# Wireless Networks for Mobile Applications

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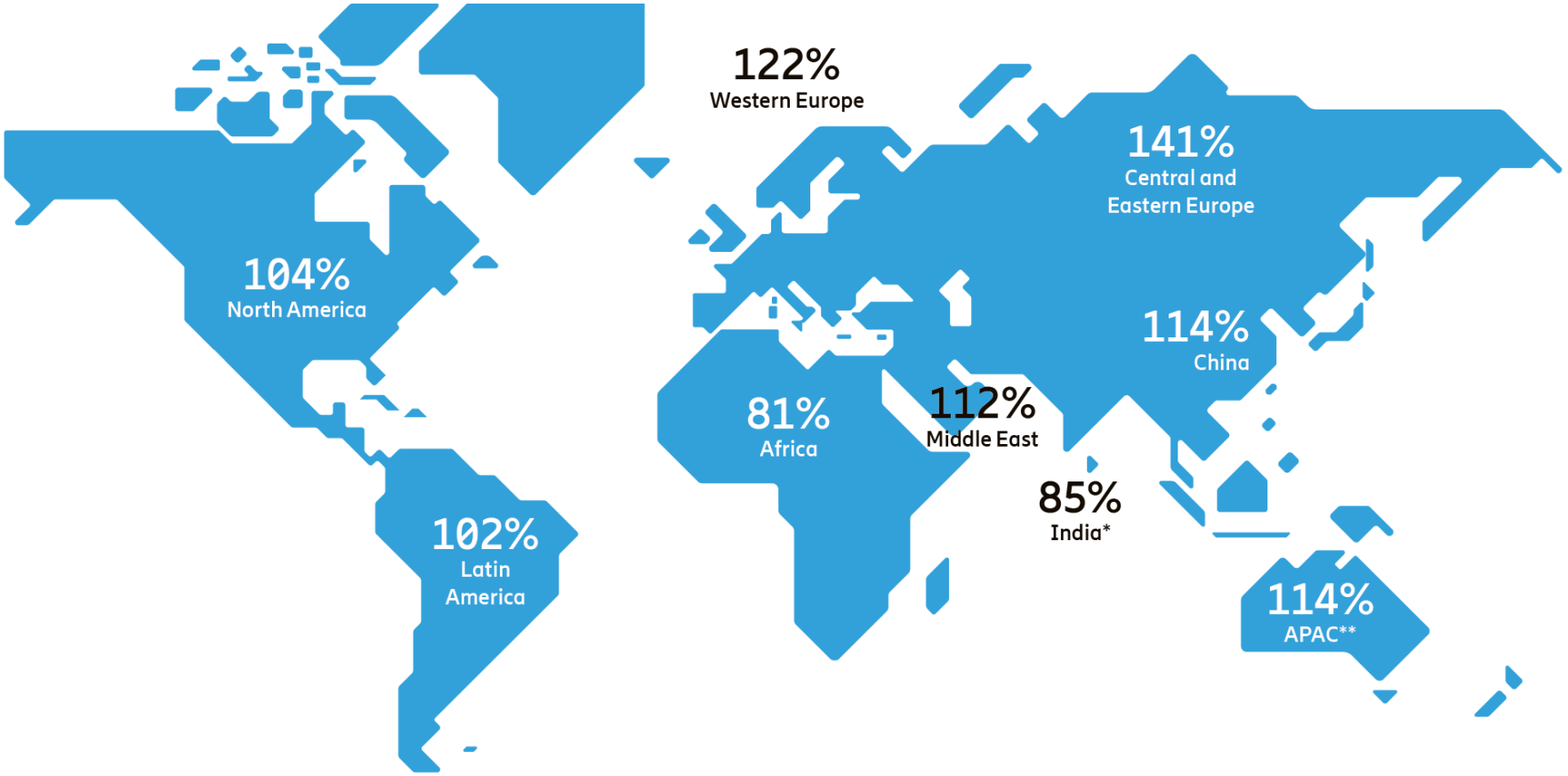
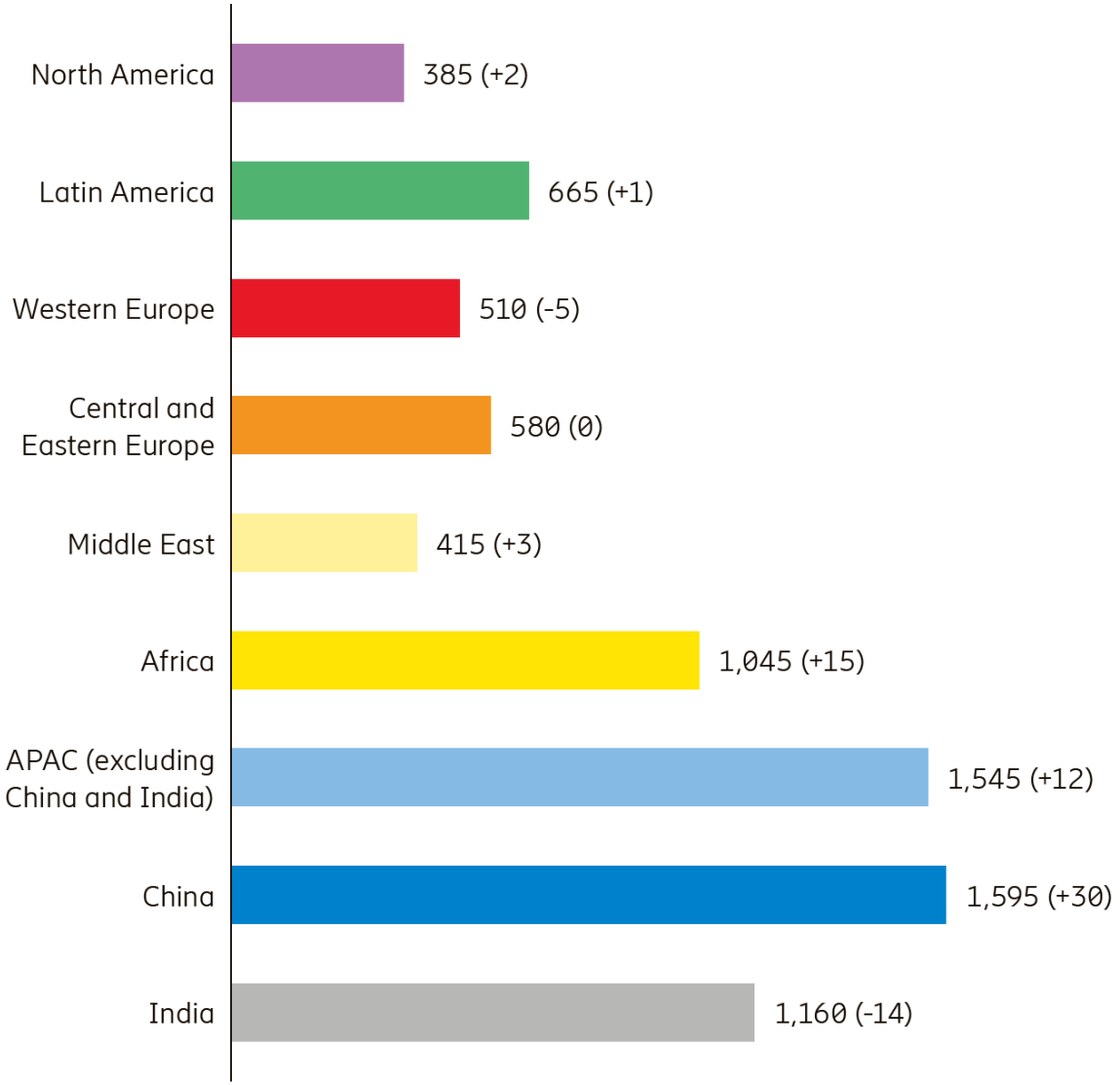
# Wireless Communication
## *Some history*

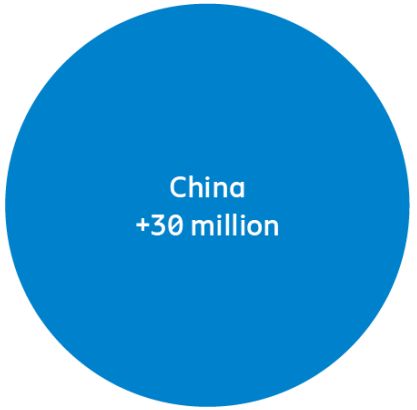
- **Ancient Systems: Smoke Signals, Carrier Pigeons, …**
  - Radio invented in the 1880s by Marconi
- **Many sophisticated military radio systems were developed during and after WW2**
- **Cellular has enjoyed exponential growth since 1988**
  - Ignited the recent wireless revolution
  - **1 billion users in 2000, 4 billion users in 2012**
  - **6 billion mobile phones, 3 billion smartphones**
  - **3G (voice+data)**
  - **4G (LTE)**
  - **5G**
  - **6G ??**

