Real-Time and Low-Power Wireless Communication with Sensors and Actuators

Behnam Dezfouli

Real-time wireless communication is currently being used for various applications such as industrial process control. This talk presents the applicability and challenges of various wireless technologies for real-time communication. We also discuss about the importance and development of a real-time mobile wireless network.

The University of Iowa
Department of Computer Science

Why wireless communication?

- **Sensors**
  - Event-based or continuous reporting
  - Sensors are typically low-power
  - e.g., sensors detect oil or gas leak

- **Actuators**
  - Perform a mechanical operation → require power cable
  - Wireless communication for sending commands
  - e.g., actuators close valves, shutdown some parts of the system, or control a mechanical arm

Note:

Industries employ various types of wireless technologies for backbone (802.11) and backhaul (cellular) communication.

In this talk we are interested in communication with sensors and actuators

Why wireless communication?

- **Interest in adding more measurement points**
  - Improving the quality of process
  - Regulatory compliance
  - Higher energy efficiency
  - Safety
  - Various industries can benefit: oil and gas, agriculture, transportation, medical, retail, hotels, restaurants, energy, manufacturing, etc.

- **Easier installation and maintenance of measurement points**
  - Installation of measurement points in hard-to-access areas
  - The cost and maintenance of wiring is high

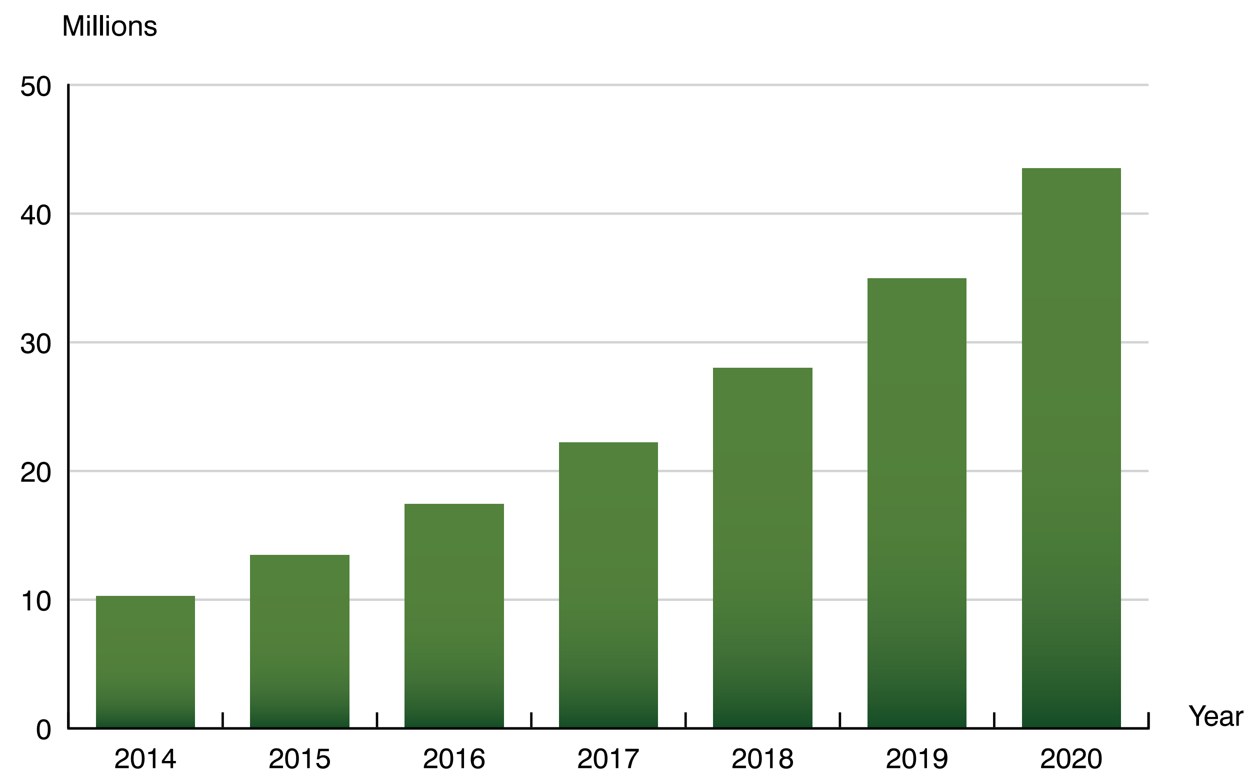
- **Predictive maintenance strategy**
  - Increases reliability and safety
  - Reduces repair cost and unplanned shutdowns

Why wireless communication?

The installation of wireless devices in industrial applications is forecasted to grow at a compound annual growth rate of 27.2 percent

- ***Reach about 43.5 million devices by 2020***

Global automation solution providers:
Emerson, GE, ABB, Honeywell, Schneider Electric, Yokogawa and Rockwell Automation



Installed base of active wireless devices in industrial automation (World 2014–2020)

Reference: BERG INSIGHT

A new design is required…

Wireless systems should satisfy:

1. Energy-efficient communication
   - A node must last for few years on batteries, or,
   - A node must be able to perform its operation through energy harvesting.
2. Bounded packet delivery delay
   - Late received data are useless, especially in process control systems
3. Reliable wireless communication
   - A process control system may require 99.9% packet delivery reliability

- Best-effort wireless networks cannot be used in mission-critical applications
- New architectures and protocols should be employed

Real-Time Communication using IEEE 802.15.4 Standard

Existing standards

Several industrial organizations, such as HART, ISA, WINA and ZigBee, have been recently working on the application of wireless technologies in industrial automation.

WirelessHART

WirelessHART (IEC 62591)

- Uses IEEE 802.15.4 standard (250 Kbps)
- Centralized network management
- Time-synchronized communication (each node is aware of its medium access timing)
- Compatibility with existing HART devices

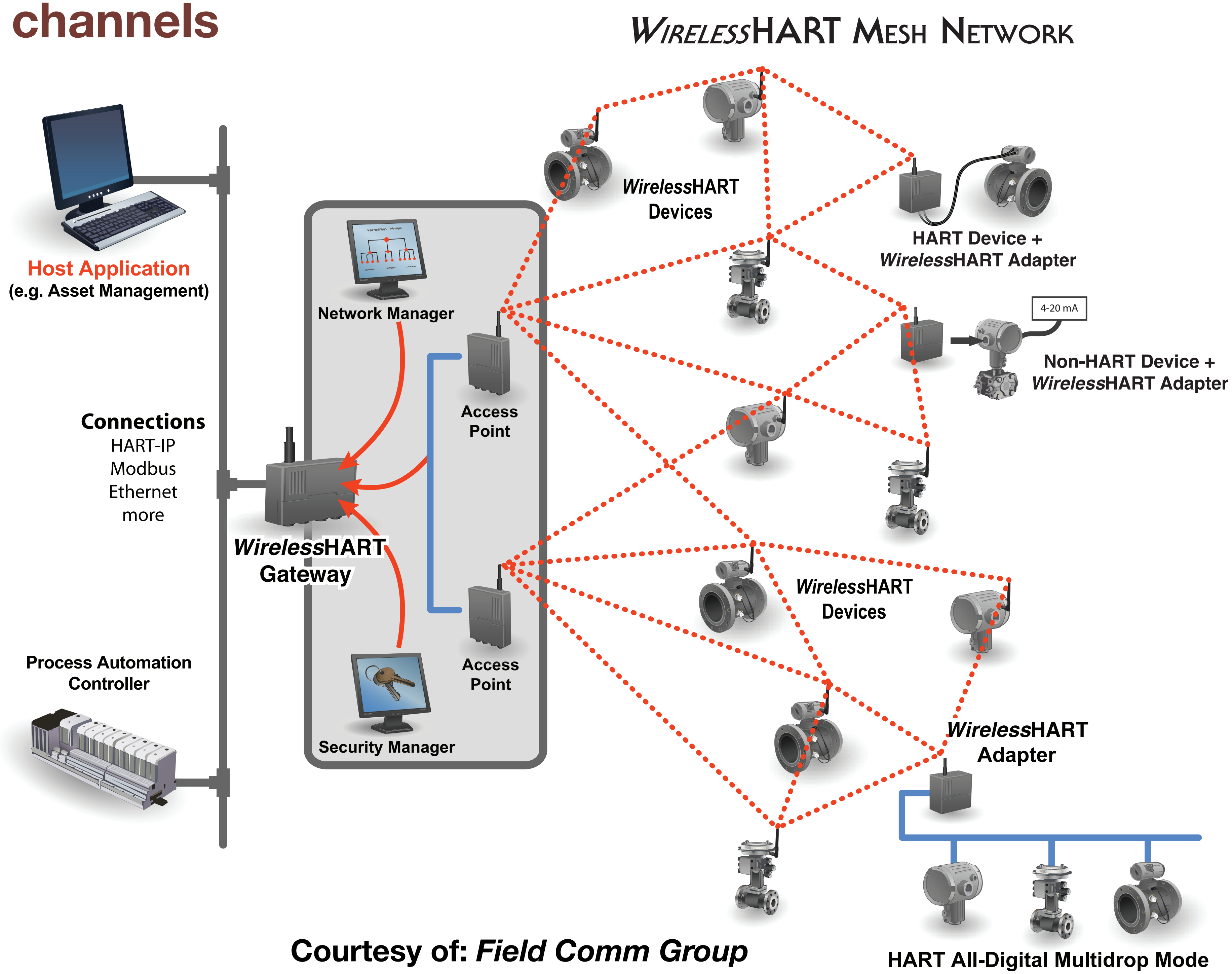
www.siemens.com/wirelesshart

Architecture of a WirelessHART network

Network Manager assigns transmission times and channels

Network Manager is aware of:

