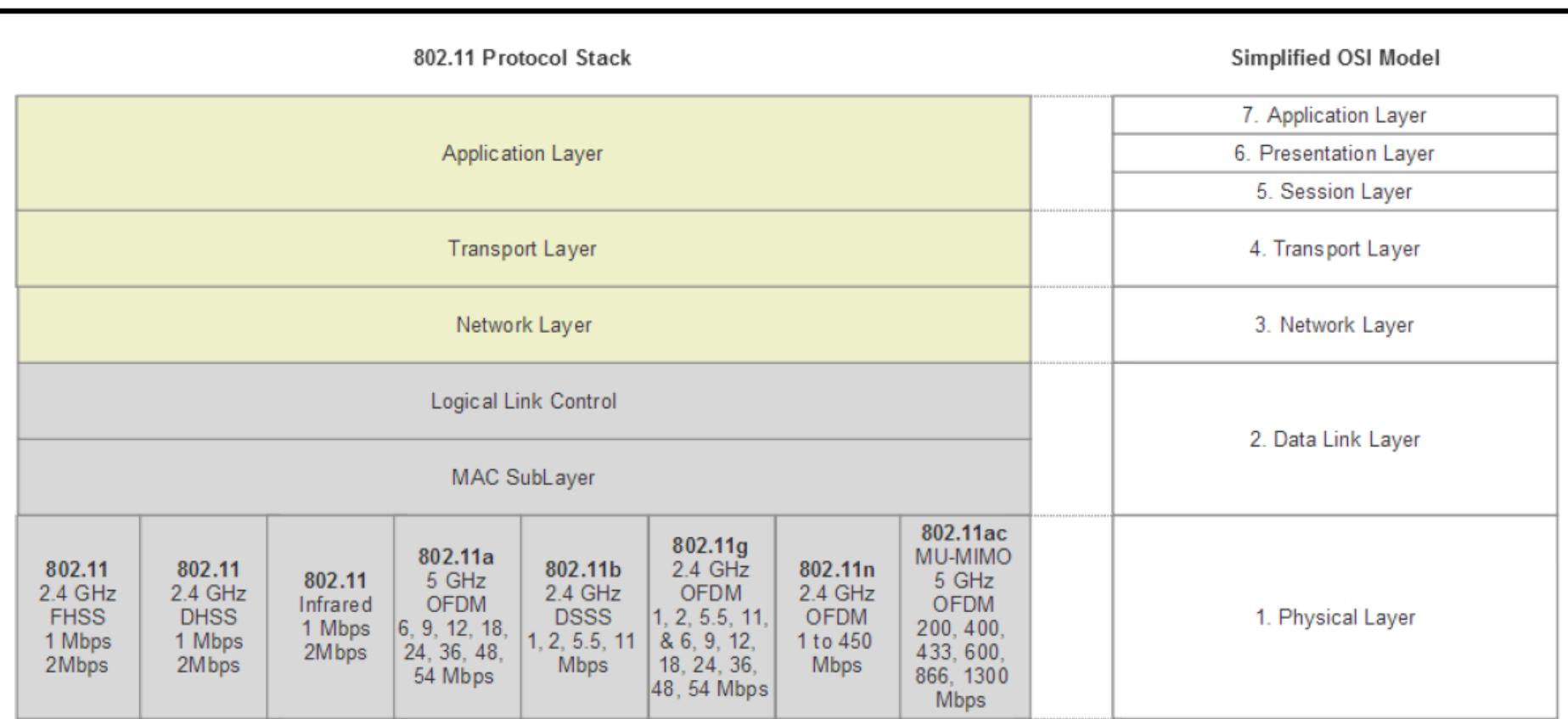
- WiFi is meant for **broadband network** connections in a confined area
- Normally less than 100 square meter per access point
- Typical range: short, 50m
- Max output power: medium/high, 0.1 W
- Bandwidth: large, up to hundreds of MB/s
- Security: suffered recent exploits, work in progress
- Cost: cheap equipment, no transmission costs
- Good for: security cameras, power meters or anything that is installed in a **fixed location, has power, and needs bandwidth**

# IEEE 802.11suit of Protocol and Comparison

| <b>IEEE 802.11 Protocol</b> | <b>Use Case</b>                                                                                                                                                                                                               | <b>Release Date</b> | <b>Frequency (GHz)</b> | <b>Bandwidth (MHz)</b> | <b>Streaming Data Rate per Channel min-max (Mbps)</b> |
|-----------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------|------------------------|------------------------|-------------------------------------------------------|
| <b>802.11</b>               | First 802.11 design                                                                                                                                                                                                           | Jun-97              | 2.4                    | 22                     | 1 to 2                                                |
| <b>a</b>                    | Release simultaneously with 802.11b<br>Less prone to interference than 802.11b                                                                                                                                                | Sep-99              | 5                      | 20                     | 6 to 54                                               |
|                             |                                                                                                                                                                                                                               |                     | 3.7                    |                        |                                                       |
|                             |                                                                                                                                                                                                                               |                     | 2.4                    | 22                     |                                                       |
| <b>b</b>                    | Release simultaneously with 802.11a<br>Significant speed increase over 802.11a at improved range                                                                                                                              | Sep-99              | 2.4                    | 22                     | 1 to 11                                               |
| <b>g</b>                    | Speed increase over 802.11b                                                                                                                                                                                                   | Jun-03              | 2.4                    | 20                     | 6 to 54                                               |
| <b>n</b>                    | Multiple antenna technology for improved speed, and range.                                                                                                                                                                    | Oct-09              | 2.4 / 5                | 20                     | 7.2 to 72.2                                           |
|                             |                                                                                                                                                                                                                               |                     |                        | 40                     | 15 to 150                                             |
| <b>ac</b>                   | Better performance and coverage over 802.11n. Wider channel and improved modulation. Allows multiple users using MU-MIMO. Introduced beamforming.                                                                             | Dec-13              | 5                      | 20                     | 7.2 to 96.3                                           |
|                             |                                                                                                                                                                                                                               |                     |                        | 40                     | 15 to 200                                             |
|                             |                                                                                                                                                                                                                               |                     |                        | 80                     | 32.5 to 433.3                                         |
|                             |                                                                                                                                                                                                                               |                     |                        | 160                    | 65 to 866.7                                           |
| <b>ah</b>                   | "WiFi HaLow"<br>Designed for IoT and sensor networks. Very low power and wider range.                                                                                                                                         | Dec-16              | 2.4 / 5                | 1 to 16                | 347                                                   |
| <b>p</b>                    | "Wireless Access in Vehicular Environments"<br>"Intelligent Transport Systems"<br>Dedicated Short Range Communication<br>Transport uses cases: toll collection, safety and collision emergencies, vehicular networking.       | Jun-09              | 5.9                    | 10                     | 27                                                    |
| <b>af</b>                   | "white WiFi" or "Super WiFi"<br>Deploy unused spectrum in TV bands to provide last mile connectivity in India, Kenya, Singapore, US and UK                                                                                    | Nov-13              | 0.470 to 0.710         | 6 to 8                 | 568                                                   |
| <b>ad</b>                   | WiGig Alliance<br>60 GHz Wireless for HD video and projectors<br>Audio and video transport and cable replacement                                                                                                              | Dec-12              | 60                     | 2160                   | 4260                                                  |
| <b>ax</b>                   | "High Efficiency Wireless (HEW)"<br>Next gen 802.11<br>4x increase in capacity over 802.11ac<br>Average increase of 4x speed per user over 802.11ac<br>Backwards compatible to 802.11a/b/g/n/ac<br>Dense deployment scenarios | 2019                | 2.4 / 5                | 20                     | 450 to 10000                                          |
|                             |                                                                                                                                                                                                                               |                     |                        | 40                     |                                                       |
|                             |                                                                                                                                                                                                                               |                     |                        | 80                     |                                                       |
|                             |                                                                                                                                                                                                                               |                     |                        | 160                    |                                                       |

# 802.11 Architecture

From a stack perspective, the 802.11 protocols reside in the link layer (one and two) of the OSI model, as shown in the following figure:

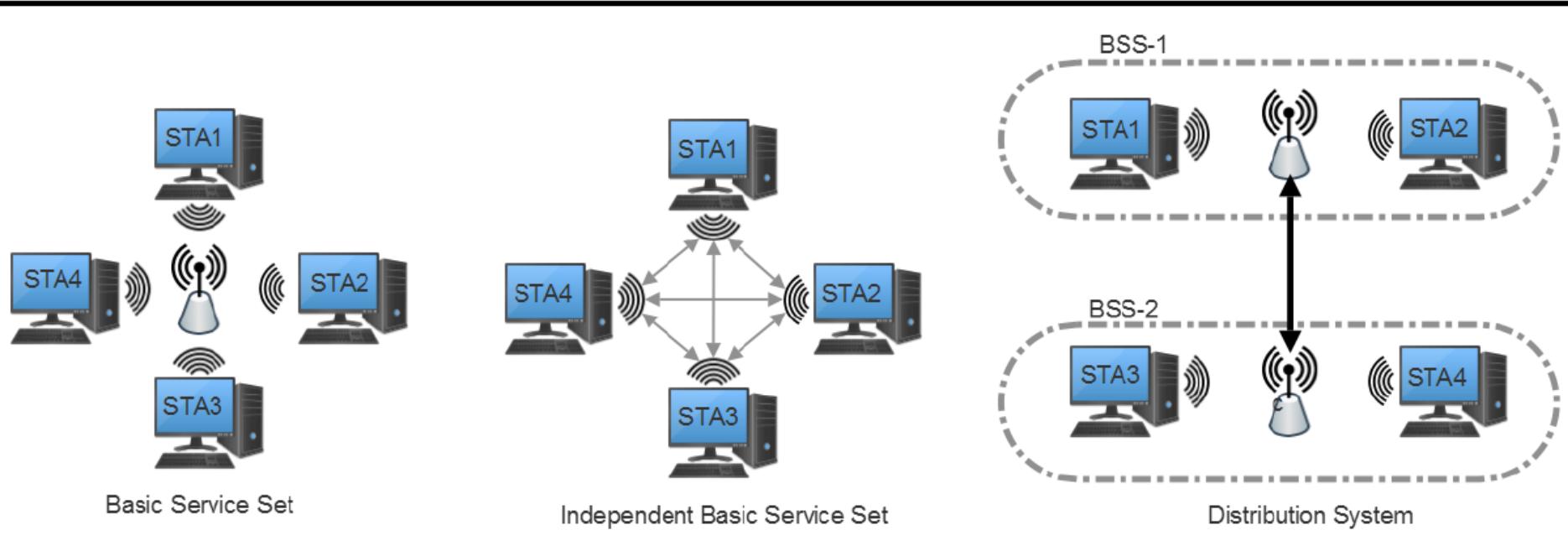


# 802.11 Topologies

802.11 systems support three basic topologies:

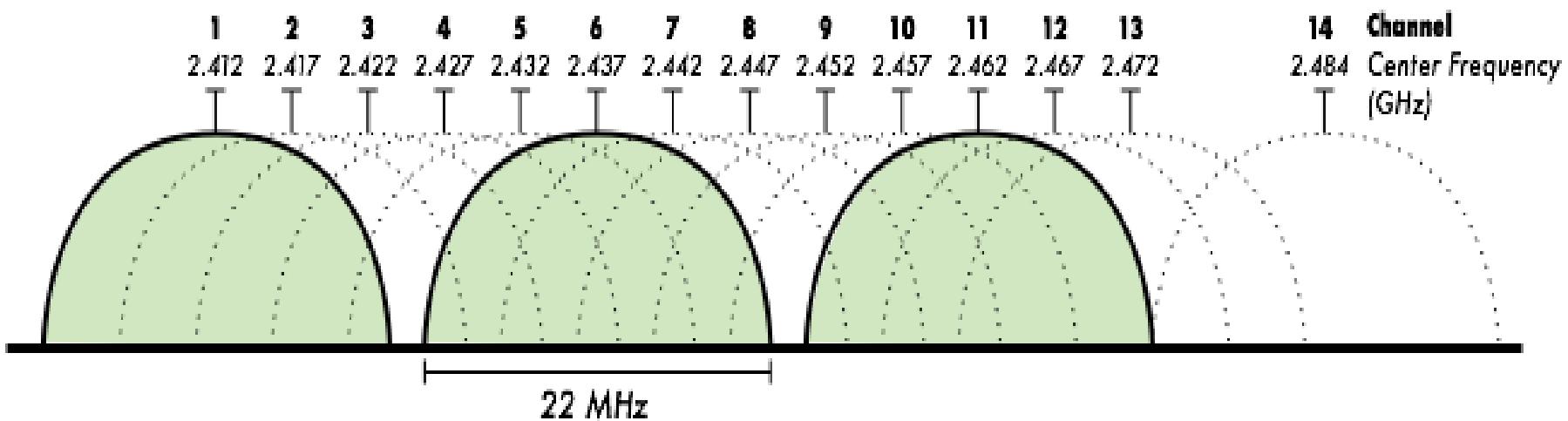
- **Infrastructure:** In this form, a **Station (STA)** refers to an 802.11 endpoint device (like a Smartphone) that communicates with a central **access point (AP)**. An AP can be a gateway to other networks (WAN), a router, or a true access point in a larger network. This is also known as **Infrastructure Basic Set Service (BSS)**. This topology is a star topology.
- **Ad hoc:** 802.11 nodes can form what is called an **Independent Basic Set Service (IBSS)** where each station communicates and manages the interface to other stations. No access point or a star topology is used in this configuration. This is a peer-to-peer type of topology.
- **Distribution system (DS):** The DS combines two or more independent BSS networks through access point interconnects.

# 802.11 Topologies Diagram



# IEEE 802.11 spectrum allocation

- The first 802.11 protocol used a spectrum in the 2 GHz and 5 GHz ISM region and evenly spaced channels roughly 20 MHz apart from each other.
- The channel bandwidth was 20MHz, but later amendments from IEEE allowed 5 MHz and 10 MHz to operate as well.
- Three of the channels are non-overlapping (1,6,11)

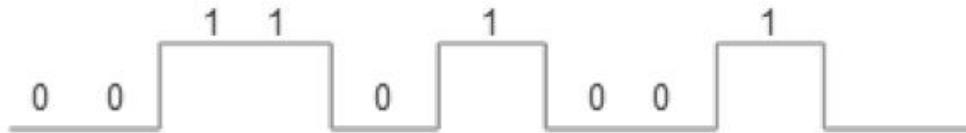


# IEEE 802.11 modulation and encoding techniques

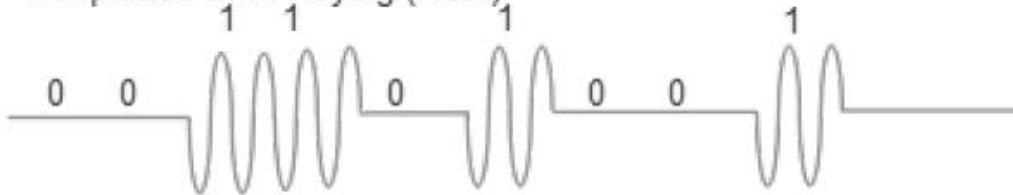
- **Amplitude Shift Keying (ASK):** This is a form of amplitude modulation. Binary 0 is represented by one form of modulation amplitude and 1 a different amplitude.
- **Frequency Shift Keying (FSK):** This modulation technique modulates a carrier frequency to represent 0 or 1. The simplest form shown in the following figure is **Binary Frequency Shift Keying (BPSK)**, which is the form used in 802.11 and other protocols.
- Bluetooth and Z-Wave, those protocols use a form of FSK called **Gaussian Frequency Shift Keying (GFSK)** that filters the data through a Gaussian filter, which smooths the digital pulse (-1 or +1) and shapes it to limit spectral width.
- **Phase Shift Keying (PSK):** Modulates the phase of a reference signal (carrier signal). Used primarily in 802.11b, Bluetooth, and RFID tags. PSK uses a finite number of symbols represented as different phase changes.

# IEEE 802.11 modulation

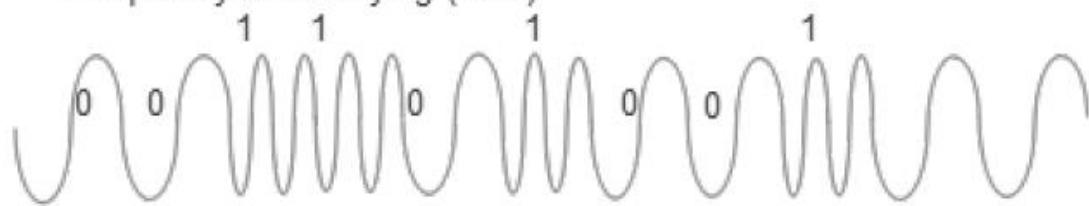
Original Digital Signal



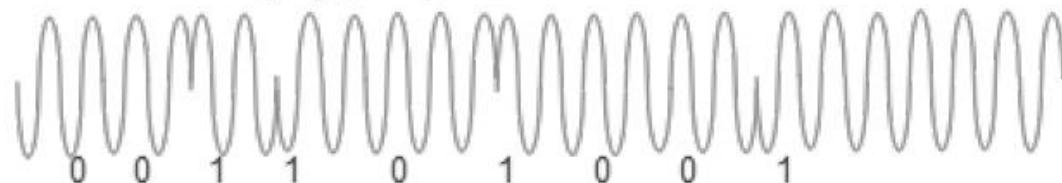
Amplitude Shift Keying (ASK)



Frequency Shift Keying (FSK)



Phase Shift Keying (PSK)



# 802.11 standards interference mitigation techniques

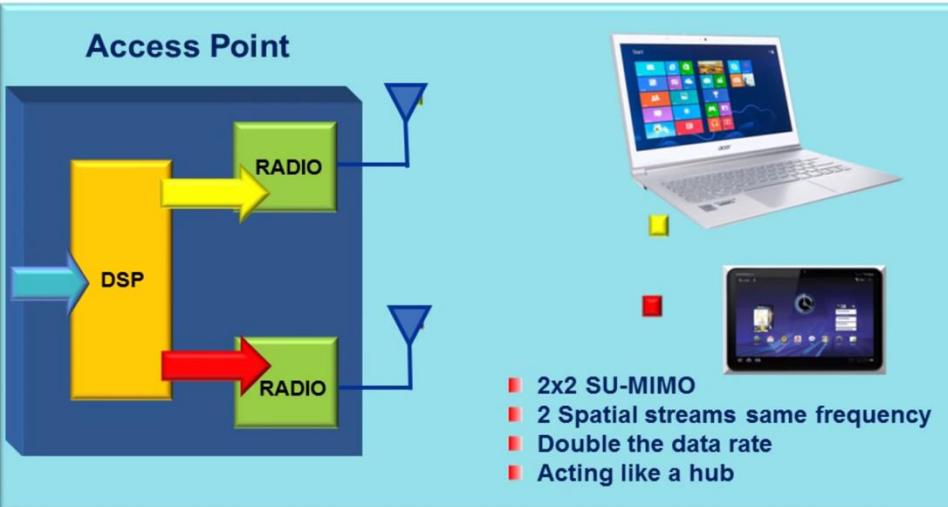
- **Frequency Hopping Spread Spectrum (FHSS):** Spreads signal over 79 nonoverlapping channels that are 1 MHz wide in the 2.4 GHz ISM band. Uses a pseudo-random number generator to start the hopping process.
- **Direct sequence spread spectrum:** First used in 802.11b protocols and has 22 MHz-wide channels. Each bit is represented by multiple bits in the signal transmitted. The data being transmitted is multiplied by a noise generator. This will effectively spread the signal over the entire spectrum evenly using a pseudorandom number sequence (called the *Pseudo-Noise* PN code).
- **OFDM:** Used in IEEE 802.11a and the newer protocols. This technique divides a single 20 MHz channel into 52 sub-channels (48 for data and four for synchronization and monitoring) to encode data using QAM and PSM.

# IEEE 802.11 MIMO

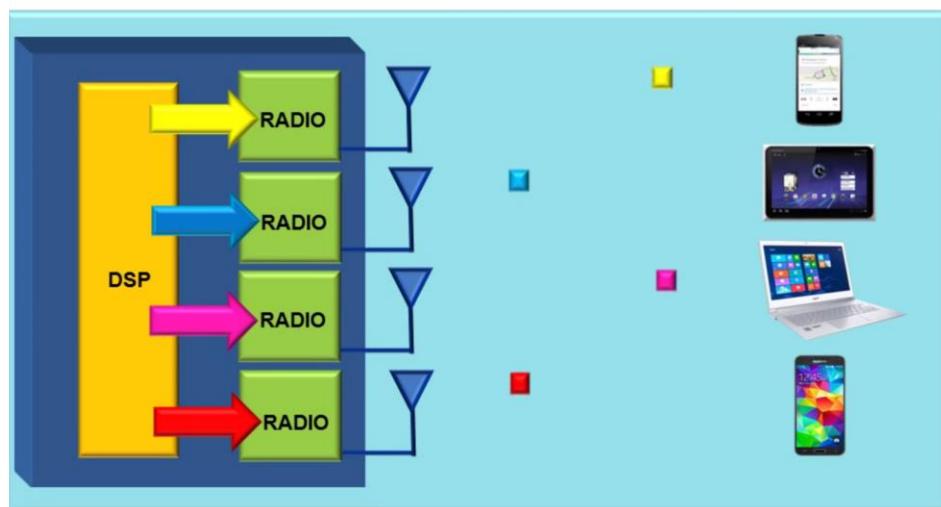
- MIMO is the acronym that refers to multiple input multiple output.
- MIMO exploits a RF phenomenon called multipath. Multipath transmission implies that signals will reflect off walls, doors, windows, and other obstructions. A receiver will see many signals each arriving at different times via different paths. Multipath tends to distort signals and cause interference, which eventually degrades signal quality (this effect is called multipath fading).
- With the addition of multiple antennas, a MIMO system can linearly increase the capacity of a given channel by simply adding more antennas. There are two forms of MIMO:
  - **Spatial diversity:** This refers to transmit-and-receive diversity. A single stream of data is transmitted on multiple antennas simultaneously using space-time coding. These provide improvements in the signal to noise ratio.
  - **Spatial multiplexing:** Used to provide additional data capacity by utilizing the multiple paths to carry additional traffic; that is, increasing the data throughput capability.