# Subscription Penetration



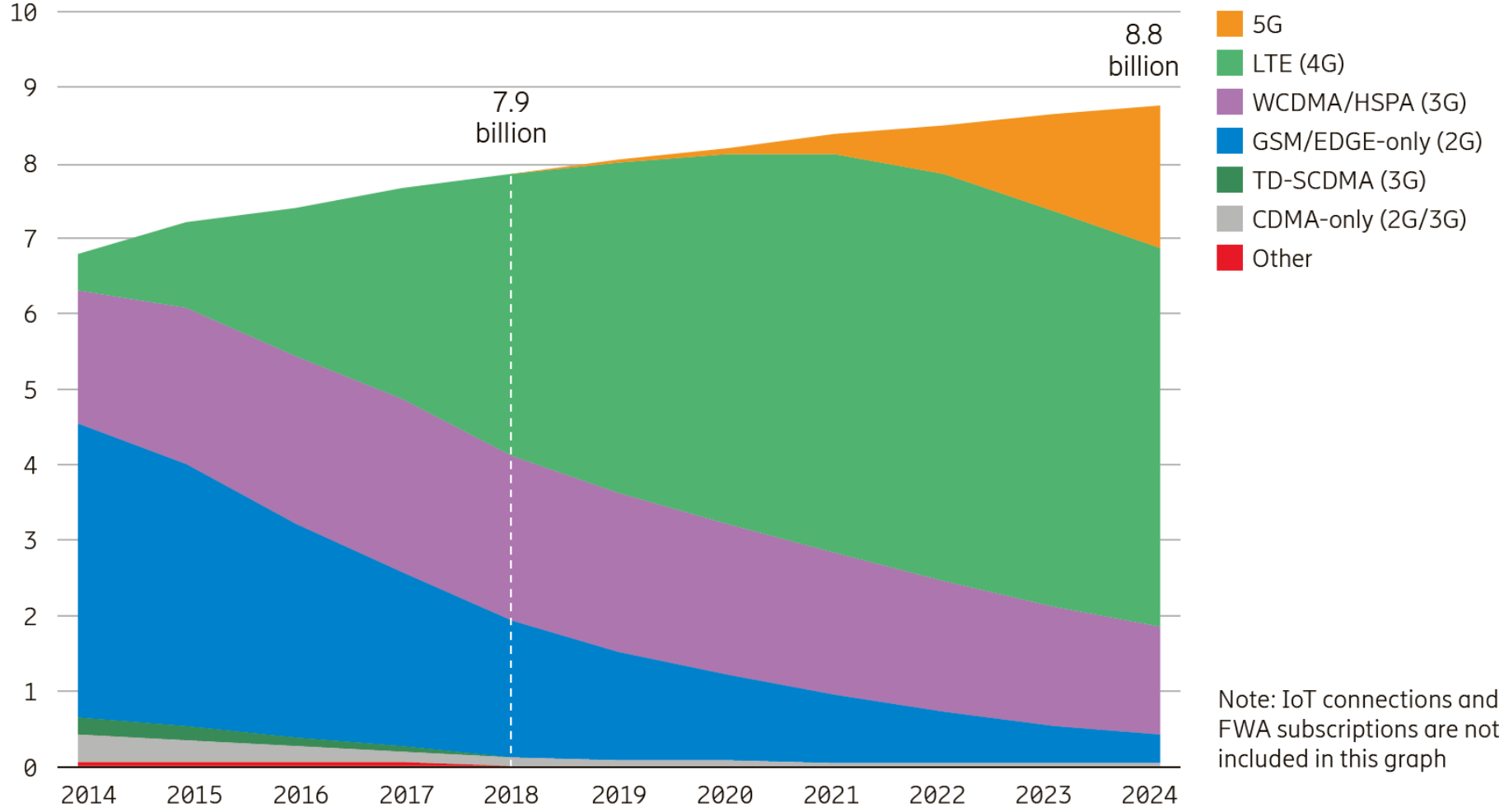
# Total and New Mobile Subscription



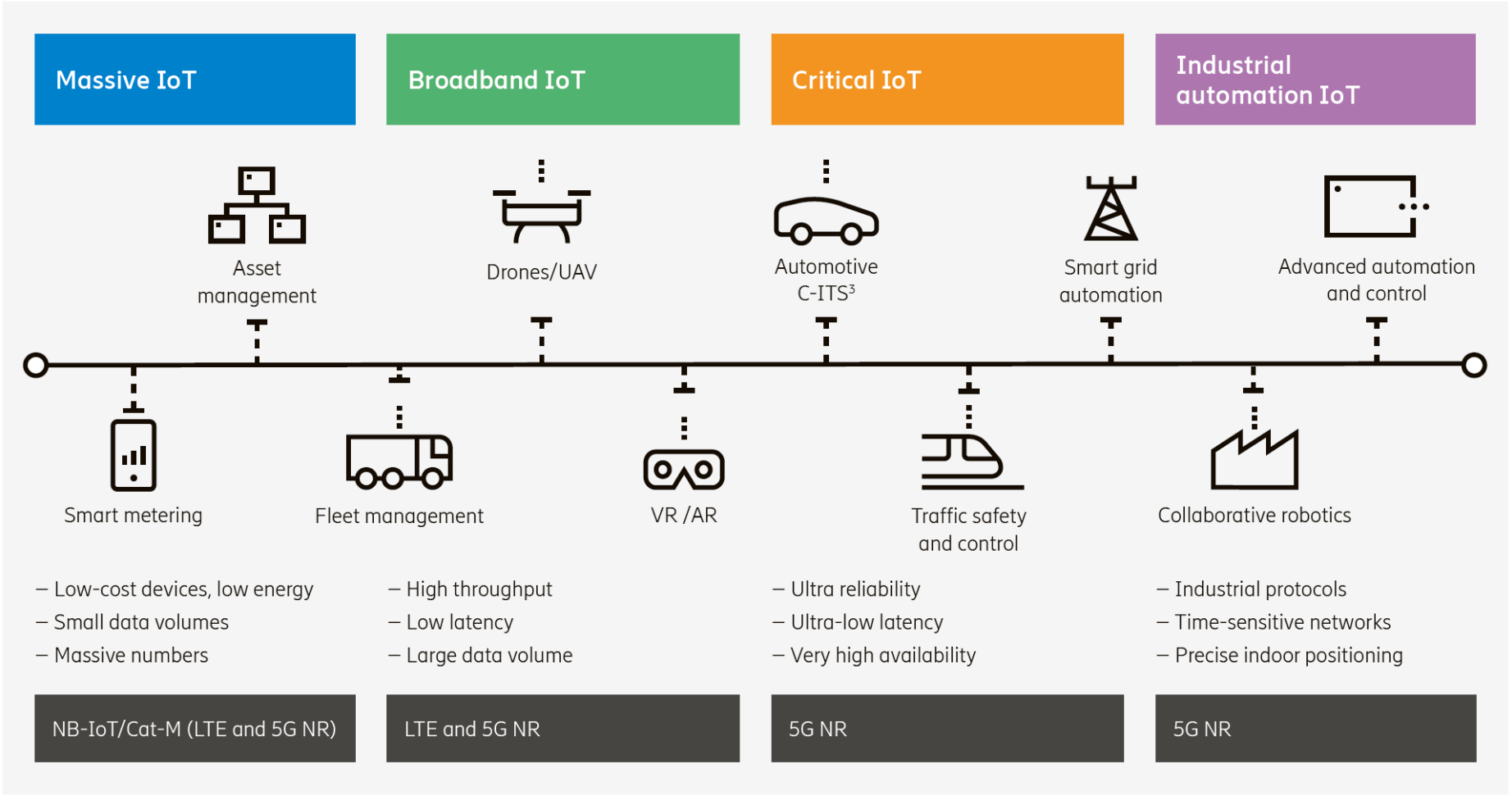


# Mobile Subscriptions by Technology (Billion)




Note: IoT connections and FWA subscriptions are not included in this graph

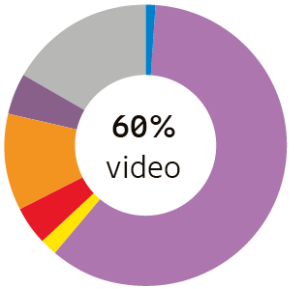
# Cellular IoT Use Case Segment



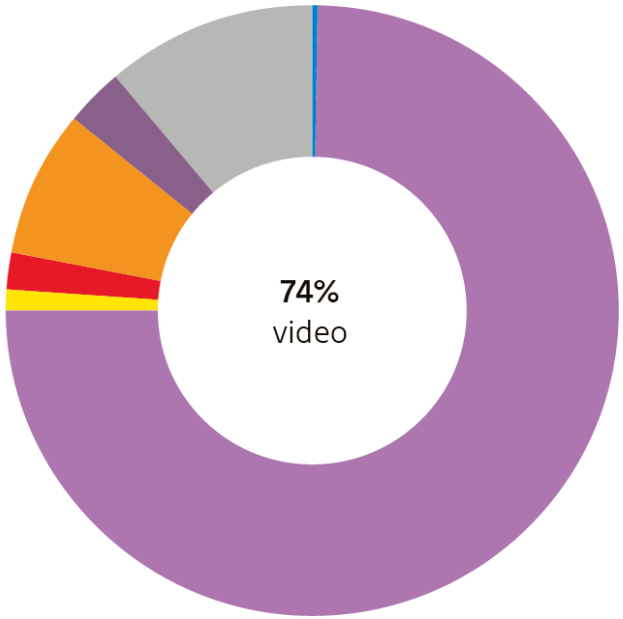
# Mobile Data Traffic by Application

**Mobile data traffic by application category per month (percent)**

Video | Audio | Web browsing | Social networking | Software download and update | Other segments | P2P file sharing




2018
**28EB**
per month

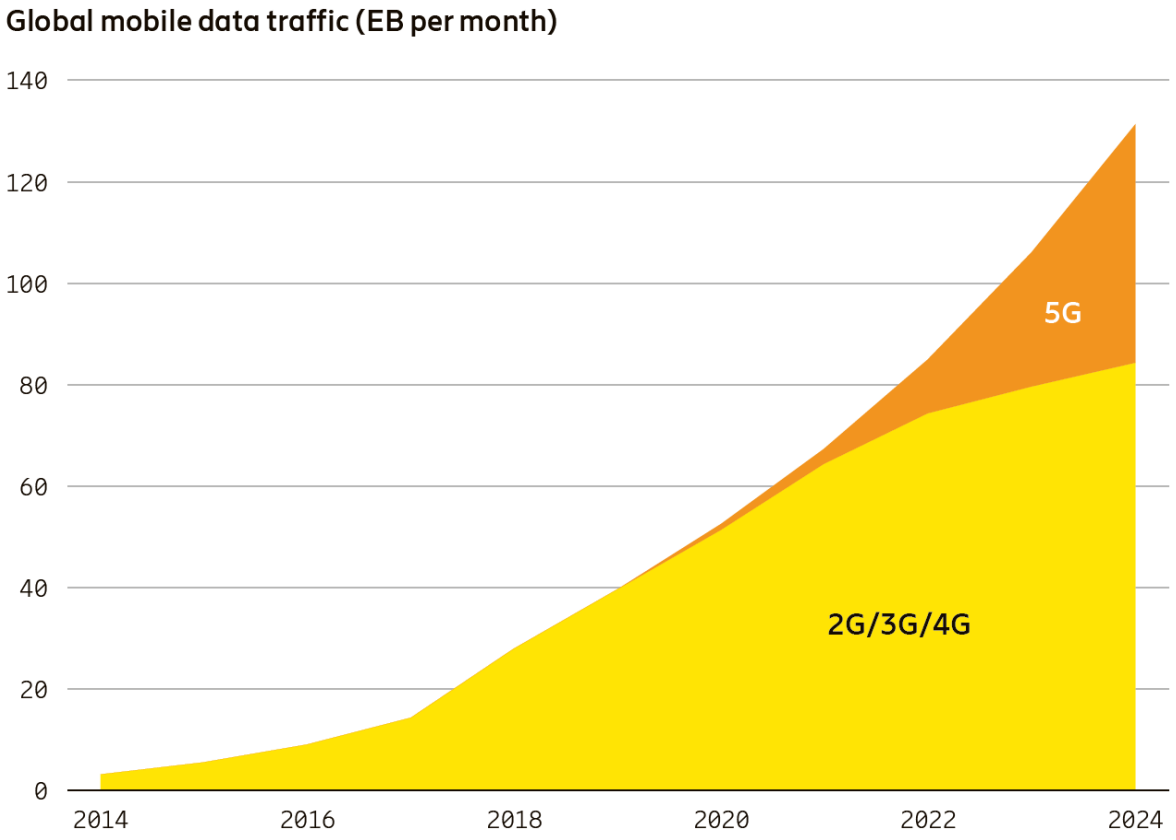


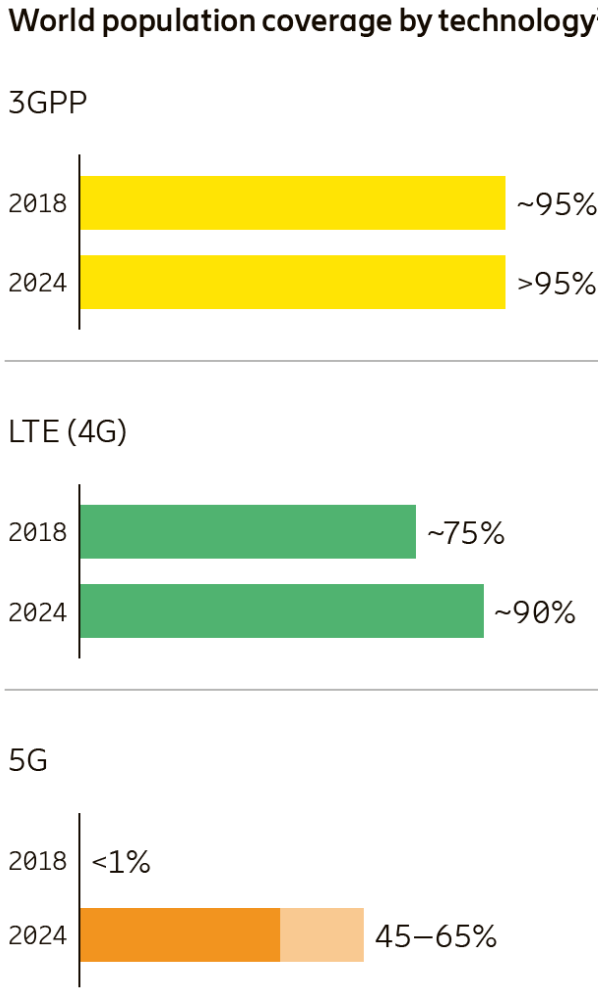

2024
**131EB**
per month

**Main drivers for video traffic growth**

– Video part of most online content (news, ads, social media, etc.)
– Growth of VoD services
– Video streaming services
– Changing user behavior – video being consumed anywhere, any time
– Increased segment penetration, not just early adopters
– Evolving devices with larger screens and higher resolutions
– Increased network performance through evolved 4G deployments
– Emerging immersive media formats and applications (HD/UHD, 360-degree video, AR, VR)