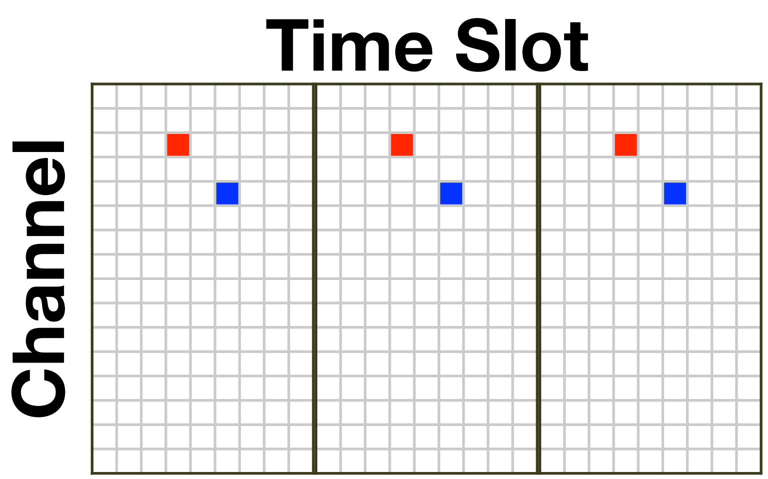
- Topology
- Channel condition
- Traffic demands

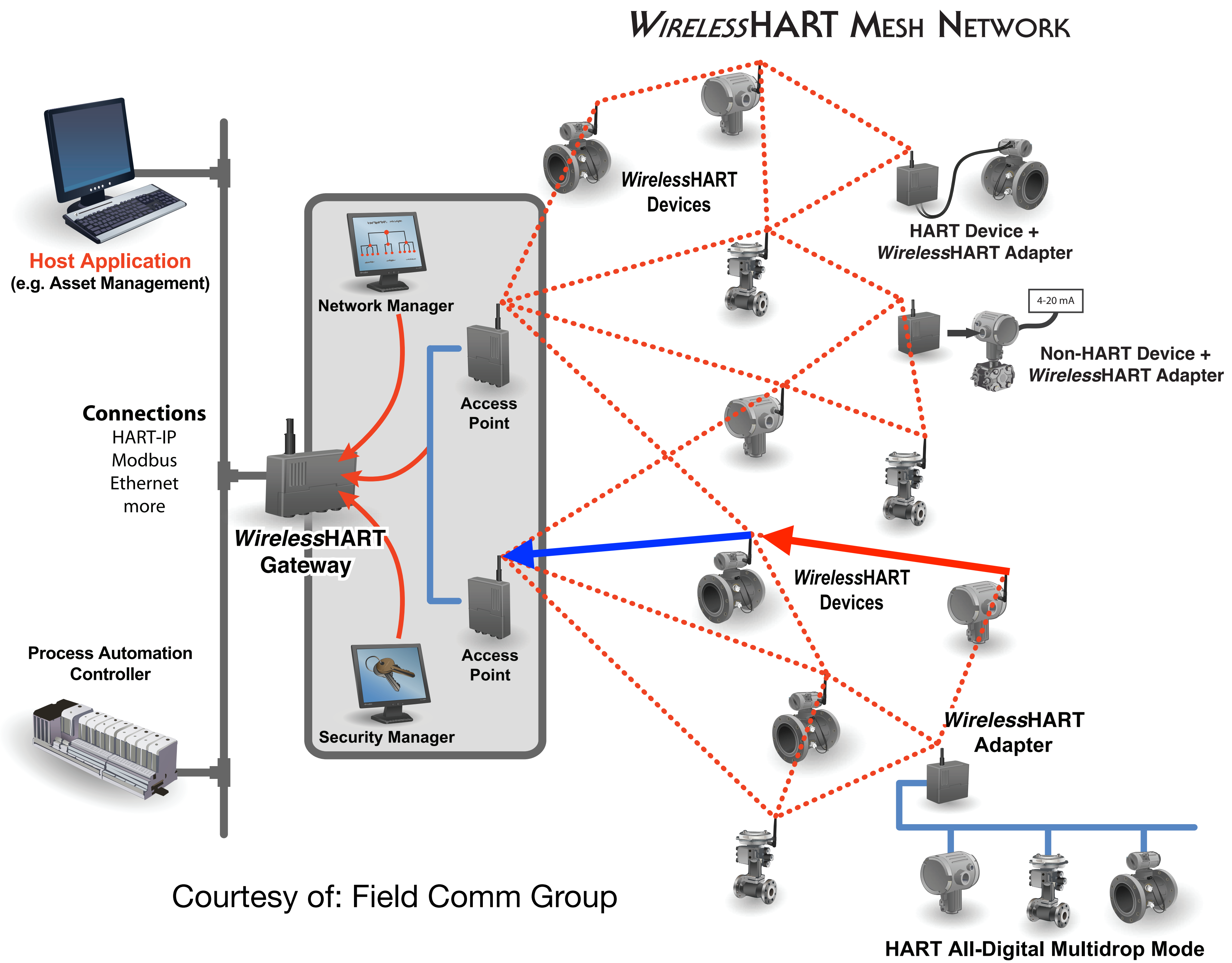


Courtesy of: *Field Comm Group*

Channel access in WirelessHART

The schedules assigned to the red and blue links





Courtesy of: Field Comm Group

Real-Time Communication using IEEE 802.11 Standard

Opportunities

- **Provides higher transmission rate**
    - 802.11 provides several Mbps (compare with 802.15.4's 250 Kbps)
    - Transmission speed is an important factor
- **Widely adopted**
    - 802.11 products show faster improvement: size, cost and power
    - 802.15.4 products represent about 2% of market share. The rest belongs to other technologies such as cellular and WiFi

Challenges

- **High energy consumption**
    - Hard to achieve long lifetime with batteries
    - Hard to employ energy harvesting technologies

- **No guarantee of data delivery delay**
    - WiFi employs contention-based medium access mechanism
    - Node density, traffic density, and interference affect packet delivery delay

Improving energy efficiency

802.11ah

- **Transmission rate: 150 Kbps (1 MHz band) - 40 Mbps (8 MHz band)**
- **Works in the sub-GHz band (900 MHz)**
  - Longer distance (1 km) and better penetration through walls and obstacles
  - ~50% longer distance compared to 802.11n
  - One access point can connect ~8000 devices
- **Improved channel access protocols to further improve energy efficiency**
- **Basically proposed to realize the Internet of Things (IoT)**
- **Supports multi user MIMO and single user beam forming**

- **Qualcomm is actively working on 802.11ah**
- **Other companies: Broadcom, Huawei, Intel, LG, Marvell, NEC, Samsung, and ZTE**

Improving timeliness

802.11e

- **Offers Quality of Service (QoS) features**
  - Prioritization of data, voice, and video transmissions
  - Supports scheduled channel access (not sophisticated)
  - Error correction mechanisms
  - Work at 2.4 GHz and 5 GHz bands

802.11n

- **Supports Multiple-Input Multiple-Output (MIMO)**
  - Higher reliability: Multiple copies can be sent through multiple antennas
  - Higher speed (with 4 Tx and 4 Rx antennas = 600 Mbps)
  - Longer distance
- **Improved channel access mechanism**
  - Send multiple consecutive packets without contention

Hardware vs software improvements

- **Hardware has been significantly improved so far**
- **Software is not sophisticated enough**

802.11 standard:

- **Provides soft real-time delivery**
  - When the load is low and interference is not severe
  - e.g., voice, video
- **Does not provide guarantee of hard real-time data delivery**
- **Uncertainty of delivery delay significantly increases with mobility and interference**