# SU-MIMO vs MU-MIMO

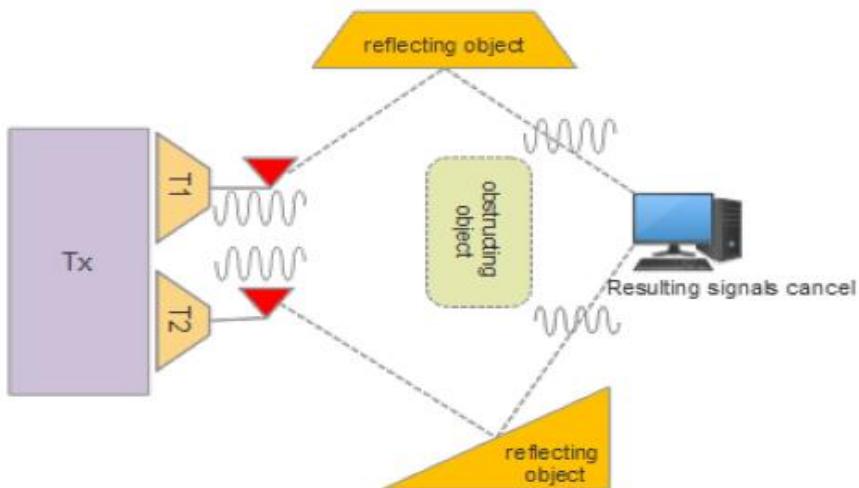
## Single User-Multiple In Multiple Out (SU-MIMO)



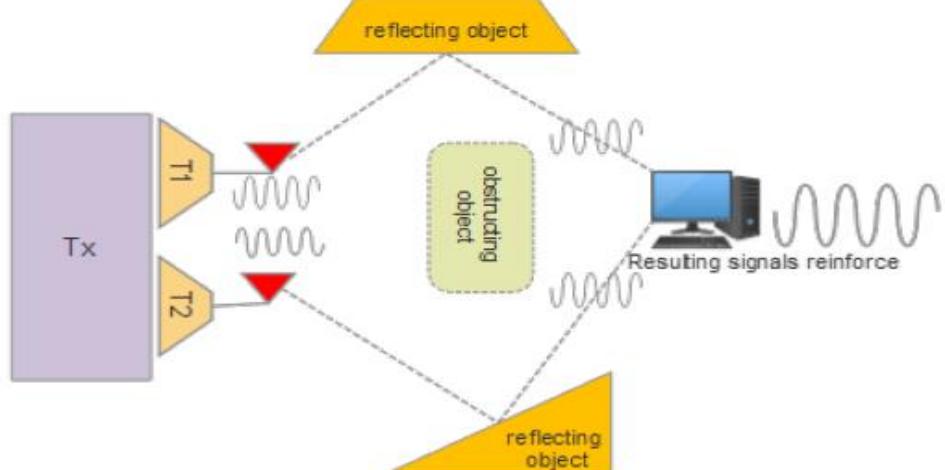
## Multi User-Multiple In Multiple Out (MU-MIMO)



Without Beamforming



With Beamforming in 802.11n



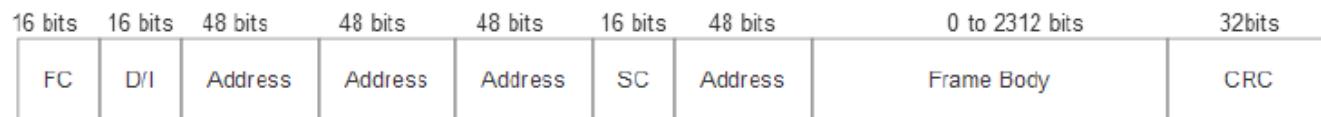
# IEEE 802.11 packet structure

## 802.11 PHY Frame

272 to 18,768 bits

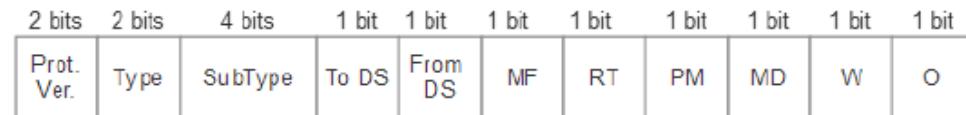


## 802.11 MAC Frame



FC: Frame Control  
D/I: Duration/Connection ID  
SC: Sequence Control

### 802.11 MAC Frame FC Header Details



Prot. Ver.: Protocol Version  
DS: Distribution System  
MF: More Fragments  
RT: Retry  
PM: Power Management  
MD: More Data  
W: Wired Equivalency Privacy Bit  
O: Order

**Address fields:** 802.11 can manage four MAC addresses in the following order:

**Address 1:** Receiver

**Address 2:** Transmitter

**Address 3/4:** Used for filtering

# IEEE 802.11 operation

- An STA is considered a device equipped with a wireless network interface controller. An STA will always be listening for active communication in a specific channel. The first phase of connecting to Wi-Fi is the scanning phase.
- After a channel is selected, the device performing the scan will receive beacons and probe requests from nearby STAs. An access point may transmit a beacon, and if the STA receives the transmission, it may progress to join the network.

The beacon packet contains information needed by the STA:

- **SSID:** Service Set ID. 1 to 32-character network name (this field can optionally be hidden by setting the SSID length to zero. Even if it is hidden the other portions of the beacon frame are transmitted as usual).
- **BSSID:** Basic Service Set ID. Unique 48-bit following layer-2 MAC address conventions. Formed by the combination of the 24-bit Organization Unique Identifier and the manufacturer's assigned 24-bit identifier for the radio chipset.

# IEEE 802.11 security

Types of authentication used on Wi-Fi WLANs and various strengths and weaknesses:

**WEP:** Wired equivalent privacy. This mode sends a key in plain text from the client. The key is then encrypted and sent back to the client. WEP uses different size keys but they are typically 128 bit or 256 bit. WEP uses a shared key, which means that the same key is available to all clients. It can be easily compromised by simply listening and sniffing for all the authentication frames coming back to clients joining a network to determine the key used for everyone.

**WPA:** Wi-Fi protected access (or WPA-Enterprise) was developed as the IEEE 802.11i security standard to replace WEP .One significant difference is WPA uses a **Temporal Key Integrity Protocol (TKIP)**, which performs per-packet key mixing and rekeying. This means that each packet will use a different key to encrypt itself, unlike in the case of WEP. Data can now be encrypted.

**WPA-PSK:** WPA pre-shared key or WPA-Personal. This mode exists where there is no 802.11 authentication infrastructure. Here, one uses a passphrase as a pre shared key. Each STA can have their own pre-shared key associated with its MAC address.

Wireless PAN: IEEE 802.15.1 & 802.15.4,  
Zigbee

# 802.15 standards

- The 802.15 group was initially formed to focus on wearable devices (coining the phrase personal area network).
- Their work has expanded significantly and now focuses on higher data rate protocols, meter to kilometer ranges, and specialty communications.
- Over one million devices are shipped each day using some form of 802.15.x protocol.
- **802.15:** Wireless personal area network definitions
- **802.15.1:** Original foundation of the Bluetooth PAN
- **802.15.4:** Low data rate, simple, simple design, multi-year battery life specifications (Zigbee)

# IEEE 802.15.4 architecture - Frequency

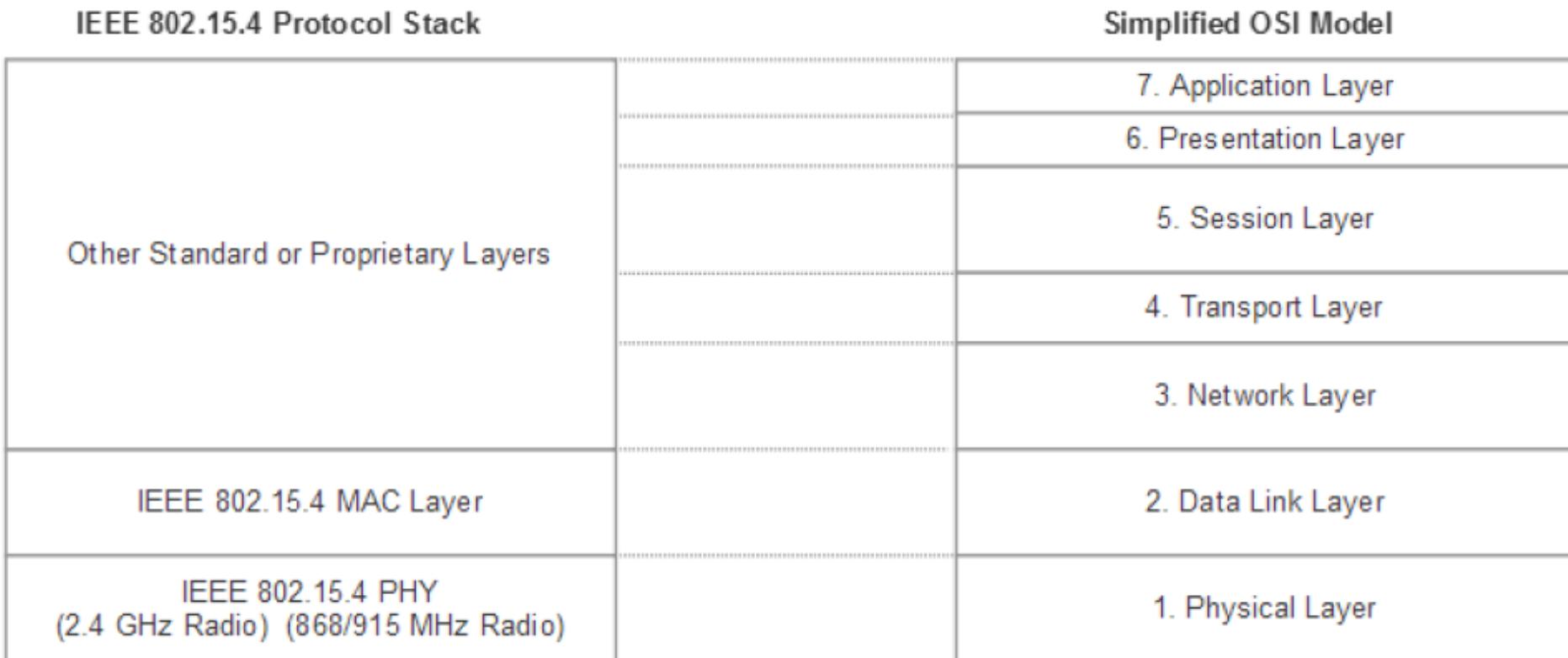
The IEEE 802.15.4 protocol operates in the unlicensed spectrum in three different radio frequency bands: 868 MHz, 915 MHz, and 2400 MHz.

| Central Frequency | Channel | Central Frequency | Channel | Central Frequency | Channel |
|-------------------|---------|-------------------|---------|-------------------|---------|
| 2405 MHz          | 11      | 868 MHz           | 0       | 906 MHz           | 1       |
| 2410 MHz          | 12      |                   |         | 908 MHz           | 2       |
| 2415 MHz          | 13      |                   |         | 910 MHz           | 3       |
| 2420 MHz          | 14      |                   |         | 912 MHz           | 4       |
| 2425 MHz          | 15      |                   |         | 914 MHz           | 5       |
| 2430 MHz          | 16      |                   |         | 916 MHz           | 6       |
| 2435 MHz          | 17      |                   |         | 918 MHz           | 7       |
| 2440 MHz          | 18      |                   |         | 920 MHz           | 8       |
| 2445 MHz          | 19      |                   |         | 922 MHz           | 9       |
| 2450 MHz          | 20      |                   |         | 924 MHz           | 10      |
| 2455 MHz          | 21      |                   |         |                   |         |
| 2460 MHz          | 22      |                   |         |                   |         |
| 2465 MHz          | 23      |                   |         |                   |         |
| 2470 MHz          | 24      |                   |         |                   |         |
| 2475 MHz          | 25      |                   |         |                   |         |
| 2480 MHz          | 26      |                   |         |                   |         |

# IEEE 802.15.4 architecture – Principle & Protocol Stack

To manage a shared frequency space, 802.15.4 and most other wireless protocols use some form of **Carrier Sense Multiple Access Collision Avoidance (CSMA/CA)**.

Since it is impossible to listen to a channel while transmitting on the same channel, collision detection schemes don't work; therefore, we use collision avoidance.



# Communications in IEEE 802.15.4

There are two types of communication in IEEE 802.15.4:

1. **Beacon** communication.
2. **Beaconless** communication.

- For a ***beacon-based network***, the MAC layer can generate beacons that allow a device to enter a PAN as well as provide timing events for a device to enter a channel to communicate.
  - The beacon is also used for battery-based devices that are normally sleeping.
  - The device wakes on a periodic timer and listens for a beacon from its neighbors.
- 
- IEEE 802.15.4 allows for ***beacon-less networking***. This is a much simpler scheme where no beacon frame is transmitted by the PAN coordinator. It implies, however, that all nodes are in a receiving mode all the time. This provides full-time contention access using unslotted CSMA/CA.
  - This mode will consume much more power than beacon-based communication.

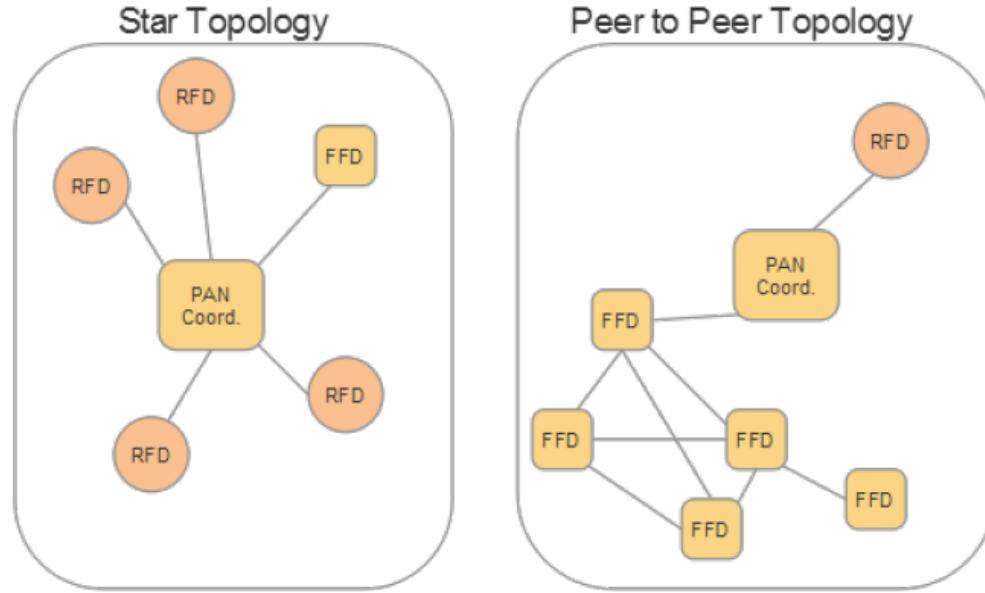
# IEEE 802.15.4 topology

There are two fundamental device types in IEEE 802.15.4:

- **Full function device (FFD)**: Supports any network topology, can be a network (PAN) coordinator and can communicate to any device PAN coordinator
- **Reduced function device (RFD)**: Limited to only a star topology, cannot perform as a network coordinator, can only communicate with a network coordinator

The ***star topology*** is the simplest but requires all messages between peer nodes to travel through the PAN coordinator for routing.

A ***peer-to-peer topology*** is a typical mesh and can communicate directly with neighbor nodes.



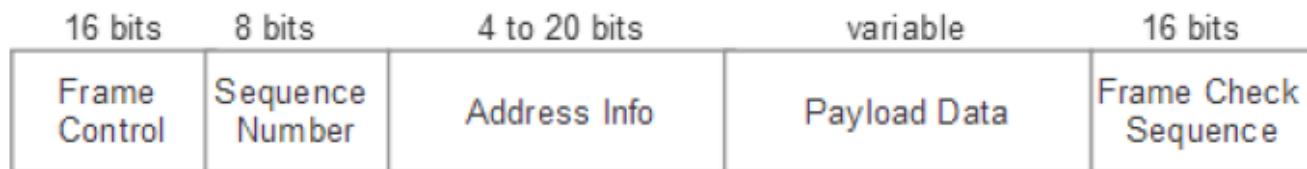
# IEEE 802.15.4 address modes and packet structure

- The standard dictates that all addresses are based on unique **64-bit values** (IEEE address or MAC address).
- However, **to conserve bandwidth and reduce the energy of transmitting** such large addresses, 802.15.4 allows a device joining a network to "trade-in" their unique 64-bit address for a short **16-bit local address**, allowing for more efficient transmission and lower energy.

## IEEE 802.15.4 PHY Packet



## IEEE 802.15.4 MAC Service Data Unit (MSDU)



# IEEE 802.15.4 start-up sequence

IEEE 802.15.4 maintains a process for startup, network configuration, and joining of existing networks. The process is as follows:

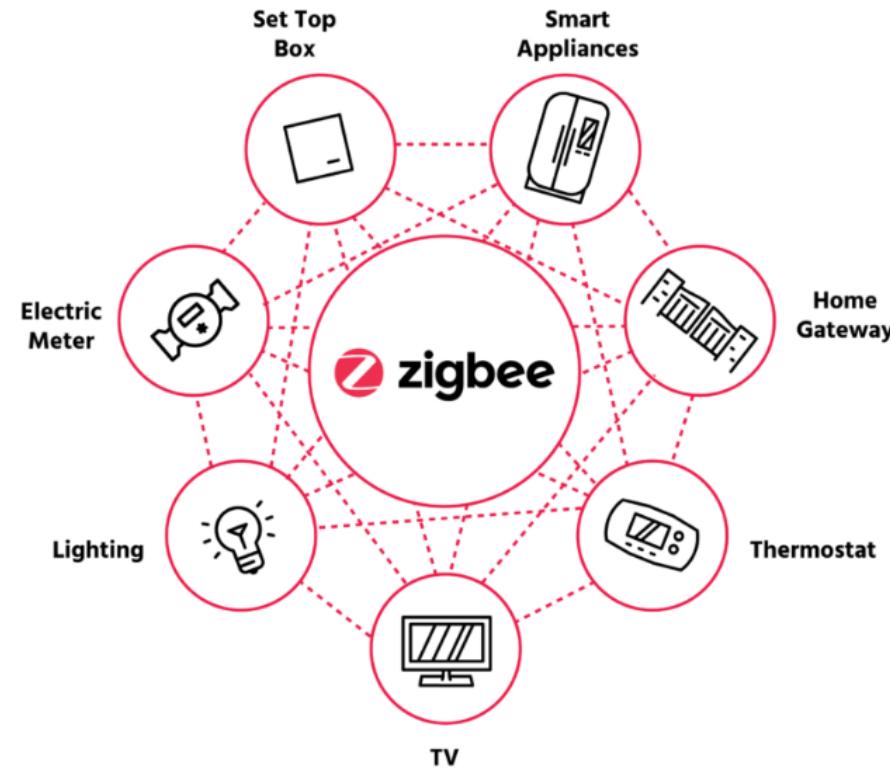
1. Device **initializes** its **stack** (PHY and MAC layers).
2. **PAN coordinator** is **created**. Each network has only one PAN coordinator.
3. The PAN coordinator will **listen** to **other networks** it has access to and **derives** a **PAN ID** that is unique to the PAN it will administer.
4. The PAN coordinator will **choose a specific radio frequency** to use for the network.
5. The network will be started by configuring the PAN coordinator and then **starting** the device in **coordinator mode**. At this point, the PAN coordinator can **accept requests**.
6. Nodes can join the network by finding the PAN coordinator using an active channel scan where it **broadcasts** a **beacon request** across all its frequency channels. In a beacon-based network, the PAN coordinator will routinely send out a beacon and the device can perform a passive channel scan and listen for the beacon. The device will then send an **association request**.
7. The PAN coordinator will determine if the **device should** or can join the network. If accepted, the PAN coordinator will **assign a 16-bit short address** to the device.

# IEEE 802.15.4 security

- The IEEE 802.15.4 standard includes security provisions in the form of **encryption** and **authentication**. The architect has flexibility in the security of the network based on cost, performance, security, and power.
- AES-based encryption which uses a block cipher with a counter mode can be used.

# Zigbee

- Zigbee is a WPAN protocol based on the IEEE 802.15.4 foundation targeted for commercial and residential IoT networking that is constrained by cost, power, and space.
- Zigbee got its name from the concept of a bee flying. As a bee flies back and forth between flowers gathering pollen, it resembles a packet flowing through a mesh network - device to device.



# Zigbee Overview

- Zigbee is based on 802.15.4 but layers on network services similar to TCP/IP. It can form networks, discover devices, provide security, and manage the network.
- It does not provide data transport services or an application execution environment.
- It is essentially a mesh network, its self-healing and ad hoc in form.

There are three principal components in a Zigbee network.