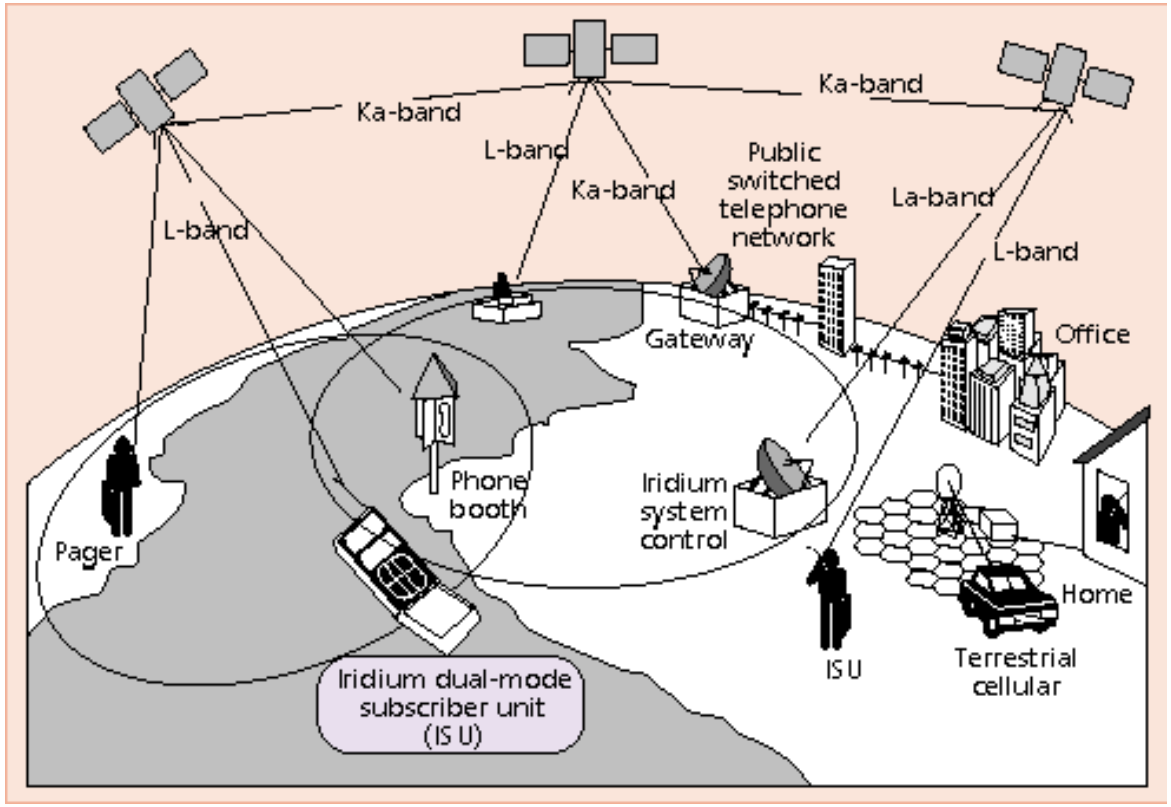
# Global Mobile Data Traffic Trends



# Also Some Spectacular Failures

- **Iridium**
  - 77 LEO Satellites (2000 Km altitude)
  - Works everywhere (even middle of desert/ocean)
  - Tsunami Warning System

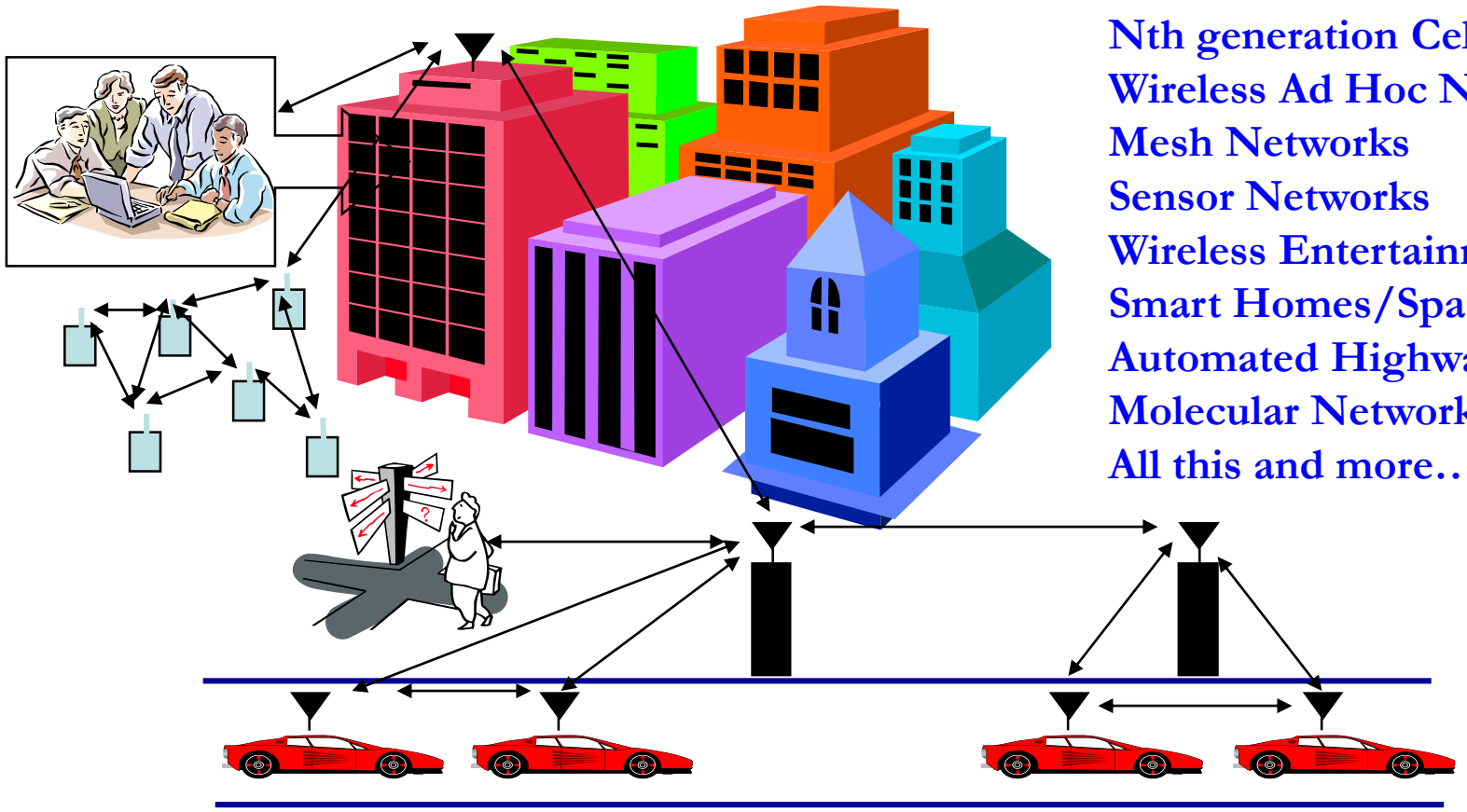



# Current Wireless Development

- Internet and laptop use exploding
- Wi-Fi, 3/4/5/6G… are growing
- Both low and high rate data demand
- Emerging interdisciplinary applications
- Smartphones open new wireless scenarios
- AR/VR/MR/tele-presence
- Tactile Internet
- Web Squared

# Future(?) Wireless Networks

***Ubiquitous Communication Among People and Devices***



**Wireless Internet access**
**Nth generation Cellular**
**Wireless Ad Hoc Networks**
**Mesh Networks**
**Sensor Networks**
**Wireless Entertainment**
**Smart Homes/Spaces**
**Automated Highways**
**Molecular Networks**
**All this and more…**

- **Constraints: Bandwidth, Delay, Energy, Connectivity**

# Design Challenges

- Wireless channels are a difficult and capacity-limited (with respect to the wired counterpart) broadcast communications medium
- Traffic patterns, user locations, and network conditions are constantly changing
- Applications are heterogeneous with hard constraints that must be met by the network
- Energy and delay constraints change design principles across all layers of the protocol stack

# Multimedia Requirements

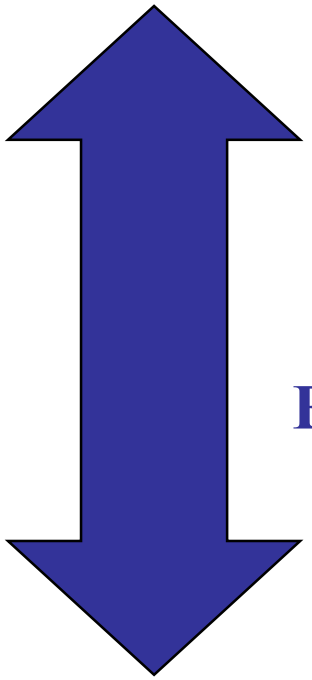
| | Voice | Data | Video | Game |
|---|---|---|---|---|
| Delay | < 100ms | - | < 100ms | < 100ms |
| Packet Loss | < 1% | 0 | < 1% | < 1% |
| BER | $10^{-3}$ | $10^{-6}$ | $10^{-6}$ | $10^{-3}$ |
| Data Rate | 8-32 Kbps | 1-100 Mbps | 1-20 Mbps | 32-100 Kbps |
| Traffic | Continuous | Bursty | Continuous | Continuous |

**One-size-fits-all protocols and design do not work well**

**Wired networks use this approach, with poor results**

# Crosslayer Design

- Hardware
- Link
- Access
- Network
- Application



**Delay Constraints**
**Rate Constraints**
**Energy Constraints**

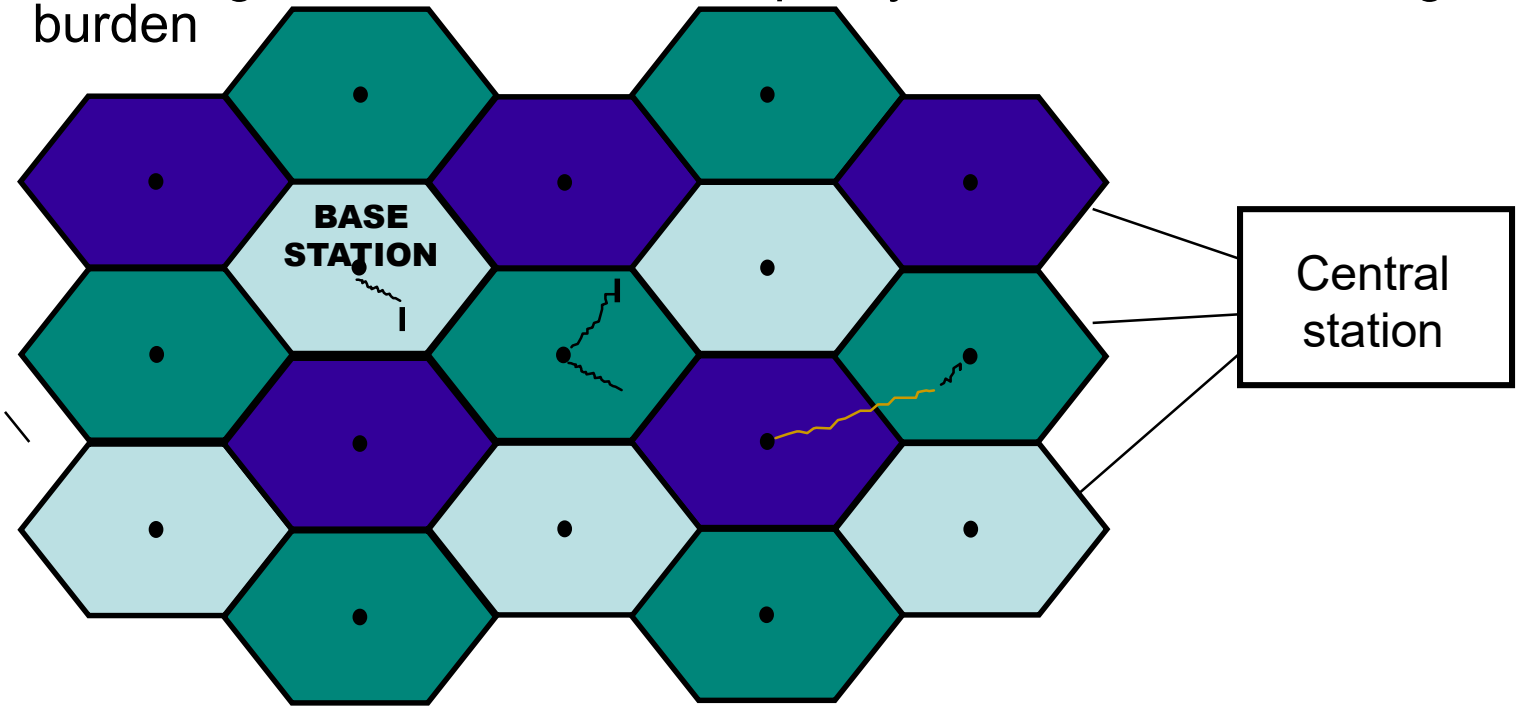
***Adapt across design layers***
***Reduce uncertainty through scheduling***
***Provide robustness via diversity***