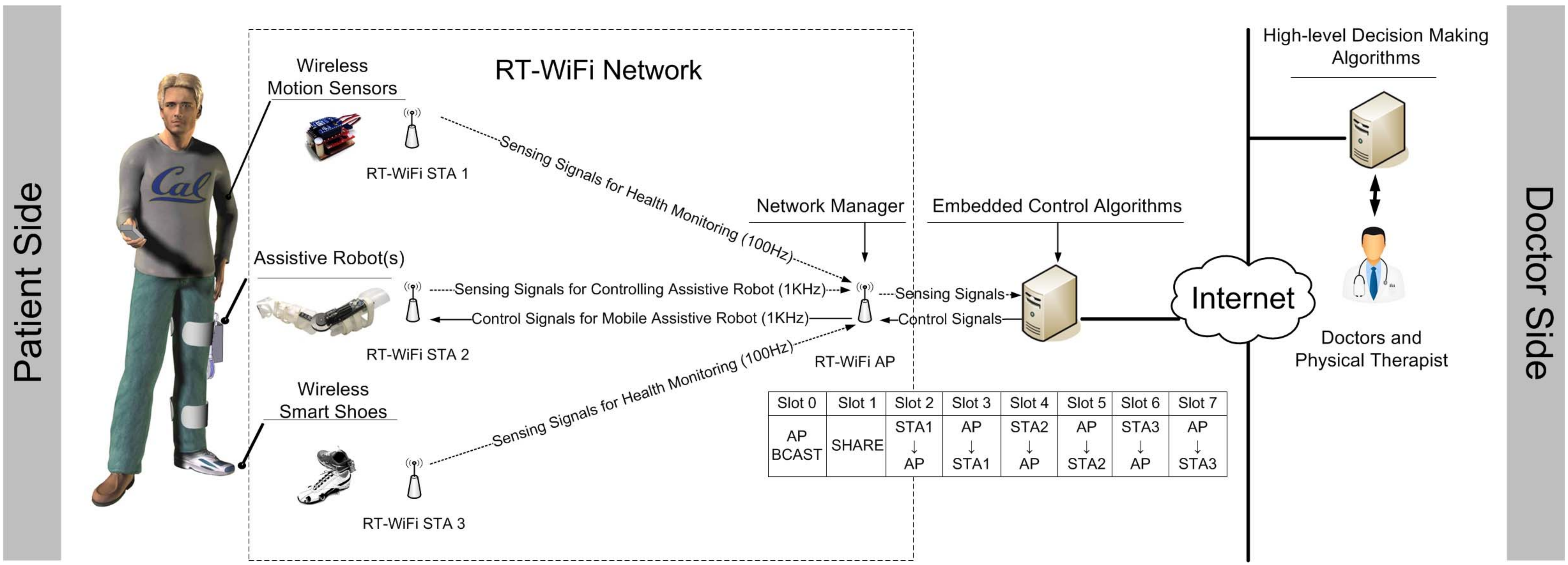
Improving control software

Using device driver or firmware for hardware control

- ”Soft–MAC” chips (such as Qualcomm Atheros) allow a fine-level control of channel access through open source drivers
- e.g., MadWiFi Linux driver, ath9k Linux driver

RT-WiFi

- Hardware: Qualcomm Atheros AR9285
- Linux wireless driver has been modified to control communication times
- Nodes request schedule from an access point



Reference: "Improving Control Performance by Minimizing Jitter in RT-WiFi Networks", RTSS 2014

Main shortcoming of existing solutions

- How to expand the network?
- **How to support mobility?**
  - Limits the applicability of these solutions to applications with mobile entities such as patients, robots, firefighters, etc.

Real-Time and Low-Power Wireless Communication with Mobile Nodes

Our goals

- Real-time communication with mobile nodes
- Real-time communication irrespective to mobility pattern
- Maximize the number of mobile nodes admitted
- The network should be energy efficient
- The network should be reliable

Challenges

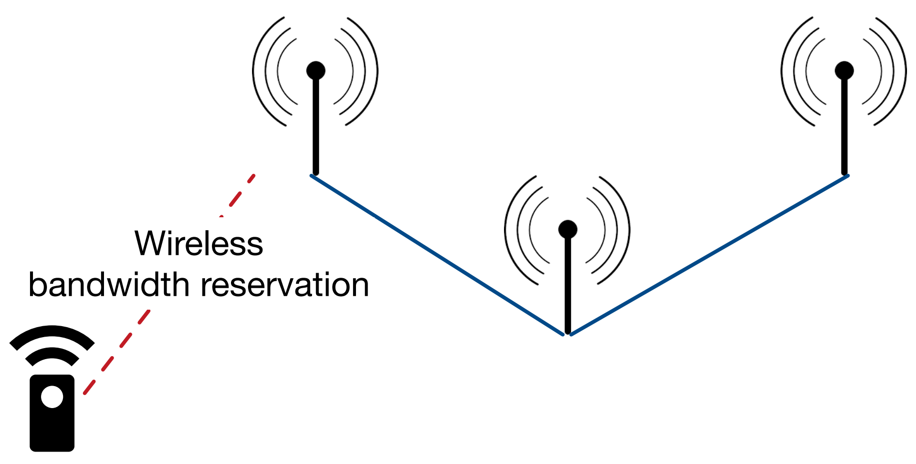
1. **Network Architecture**
   Which architecture is suitable for mission-critical applications

2. **Network Management**
   New algorithms should be implemented in Network Manager to support mobility

Network architecture

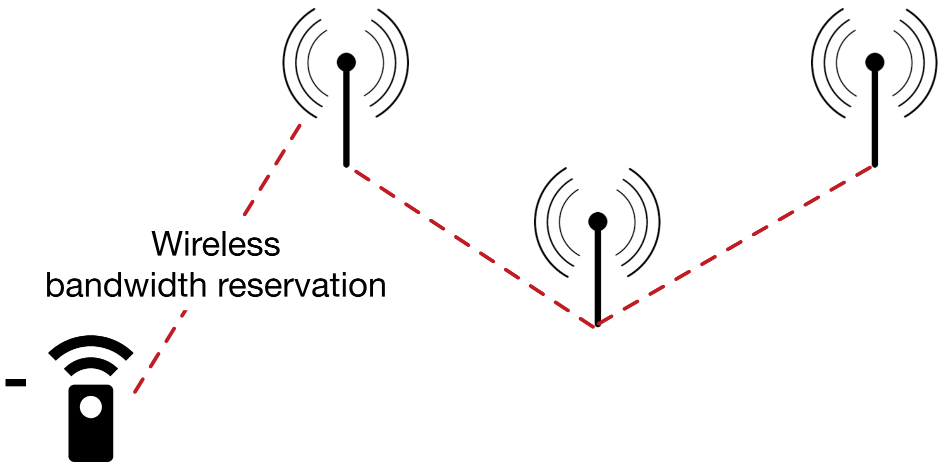
Wired infrastructure

- **Base stations are connected through wire links**
- Similar to cellular (3G, 4G) and WiFi networks
- Bandwidth reservation only between mobile-infrastructure
- Harder network deployment