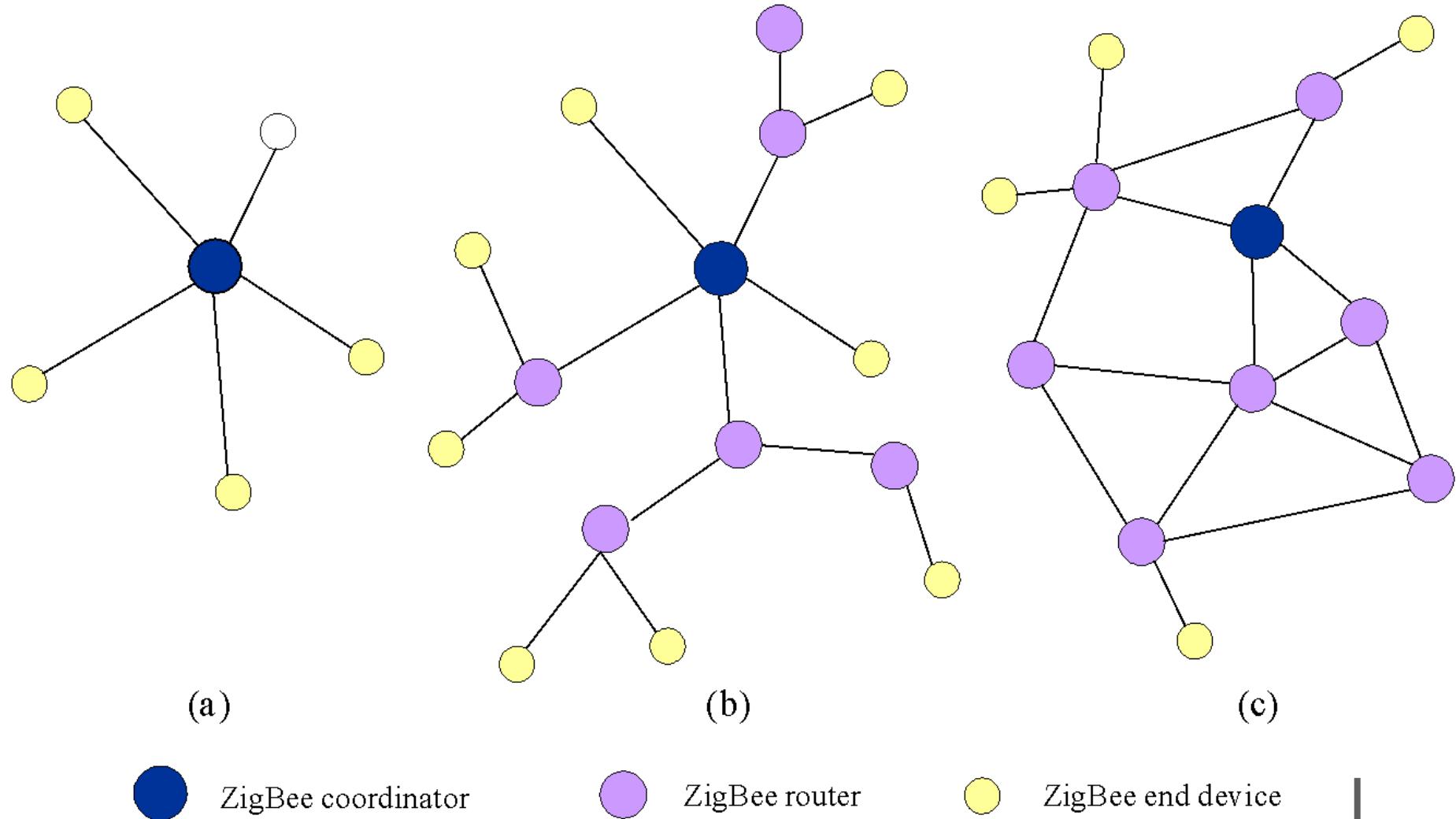
**Zigbee controller (ZC):** Highly capable device on a Zigbee network that is used to form and initiate network functions. Each Zigbee network will have a single ZC that fulfills the role of an 802.15.4 2003 PAN coordinator (FFD).

**Zigbee router (ZR):** This component is optional but handles some of a load of mesh network hopping and routing coordination. It too can fulfill the role of an FFD and has an association with the ZC.

**Zigbee end device (ZED):** This is usually a simple endpoint device such as a light switch or thermostat. It contains enough functionality to communicate with the coordinator. It has no routing logic; therefore, any messages arriving at a ZED that are not targeted to that end device are simply relayed.

# Zigbee Topologies

Three kinds of networks are supported: **star**, **tree**, and mesh networks



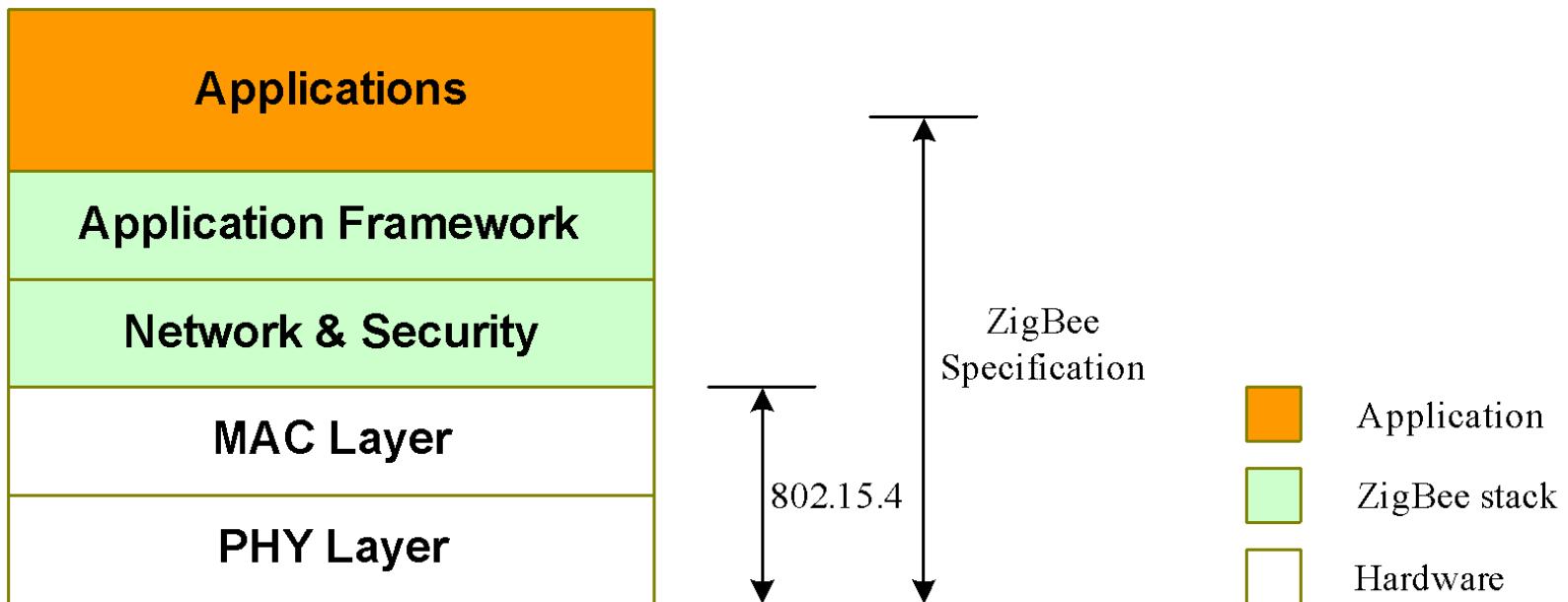
# Zigbee Data Traffic

Zigbee targets three different types of data traffic.

- **Periodic data** is delivered or transmitted at a rate defined by the applications (for example, sensors periodically transmitting).
- **Intermittent data** occurs when an application or external stimulus occurs at a random rate. A good example of intermittent data suitable for Zigbee is a light switch.
- **Repetitive low latency data.** Zigbee allocates time slots for transmission and can have very low latency, which is suitable for a computer mouse or keyboard.

# Zigbee PHY and MAC

- Zigbee operates primarily in the 2.4 GHz ISM band.
- It also operates at 868 MHz and 915 MHz because of the lower frequency, it has better propensity to penetrate walls and obstacles over traditional 2.4 GHz signals.
- Zigbee does not use all the IEEE802.15.4 PHY and MAC specifications.
- Zigbee does make use of the CSMA/CA collision avoidance scheme.
- It also uses the MAC level mechanism to prevent nodes from talking over each other.



# Zigbee addressing

- The Zigbee protocol, as shown, resides on top of the 802.15.4 PHY and MAC layers and reuses its packet structures.
- The network diverges at the network and application layers.

Zigbee uses two unique addresses per node:

**Long address (64 bit):** Assigned by the manufacturer of the device and is immutable. Uniquely identifies the Zigbee device from all other Zigbee devices. This is the same as the 802.15.4 64-bit address. The top 24 bits refer to the organizational unique identifier (OUI) and the bottom 40 bits are managed by the OEM.

**Short address (16 bit):** This too is the same as the PAN ID of the 802.15.4 specification and is also optional.

# Zigbee Routing Protocol

Zigbee can route packets in multiple manners:

- **Broadcasting:** Transmit packet to all other nodes in the fabric.
- **Mesh routing (table routing):** If a routing table for the destination exists, the route will follow the table rules accordingly. Very efficient. Zigbee will allow a mesh and table to route up to 30 hops away.
- **Tree routing:** Unicast messaging from one node to another. Tree routing is purely optional and can be disallowed from the entire network. It provides better memory efficiency than mesh routing since a large routing table doesn't exist. Tree routing does not have the same connection redundancy as a mesh, however. Zigbee supports tree routing hops up to 10 nodes away.
- **Source routing:** Used primarily when a data concentrator is present. This is how Z-Wave provides mesh routing.

# Zigbee association

- **Zigbee end devices (ZED)** do not participate in routing. End devices communicate with the parent, who is also a router.
- When a **Zigbee coordinator (ZC)** allows for a new device to join a network, it enters a process known as an *association*. If a device loses contact with its parent, the device can at any time rejoin through the process known as *orphaning*.
- To formally join a Zigbee network, a *beacon request* is broadcast by a device to ask for subsequent beacons from devices on the mesh that are authorized to allow new nodes to join. At first, only the PAN coordinator is authorized to provide such a request; after the network has grown, other devices may participate.

# 6LowPAN

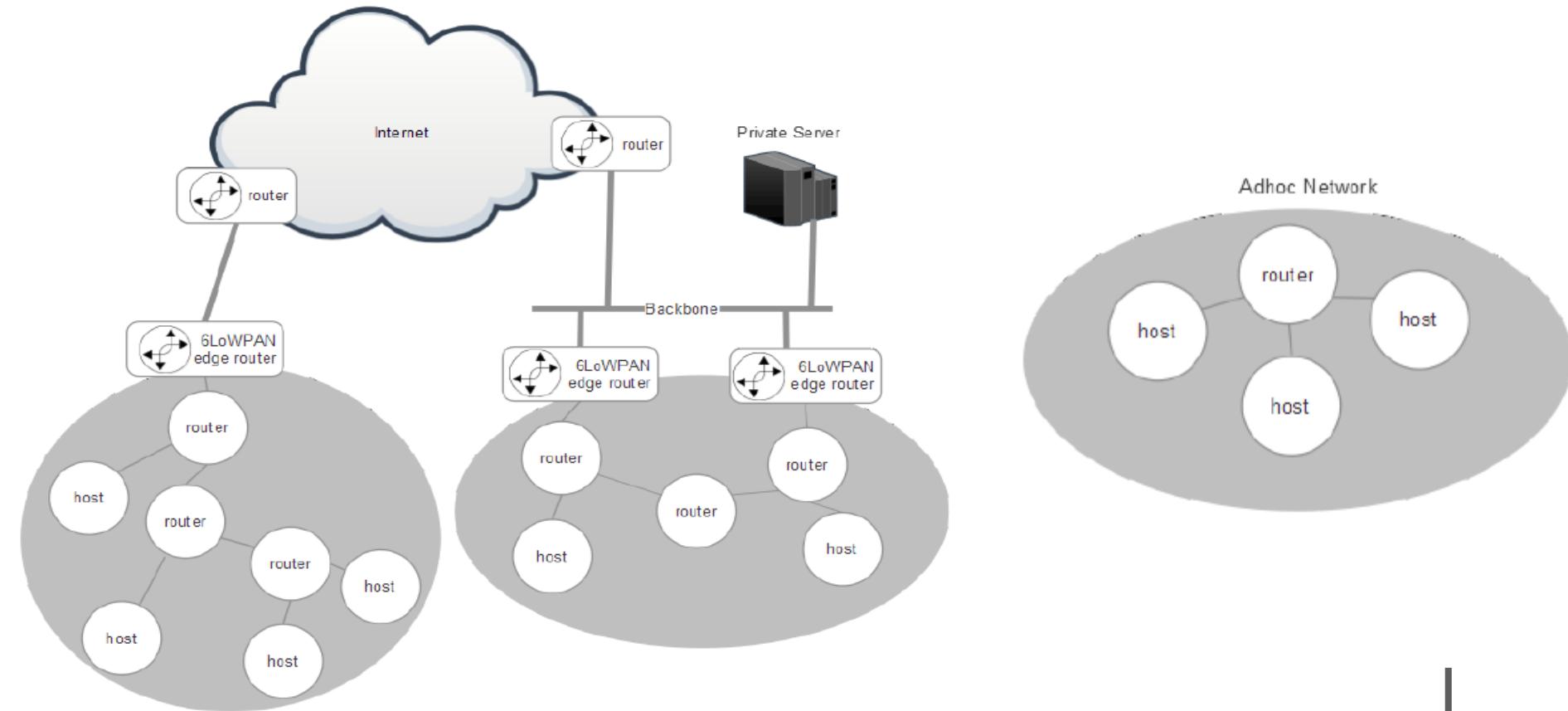


IPv6-based Low-power  
Wireless Personal Area Networks

- To bring IP addressability to the smallest and most resource-constrained devices, the concept of 6LoWPAN was formed in 2005.
- 6LoWPAN is an acronym that stands for IPV6 over low power WPANs. The intent is for IP networking over low-power RF communication systems for devices that are power and space constrained and do not need high bandwidth networking services.
- The protocol can be used with other WPAN communications such as 802.15.4 as well as Bluetooth, sub-1 GHz RF protocols, and **power line controller (PLC)**.
- The principal advantage of 6LoWPAN is that the simplest of sensors can have IP addressability and act as a network citizen over 3G/4G/LTE/Wi-Fi/Ethernet routers.
- A secondary effect is that IPV6 provides significant theoretical addressability of 2128 or  $3.4 \times 10^{38}$  unique addresses. Therefore, IPV6 is well-suited for IoT growth.

# 6LoWPAN topology

- 6LoWPAN networks are mesh networks residing on the periphery of larger networks.
- The topologies are flexible, allowing for ad hoc and disjointed networks without any binding to the internet or other systems, or they can be connected to the backbone or the internet using edge routers.



# 6LoWPAN- Types of Nodes

There are three types of nodes within the 6LoWPAN mesh:

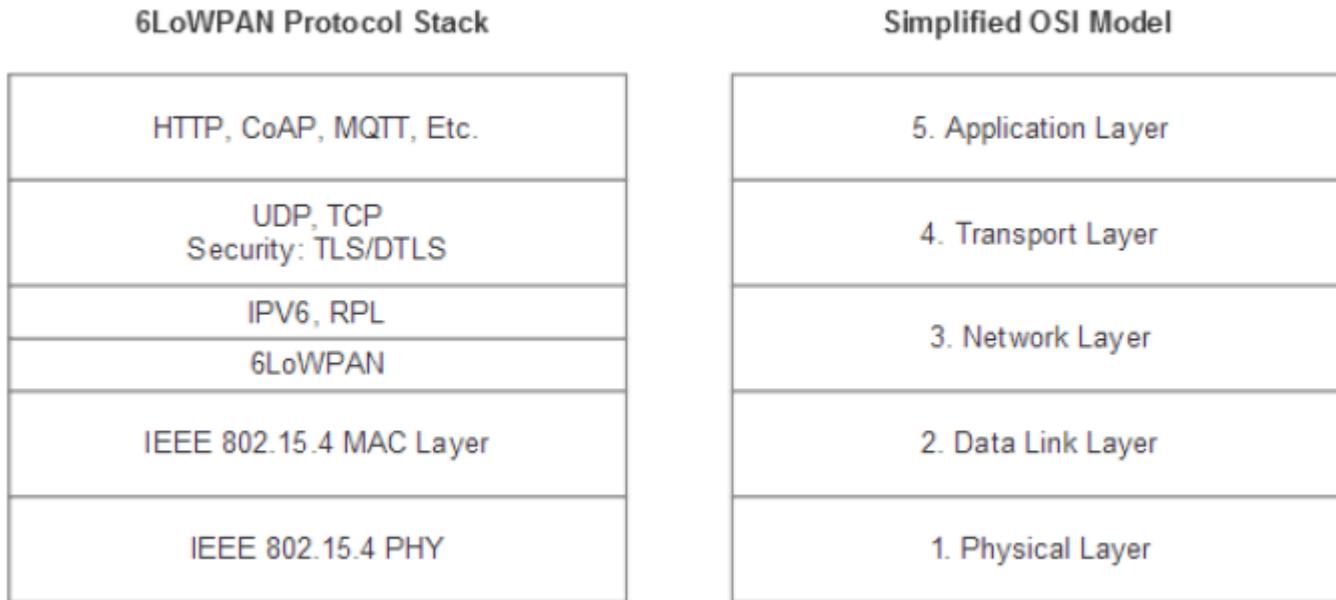
- **Router nodes:** These nodes marshal data from one 6LoWPAN mesh node to another. Routers can also communicate outward to the WAN and internet.
- **Host nodes:** Hosts in the mesh network cannot route data in the mesh and are simply endpoints consuming or producing data. Hosts are allowed to be in sleep states, occasionally waking to produce data or receive data cached by their parent routers.
- **Edge routers:** These are the gateways and mesh controllers usually at a WAN edge. A 6LoWPAN mesh would be administered under the edge router.

Nodes are free to move and reorganize/reassemble in a mesh. For that matter, a node can move and associate with a different edge router in a multi-home scenario or even move between different 6LoWPAN meshes.

In an ad hoc mesh without an edge router, a 6LoWPAN router node could manage a 6LoWPAN mesh. This would be the case when WAN connectivity to the internet is not necessary.

# 6LoWPAN- Protocol Stack

To enable 6LoWPAN on a form of communication media such as 802.15.4 there is a set of recommended features necessary to support an IP protocol. These features include framing, unicast transmission and addressing.

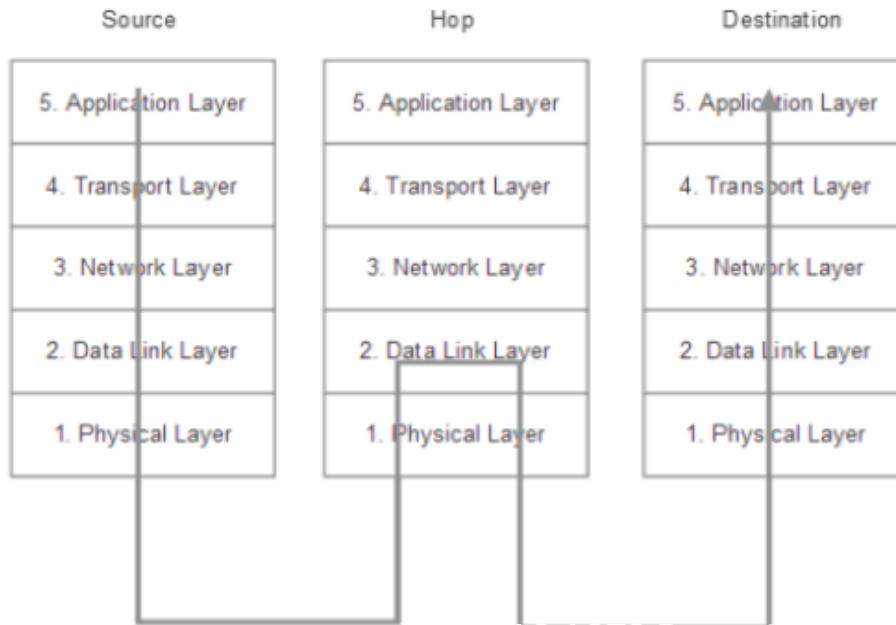


# 6LoWPAN- Mesh Network routing

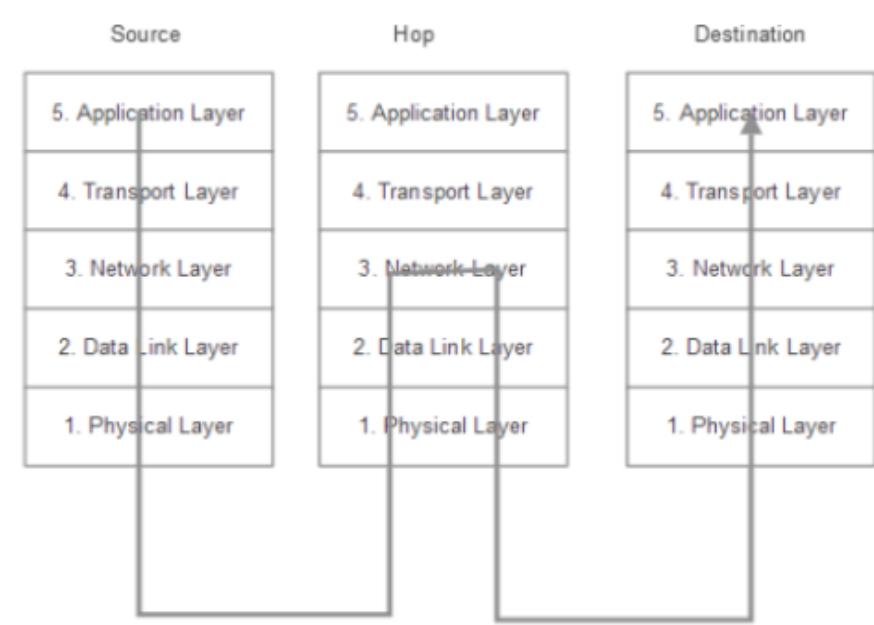
6LoWPAN mesh networks utilize two schemes for routing:

- **Mesh-under network:** A message is broadcast in a single domain and is sent to all devices in the mesh. This method generates considerable traffic. Mesh-under routing will move from hop to hop in the mesh but only forward packets up to layer two (data link layer) of the stack. 802.15.4 handles all the routing for each hop in layer two.
- **Route-over network:** In a route-over topology, networks will incur the charge of forwarding packets up to layer three (network layer) of the stack. Route-over schemes manage routes at an IP level. Each hop represents one IP router.