# Current Wireless Systems

- Cellular Systems
- Wireless LANs
- Wireless Mesh Network
- Satellite Systems
- Bluetooth
- RFID
- D2D
- …

# Cellular Systems: Reuse channels to maximize capacity

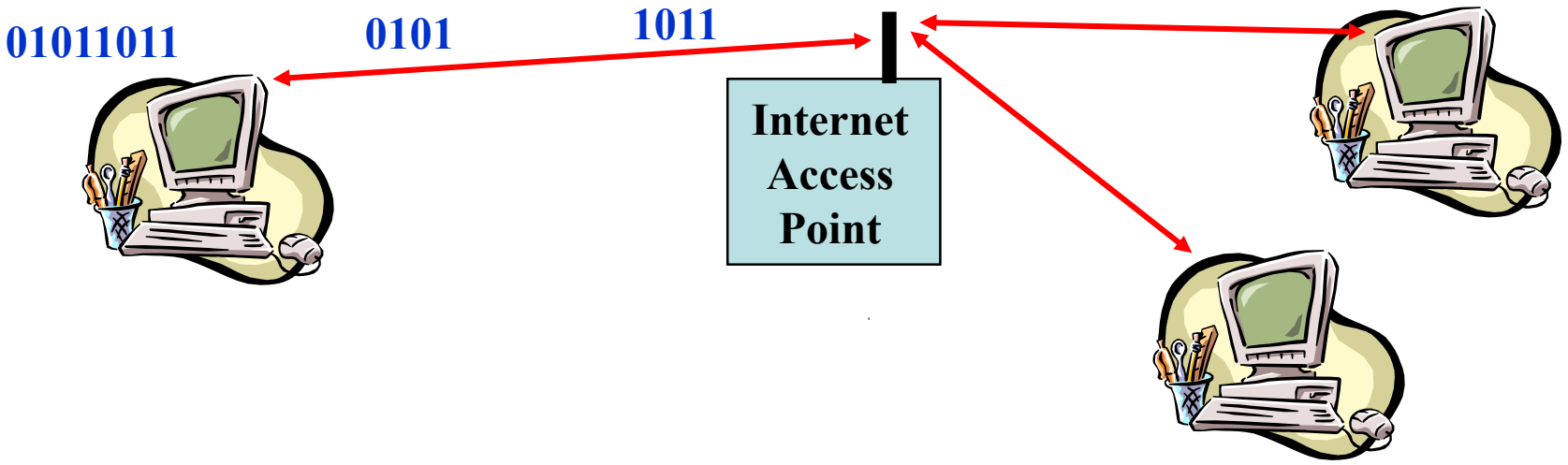
- Geographic region divided into cells
- Frequencies/timeslots/codes reused at spatially-separated locations.
- Co-channel interference between same color cells.
- Base stations coordinate handoff and control functions
- Shrinking cell size increases capacity, as well as networking burden



# Cellular Design:
## Voice and Data

- Data is bursty, whereas voice is continuous
  - Typically require different access and routing strategies
- 3G “widens the data pipe”:
  - 384 Kbps (now even 1.6 Mbps – 3.2 Mbps – 7.2 Mbps)
  - Packet-based switching for both voice and data
- 4G… 5G… more and more focused on data
  - High bandwidth
  - High reliability
  - Low latency

# Wireless Local Area Networks (WLANs)



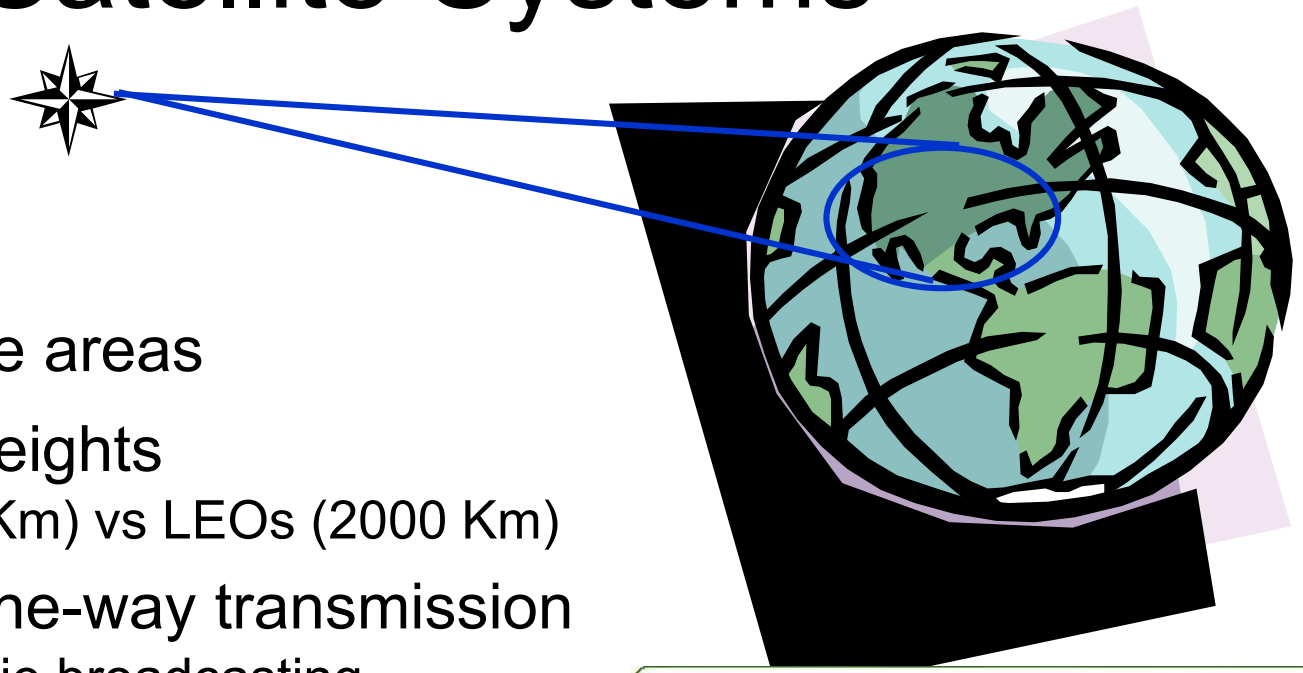

- WLANs connect "local" computers (100m range)
- Breaks data into packets
- Channel access is shared (random access)
- Backbone Internet provides best-effort service
  - Poor performance in some apps (e.g. video)

# Wireless LAN Standards

- 802.11b (Old Generation)
  - Standard for 2.4GHz ISM band (80 MHz)
    - Frequency hopped spread spectrum
  - 1 - 11 Mbps, 100m range (nominal)
- 802.11g (Legacy Standard)
  - Standard in 2.4 GHz and 5 GHz bands
    - OFDM (***Orthogonal Frequency-Division Multiplexing*** )
  - Speeds up to 54 Mbps (nominal)
- 802.11n (Current Generation)
  - Standard in 2.4 GHz and 5 GHz bands
    - OFDM with time division
  - With MIMO (**Multiple-Input and Multiple-Output**), multiple channels
  - Up to 300 Mbps (nominal)
- 802.11ac (Current/Emerging Generation)
  - Standard in 2.4 GHz and 5 GHz bands
    - OFDM with time division
  - More MIMO (**Multiple-Input and Multiple-Output**), multiple channels
  - Up to 500 Mbps (nominal) for single connection
- 802.11s, 802.11p,…

**Next years? all WLAN cards will have all standards**

# Satellite Systems



- Cover very large areas
- Different orbit heights
  - GEOs (39000 Km) vs LEOs (2000 Km)
- Optimized for one-way transmission
  - Radio and movie broadcasting
- Most two-way systems (Iridium) struggling or bankrupt
  - Expensive alternative to terrestrial system
  - A few ambitious systems on the horizon

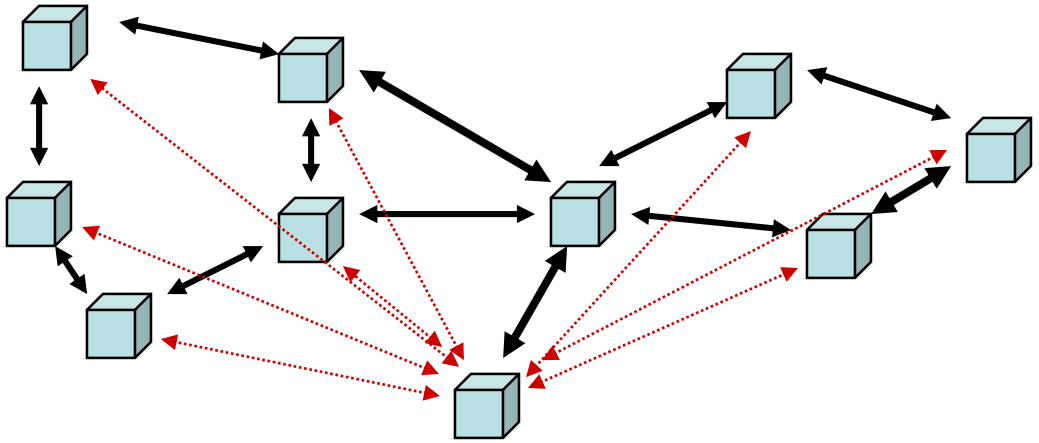
# Bluetooth

- Cable replacement RF technology (low cost)
- Short range (10m, extendable to 100m through multihop)
- 2.4 GHz band (crowded)
- 1 Data (700 Kbps) and 3 voice channels
- Widely supported by telecommunications, PC, and consumer electronics companies
- Few applications beyond cable replacement

# Emerging Systems

- Ad hoc wireless networks
- Mesh networks
- Sensor networks
- Distributed control networks
- MANET/VANET/FANET
- Underwater networks
- Molecular networks
- …