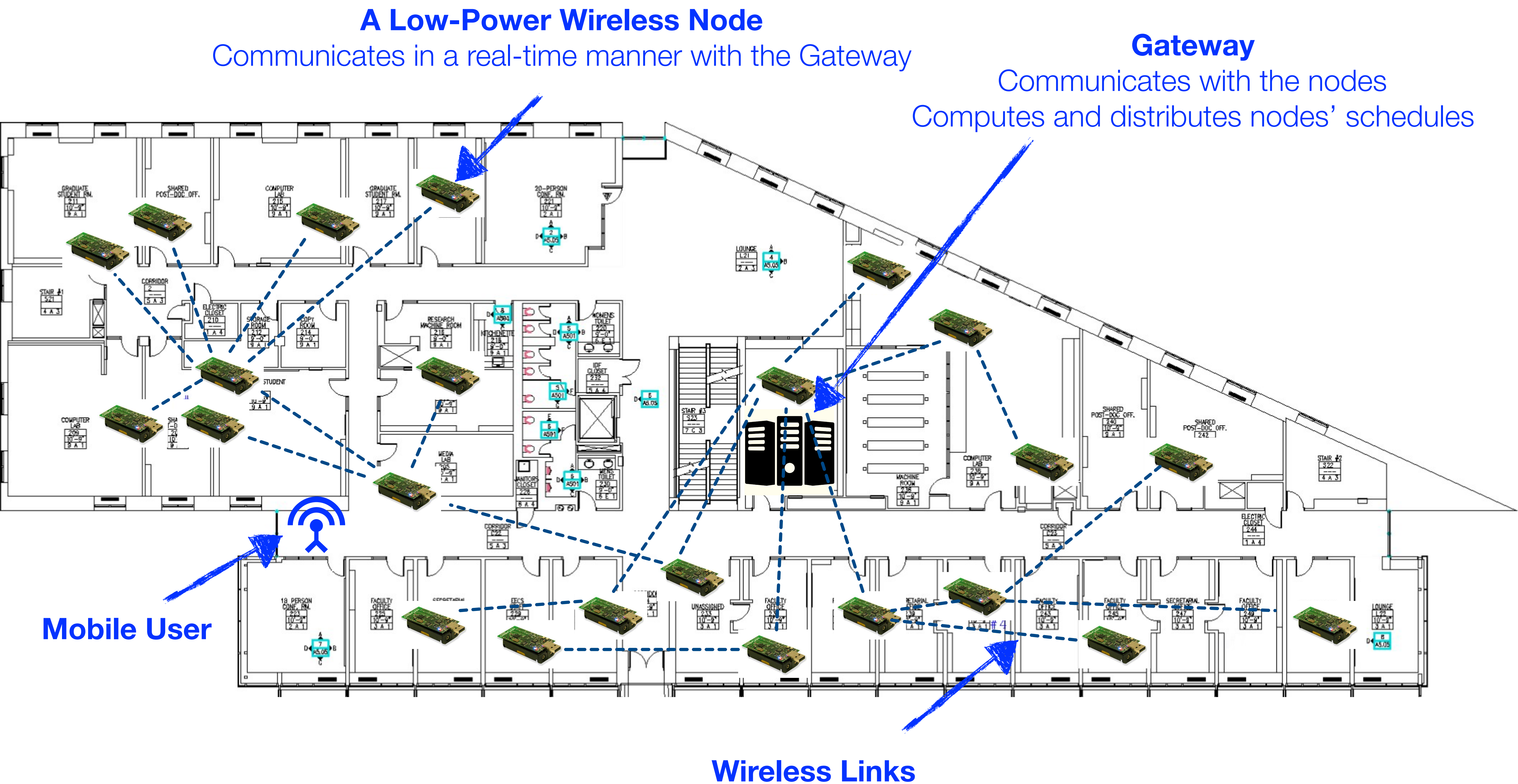


Wireless infrastructure (Our choice)

- **A multi-hop wireless infrastructure**
- Easier network deployment
- Bandwidth reservation between infrastructure-infrastructure as well as mobile-infrastructure