Mesh-Under (layer 2) Routing



Route-Over (layer 3) Routing



# 6LoWPAN- Header Compression

IPv6 on an 802.15.4 link poses some challenges that must be overcome to make 6LoWPAN usable.

- **First** is the fact that IPv6 has a **Maximum Transmission Unit(MTU)** size of 1280 bytes, while 802.15.4 has a limit of 127 bytes which leads to **fragmentation**.
- **Second issue** is that IPv6 in general adds **significant header overhead** to an already bloated protocol. For example, in IPv6 headers are 40 bytes long.

**Header compression** is a means to **compress and remove redundancy** in the IPv6 standard header for efficiency reasons.

## IPv6 Header

| 4 bits  | 8 bits        | 20 bits    | 16 bits    | 8 bits      | 8 bits    | 64 bit prefix, 64 bit HD | 64 bit prefix, 64 bit HD |
|---------|---------------|------------|------------|-------------|-----------|--------------------------|--------------------------|
| Version | Traffic Class | Flow Label | Flow Label | Next Header | Hop Limit | Source Address           | Destination Address      |

## 1. Within 6LoWPAN mesh

FF80::00FF:1234:4321:0001 → FF80::00FF:1234:4321:0002

8 bits      8 bits

|          |              |
|----------|--------------|
| Dispatch | Comp. Header |
|----------|--------------|

## 2. Communication from 6LoWPAN device to known address outside mesh

1003::9876:ABCD:0000:0001 → 1003::1234:4321:AAAA:BBBB

8 bits      8 bits      8 bits      8 bits      64 bit HD

|          |              |     |           |                     |
|----------|--------------|-----|-----------|---------------------|
| Dispatch | Comp. Header | CID | Hop Limit | Destination Address |
|----------|--------------|-----|-----------|---------------------|

# 6LoWPAN- Fragmentation

Fragmentation is a secondary issue, since the MTU sizes are incompatible between 802.15.4 (127 bytes) and IPv6 at 1280 bytes. The fragmentation system will divide each IPv6 frame into smaller segments. On the receiving side, the fragments will be reassembled.

- **Mesh-under routing fragmentation:** Fragments will be reassembled only at the final destination. All fragments need to be accounted for during reassembly. If any are missing, the entire packet needs retransmission.
- **Route-over routing fragmentation:** Fragments will be reassembled at every hop in the mesh. Each node along the route carries enough resources and information to rebuild all fragments.

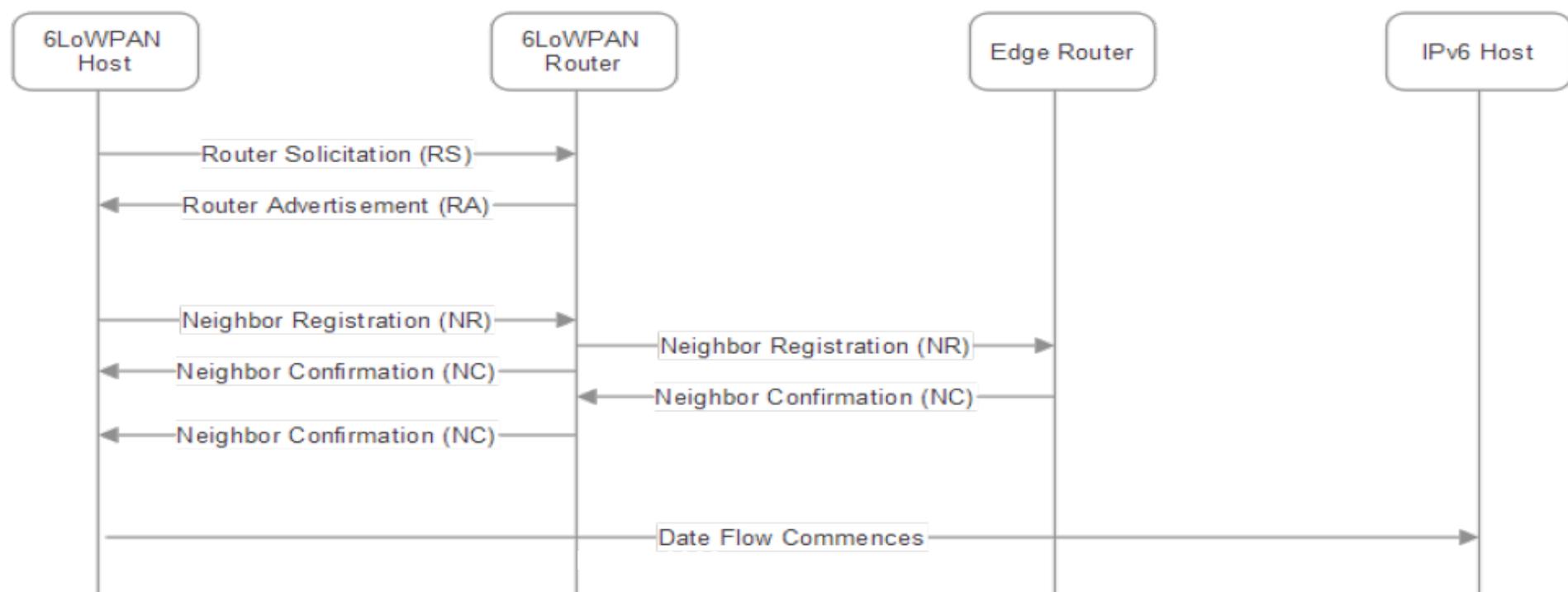
6LoWPAN Fragmentation Header

|                 | 8 bits                       | 8 bits        | 16 bits      |                 |     |
|-----------------|------------------------------|---------------|--------------|-----------------|-----|
| 802.15.4 Header | 6LoWPAN Fragmentation Header | Datagram Size | Datagram Tag | Datagram Offset | FCS |

# 6LoWPAN- Neighbor Discovery

This is a formal contract between neighbor nodes in the mesh and allows nodes to communicate with each other. ND is the process of discovering new neighbors, as a mesh can grow, shrink and transform, resulting in new and changing neighbor relations. There are two basic processes and four message types in ND:

- **Finding neighbors:** This includes **Neighbor Registration (NR)** and **Neighbor Confirmation (NC)** phases
- **Finding routers:** This includes **Router Solicitation (RS)** and **Router Advertisement (RA)** phases



# LTE, the 4th generation mobile network system



- LTE supports voice calls, but designed for **scalability and wireless broadband**
- Range normally less than GSM, but **data rate is orders of magnitude greater**
- Typical range: long, 2Km
- Max output power: medium/high, 0.2 W
- Bandwidth: large, up to hundreds of MB/s
- Security: multiple unique identifiers, static keys, and encryption methods
- Cost: depends on the telco operator
- Good for: **broadband wireless internet connection**, also for streaming security camera videos

- **Low speed, but long range and low power** communication protocol
- Open specification so anyone is free to implement the protocol
- Typical range: long, 5-10 km
- Max output power: low, 0.025 W
- Bandwidth: very low, between 290 bps and 50 kbps
- Security: protocol to exchange to set unique set of AES keys
- Cost: cheap client equipment, needs access point or service provider
- Good for: isolated or private network on a farm or in a city, **ideal for sensors that only seldomly send a value**, like a soil moisture sensor sending its measurements every 10 minutes or a water trough alarming that it is empty

# LoRaWAN- Where its placed

Power consumption / Bandwidth



Range

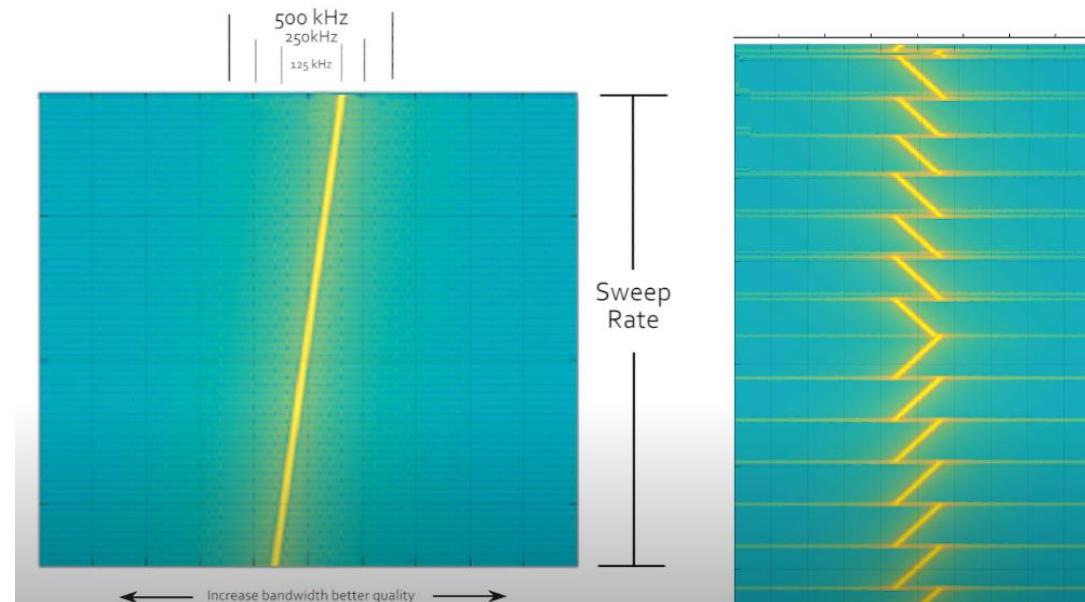
# LoRaWAN

- LoRa is a **physical layer** for a long-range and low-power IoT protocol while LoRaWAN represents the **MAC layer**.
- These proprietary LPWAN technologies and carriers have the advantage of using the **unlicensed spectrum** and that, simply, is reducing data plan cost.
- LoRaWAN will be **5x to 10x lower in their data rates** compared to traditional 3G or LTE connections for large volume deployments (>100,000 units).
- A single LoRaWAN gateway has the **potential to cover a significant amount of area**. Example *Belgium, with a land area of 30,500 km<sup>2</sup>, is completely covered by seven LoRaWAN gateways*.

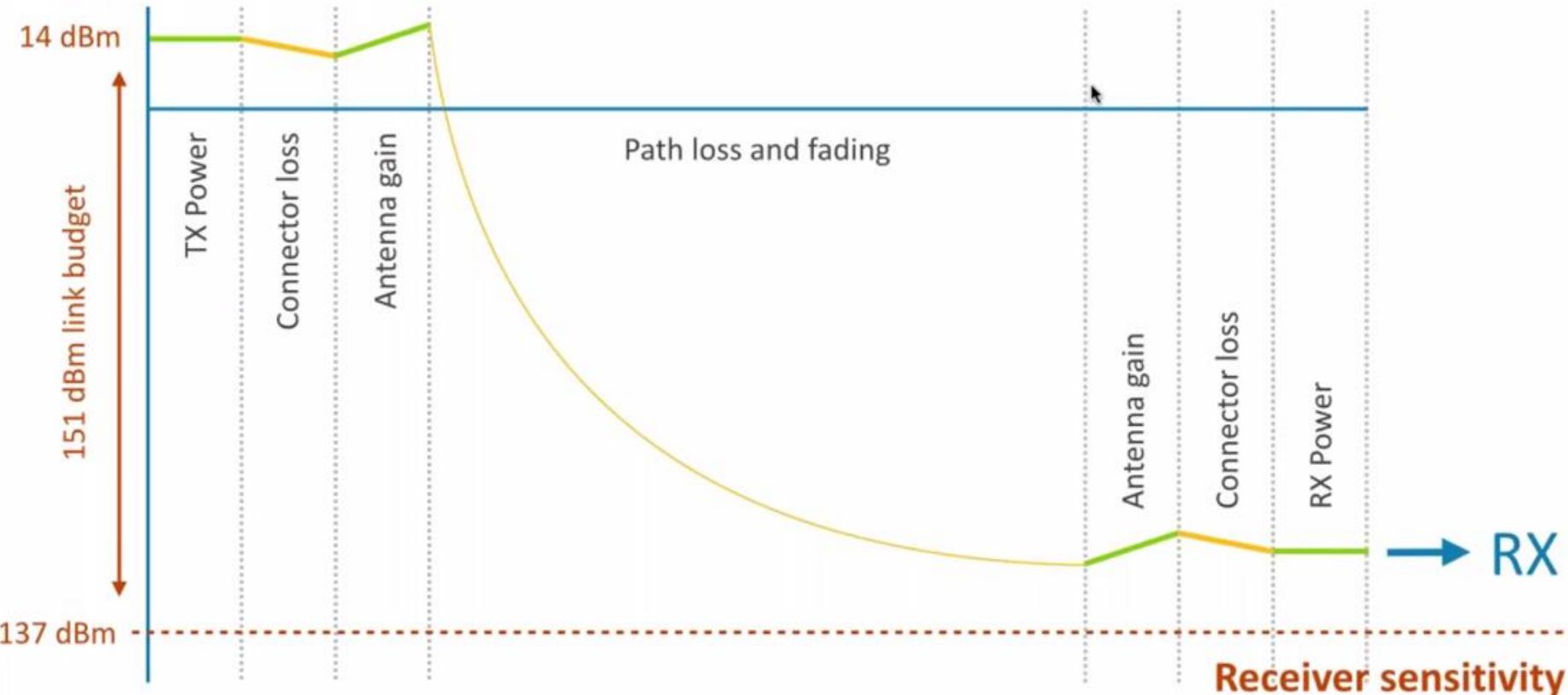
# LoRa Physical Layer

- LoRa represents the physical layer of a LoRaWAN network. It manages the **modulation, power, receiver and transmission** radios, and signal conditioning.
- The architecture is based on the following bands in ISM license-free space:
  - **915 MHz**: In the USA with power limits but no duty cycle limit.
  - **868 MHz**: In Europe with a 1% and 10% duty cycle.
  - **433 MHz**: In Asia.

A derivative of [\*\*Chirp Spread Spectrum \(CSS\)\*\*](#) is the modulation technique used in LoRa. CSS balances data rate with sensitivity in a fixed channel bandwidth.



# LoRa High Link Budget



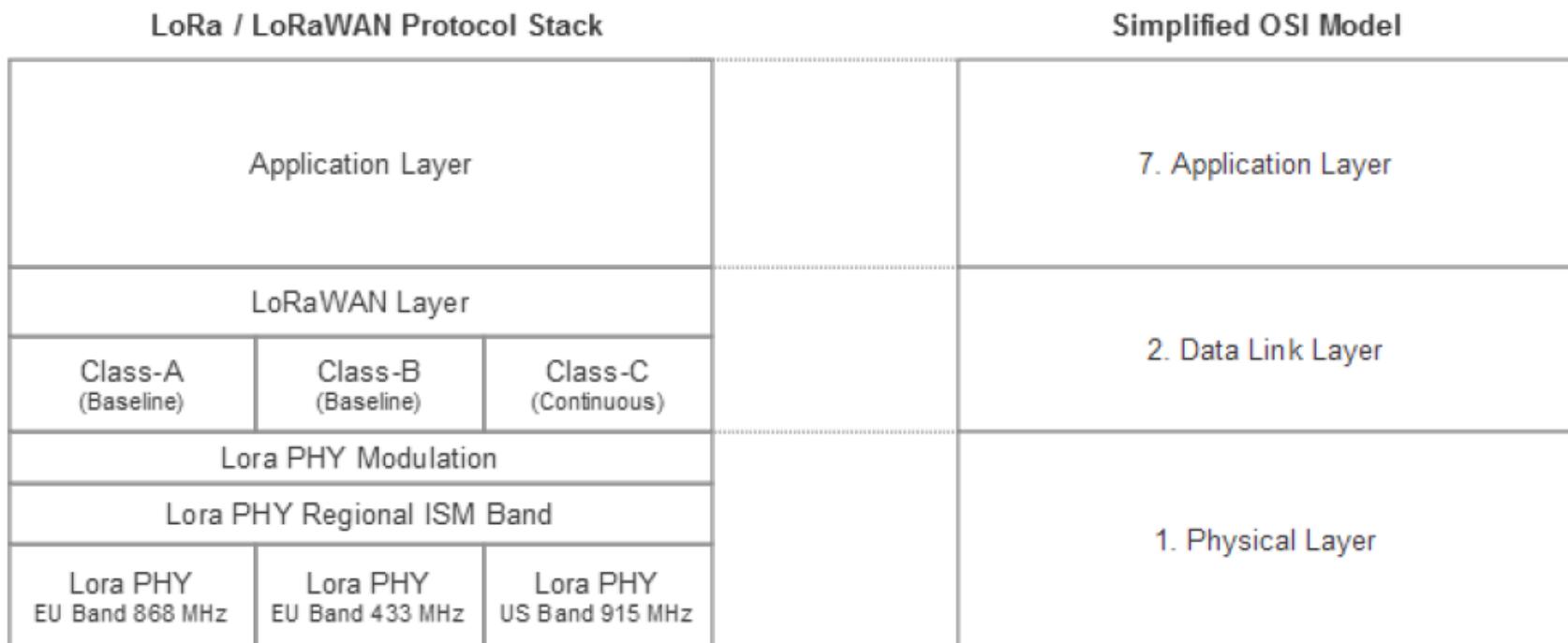
# LoRaWAN MAC Layer

LoRaWAN represents the MAC that resides on top of a LoRa PHY.

The LoRaWAN **MAC** is an **open protocol** while the **PHY is closed**.

There are three MAC protocols that are part of the data link layer. These three-balance latency with energy usage.

- **Class-A** is the best for energy mitigation while having the highest latency.
- **Class-B** is between Class-A and Class-C.
- **Class-C** has minimum latency but the highest energy usage.



# Device Classes

Flexibility in power conservation versus fast network initiated transmission

## Class A 😴

### Device initiated communication

Devices are typically in deep sleep and send messages on intervals and/or events

Only after uplink transmission, there is a receive window for downlink messages

Best for most sensor applications and battery conservation

## Class B 🕒

### Time synchronized communication

The network broadcasts beacons for devices to sync time

In so-called ping slots, devices wake up and the network may send downlink messages

Best for most downlink intensive applications

## Class C ⚡

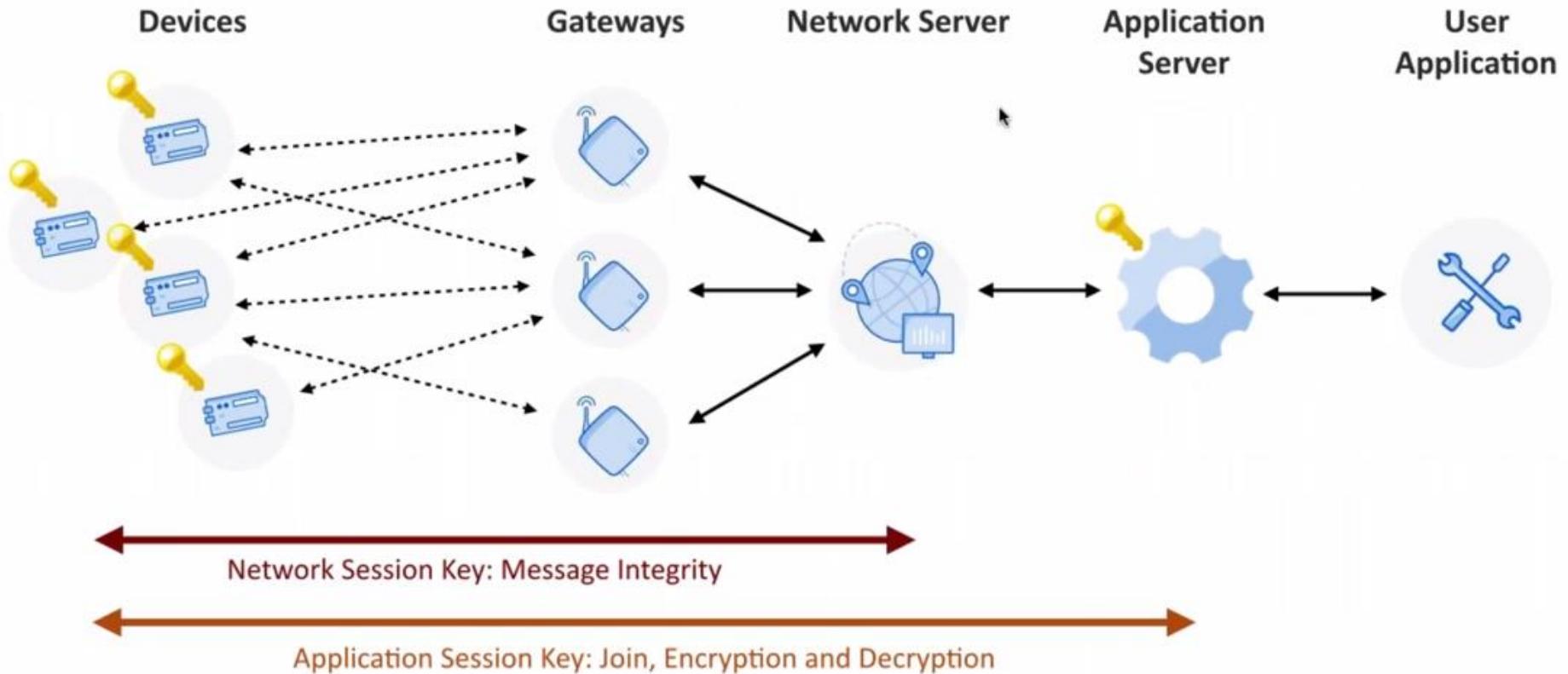
### Network initiated communication

The devices are continuously listening, often temporarily or on power supply

The network can send downlink message at any given time

Best for downlink intensive applications that require low latencies

# LoRaWAN Topology



- **Low speed and low power, but also long range**
- Meant for remote meter reading, also used for any remote data uplink
- Proprietary network and protocol
- Typical range: long, 24 km, global (partial) coverage  
<https://www.sigfox.com/en/coverage>
- Max output power: low, 0.025 W
- Bandwidth: very low, up to 140 messages per object per day, 12 bytes payload, 100 bps
- Security: no encryption
- Cost: cheap client equipment, for transmission about 1/12€ per device per year
- Good for: remote electricity or water meter reading, mostly useful if you do not need to send data to the device

# NB-IoT Introduction



- **Low Power Wide area network**
- Narrow Band IoT also known as Cat-M2/CAT-NB
- Based on 4G/LTE
- Features Deep Indoor Penetration
- Long Battery Life
- Connections of Thousands of Devices in a Cell
- Cost Efficient Implementation
- Good Network Coverage in difficult environment e.g. basement or remote regions
- Optimal security through end-to-end encryption
- Applications
  - Focused on very low data rates, ideal for simple sensor application
  - Smart Meter
  - Agriculture
  - Home Automation
  - Street lighting

# NB-IoT Features

- NB-IoT, also known as Cat-NB
- Cat-NB operates in the licensed spectrum.
- The goal is to reduce power (10-year battery life), extend coverage (+20 dB), and reduce cost (\$5 per module).
- Cat-NB is based on the Evolved Packet System (EPS) and optimizations to the Cellular Internet of Things (CIoT).
- Channels are much narrower than even the 1.4 MHz Cat-M1, cost and power can be reduced even further.

