WiFiRe:
Broadband wireless for rural areas

a creative-commons collaborative effort across

Take-Away

- What is WiFiRe?
  - One liner: A WiMAX-like MAC over a WiFi PHY.

- Key Differentiators:
  - WiFi PHY extended for long range (15-20 Km) using sectorized and directional antennas.
  - Single WiFi channel shared among all the sectors.
  - Multi-sector co-ordination by the scheduler.

Participants

- IIT Madras – Bhaskar Ramamurthi
  - Economics; hardware; deployment aspects

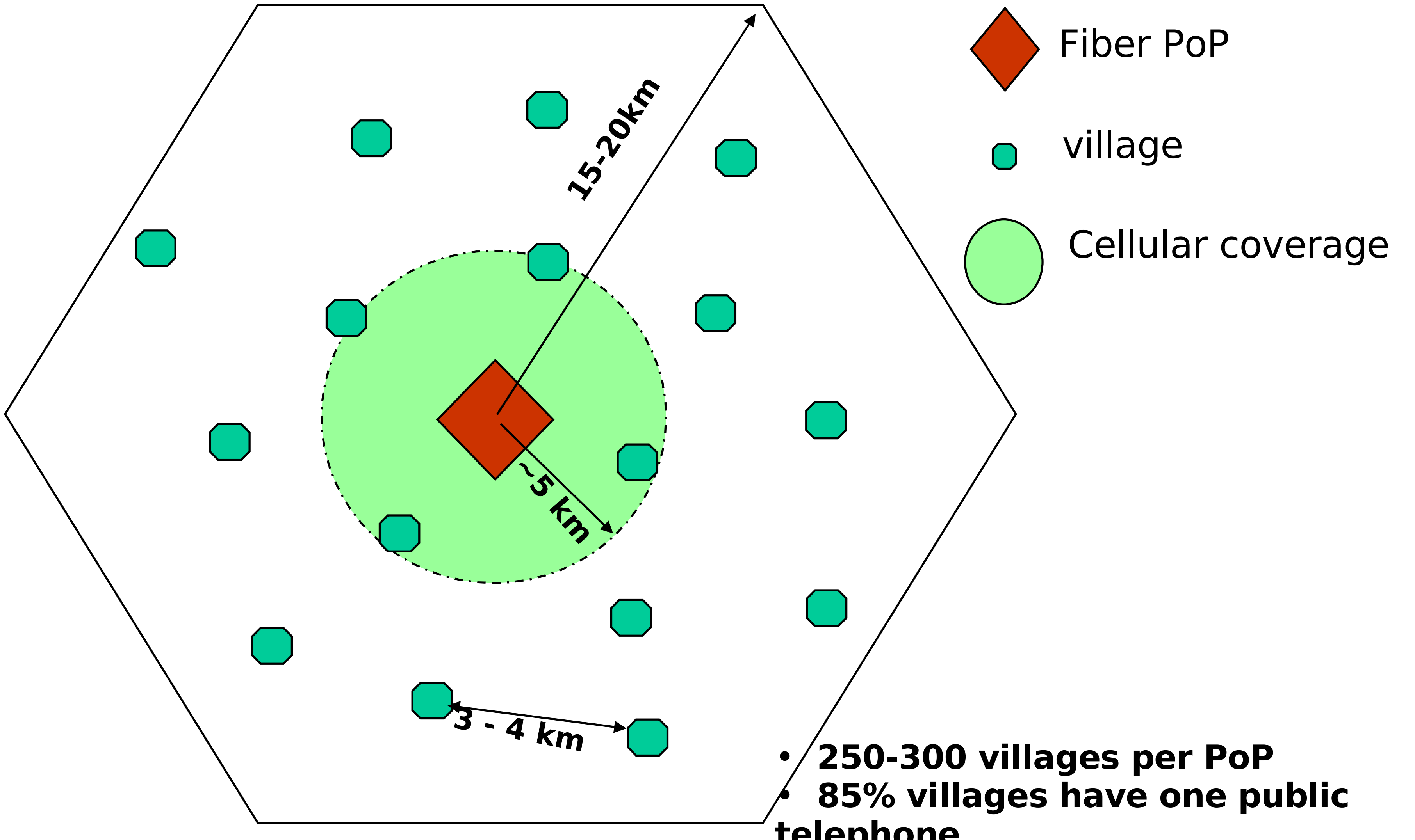
- IISc Bangalore – Anurag Kumar
  - Capacity analysis; scheduler design