# Ad-Hoc Networks

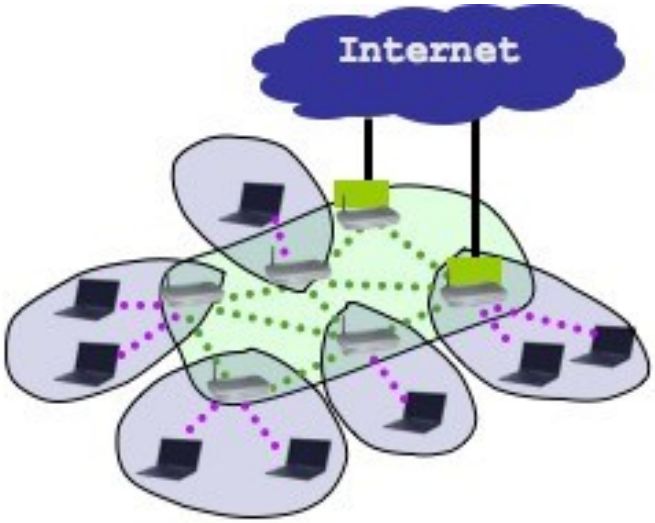


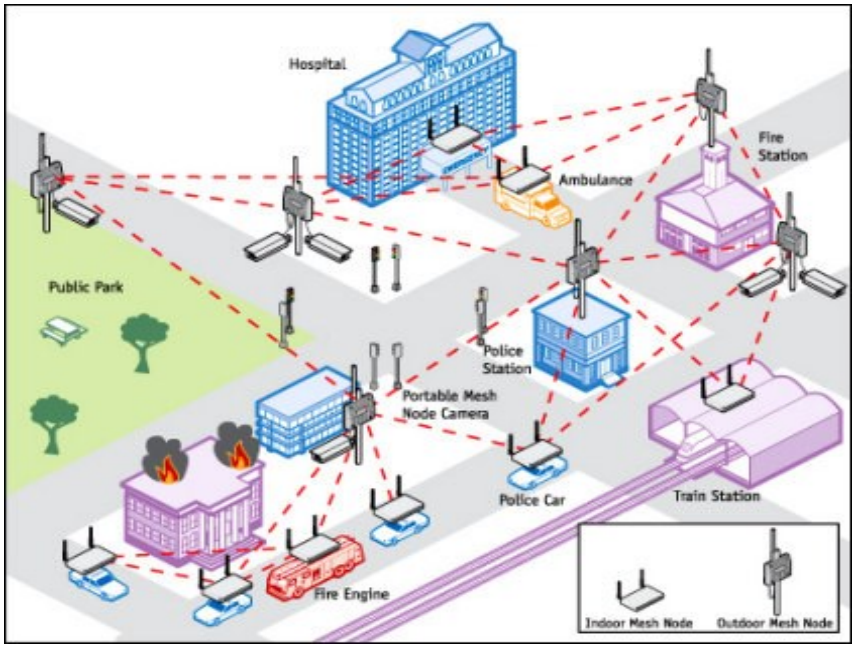
- Peer-to-peer communications
- No backbone infrastructure
- Routing can be multihop
  - to extend area of coverage or to reduce interferences (through short range communication)
- Topology is dynamic
- Fully connected with different links

# Design Issues

- Ad-hoc networks provide a flexible network infrastructure for many emerging applications
- The capacity of such networks is generally unknown
- Transmission, access, and routing strategies for ad-hoc networks are generally ad-hoc
- Crosslayer design critical and very challenging
- Energy constraints impose interesting design tradeoffs for communication and networking

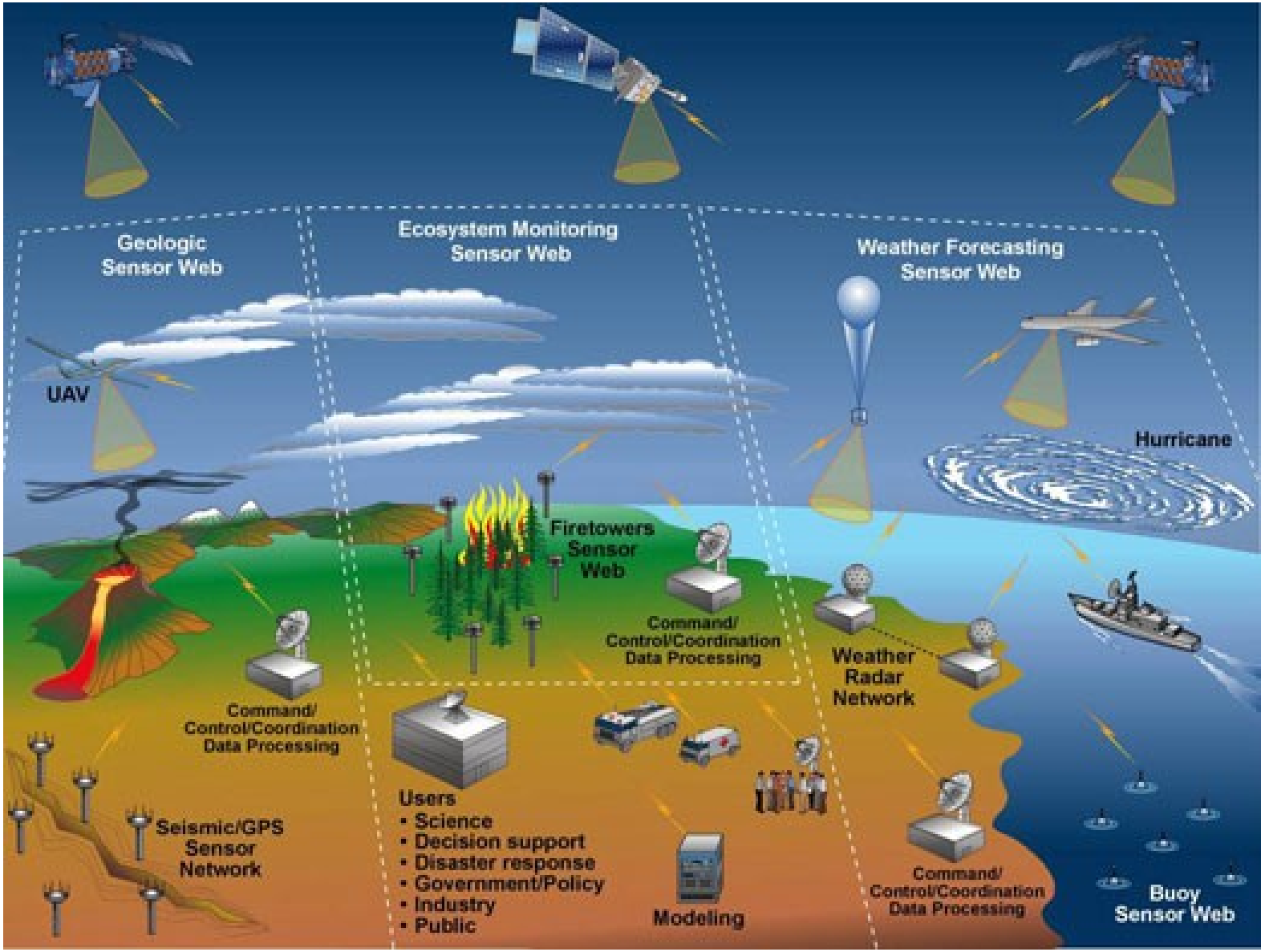
# Mesh Networks



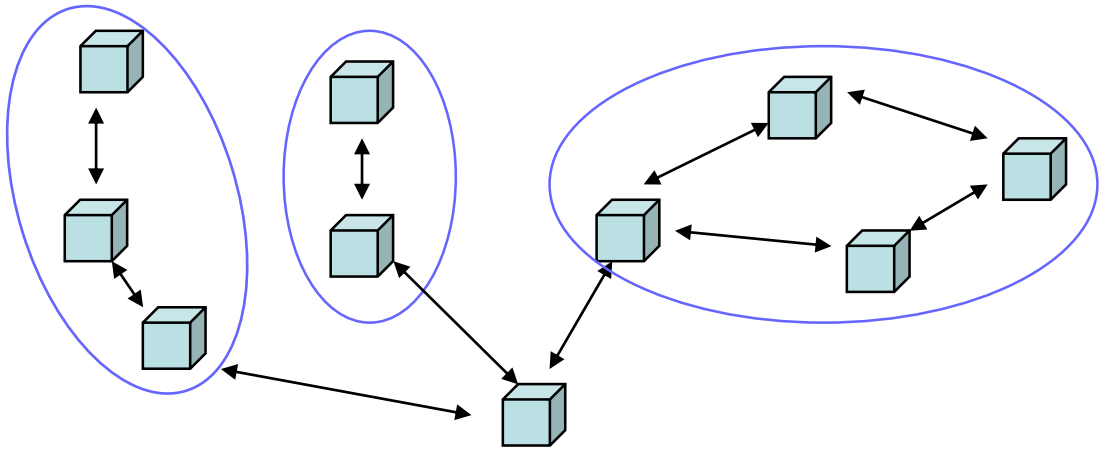

- Ad hoc opportunistic extension of a fixed urban infrastructure
- Purposes: to create a low-cost, easily deployable, high performance wireless coverage
- Challenges:
  - optimum routing protocols to achieve fairness and load balancing
  - quality-of-service (QoS)
  - MAC/network protocols for multimedia applications
  - efficient autonomous operation when the infrastructure fails.

# Sensor Networks



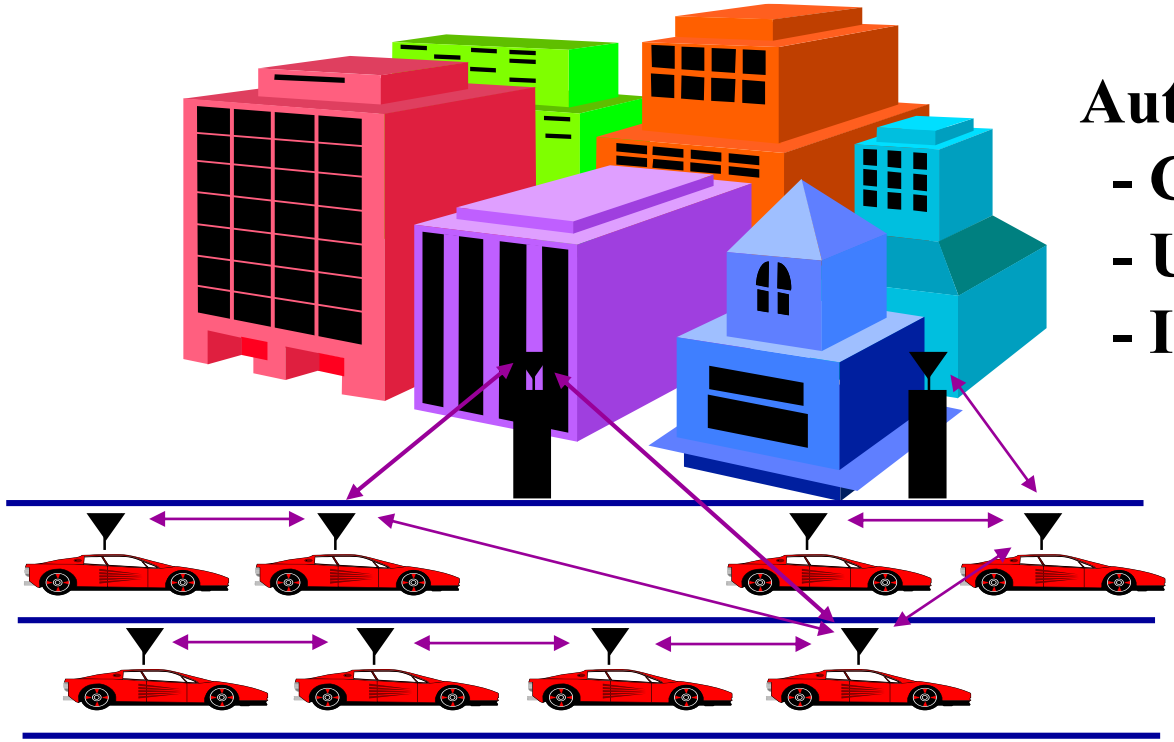
# Sensor Networks

*Energy is the driving constraint*



- Nodes powered by non-rechargeable batteries
- Data flows to centralized location
- Low per-node rates but up to 100,000 nodes
- Data highly correlated in time and space
- Nodes can cooperate in transmission, reception compression, and signal processing