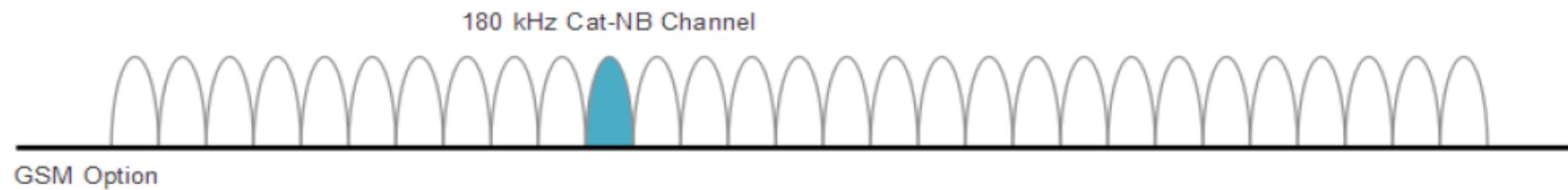
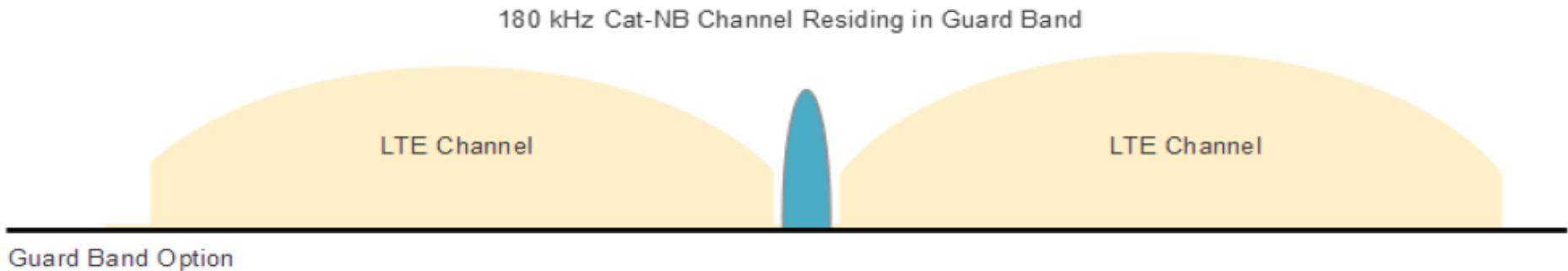
Significant differences between Cat-NB and Cat-M1 include:

1. **Very narrow channel bandwidth:** As with Cat-M1, which reduced the channel width to 1.4 MHz, Cat-NB reduces it further to 180 kHz for the same reasons (reducing cost and power).
2. **No VoLTE:** As the channel width is so low, it does not have the capacity for voice or video traffic.
3. **No mobility:** Cat-NB will not support handover and must remain associated with a single cell or remain stationary. This is fine for the majority of secured and fastened IoT sensor instruments.

# NB-IoT Deployment Options

- Since the channel width is so small (180 kHz), it allows for the opportunity to bury the Cat-NB signal
  1. inside a larger LTE channel (**In-band**)
  2. replace a **GSM channel**,
  3. even exist in **the guard channel** of regular LTE signals.
- **In-band** provides a massive amount of spectrum to use as the LTE bands are much larger than the 180 kHz band. This allows for deployments of up to 200,000 devices in theory per cell. In this configuration, the base cell station will multiplex LTE data with Cat-NB traffic.
- Using Cat-NB as the LTE **guard band** is a unique and novel concept. Since the architecture re-uses the same 15 kHz subcarriers and design, it can be accomplished with existing infrastructure.
- The GSM option is simplest and fastest to market. Some portions of the **existing GSM traffic** can be replaced with NB-IoT

# NB-IoT Deployment Options



# Other Wireless Protocols

- LTE Cat-M
  - use cellular channels for long range, limited bandwidth communication
  - still in development or with limited coverage
- Satellite
  - huge coverage
  - extremely expensive

# Outline

## 1. Introduction to IoT

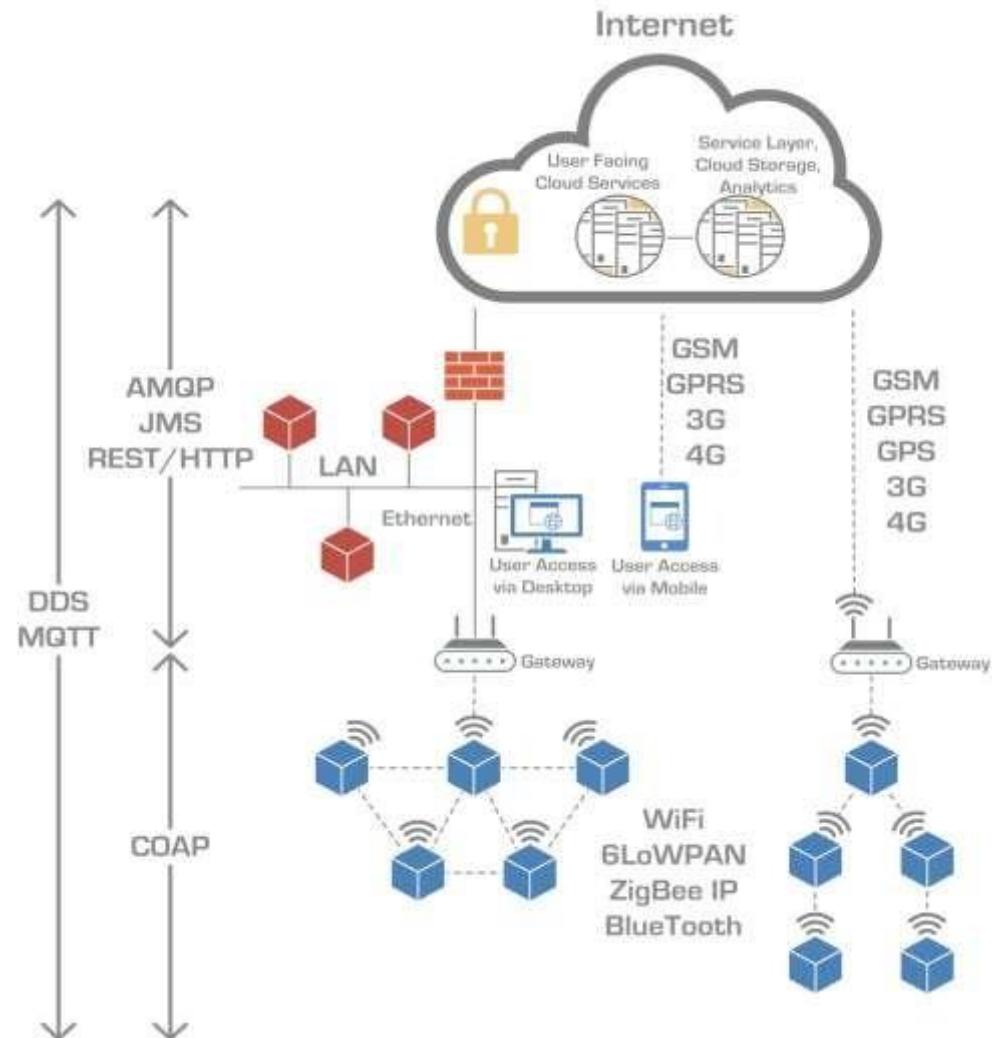
- definition, enabling technologies and concepts to better understand the general framework of IoT solutions
- layering architecture, cloud computing vs. fog computing

## 2. Most relevant components of IoT solutions

- devices, wireless communication protocols, **data exchange protocols**

# IoT Connectivity Problem Space

- Wired/wireless protocols to transport bits
- **Messaging protocols to transfer data**
- **Data:** information and commands described following a given syntax and semantic
- **Messaging protocols to exchange data:** encapsulate data and transmit it via wired/wireless protocols



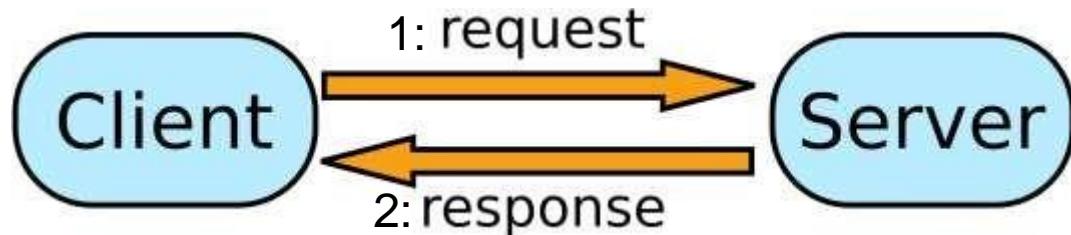
# Data Exchange Protocols

- How to encapsulate information and commands in messages?
- Data from gateways to servers: who should initiate the communication?
  - **push**: gateways autonomously decide to send messages to servers, e.g., when new sensed values are available
  - **pull**: servers ask to gateways to send messages, e.g., only when servers actually require sensed values
- Two primary models
  - **request/response**, can be push or pull
  - **publish/subscribe**, usually only push
- Several protocols:
  - request/response: REST/HTTP, CoAP, ...
  - publish/subscribe: MQTT, AMQP, DDS, ...

# Multiple Protocols supporting Different Features

- Several protocols thriving to become a de facto standard
- It could be difficult to pick up the **best solution**, since it **depends on requirements** of a given application domain
- Some request/response protocols:
  - REST architectural principles (REpresentational State Transfer), 2000
  - CoAP (Constrained Application Protocol), 2014 (also pub/sub)
- Some publish/subscribe protocols:
  - MQTT (Message Queue Telemetry Transport), 1999
  - AMQP (Advanced Message Queuing Protocol), 2003
  - DDS (Data Distribution Service), v1.0 2003; v1.2 2007
- At different level of abstractions, LonWorks (1999), Modbus (1979)...

# Request/Response model



- A **client application** requests services (e.g., send data, require data, perform an addition) and a server application responds to the service request (e.g., by providing the data or the addition results)
- **Direct communication** between client and server
- Data exchange only if **the client starts the communication**
  - the server is not able to contact the client autonomously
- Typical interactions in the IoT scenario:
  - **push**: sensors send data to servers
  - **pull**: actuators request to servers new configurations

# REST - REpresentational State Transfer

- REST is not an actual protocol, but substantially a **solution architectural style**
- Promote **client/server** and **stateless** interaction, oriented to the usage of **caching** opportunities, also with possibility of code-on-demand to clients
- Usually based on HTTP, the protocol used to surf the Web
- Very simple, but each time the client has to start the communication from the beginning

# REST: Identifying and Interacting with Resources

- **URI (Uniform Resource Identifier) to identify the remote resource**
  - any resource has a **persistent identifier**
  - do not transfer resources but their representations via HTTP
  - **endpoint** for a service managing user information:  
[www.examples.com/resources/users](http://www.examples.com/resources/users)
- **HTTP method to interact** with remote resources in a standard manner
  - **GET, retrieve** a specific resource (by id) or a collection of resources
  - **PUT, create** a new resource
  - **POST, update** a specific resource (by id)
  - **DELETE, remove** a specific resource by id

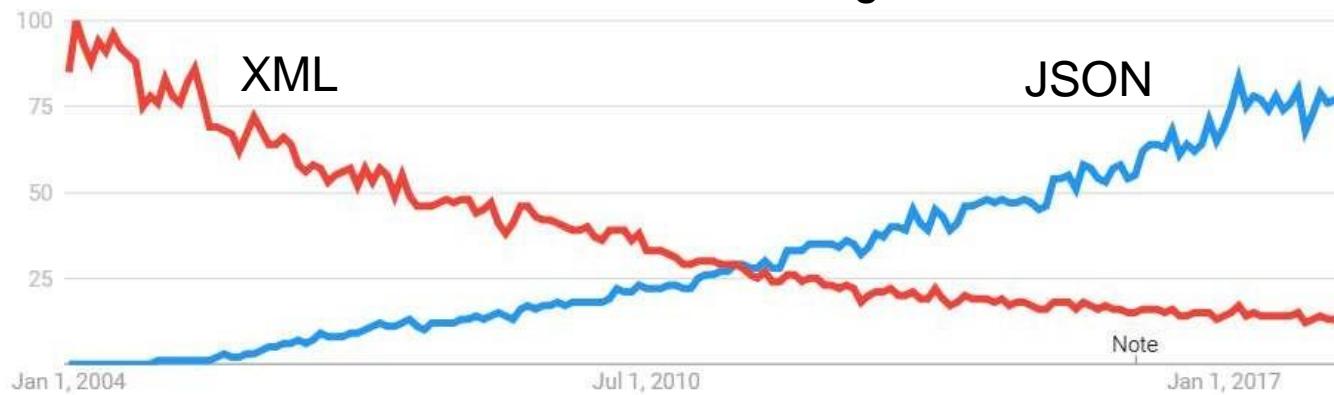
# REST: Endpoint Examples

- Remote resource: a software component managing users

| HTTP Method | URI                                                                                        | Operation                 |
|-------------|--------------------------------------------------------------------------------------------|---------------------------|
| GET         | <a href="http://www.examples.com/resources/users">www.examples.com/resources/users</a>     | Get list of users         |
| GET         | <a href="http://www.examples.com/resources/users/1">www.examples.com/resources/users/1</a> | Get the user with id 1    |
| DELETE      | <a href="http://www.examples.com/resources/users/1">www.examples.com/resources/users/1</a> | Delete the user with id 1 |
| POST        | <a href="http://www.examples.com/resources/users/2">www.examples.com/resources/users/2</a> | Update the user with id 2 |
| PUT         | <a href="http://www.examples.com/resources/users/1">www.examples.com/resources/users/1</a> | Insert the user with id 1 |

# REST: Formatting data

Google Trends: 2014-2018



- JavaScript Object Notation (JSON) most spread syntax for **formatting/serializing data**, e.g., objects, arrays, numbers, strings, booleans, and null
- Resource: a group of users, each one with a first name and a last name

```
{“users”:
 [
 { “firstName”:”John”, “lastName”:”Doe” },
 { “firstName”:”Anna”, “lastName”:”Smith” },
 { “firstName”:”Peter”, “lastName”:”Jones” }
]
}
```

# REST: AWS IoT example

- Adds a thing to a thing group

**PUT /thing-groups/addThingToThingGroup**

HTTP/1.1

Content-type: application/json

```
{
 "thingArn": "string",
 "thingGroupArn": "string",
 "thingGroupName": "string",
 "thingName": "string"
}
```

- Manage “shadows” of things

**POST endpoint/things/thingName/shadow**

HTTP/1.1

```
{ Content-type: application/json

 "state":
 {
 "desired":
 {
 "color" : { "r" : 10 },
 "engine" : "ON"
 }
 }
}
```

# CoAP - Constrained Application Protocol

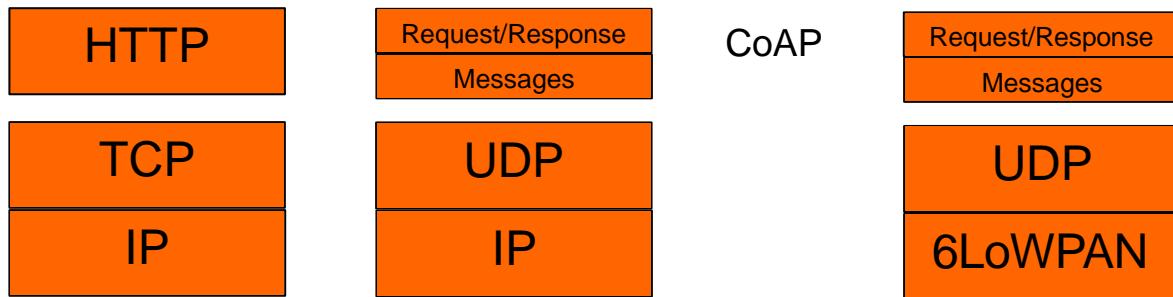


- Designed for M2M/IoT applications such as smart-metering, e-health, building and home automation with:
  - **constrained nodes**, e.g., 8-bit microcontrollers with 16KB RAM and battery-operated
  - **constrained networks**, e.g., Wireless Sensor Networks
- Low-overhead **request/response** protocol that also supports discovery of services/resources
- Based on **UDP** communications (with multicast)
- Inspired by (and compatible with) the **HTTP protocol** and REST architectures: CoAP is a specialized Web transfer protocol

# CoAP Features

- **Web RESTful protocol** fulfilling M2M requirements in constrained environments
- **Simple request/response HTTP mapping**, to access CoAP resources via HTTP
- **URI** and Content-type support (a sensor is identified by an URI)
- **Low header overhead** and parsing complexity
- **Security** binding to Datagram Transport Layer Security (DTLS)
- UDP binding with **optional reliability**, supporting unicast and multicast
- **Asynchronous** message exchanges
- Services and resources **discovery**
- Also **publish/subscribe** (and push notifications)
- Simple **caching** (max-age parameter)
- CoAP implementations in many programming language, e.g., C, C++, and Java

# CoAP Messaging

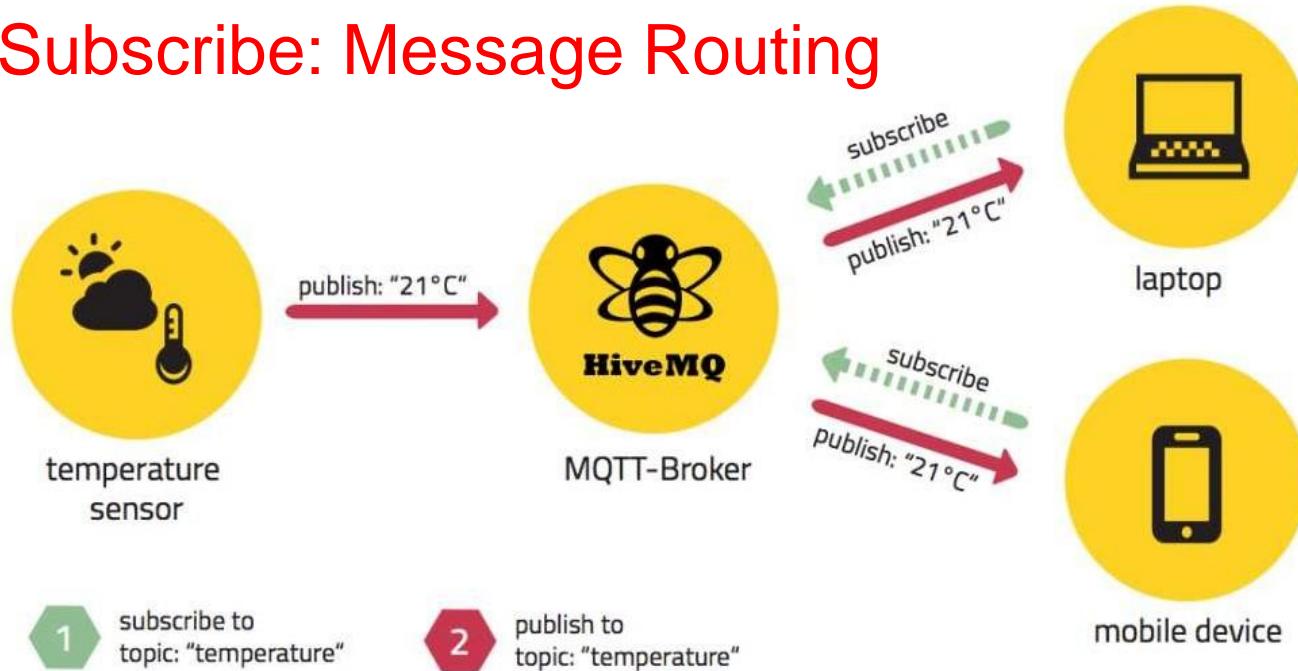


- Duplicate detection and optional reliability
- Possible messages:
  - confirmable message (CON), wait for ACK
  - acknowledgement message (ACK), in response to CON
  - non-confirmable message (NON), no need to wait for ACK
- CoAP on top of UDP allows for multicast requests