Wireless infrastructure



Impact of mobility

Low energy consumption

↓

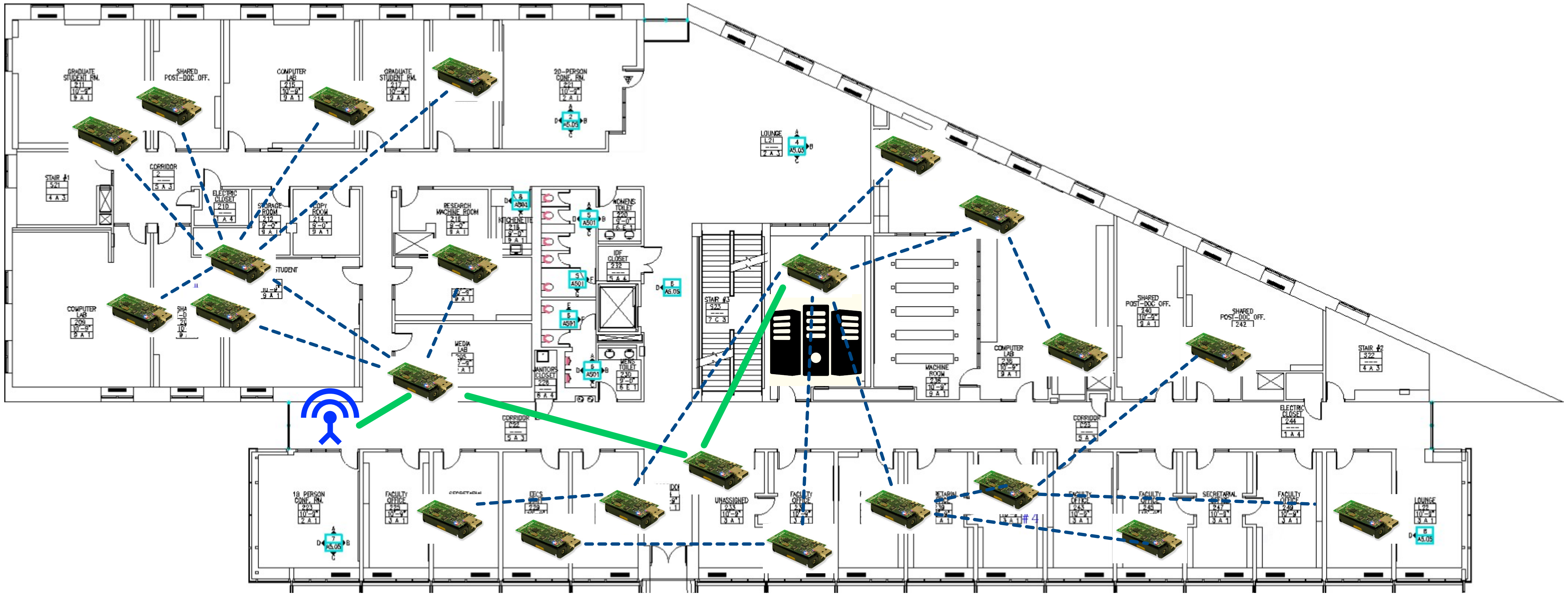
Short communication range

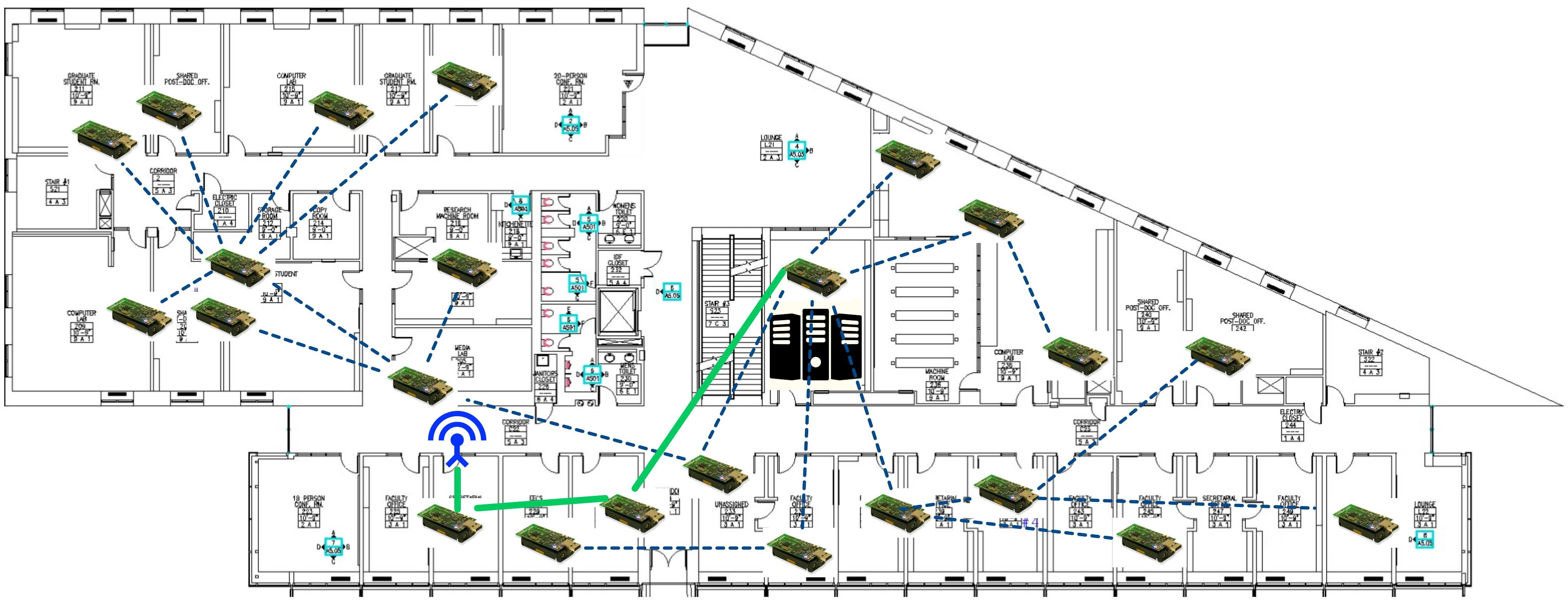
↓

Frequent association with infrastructure nodes

↓

Frequent changes in data forwarding paths





Impact of mobility

Frequent association

Frequent request for bandwidth reservation

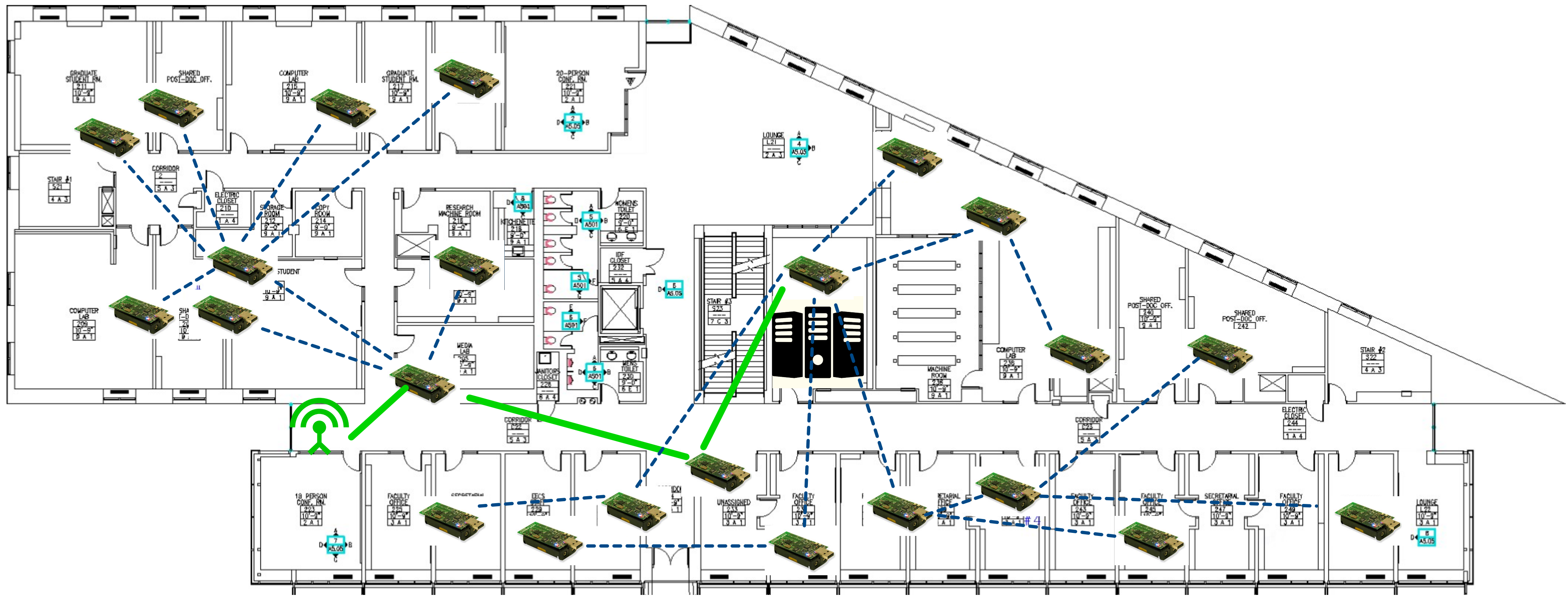
Consumes lots of bandwidth and energy resources

The Gateway may fail to reserve bandwidth over a new path

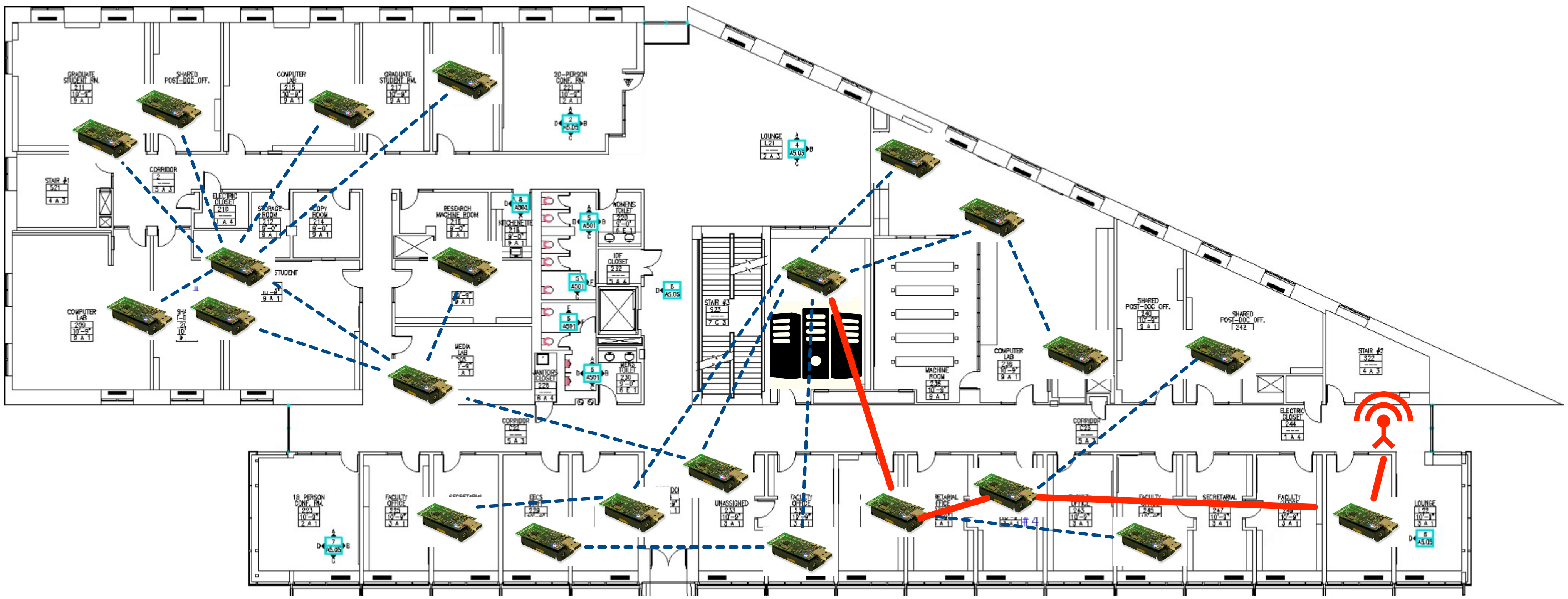
disconnection and violation of real-time delivery

Impact of mobility

Successful bandwidth reservation



Failed bandwidth reservation: Disconnection and violation of real-time data delivery



Impact of mobility

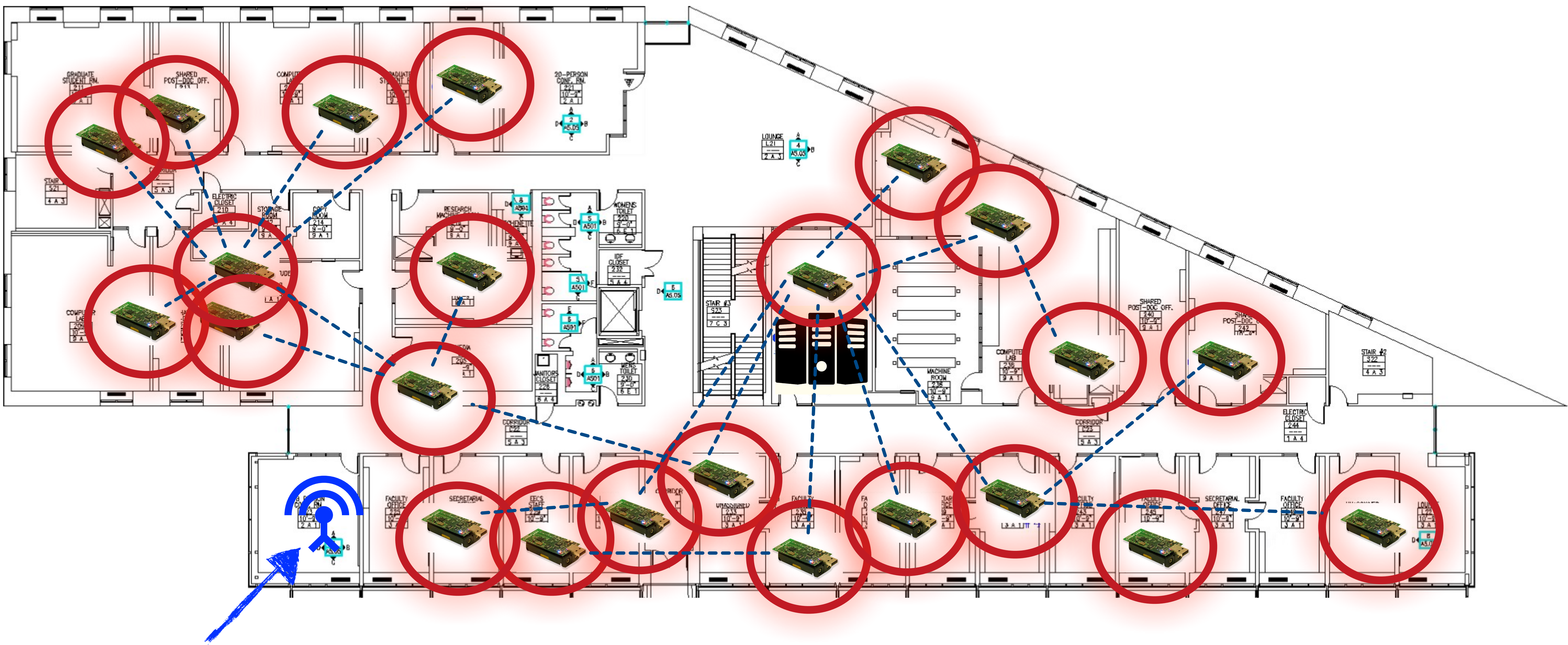
Real-time and low-power communication with mobile nodes requires: ***bandwidth reservation over the potential communication paths upon node admission***