# Distributed Control over Wireless Links

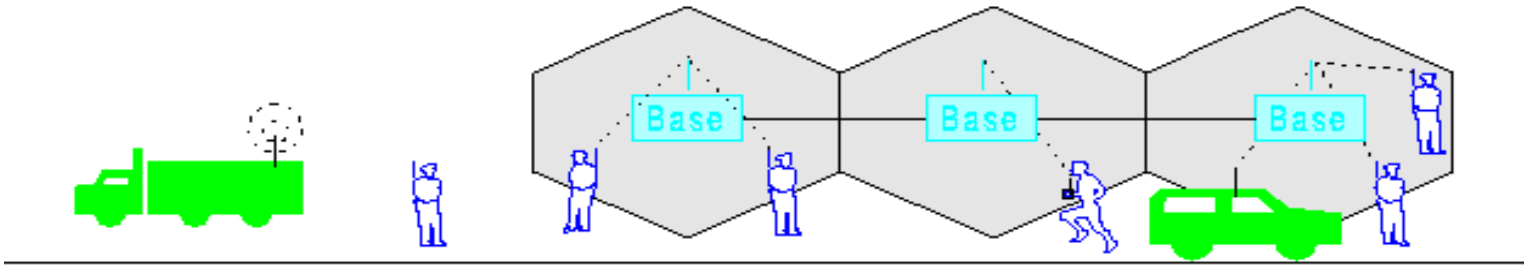


**Automated Vehicles**
- **Cars**
- **UAVs**
- **Insect flyers**

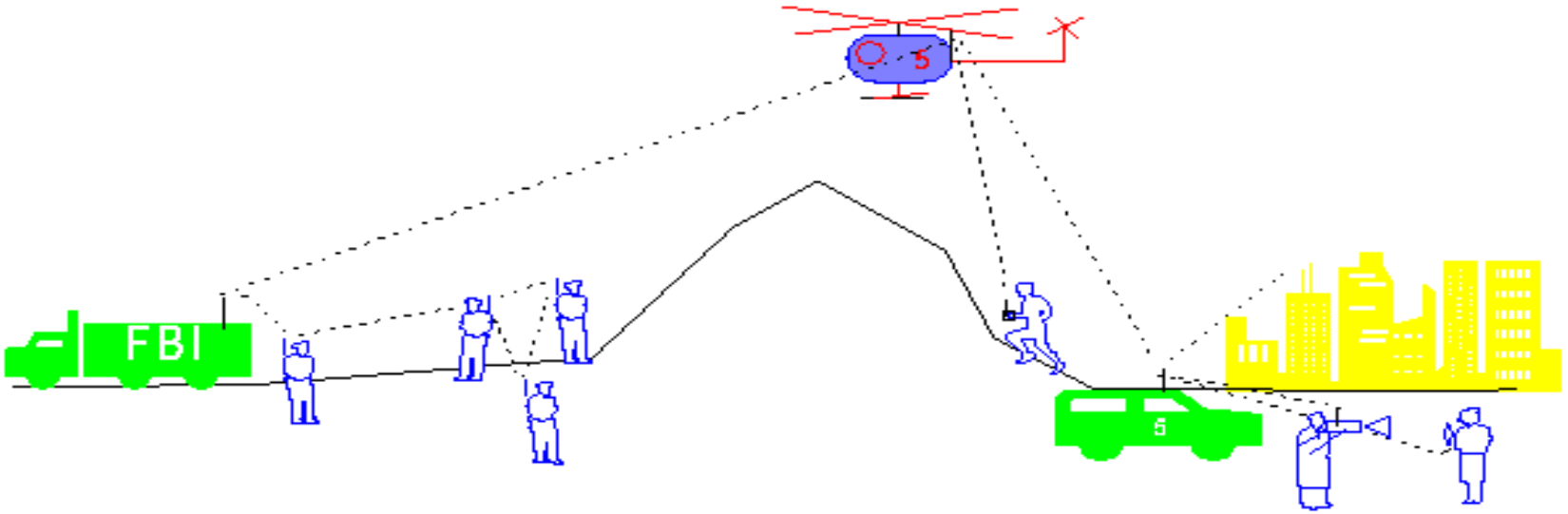
- Packet loss and/or delays impacts controller performance.
- Controller design should be robust to network faults.
- Joint application and communication network design.

# Mobile Ad-Hoc Network (MANET)

**Infrastructure Network (WiFi or 3G/4G)**




**Ad Hoc, Multihop wireless Network**



# Ad Hoc Network Characteristics (Again…)

- Instantly deployable, re-configurable (no fixed infrastructure)
- Created to satisfy a “temporary” need
- Portable (e.g., sensors), mobile (e.g., cars)

# Traditional Ad Hoc Network Applications

Military

- Automated battlefield

Civilian

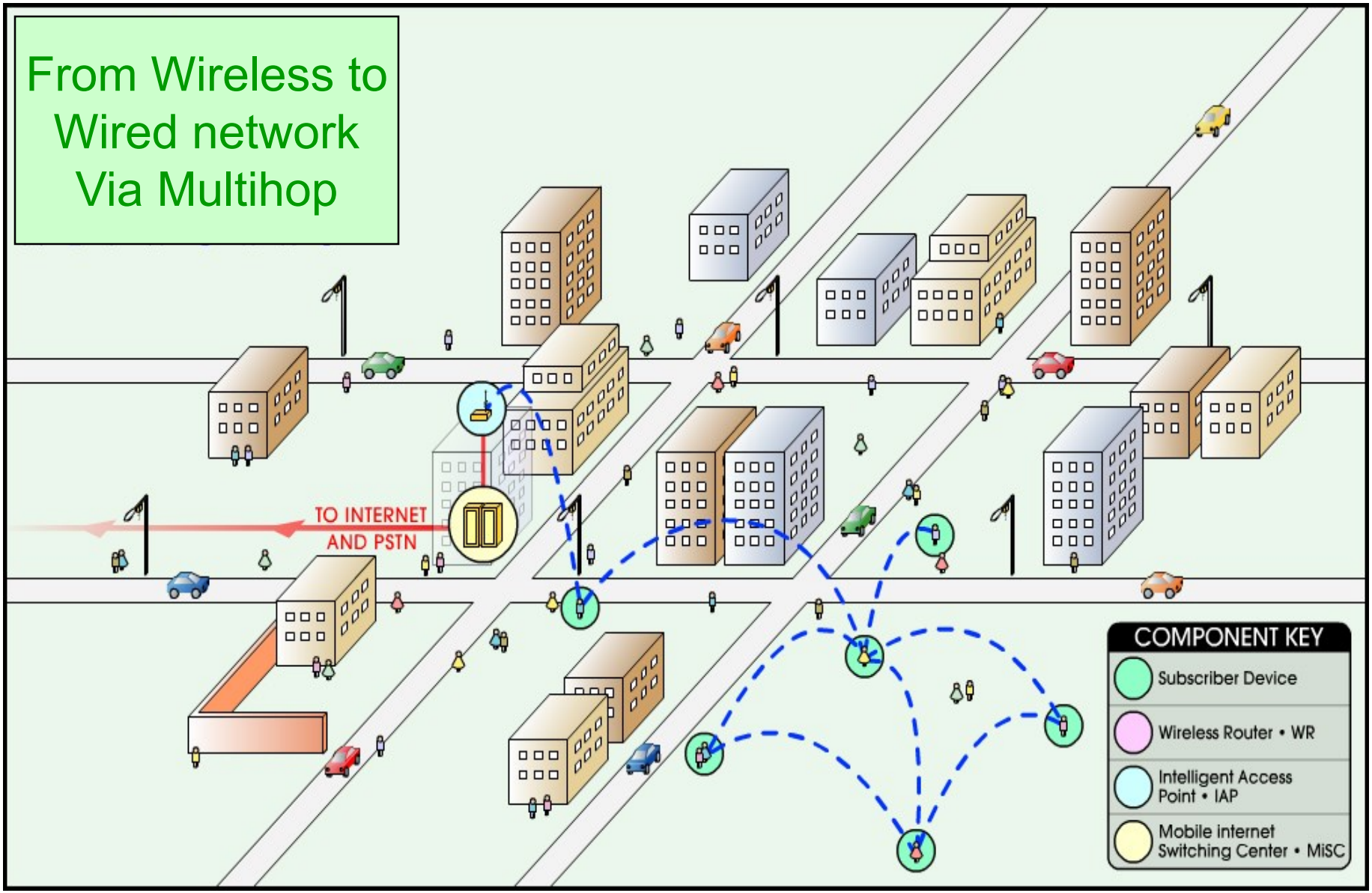
- Disaster Recovery (flood, fire, earthquakes etc)
- Law enforcement (crowd control)
- Homeland defense
- Search and rescue in remote areas
- Environment monitoring (sensors)
- Space/planet  exploration

# Opportunistic Ad Hoc Nets

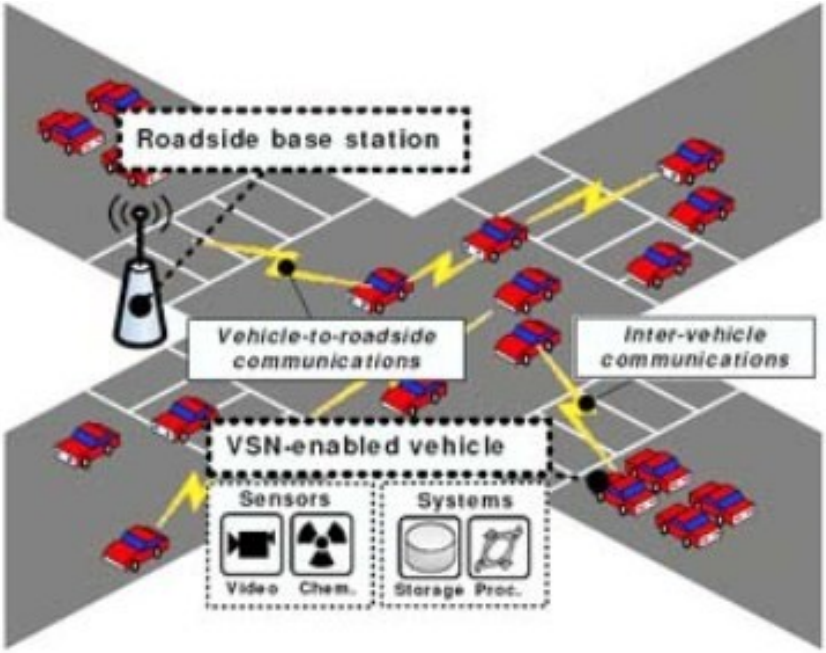
- Driven by “commercial” application needs
  - Indoor W-LAN extended coverage
  - Group of friends sharing via Bluetooth
  - Peer-2-Peer networking in the vehicle grid

- Access to Internet:
  - available, but it can be “opportunistically” replaced by the “ad hoc” network (if too costly or inadequate)

# Urban “Opportunistic” Ad Hoc Nets



# Vehicular Ad-Hoc Network (VANET)




DSRC CHARACTERISTICS

| Parameter | Value |
|---|---|
| Range | 1000m |
| Frequency Band | 5.9Ghz |
| Speed | $\leq$ 85mph |
| Data Rates | 6-27Mbps(depending on Range) |