# Publish/Subscribe model

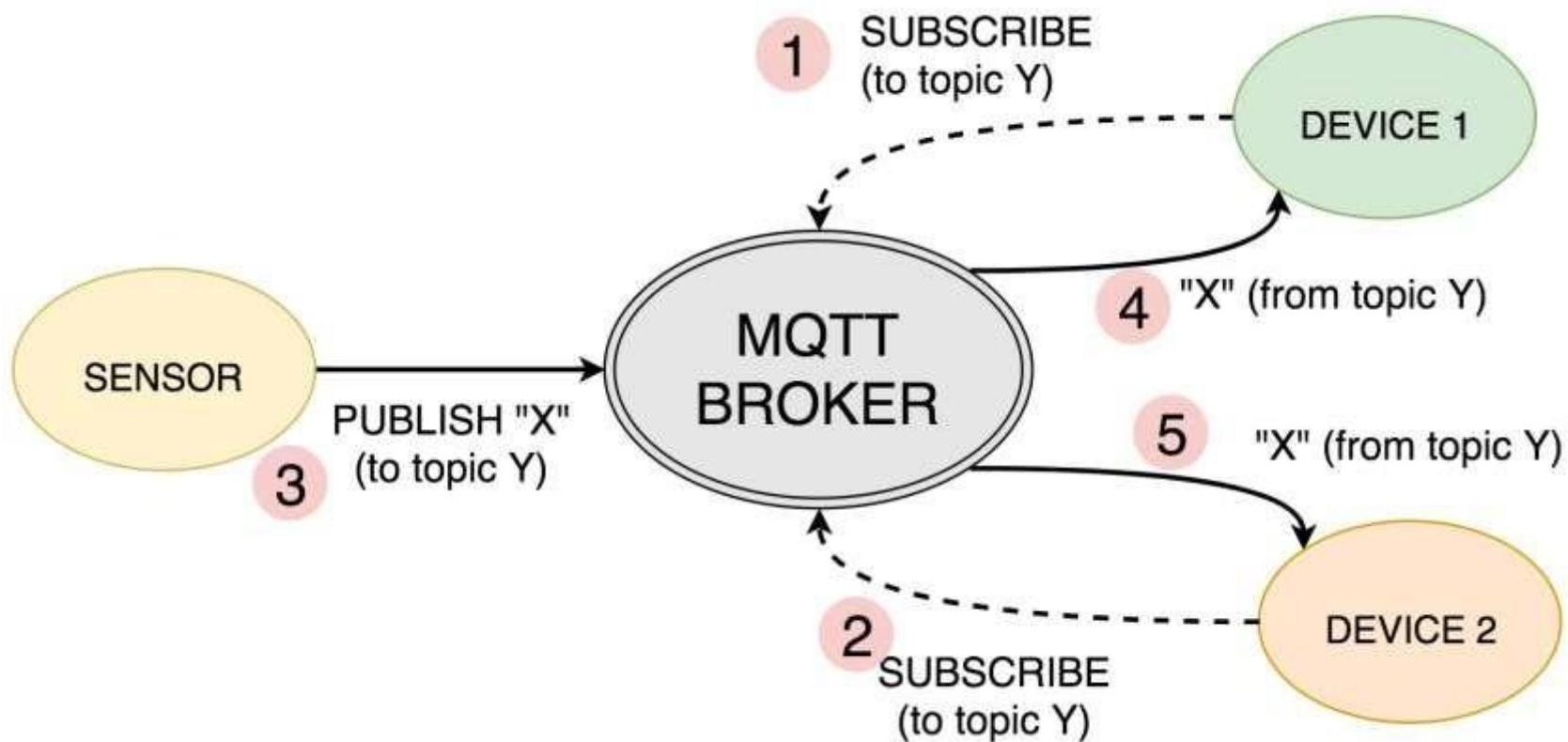
- Publish/subscribe (pub/sub) pattern alternative to traditional client-server model, where a client communicates directly with an endpoint
- Roles:
  - **publisher**: a client sending a message
  - **subscriber**: one or more receivers waiting for the message
  - **broker**: a central component receiving and distributing messages to interested receivers

# Publish/Subscribe: Message Routing



- The broker **routes messages** (i.e., selects receivers of a message) based on:
  - **Message Topic:** a subject, part of each message. Receiving clients subscribe on the topics they are interested in with the broker and from there on they get all message based on the subscribed topics
  - **Message Type:** depending on the type of the message
  - **Message Header:** depending on a set of fields of the message
  - **Message Content:** possibly depending on the whole message content (expressive but expensive)

# Publish/Subscribe: Typical Sequence



# Publish/Subscribe: Decoupling

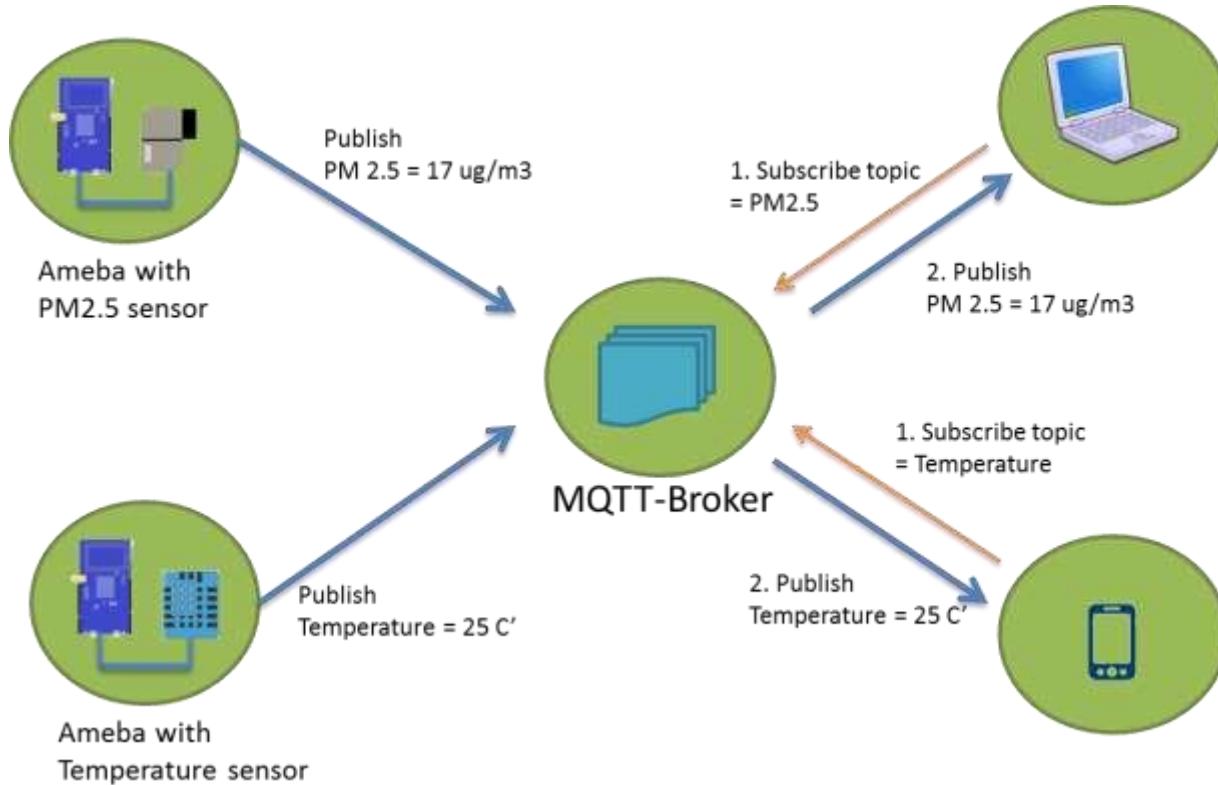
- **Space decoupling:** publisher and subscriber do not need to know each other (by ip address and port for example)
- **Time decoupling:** publisher and subscriber do not need to run at the same time
- **Synchronization decoupling:** operations on both components are not halted during publish or receiving
- Event system as **logically centralized** system
  - anonymous communication
  - possibility to use filters (on headers or entire messages)
  - basic primitives: subscribe, unsubscribe, publish

# MQTT - Message Queue Telemetry Transport



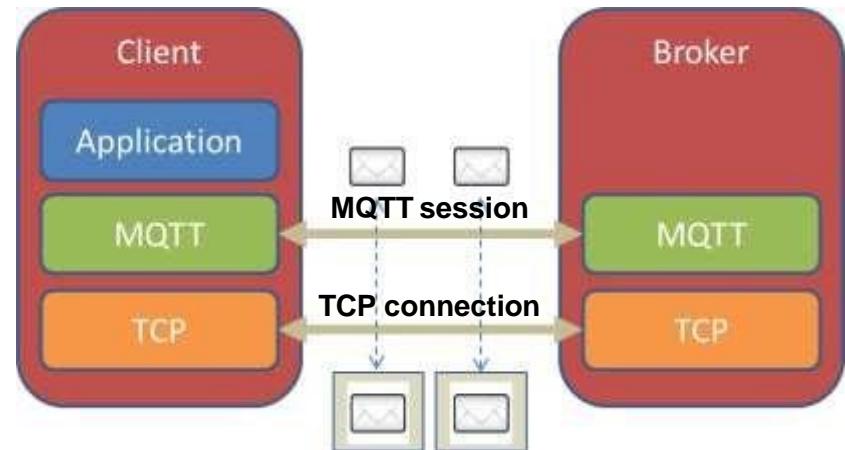
- IBM developed WebSphere MQ as a message-based backbone mainly for Enterprise Application Integration (EAI), MQTT is its evolution:
  - an open standard but it is strongly supported by IBM
  - designed to permit WebSphere MQ to talk with constrained (smart) devices at the edge of the network
- **MQTT: simple, lightweight, broker-based, publish/subscribe, open messaging protocol**
- Ideal for use in **constrained nodes and networks**
  - on embedded devices with limited processor or memory resources
  - where the network is expensive, has low bandwidth or is unreliable
- MQTT-SN for wireless sensor networks, aimed at embedded devices on non-TCP/IP networks (such as Zigbee).

# MQTT: Typical Use Case



1. Subscribe to one ore more topic
2. Publish to a topic
3. Receive messages related to subscribed topics

# MQTT: Features (1)



- **Publish/subscribe** message pattern to provide
  - one-to-many message distribution
  - decoupling of applications
- Use of **TCP/IP** to provide basic network connectivity
- **Small transport overhead** (minimal header length just 2 bytes) and protocol exchanges minimised to reduce network traffic
- **Easy to use** with few commands: connect, subscribe, publish, disconnect
- **Retained messages**: an MQTT broker can retain a message that can be sent to newly subscribing clients

## MQTT: Features (2)

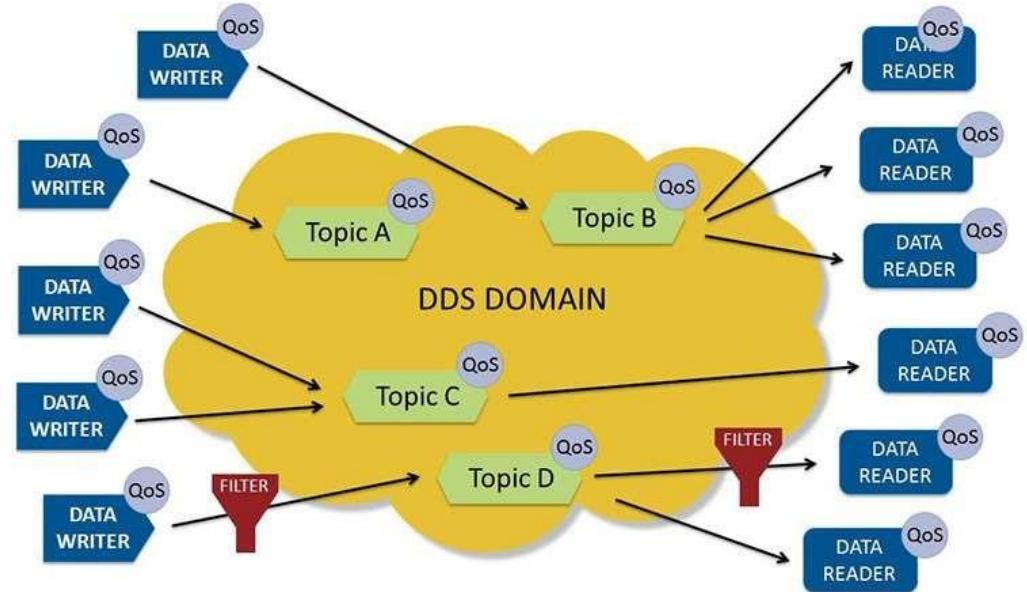
- **Three message delivery semantics** with increasing reliability and cost:
  - Quality of Service (QoS): at least once, at most once, exactly once
- **Durable connection**: client subscriptions remain in effect even in case of disconnection
  - subsequent messages with high QoS are stored for delivery after connection reestablishment
- **Wills**: a client can setup a will, a message to be published in case of unexpected disconnection, e.g., an alarm
- MQTT is a protocol adopted in several platforms: there are MQTT brokers in WebSphere, Mosquitto, RabbitMQ, etc. and clients in several languages

# AMQP – Advanced Message Queuing Protocol



- **Richer semantic** than MQTT, e.g., supports topics and queues, but also **heavier**, e.g., the broker is much more complex
- AMQP implementations, e.g., Apache Qpid, focus on providing **several features**: queuing, message distribution, security, management, clustering, federation, heterogeneous multi-platform support
  - most of them (possibly) not essential in the IoT scenario
- Originally developed at JPMorgan Chase in London, AMQP was designed as a message-oriented protocol for the integration of enterprise IT components (Enterprise Message Bus)

# DDS - Data Distribution Service



- Publish/subscribe, but **broker-less** (based on multicast)
  - **scalable, real-time, dependable, high performance** and **interoperable**
- Proposed in several **mission-critical environments** where performance and reliability are essential, e.g., industrial automation, financial applications, air traffic control and management, and even military environments
  - <http://twinoakscomputing.com/datasheets/DDS-Brochure.pdf>
- Standard developed by the Object Management Group

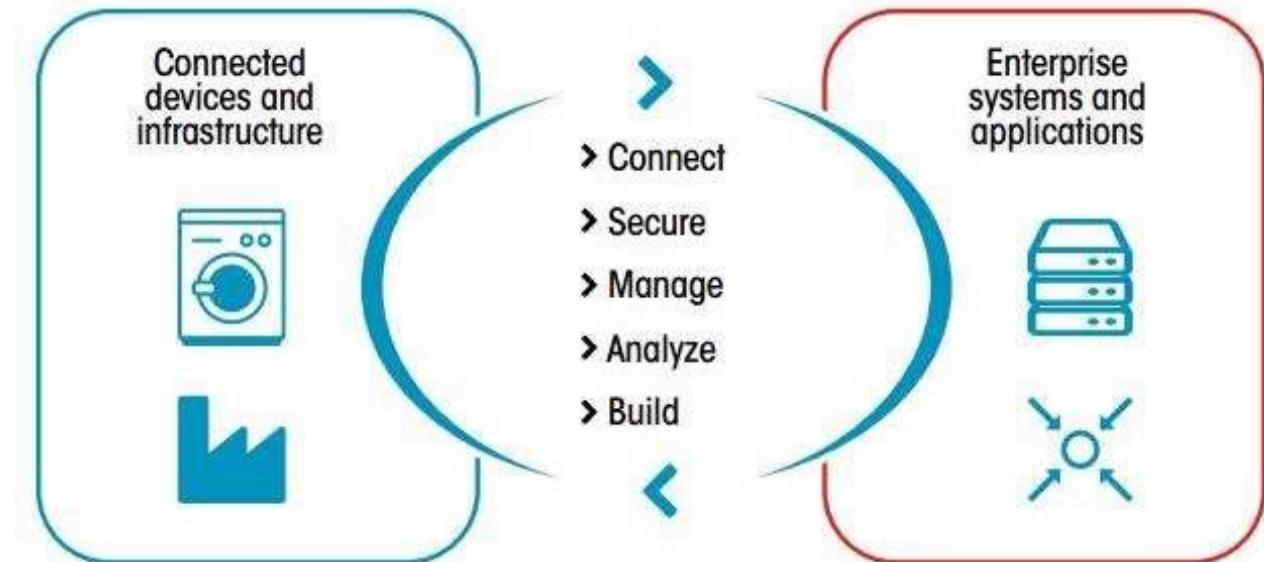
- Not actually an IoT platform, but an interesting **messaging infrastructure**
- **Robust** messaging for applications
- **Reliable** message delivery
- Distributed deployment as **clusters** for high availability and throughput
- **Federate** across multiple availability zones and regions.
- **Multi-Protocol**: AMQP, MQTT, HTTP, etc.
- **Managing and monitoring** via HTTP-API, command line tool, and UI
- Runs on all major operating systems
- Supports a huge number of developer platforms
- Open source and commercially supported

# RabbitMQ: Durable, Persistent, and Synchronized

- Exchanges (Topics) and Queues can be **durable**
  - capable of surviving to a broker restart (as opposed to transient)
- Messages can be defined as **persistent**
  - only persistent messages survive exchange/queue/brokers/channel failures
- **Synchronization**
  - **automatic** acknowledgement model, i.e., verify that the message is actually delivered to the application waiting for it
  - **explicit** acknowledgement model, i.e., wait for explicit acknowledgment sent back by the application
    - immediately at message reception, after processing, ...

# IoT Platforms

## IoT software platform



- IoT Platform between things/devices and business applications
  - **connect** devices to gather information
  - **secure** communication with devices and applications
  - **manage** devices to control their behavhior
  - **analyze** data, e.g., with AI
  - **build** applications, also interacting with CRM/ERP/...

# Several IoT Platforms

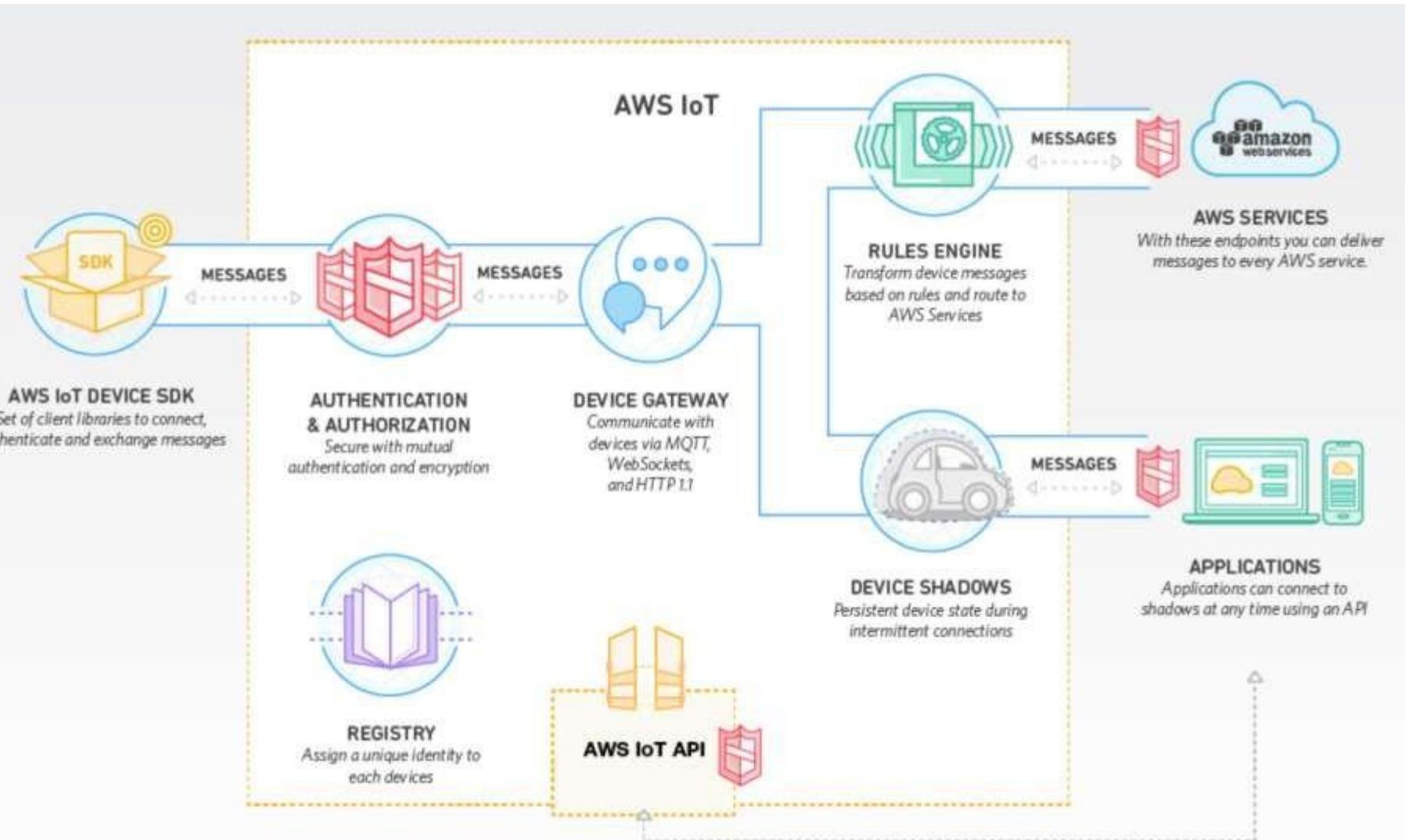
We go a bit deeper into a selection of the many available ones:

- Amazon Web Services (AWS) IoT
- Microsoft Azure IoT Hub
- Mindsphere by Siemens
- EdgeXFoundry

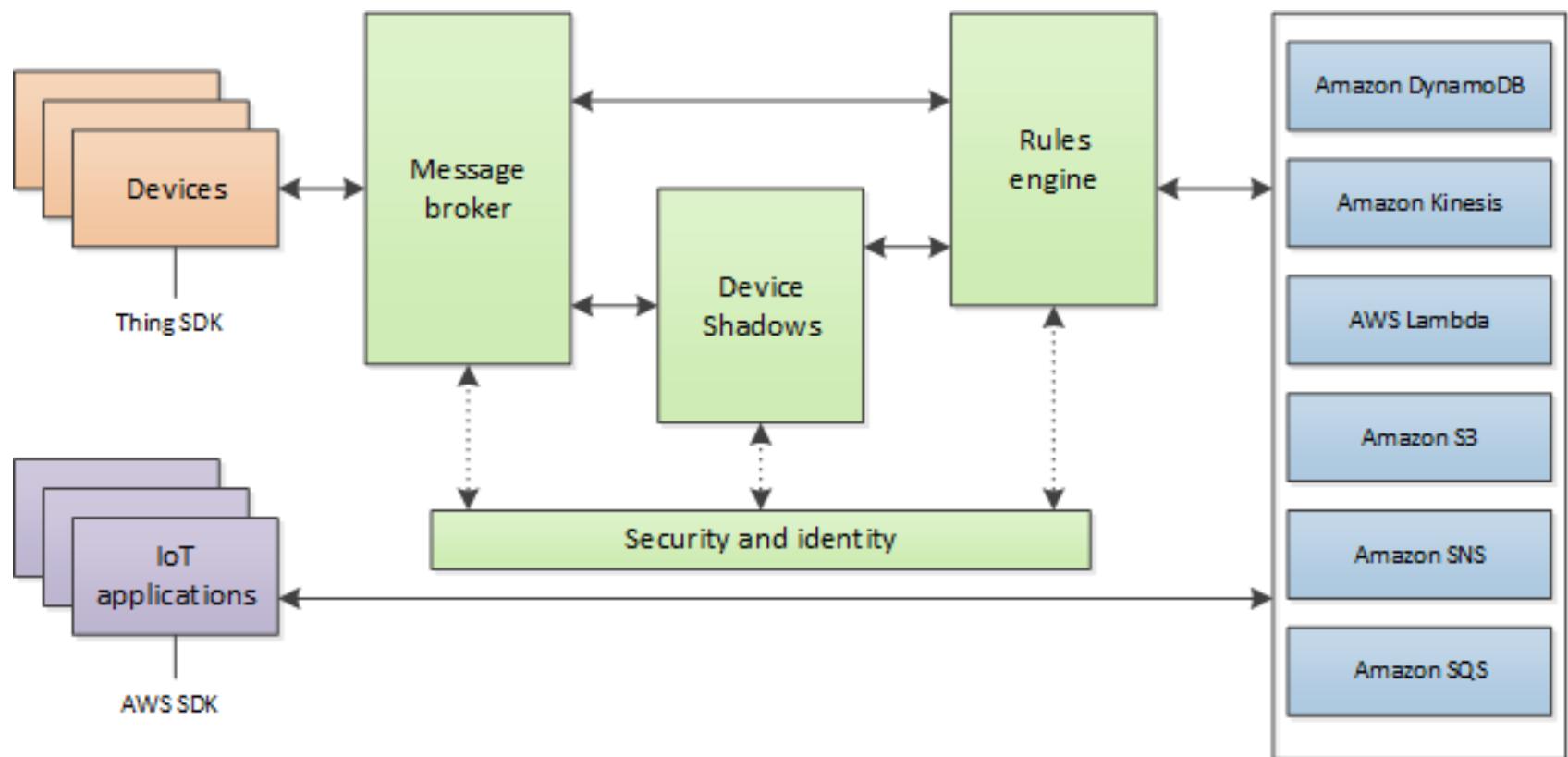
And several others:

- Google Cloud Platform
- ThingWorx IoT Platform
- IBM Watson
- Carriots
- Kaa
- ...