- IIT Bombay
  - Protocol Specification, Implementation, Performance analysis, Verification

  - Many participating faculty: Sridhar Iyer, Krishna Paul, Anirudha Sahoo, Om Damani, Bhaskar Raman, Varsha Apte, Krishna S, Puru Kulkarni
  - Many MTPs (2 batches): Shravan, Sameer, Venkat, Sudheer, Janak, Ranjith, Sreedhar, Kedar

The Need:
Design Drivers

Rural India : Background



- **250-300 villages per PoP**
- **85% villages have one public telephone**
- **Each village: average 250 households**

Rural India: Some numbers

- 70% of India’s population or about 750 million.
- 600,000 villages, 85% of which are on flat terrain.

- Roughly 250 households cluster in a village.
- Villages spaced 2-3 Km apart, spread around the market towns, which are spaced 30-40 Km apart.
- Each town serves a catchment of around 250-300 villages.

- Optical fiber backbone passes through these towns.
- Cellular coverage extends only about 5 Km from the town.

Rural India: Some economics

- Income levels are lower than the national average:
  - Average monthly income is around Rs. 3000/- per month.
  - Only 2.5% of households earn more than Rs. 25000/- p.m.
  - Less than Rs. 100/- p.m. can be spent on telecom services by an average household.
- ARPU is not sufficient to interest traditional cellular operators.
- A public kiosk, providing a basket of services, is the key to Internet and telephony access.
  - Assuming 2 kiosks per village, the revenue of each can be only of the order of Rs. 4500 per month. (CAPEX ~ Rs 15K).
  - Most of a kiosk's income is expected to be from voice traffic.
  - A kiosk can expect at most 1 or 2 voice calls to be made on a continuous basis.

Technology requirements

- Low cost - capital and operation expenditure.
- Broadband – 256 kbps sustained per kiosk.
- Guaranteed QoS for voice traffic.

- One way to get there:
  - Avoid spectrum licensing and regulatory issues.
  - Use mass produced, off-the-shelf, components.
  - Choose simple topologies for deployment.

  - Implement efficient medium access control and intelligent scheduling mechanisms.

Present day technology alternatives

- Mobile cellular technologies – GSM/GPRS; CDMA
  - Low population-density → low ARPU.
  - Licensed band → high deployment cost.

- Proprietary technologies – corDECT; iBurst; FlashOFDM
  - Low volumes →high cost.

- WiMAX today
  - Low volumes →high cost.
  - Spectrum licensing issues.

- WiFi
  - low-cost chipset, free radio spectrum.
  - How about its range and efficiency?

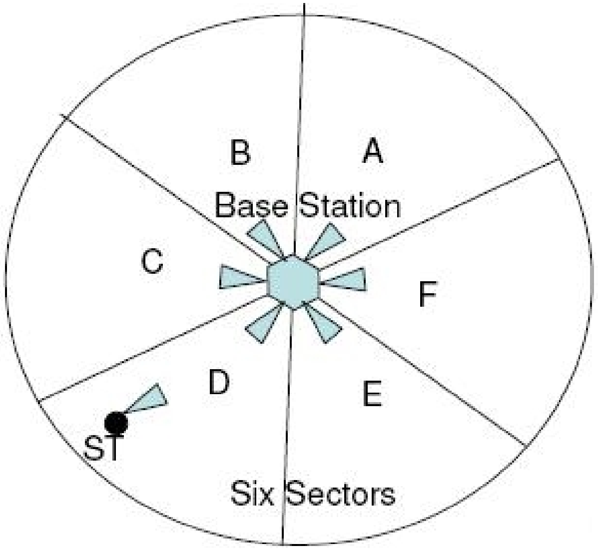
WiFi based long range communications

- Attraction:
  - Delicensing of the spectrum.
  - Availability of low-cost, mass produced, WiFi chipsets.
- Range extension:
  - Several experiments with off-the-shelf equipment have demonstrated the feasibility of using WiFi for long-distance rural point-to-point links.
  - Link margin is quite adequate for line-of-sight outdoor communication over flat terrain for about 15 kms of range.
- Efficiency:
  - WiFi MAC is not suited for maximizing capacity or for providing QoS guarantees.
  - DCF (CSMA/CA) is inefficient for long range communication.
  - PCF is inefficient when the spectrum is reused in sectors.