# Vehicle Communications: Apps

## PUBLIC / SAFETY

- APPROACHING EMERGENCY VEHICLE ASSISTANT
- EMERGENCY VEHICLE SIGNAL PREEMPTION
- OPTIMAL SPEED ADVISORY
- TRANSIT VEHICLE SIGNAL PRIORITY
- EMERGENCY VEHICLE VIDEO RELAY
- STOP LIGHT ASSISTANT – INFRASTRUCTURE
- INTERSECTION COLLISION WARNING/AVOIDANCE
- COOPERATIVE COLLISION WARNING [V-V]
- INFRASTRUCTURE BASED TRAFFIC MANAGEMENT – VEHICLES AS PROBES
- WORK ZONE WARNING
- ROAD CONDITION WARNING
- VEHICLE BASED PROBE DATA COLLECTION
- TRAFFIC INFORMATION
- COOPERATIVE VEHICLE SYSTEM – PLATOON
- RAILROAD COLLISION AVOIDANCE
- LOCATION BASED PROBE DATA COLLECTION
- TRANSIT VEHICLE DATA TRANSFER (gate)
- ON-BOARD SAFETY DATA TRANSFER
- VEHICLE SAFETY INSPECTION
- DRIVER'S DAILY LOG

## PRIVATE

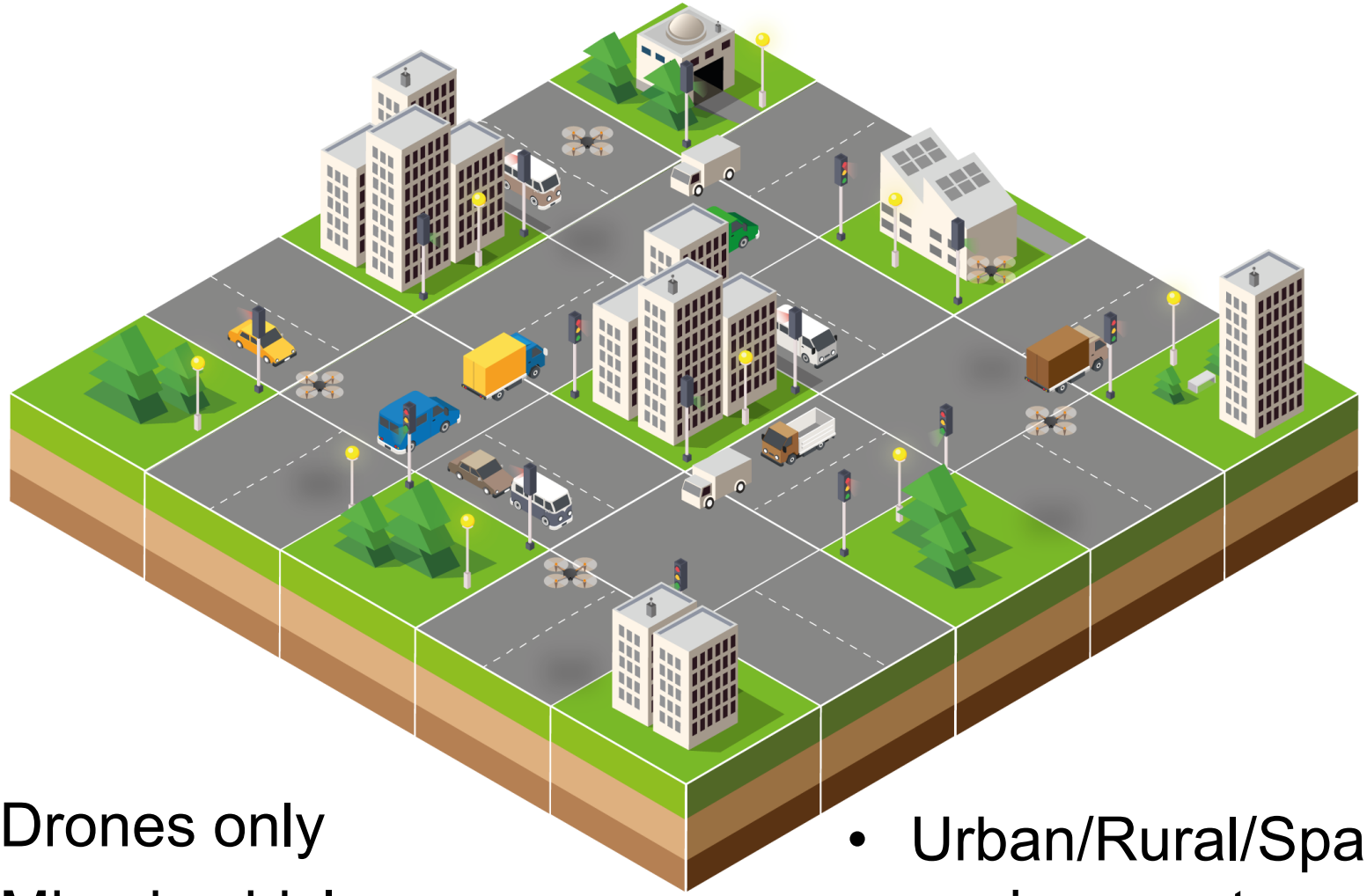
- DATA TRANSFER / CVO / TRUCK STOP
- DATA TRANSFER / TRANSIT VEHICLE (yard)
- ACCESS CONTROL
- DRIVE-THRU PAYMENT
- PARKING LOT PAYMENT
- DATA TRANSFER / INFOFUELING
  - ATIS DATA
  - DIAGNOSTIC DATA
  - REPAIR-SERVICE RECORD
  - VEHICLE COMPUTER PROGRAM UPDATES
  - MAP and MUSIC DATA UPDATES
  - VIDEO UPLOADS
- ENHANCED ROUTE PLANNING and GUIDANCE
- RENTAL CAR PROCESSING
- UNIQUE CVO FLEET MANAGEMENT
- TRANSIT VEHICLE REFUELING MANAGEMENT
- LOCOMOTIVE FUEL MONITORING
- DATA TRANSFER / LOCOMOTIVE

Internet Applications!

ATIS - Advanced Traveler Information Systems
CVO - Commercial Vehicle Operations

**RED – Long Range Applications (up to 1000 meters)**
**BLUE – Medium/Long Range Applications (90-300 m)**
**BLACK – Medium Range Application (Up to 90 meters)**

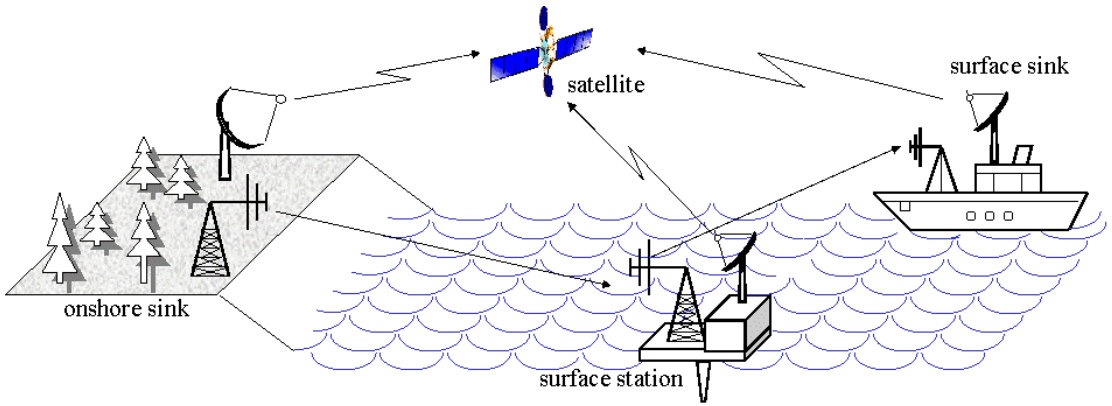
# Flying Ad-Hoc Network (FANET)

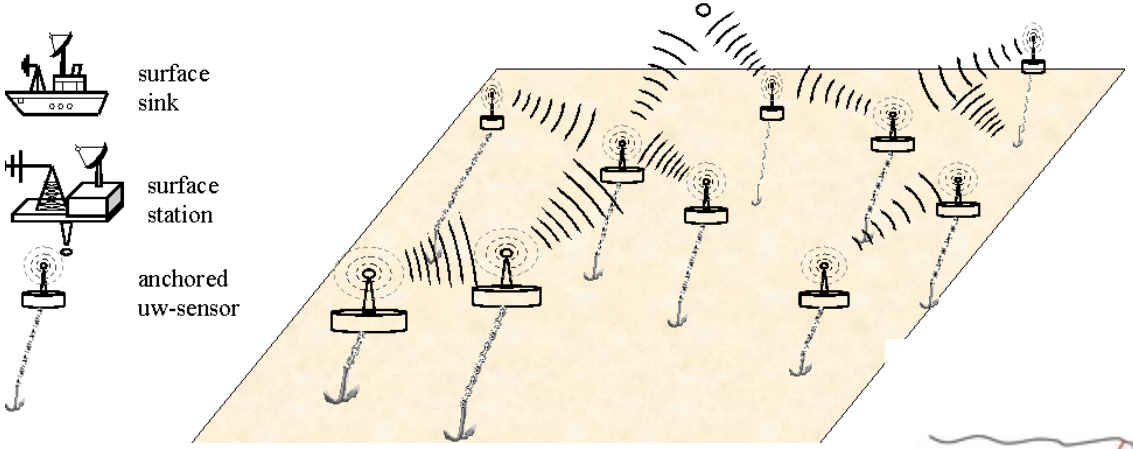


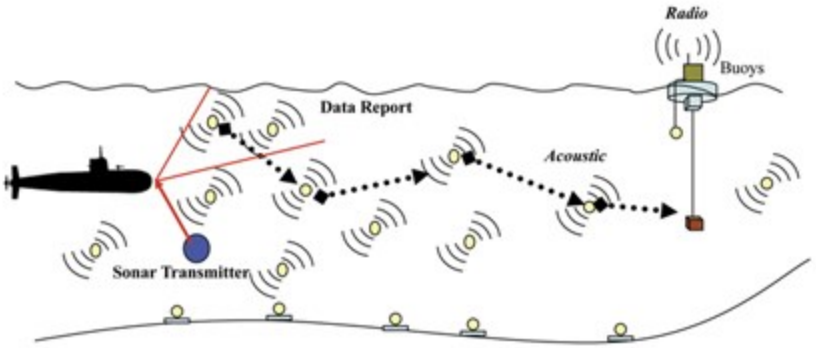
- Drones only
- Mixed vehicles

- Urban/Rural/Space environment

# Underwater Sensor Networks



# Radio Frequency IDentification (RFID)


- Based on magnetic fields
- Tags: active vs passive
- Used in supply chain instead of barcodes
  - No need for direct optical reading
- Standards under development