# Amazon Web Services (AWS) IoT



# AWS IoT: Architecture



- <https://docs.aws.amazon.com/iot/latest/developerguide/aws-iot-how-it-works.html>

# AWS IoT: Main Components (1)

- **AWS IoT Device SDK** connects devices to AWS IoT by using the MQTT, HTTP, or WebSockets protocols
  - the Device SDK supports C, Java, JavaScript, Arduino, iOS, Android,...
- **Device Gateway** supports (secure) communication with devices, by using a (1:1 or 1:n) **publish/subscribe** model
  - supports MQTT, WebSockets, and HTTP 1.1 protocols
- **Authentication and Authorization** with mutual authentication and encryption
  - authentication with native AWS (called ‘SigV4’) as well as X.509 certificate based authentication
  - AWS facilitates the whole certificate process management
- **Registry** assigns a **unique identity** to each device
  - also supports **metadata** describing capabilities of devices, e.g., whether a sensor reports temperature and if data in Fahrenheit or Celsius

## AWS IoT: Main Components (2)

- **Device Shadows**, i.e., persistent, virtual version of devices
  - applications or other devices exchange messages and **interact through the Shadow Device**
  - Device Shadows **persist** the last reported state and desired future state of each device even when the device is offline
  - exploit it to **retrieve the last reported state** of a device or **set a desired future state** through the API or using the rules engine
- **Rules Engine**, supporting to build IoT applications that gather, process, analyse, and act on data generated by connected devices
  - evaluates inbound messages published into AWS IoT and **transforms and delivers** them to another device or a cloud service, based on business rules you define
  - a rule can apply to data from one or many devices, and it can take one or many actions in parallel

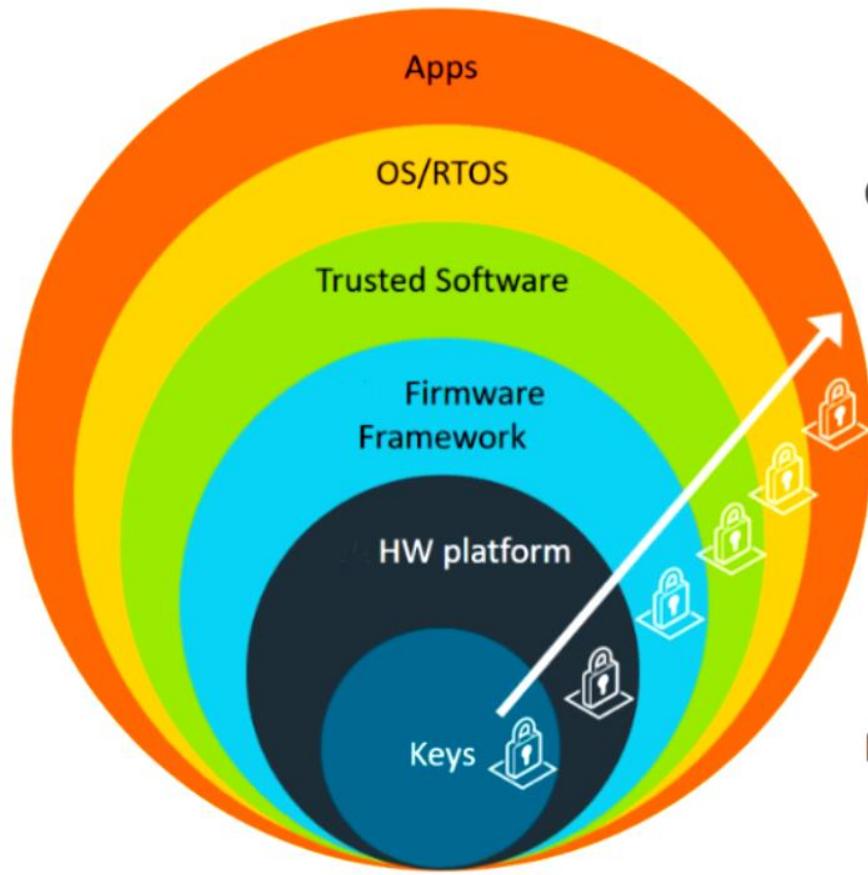
# Cryptographic Fundamentals & IoT Security

# Introduction to IoT Security

## Cybersecurity versus IoT security and cyber-physical systems

- A large element of what distinguishes the IoT from cybersecurity is what many industry practitioners today refer to as cyber-physical systems.
- Cybersecurity, generally does not address the physical and security aspects of the hardware device or the physical world interactions it can have.
- Digital control of physical processes over networks makes the IoT unique in that the security equation is not limited to basic information assurance principles of confidentiality, integrity and so on, but also that of physical resources and machines that originate and receive that information in the physical world. In other words, the IoT has very real analog and physical elements. IoT devices are physical things, many of which are safety-related. Therefore, the compromise of such devices may lead to physical harm of persons and property, even death.

# Onion Model for IoT Security



OS/RTOS

Trusted Apps/Libs

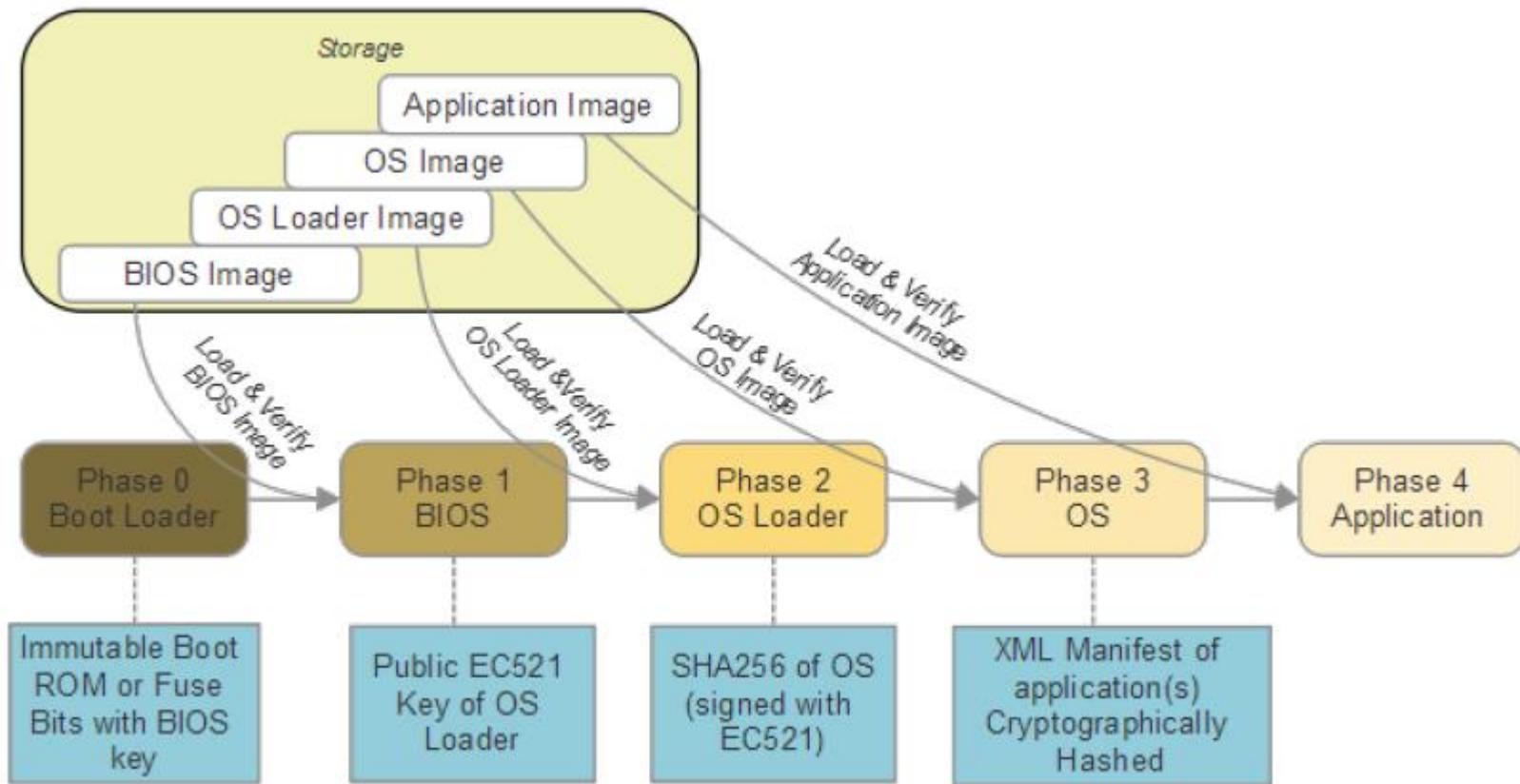
Extended Root of Trust

Initial Root of Trust: Dependable Security functions

Provisioned keys/certs

# Root of Trust

- Here is a five-phase boot building up a Chain of Trust and starting with a Boot Loader in immutable read-only memory.



- Each phase maintains a public key that is used to verify the authenticity of the next component loaded.

# Common IoT attack types

There are many attack types to cover however, the following list provides some of the most significant as they relate to the IoT:

- Wired and wireless scanning and mapping attacks
- Protocol attacks
- Eavesdropping attacks (loss of confidentiality)
- Cryptographic algorithm and key management attacks
- Spoofing and masquerading (authentication attacks)
- Operating system and application integrity attacks
- Denial of service and jamming
- Physical security attacks (for example, tampering, interface exposures)
- Access control attacks (privilege escalation)

# Cryptography and its role in securing the IoT

- Cryptography provides an indispensable tool set for securing data, transactions, and personal privacy in our so-called information age.
- When properly implemented, cryptography can provide the following security features to any data whether in transit or at rest:

| Security feature | Cryptographic service(s)                                         |
|------------------|------------------------------------------------------------------|
| Confidentiality  | Encryption                                                       |
| Authentication   | Digital signature or<br><b>Message authentication code (MAC)</b> |
| Integrity        | Digital signature or MAC                                         |
| Non-repudiation  | Digital signature                                                |

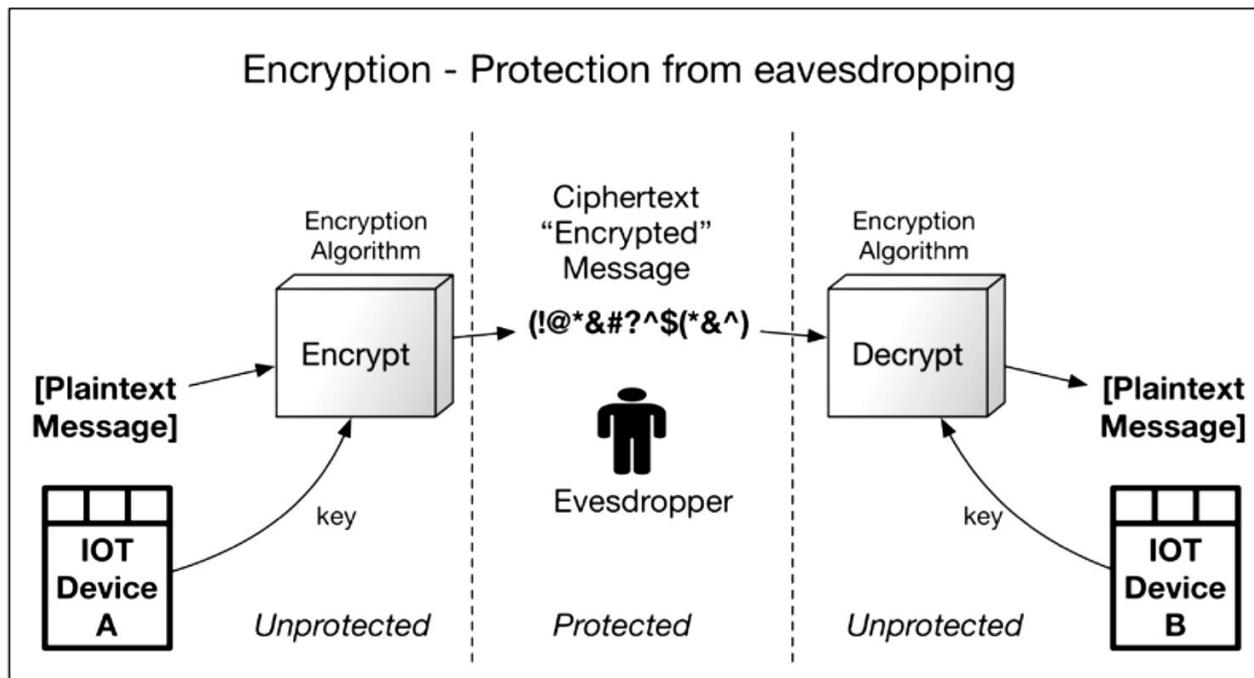
# Cryptography

Cryptographic primitive types fall into the following categories:

- Encryption (and decryption):
  - Symmetric
  - Asymmetric
- Hashing
- Digital signatures
  - **Symmetric**: MAC used for integrity and data-origin authentication
  - **Asymmetric**: **Elliptic curve (EC)** and **integer factorization cryptography (IFC)**. These provide integrity, identity, and data-origin authentication as well as non-repudiation
- **Random number generation**: The basis of most cryptography requires very large numbers originating from high entropy sources

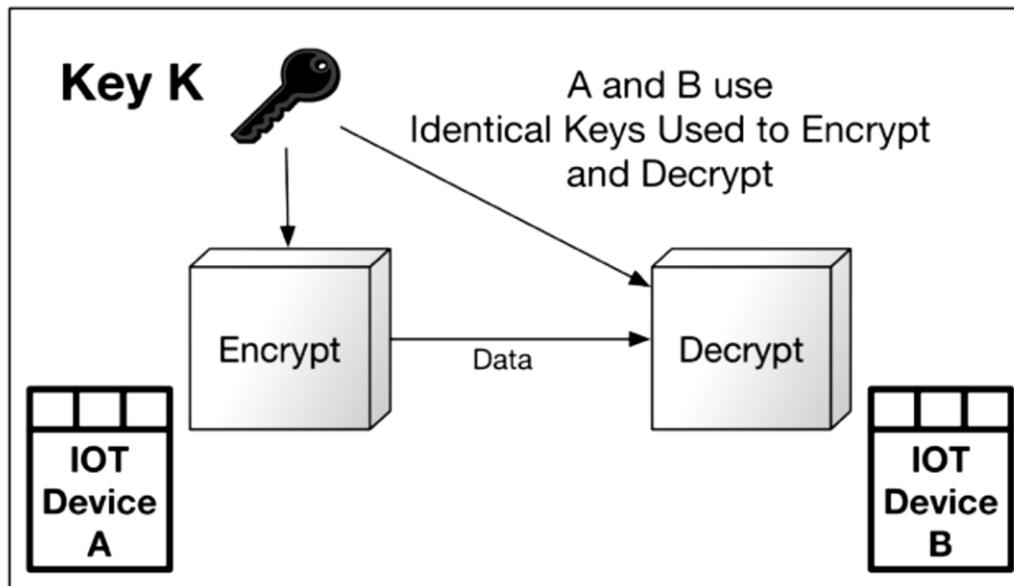
# Encryption and decryption

- Encryption is the cryptographic service most people are familiar with as it is used to so-called scramble or mask information so that unintended parties cannot read or interpret it.
- It is used to protect the confidentiality of the information from eavesdroppers and only allow it to be deciphered by intended parties.



# Symmetric encryption

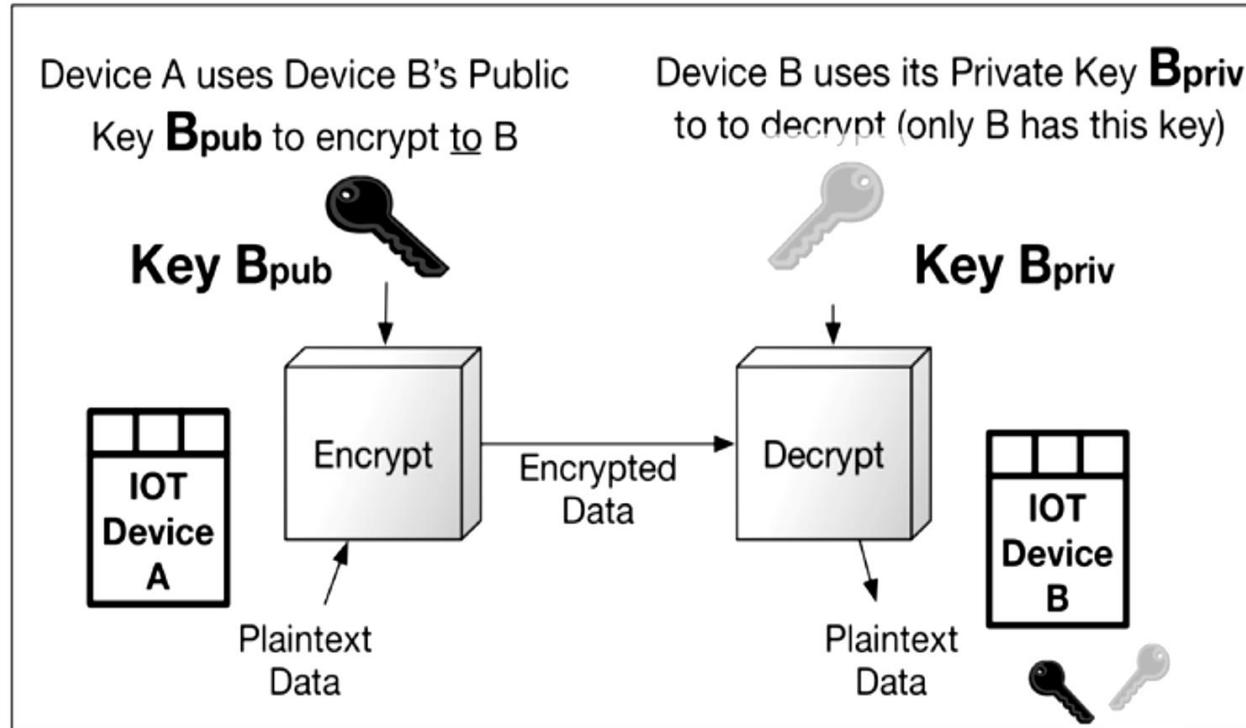
- Symmetric encryption simply means the sender (encryptor) and the receiver (decryptor) use an identical cryptographic key.