One Solution: WiFiRe

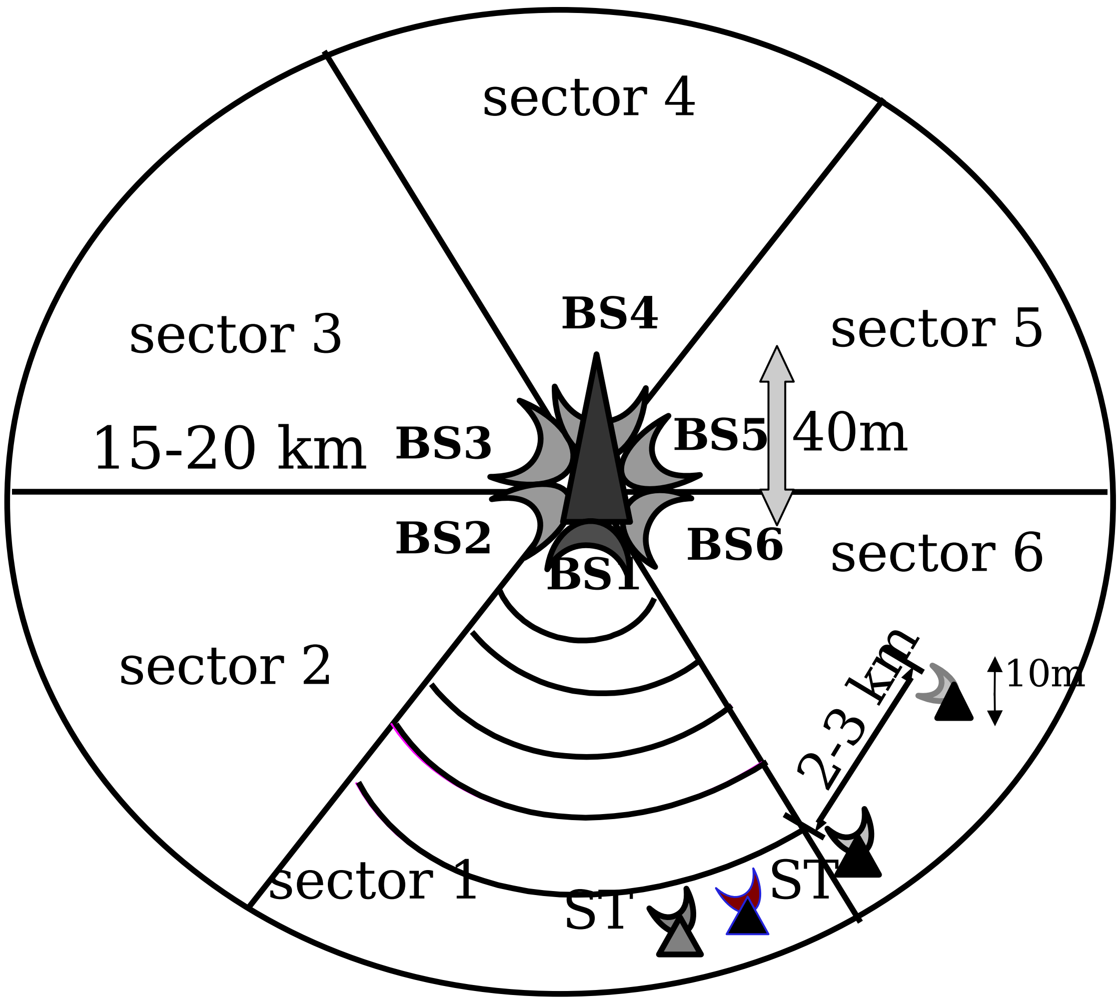
WiFiRe architecture

- 40 m tower at the base station (BS).
- 10-12 m poles at the subscriber terminals (ST).
- system gain 150 dB.
- Network configuration is star topology.
  - 15 km radius