# Nano-Networks

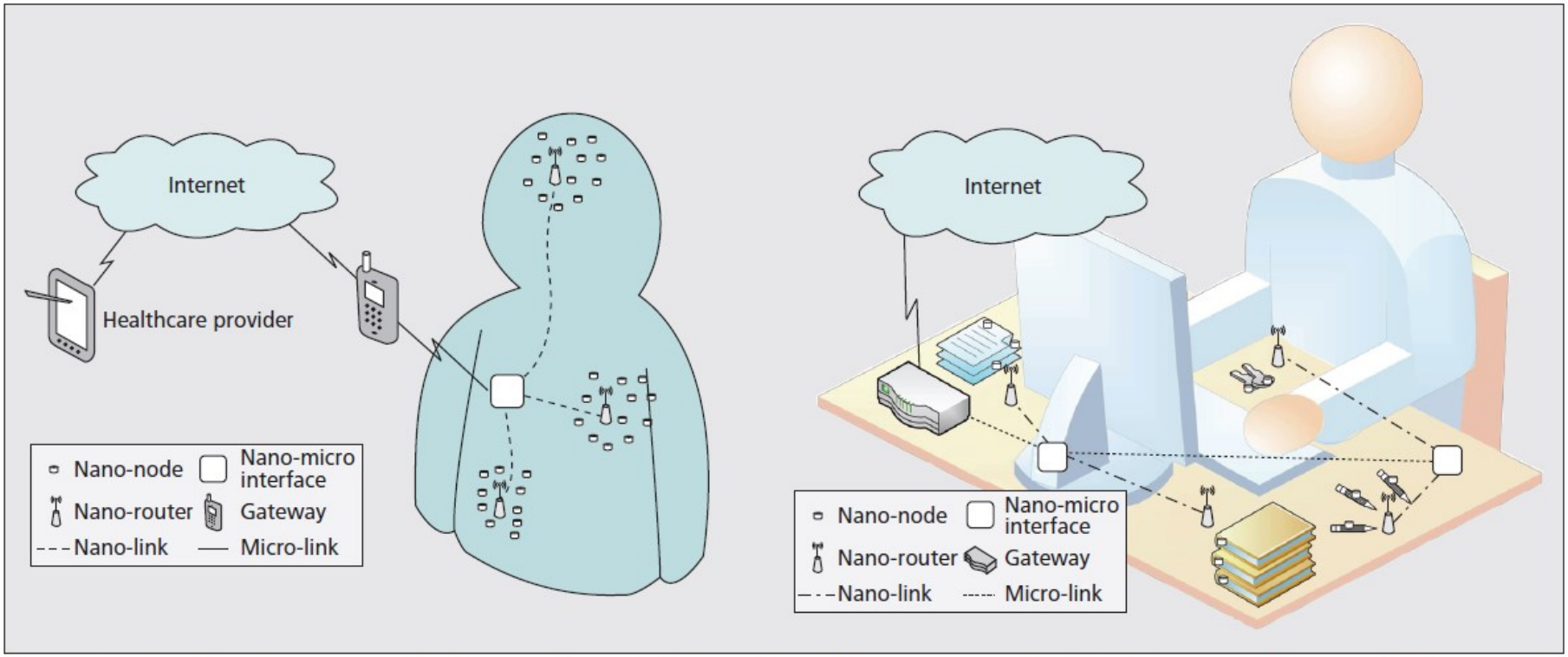
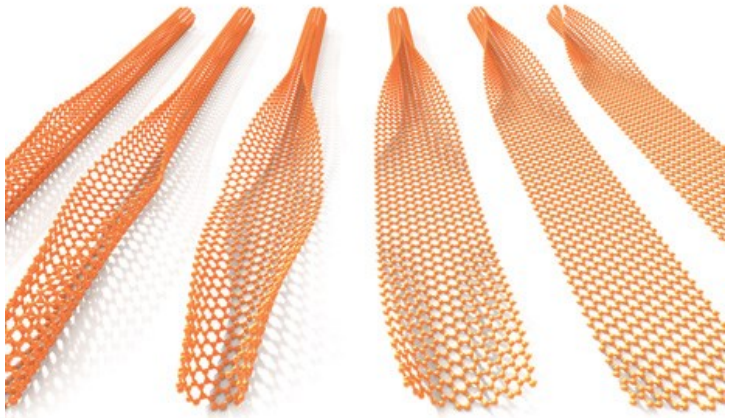


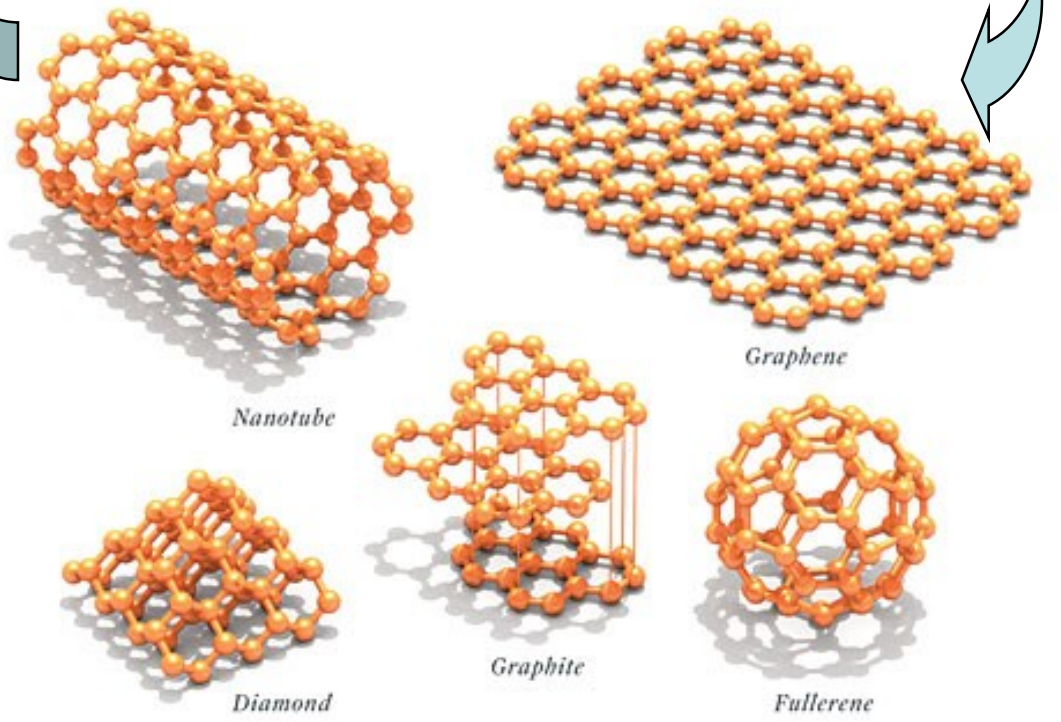

**Figure 1.** *Network architecture for the Internet of Nano-Things: a) Intrabody nanonetworks for healthcare applications; b) The interconnected office.*

# 2010 Nobel Prize in Physics

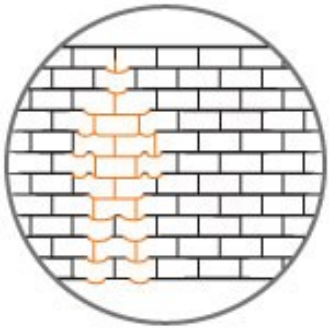
Through a mixture of sulfuric acid and potassium permanganate



Unzip carbon nanotubes




**Extraordinary applications**



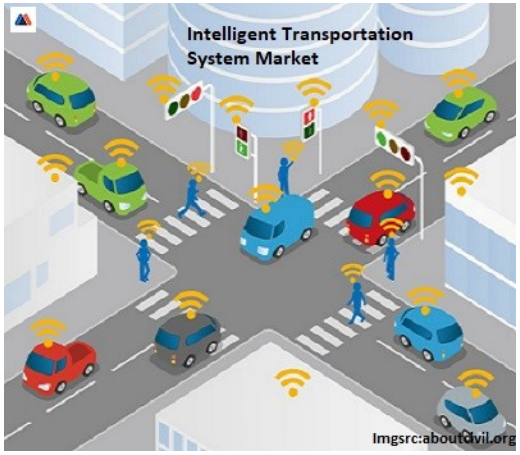
# Main Points

- The wireless vision encompasses many exciting systems and applications
- Technical challenges transcend across all layers of the system design
- Wireless systems have limited performance and interoperability
- Standards and spectral allocation heavily impact the evolution of wireless technology
- Huge potential for future applications and systems

# Case Studies and Project Topics

## Internet of Space Things (Cubesat)

## Intelligent Transportation System

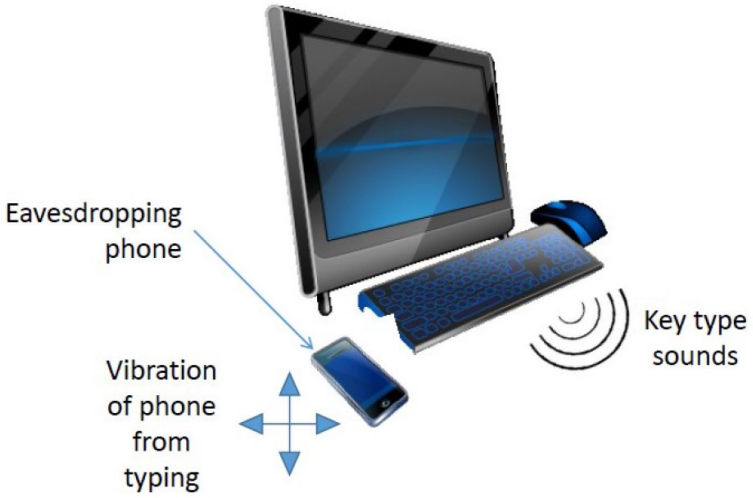


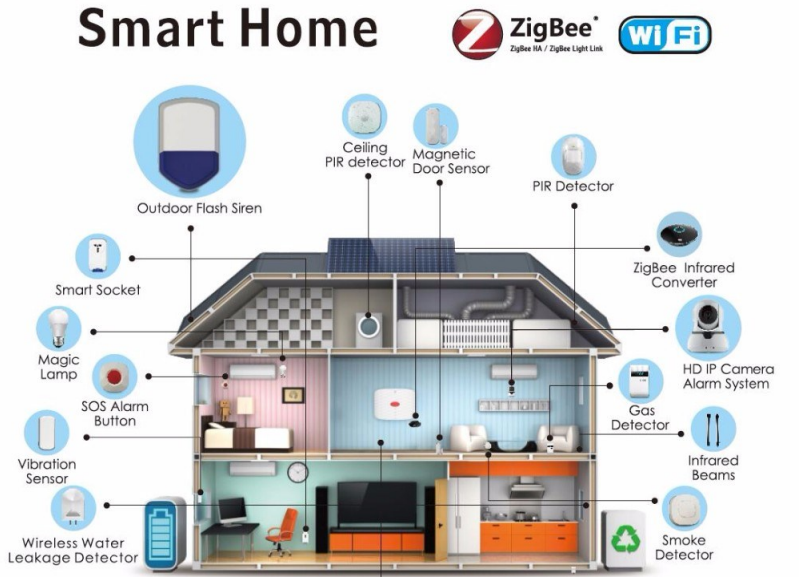

## AR and Interactive Games

## Industry 4.0

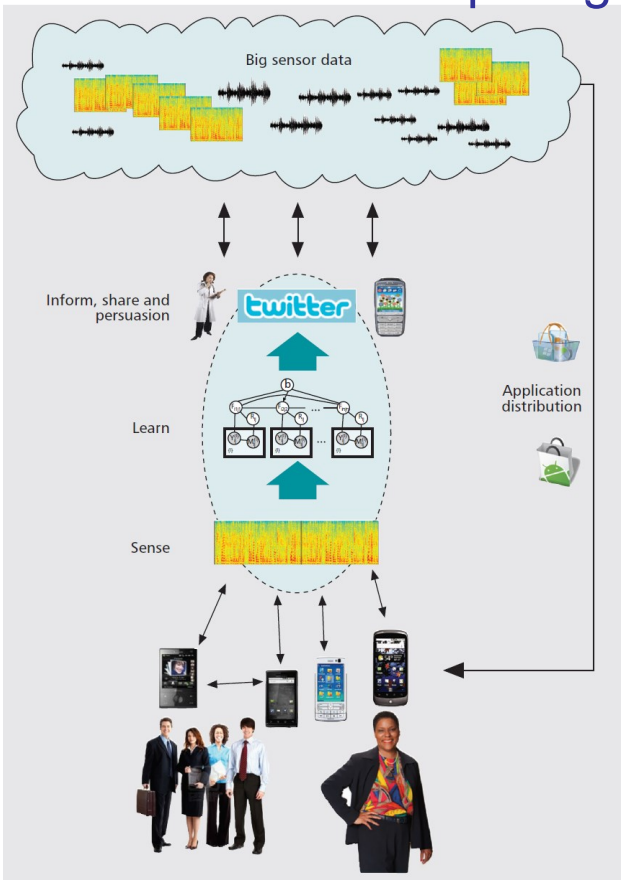
# Case Studies and Project Topics

## Side Channel Attacks




## Mobile Sensing & Mobile Cloud Computing




And more…