- Symmetric algorithms consist of a ciphering operation using the plaintext or ciphertext input, combined with the *shared* cryptographic key. Common ciphers include the following:
  - **AES—advanced encryption standard**
  - Blowfish
  - DES and triple-DES

# Asymmetric encryption

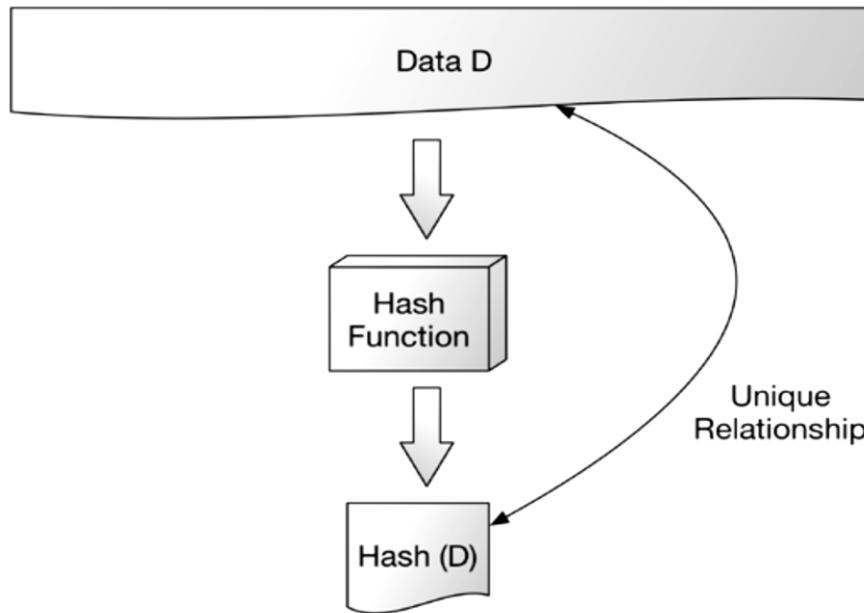
- Asymmetric encryption simply means there are two different, pairwise keys, one public and the other private, used to encrypt and decrypt, respectively



- The only asymmetric encryption algorithm in use today is that of **RSA** (**Rivest, Shamir, Adelman**),

# Hashes

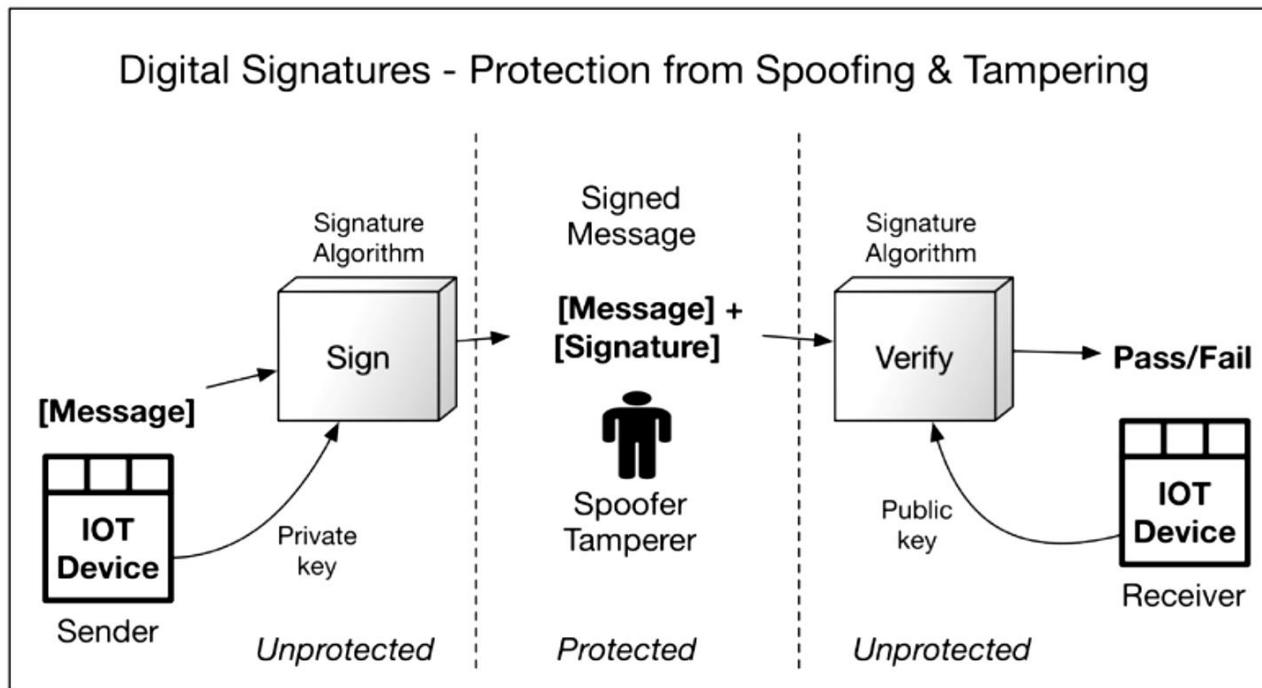
- Cryptographic hashes are used in a variety of security functions for their ability to represent an arbitrarily large message with a small sized, unique thumbprint (the hash). They have the following properties:



- They are designed **not to disclose any information about the original data** that was hashed (this is called resistance to first pre-image attacks)
- They are designed to **not allow two different messages to have the same hash** (this is called resistance to second pre-image attacks and collisions)
- They produce a very **random-looking value (the hash)**

# Digital signatures

- A **digital signature** is a cryptographic function that provides integrity, authentication, data origin, and in some cases, non-repudiation protections.
- Like a hand-written signature, they are designed to be unique to the *signer*, the individual or device responsible for signing the message and who possesses the signing key.



## Symmetric (MACs)

- Signatures can also be generated using symmetric cryptography. Symmetric signatures are also called MAC
- MACs are used in a variety of protocols, such as SSL, TLS, IPSec, and many others. Examples of MACs include the following:
  - HMAC-SHA1
  - HMAC-SHA256

# Random number generation

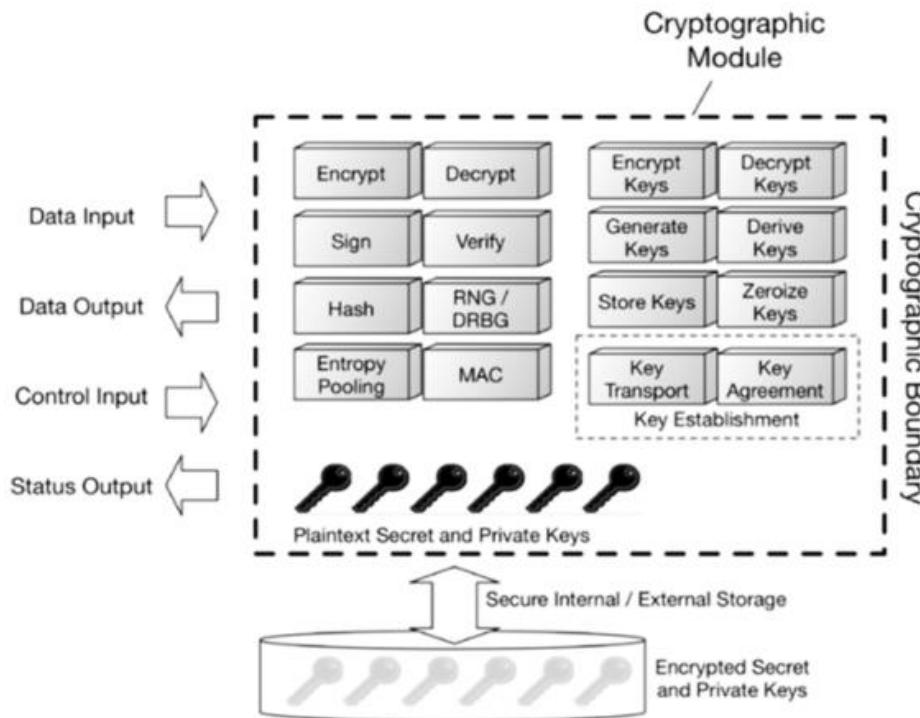
- Randomness of numbers is a keystone of cryptography given their use in generating several different cryptographic variables such as keys. Large, random numbers are difficult to guess or iterate through (brute force), whereas highly deterministic numbers are not.
- Random number generators—RNGs—come in two basic flavors, deterministic and nondeterministic.
  - Deterministic simply means they are algorithm-based and for a single set of inputs they will always produce the same output.
  - Non-deterministic means the RNG is generating random data in some other fashion

# Cipher suites

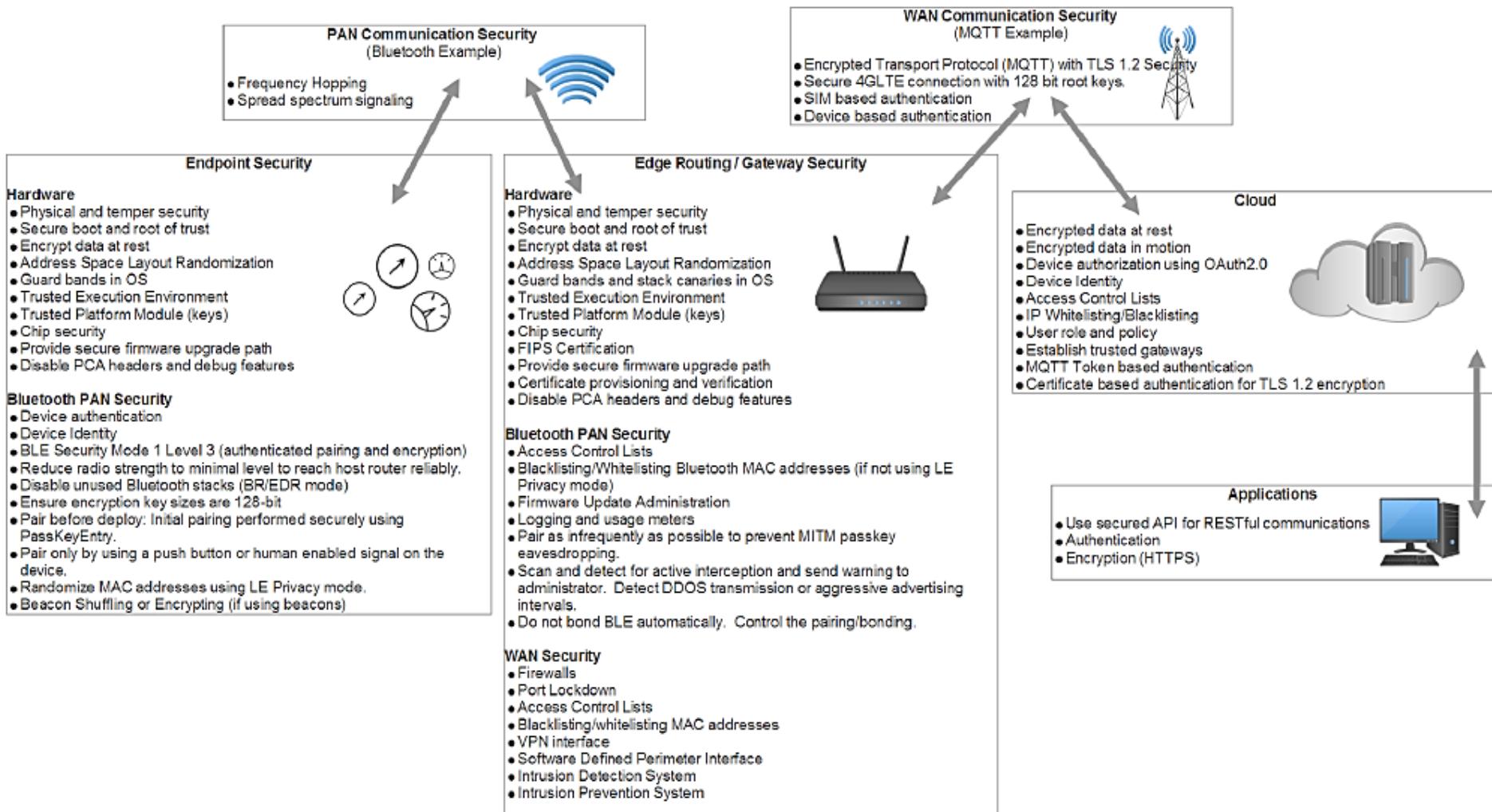
- The fun part of applied cryptography is combining one or more of the above algorithm types to achieve specifically desired security properties. In many communication protocols, these algorithm groupings are often called **cipher suites**.
- An example TLS cipher-suite enumeration and their interpretation is as follows:
- TLS\_RSA\_WITH\_AES\_128\_GCM\_SHA256, which interprets to using:
  - RSA algorithm for the server's public key certificate authentication (digital signature). RSA is also the public key-based key transport (for passing the client-generated pre-master secret to the server).
  - AES algorithm (using 128-bit length keys) for encrypting all data through the TLS tunnel.
  - AES encryption is to be performed using the **Galois counter mode (GCM)**; this provides the tunnel's ciphertext as well as the MACs for each TLS datagram.
  - SHA256 to be used as the hashing algorithm.

# Cryptographic module principles

A cryptographic implementation can be realized in hardware, software, firmware, or some combination thereof, and is responsible for processing the cryptographic algorithms and securely storing cryptographic keys (remember, compromise of your keys means compromise of your communications or other data).



# Sensor to cloud holistic security



Bluetooth-enabled sensors communicating through an edge gateway ultimately to a cloud service. Each layer needs to provide integrity and protection. Security involves both hardware and software components. This includes the security of physical devices to prevent tampering, radio signals to prevent jamming and DOS, Root of Trust hardware and ASLR to prevent malicious code injection, data by use of encryption, pairing and association by use of authentication, network through VPNs and firewalls, and so on.

# 5G Introduction

- 5G (or 5G-NR for new radio) is the next generation IP-based communication standard being drafted and designed to replace 4G-LTE.
- 5G promises to deliver substantial abilities for IoT, commercial, mobile, and vehicular use cases.
- 5G also improves bandwidth, latency, density, and user cost.
- 5G is not a continuing evolution of 4G; it derives from 4G but is a new set of technologies.
- In our scope , we will only discuss elements that pertain to IoT use cases or are of merit and have the potential to become part of the 5G specification.

# 5G features

The consensus of features in 5G that should be understood and have a good prospect of being in the final release are:

## 1. Enhanced Mobile Broadband (eMBB):

- 1 to 10 GBps connections to UEs/endpoints in the field (not theoretical)
- 100% coverage across the globe (or perception of)
- 10 to 100x the number of connected devices over 4G-LTE
- Connectivity at a speed of 500 km/h

## 2. Ultra-Reliable and Low-Latency Communications (URLLC):

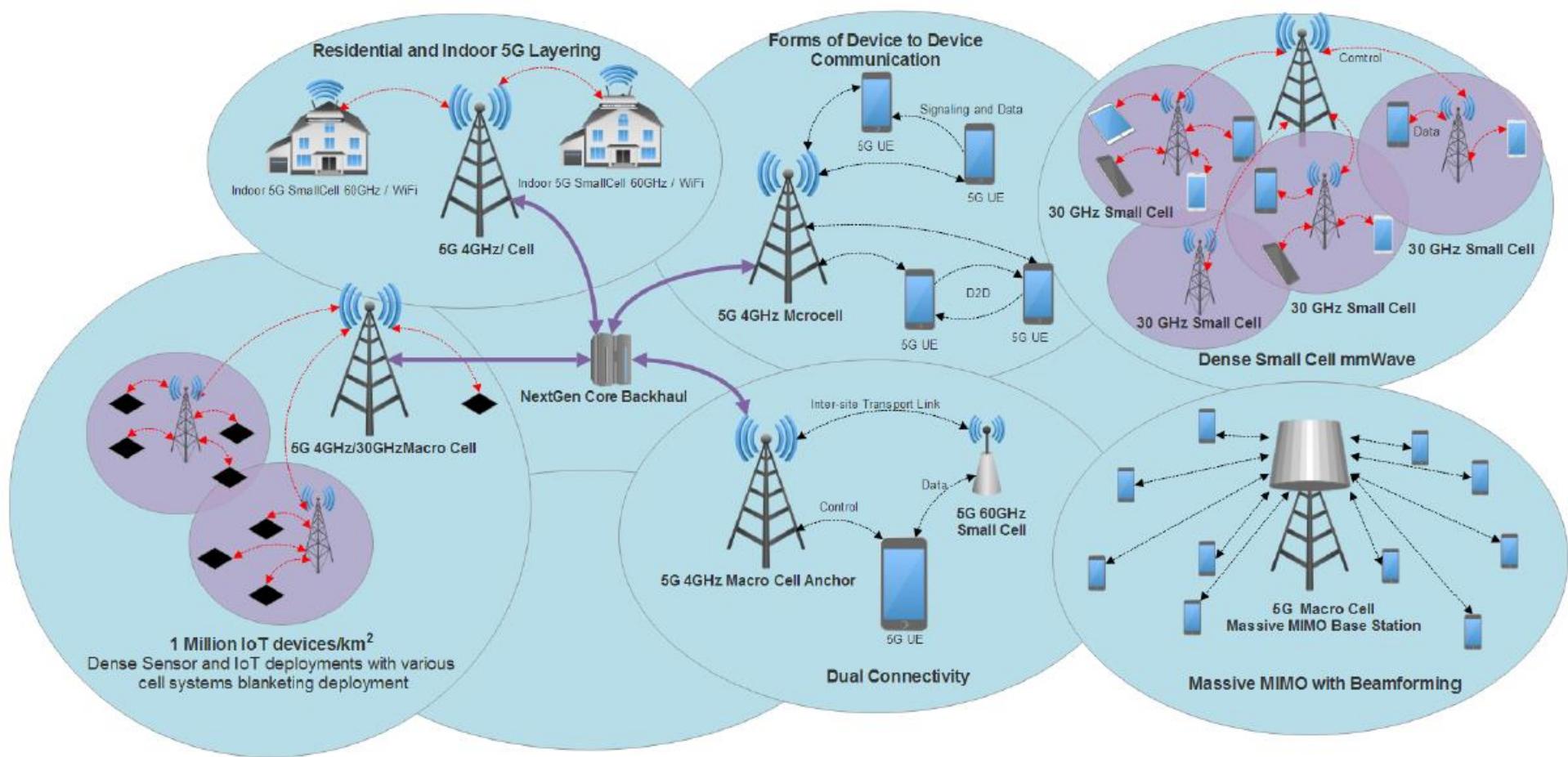
- Sub < 1 ms end-to-end round-trip latency
- 99.999% availability (or perception of)

## 3. Massive Machine Type Communications (mMTC):

- 1000x bandwidth per unit area; this implies roughly 1 million nodes in 1 km<sup>2</sup>

- Up to a 10 year battery life on endpoint IoT nodes
- 90% reduction in network energy usage:

# 5G Topologies



From left to right: 1 million node density through small cells and macrocell deployment. Indoor and home use of 60 Ghz with macrocell at 4 Ghz backhaul. Dual connectivity example with split control and data planes using two radios for user data and 4 GHz microcells for the control plane. Device to device connectivity. Massive MIMO with beamforming from a single mmWave antenna. Density increase with a mix of small cells in mmWave for blanket coverage of user data.

# 5G Frequencies

- Current 4G-LTE systems mainly use frequencies below the 3 GHz range.
- 5G will radically change the spectrum usage. 5G may use a multitude of frequencies.
- Under strong consideration is the use of **millimeter waves (mmWave)** in the unlicensed 24 to 100 GHz range.
- These frequencies directly address Shannon's Law by increasing the bandwidth  $B$  of the law with extremely wide channels. Since the mmWave space is not saturated or sliced up by various regulatory bodies, channels as wide as 100 MHz in the 30 GHz to 60 GHz frequencies are possible.
- This will provide the technology to support multi-gigabit per second speeds.
- The principal issues with mmWave technology are free space path loss, attenuation, and penetration.
- Free path loss is significant only if the antenna gain is independent of frequency. If we keep the antenna area constant, it is possible to mitigate the effects of path loss.
- This requires **Massive-MIMO (M-MIMO)** technology. M-MIMO will incorporate macrocell towers with 256 to 1024 antennas. Beamforming at the macrocell will be used as well.

# 5G New Waveforms

4G-LTE uses OFDM, which works well for large data transmissions. However, for IoT the packets are much smaller. The overhead for OFDM also impacts latency in very dense IoT deployments. Hence, new waveforms are being architected for consideration:

- **Non-orthogonal Multiple Access (NOMA)**: Allows multiple users to share a wireless medium.
- **Filter Bank Multi-Carrier (FBMC)**: Controls the shape of subcarrier signals to remove side-lobes through DSPs.
- **Sparse Coded Multiple Access (SCMA)**: Allows data to be mapped to different code from different codebooks.

# Summary

| Feature                       | 1G                     | 2/2.5G                                            | 3G                                                    | 4G                                     | 5G                                   |
|-------------------------------|------------------------|---------------------------------------------------|-------------------------------------------------------|----------------------------------------|--------------------------------------|
| First Availability            | 1979                   | 1999                                              | 2002                                                  | 2010                                   | 2020                                 |
| ITU-R Specification           | NA                     | NA                                                | IMT-2000                                              | IMT-Advanced                           | IMT-2020                             |
| ITU-R Frequency Specification | NA                     | NA                                                | 400 MHZ to 3 GHz                                      | 450 MHz to 3.6 GHz                     | TBD                                  |
| ITU-R Bandwidth Specification | NA                     | NA                                                | Stationary: 2 Mbps<br>Moving: 384 Kbps                | Stationary: 1 Gbps<br>Moving: 100 Mbps | Min Down: 20 Gbps<br>Min Up: 10 Gbps |
| Typical Bandwidth             | 2 Kbps                 | 14.4-64 Kbps                                      | 500 to 700 Kbps                                       | 100 to 300 Mbps (peak)                 | TBD?                                 |
| Usage/Features                | Mobile telephony only. | Digital voice, SMS text, caller-ID, one-way data. | Superior audio, video, and data.<br>Enhanced roaming. | Unified IP and seamless LAN/WAN/WLAN.  | IoT, ultra density, low latency.     |

## Cont..

|                                   |                 |                                                                  |                                       |                         |                                |
|-----------------------------------|-----------------|------------------------------------------------------------------|---------------------------------------|-------------------------|--------------------------------|
| <b>Standards and Multiplexing</b> | AMPS            | 2G:<br>TDMA,<br>CDMA,<br>GSM<br>2.5G:<br>GPRS,<br>EDGE,<br>1xRTT | FDMA,<br>TDMA<br>WCDMA,<br>CDMA-2000  | CDMA                    | CDMA                           |
| <b>Handoff</b>                    | Horizontal      | Horizontal                                                       | Horizontal                            | Horizontal and vertical | Horizontal and vertical        |
| <b>Core Network</b>               | PSTN            | PSTN                                                             | Packet Switch                         | Internet                | Internet                       |
| <b>Switching</b>                  | Circuit         | Circuit for access network and air network                       | Packet-based except for air interface | Packet-based            | Packet-based                   |
| <b>Technology</b>                 | Analog Cellular | Digital Cellular                                                 | Broad bandwidth CDMA, WiMAX, IP-based | LTE Advanced Pro-based  | LTE Advanced Pro-based, mmWave |