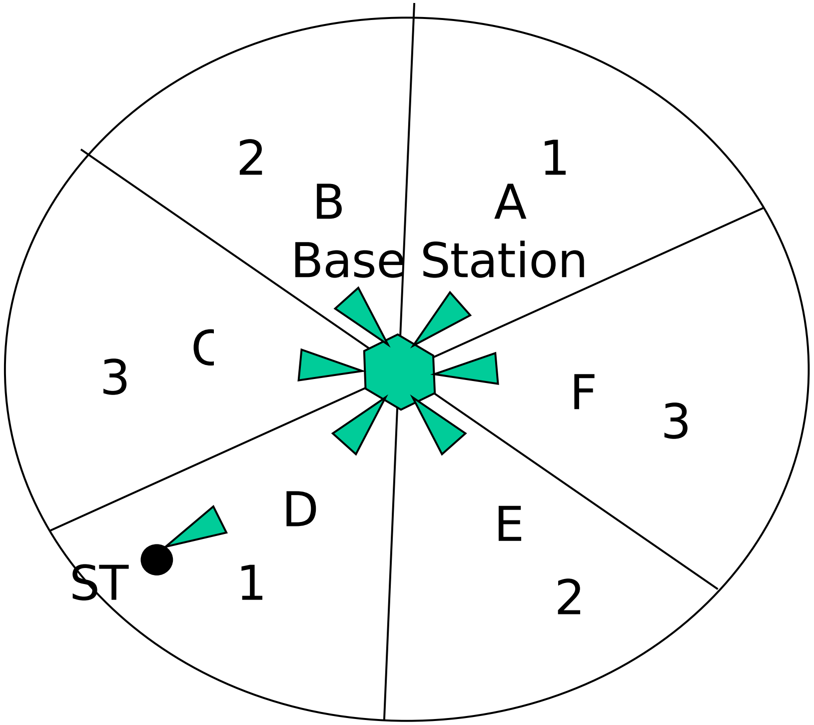
- Sectorized antennas at BS.
- Single fixed ST in each village.
- Directional antenna at each ST.
- Voice and data terminals in the village connected by a LAN.

WiFiRe - Architecture

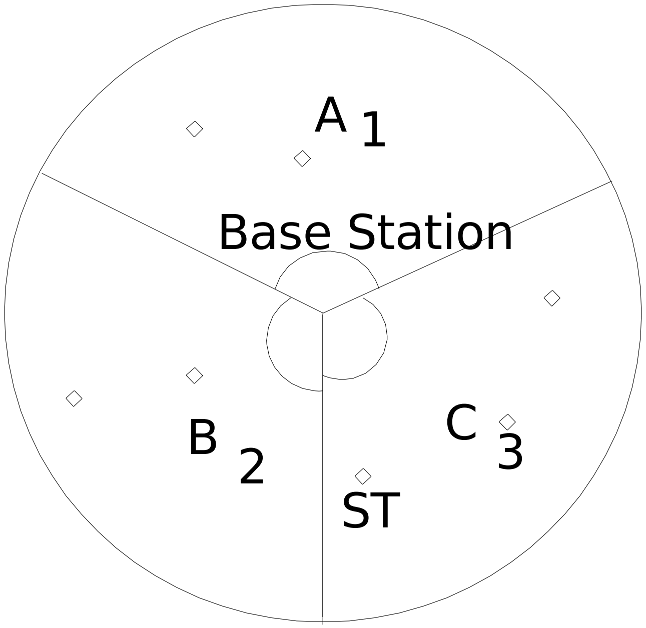


- Base Station at PoP (40m height)
- Subscriber station in each village (10m height)
- 6 sectors and directional antennas
- 802.11 PHY and WiMAX-like MAC