- Existing scheduling algorithms (e.g., used by WirelessHART)
  - Inefficient bandwidth reservation

New algorithms are required to cleverly reserve bandwidth for mobile nodes…

Mobile node admission

Infrastructure nodes regularly broadcast beacon packets

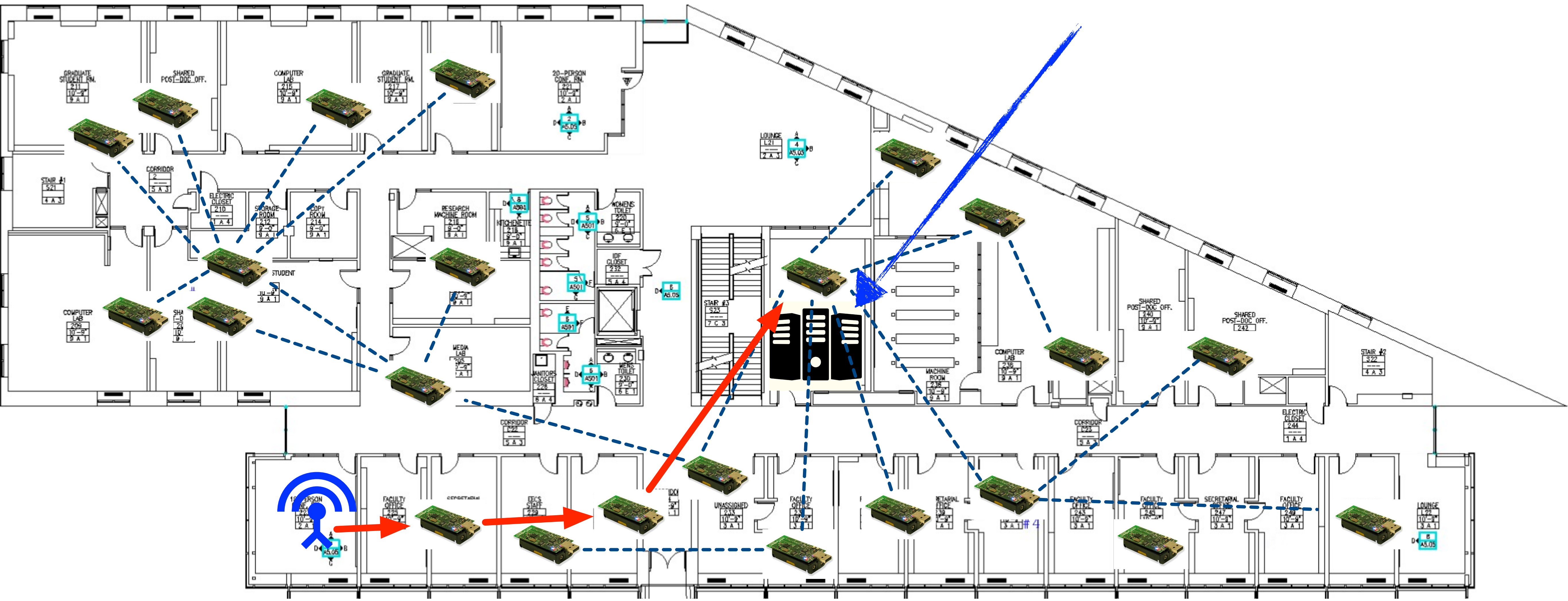


This allows the mobile nodes to discover nearby nodes

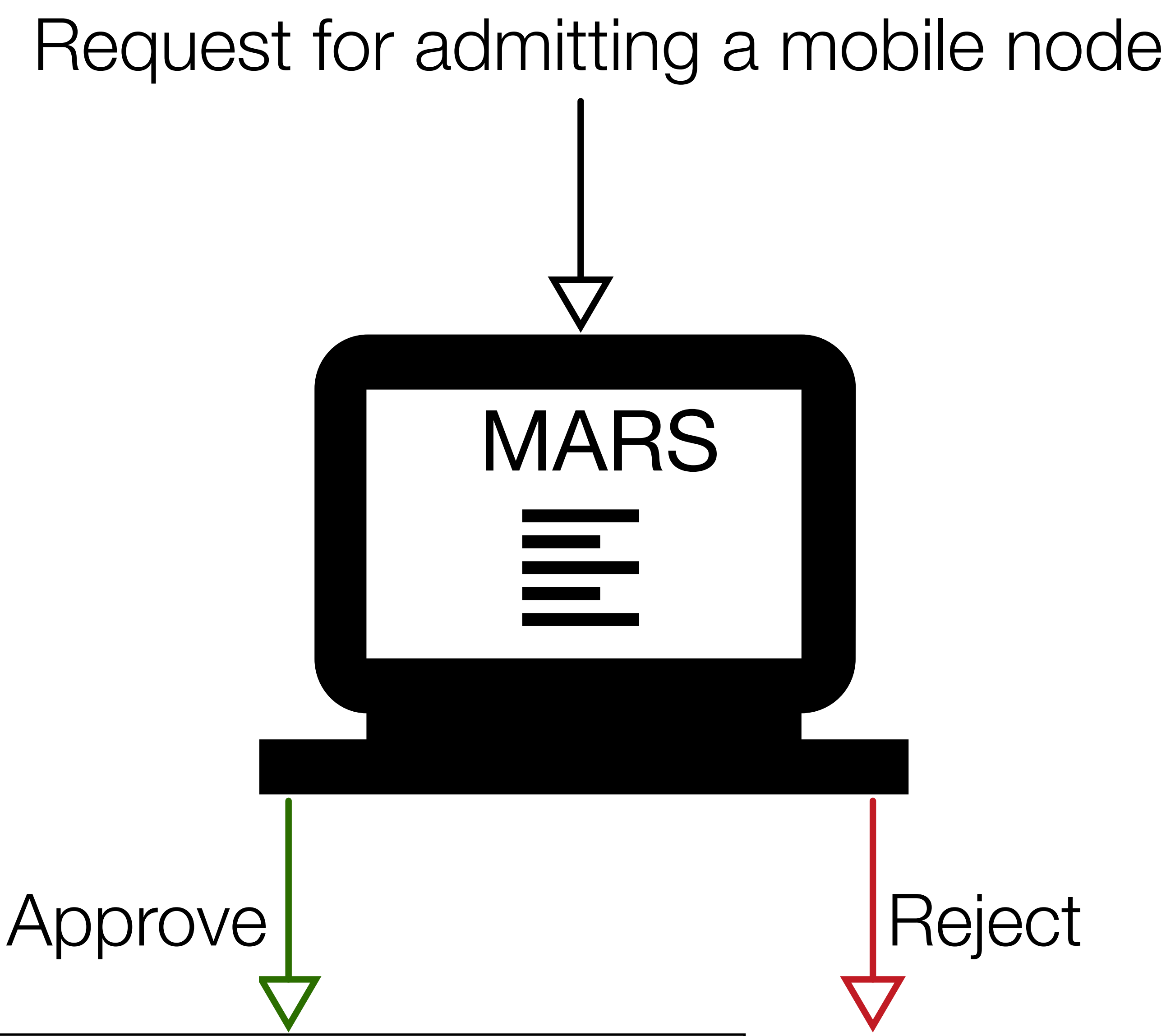
Mobile node admission

The mobile node sends a join request

The Gateway (Network Manager) should decide about the admission of mobile node