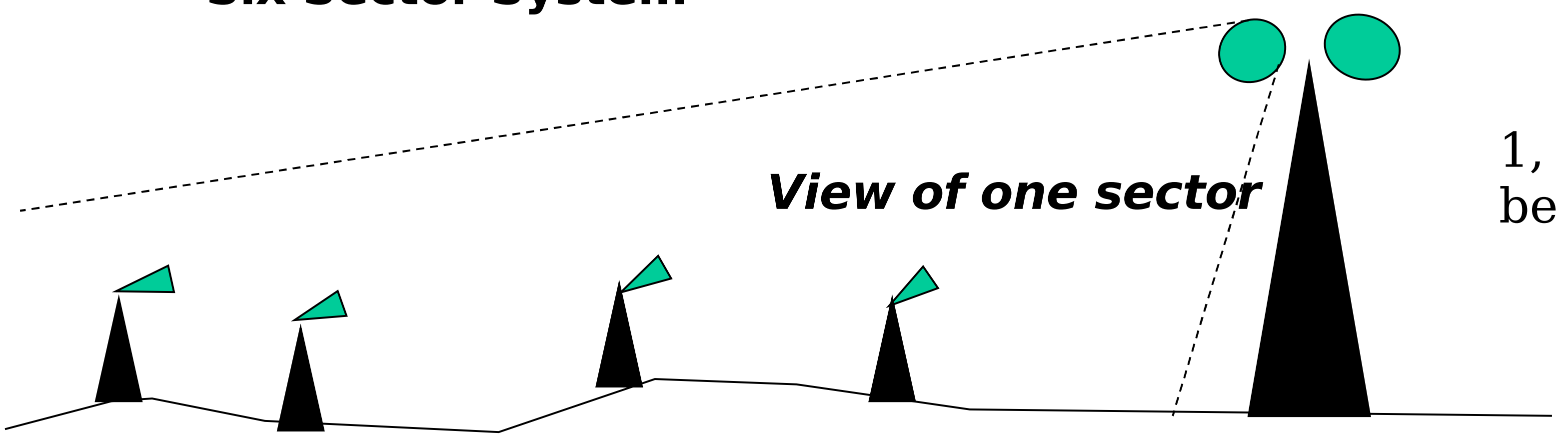
Architecture – Multi-sector system



Six Sector System

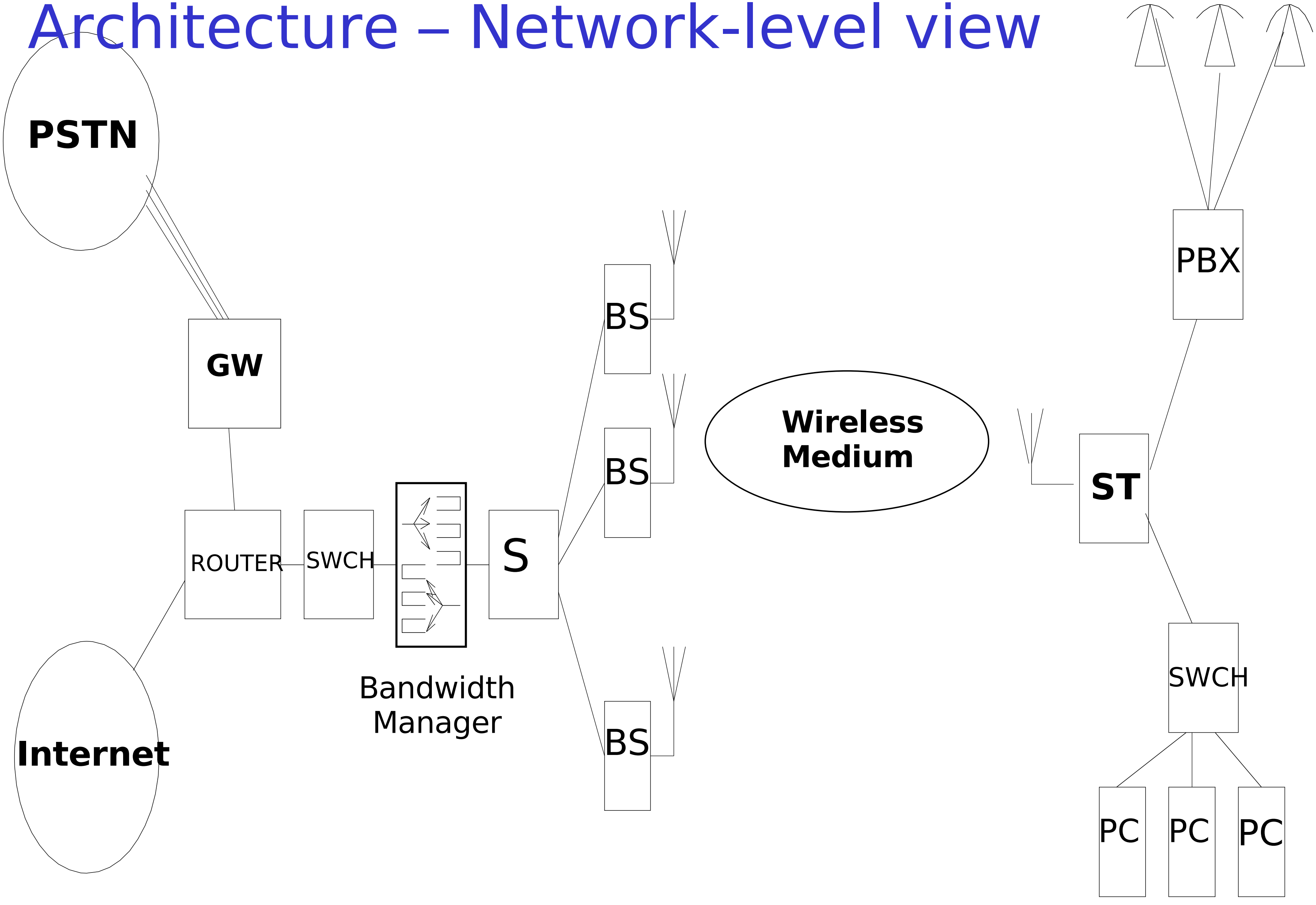