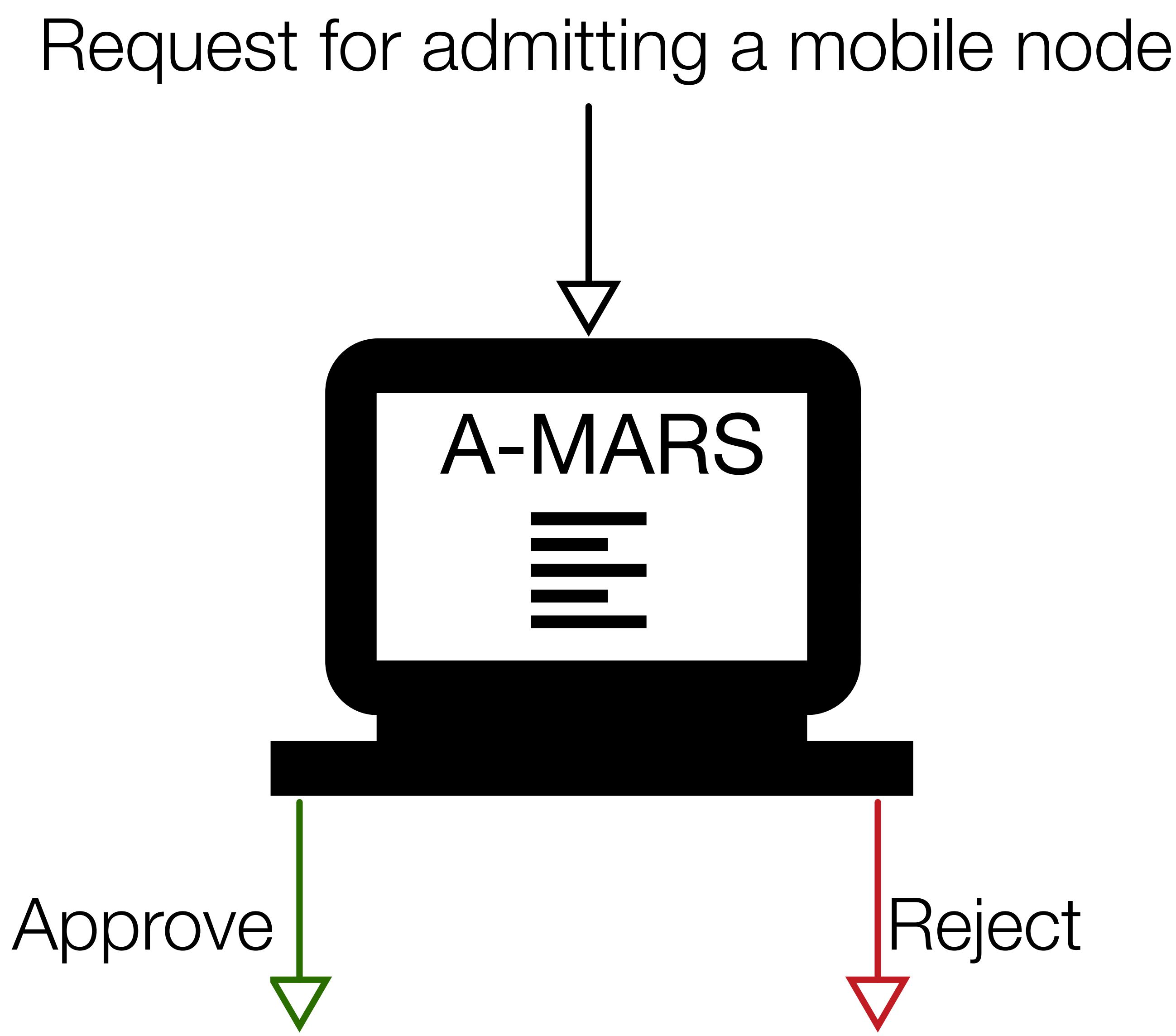
Mobility-Aware Real-time Scheduling (MARS)



Bandwidth reservation for:
new mobile node + existing nodes

Distribute the transmission schedules for:
new mobile node + existing nodes

Additive Mobility-Aware Real-time Scheduling (A-MARS)



Bandwidth reservation for:
new mobile node

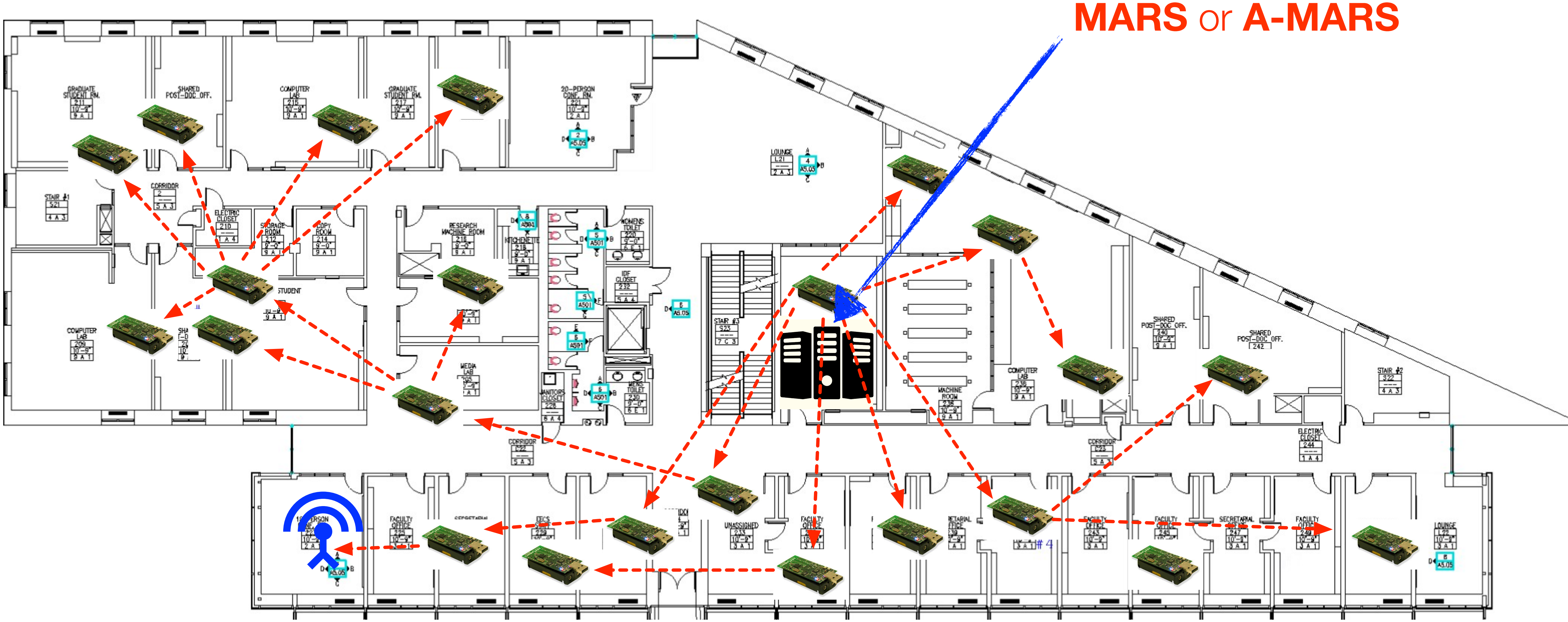
Distribute the transmission schedules for:
new mobile node

Network Architecture

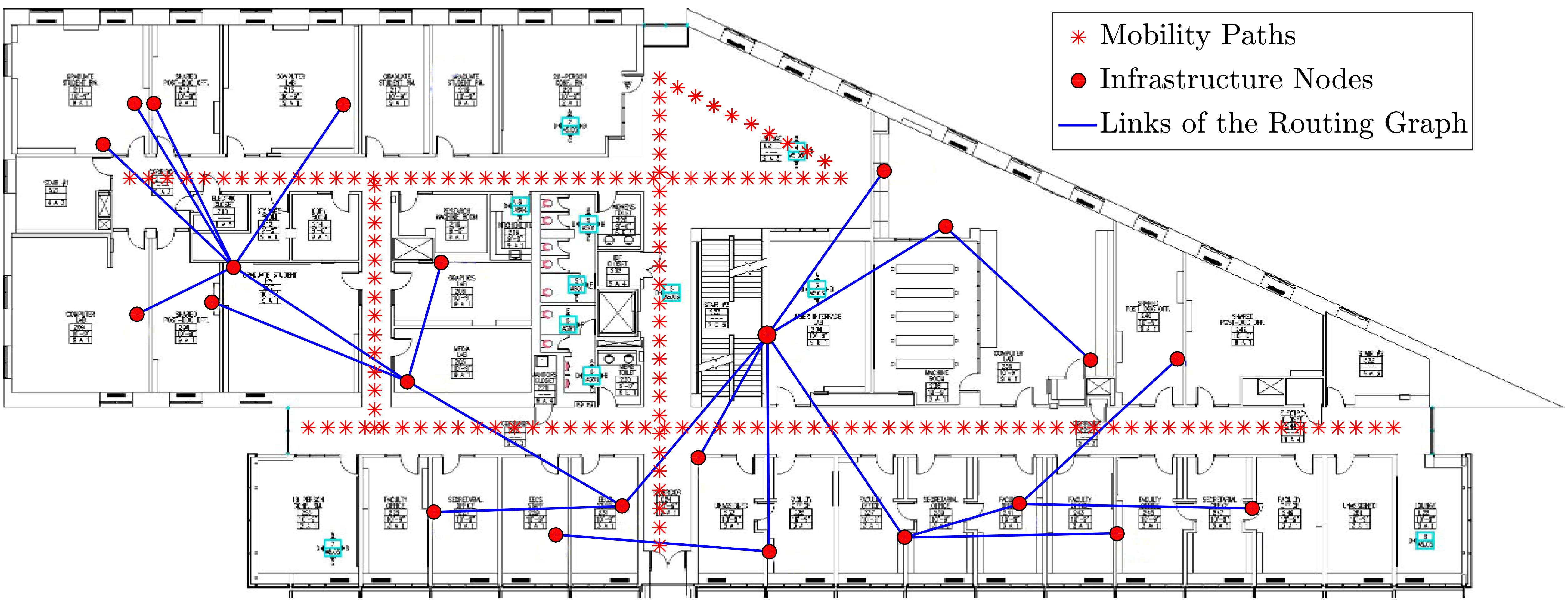
New transmission schedules should be distributed

Gateway

Includes the implementation of: MARS or A-MARS



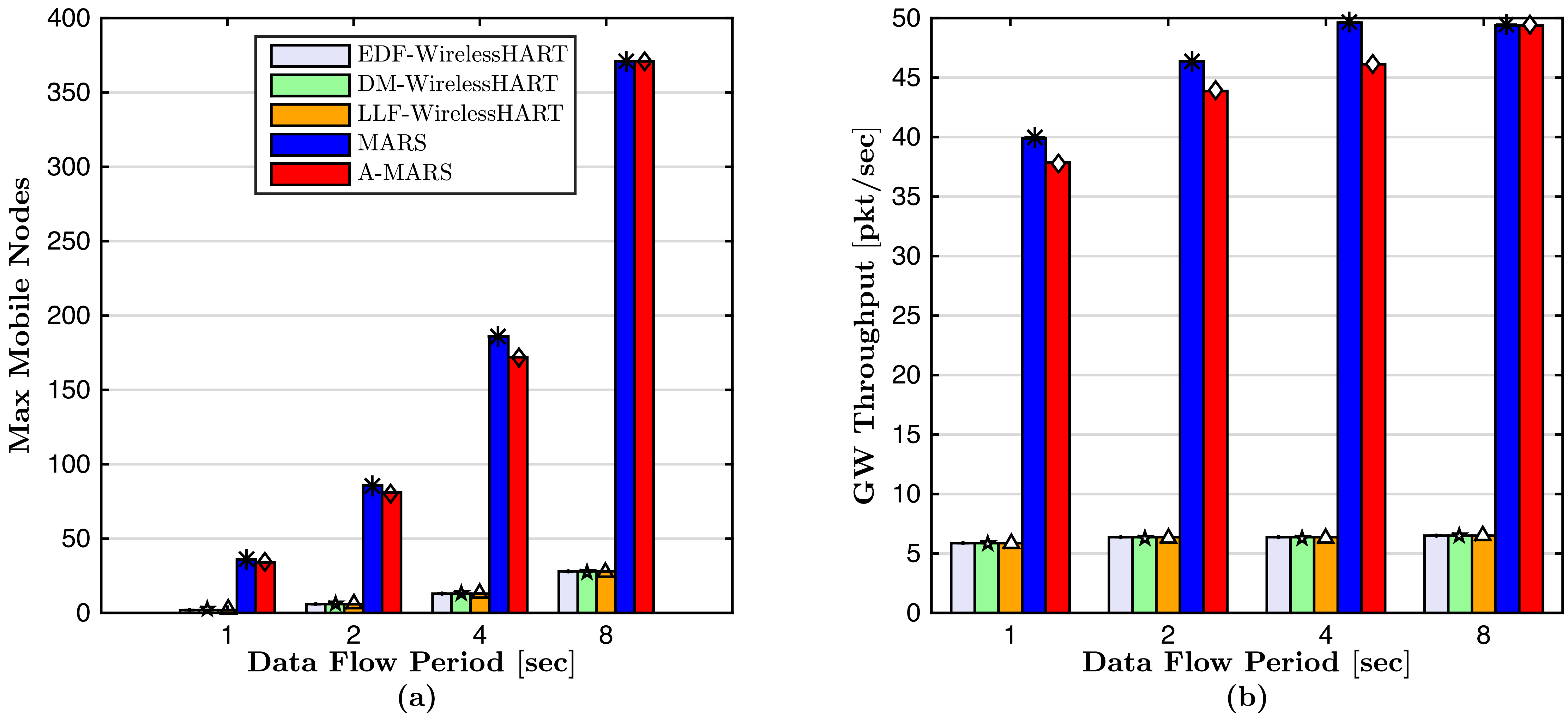
Evaluation



Mobility Paths
Infrastructure Nodes
Links of the Routing Graph

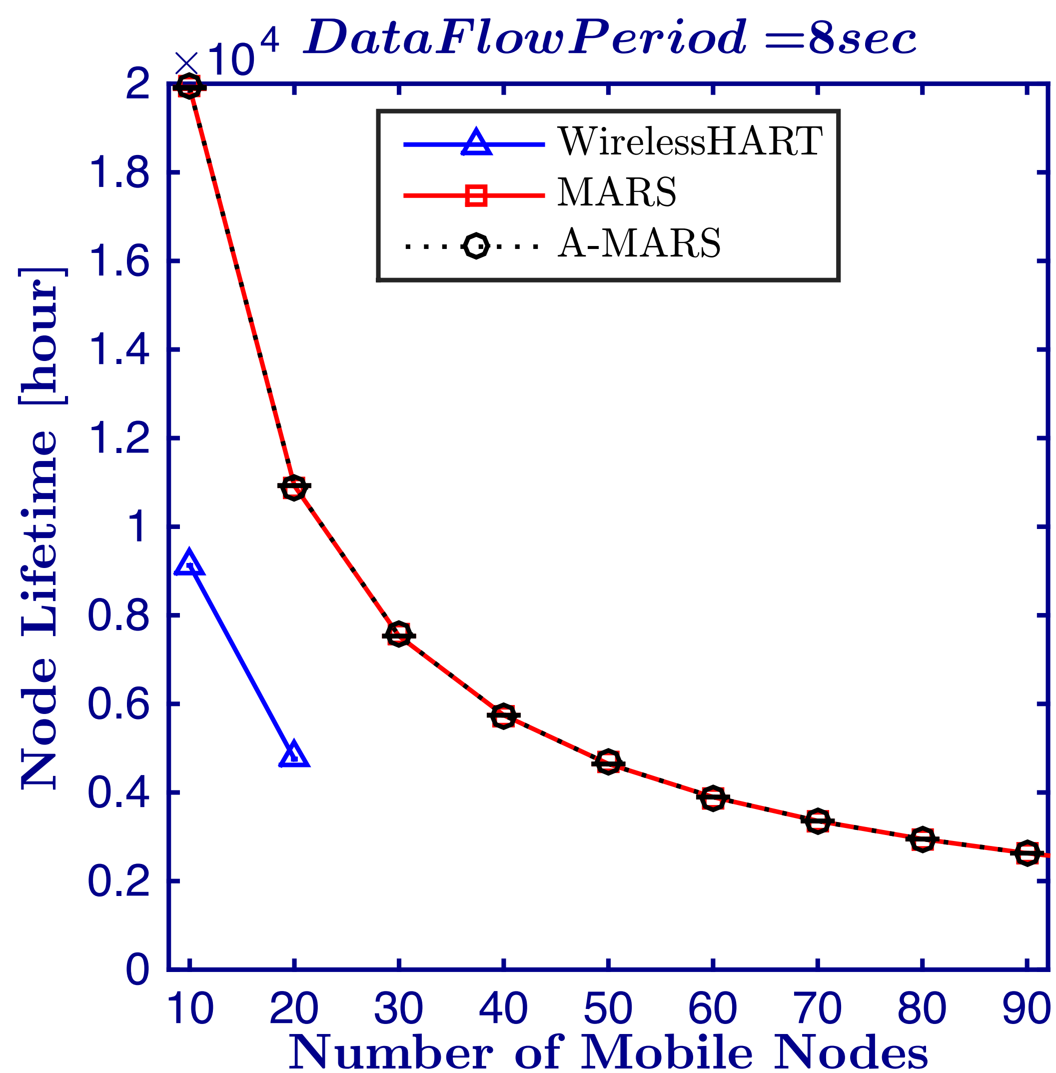
Evaluation

WirelessHART against MARS and A-MARS



Our proposed protocols significantly increase the number of admitted mobile nodes through increasing bandwidth reservation efficiency

Evaluation



For the same number of mobile nodes admitted, our network provides higher lifetime

Conclusion

- Real-time wireless communication is a reality today
- Standards such as WirelessHART and ISA 100 employ 802.15.4 technology
- New real-time applications require higher transmission speed
- 802.11 requires improvement in terms of delay guarantee and energy efficiency
- We have developed a real-time and low-power mobile wireless network
- Our developed network guarantees real-time communication with mobile nodes irrespective to the mobility pattern of the nodes
- We are extending our work to support real-time communication over existing 802.11 networks