Three Sector System

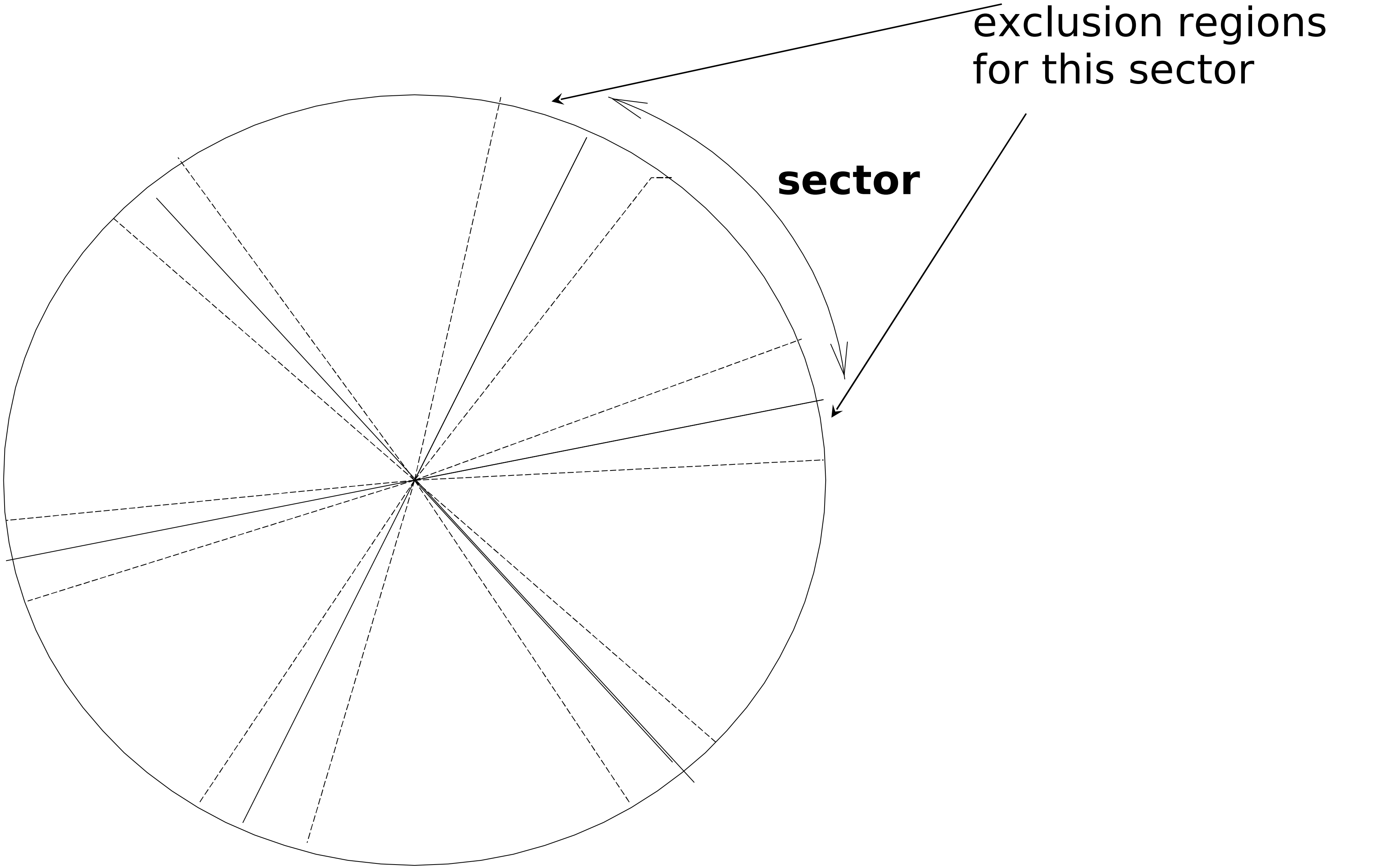


1, 2, 3 are beacon IDs

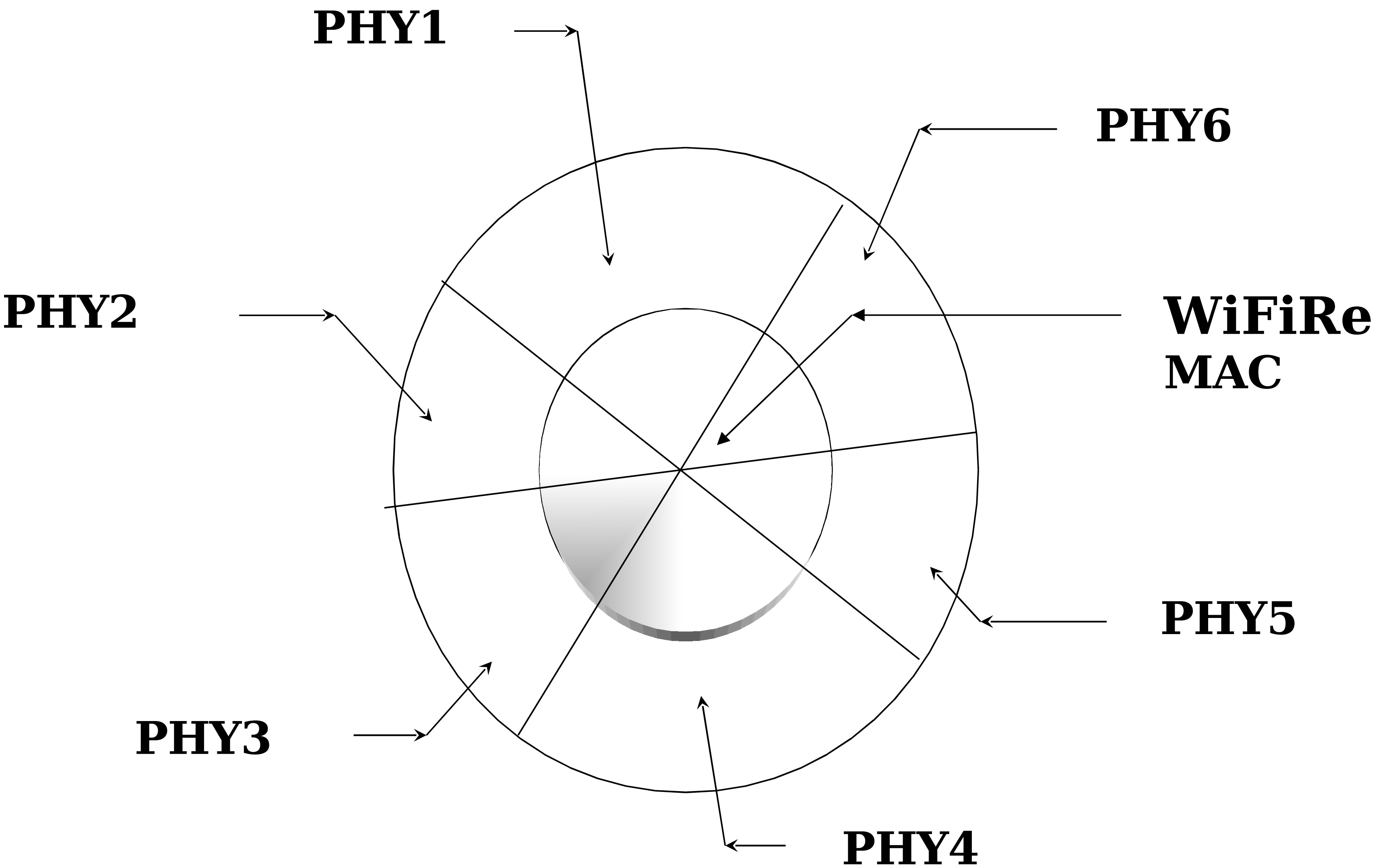
Architecture – Network-level view



Architecture – Interference Pattern



Architecture – Multiple PHY, Single MAC



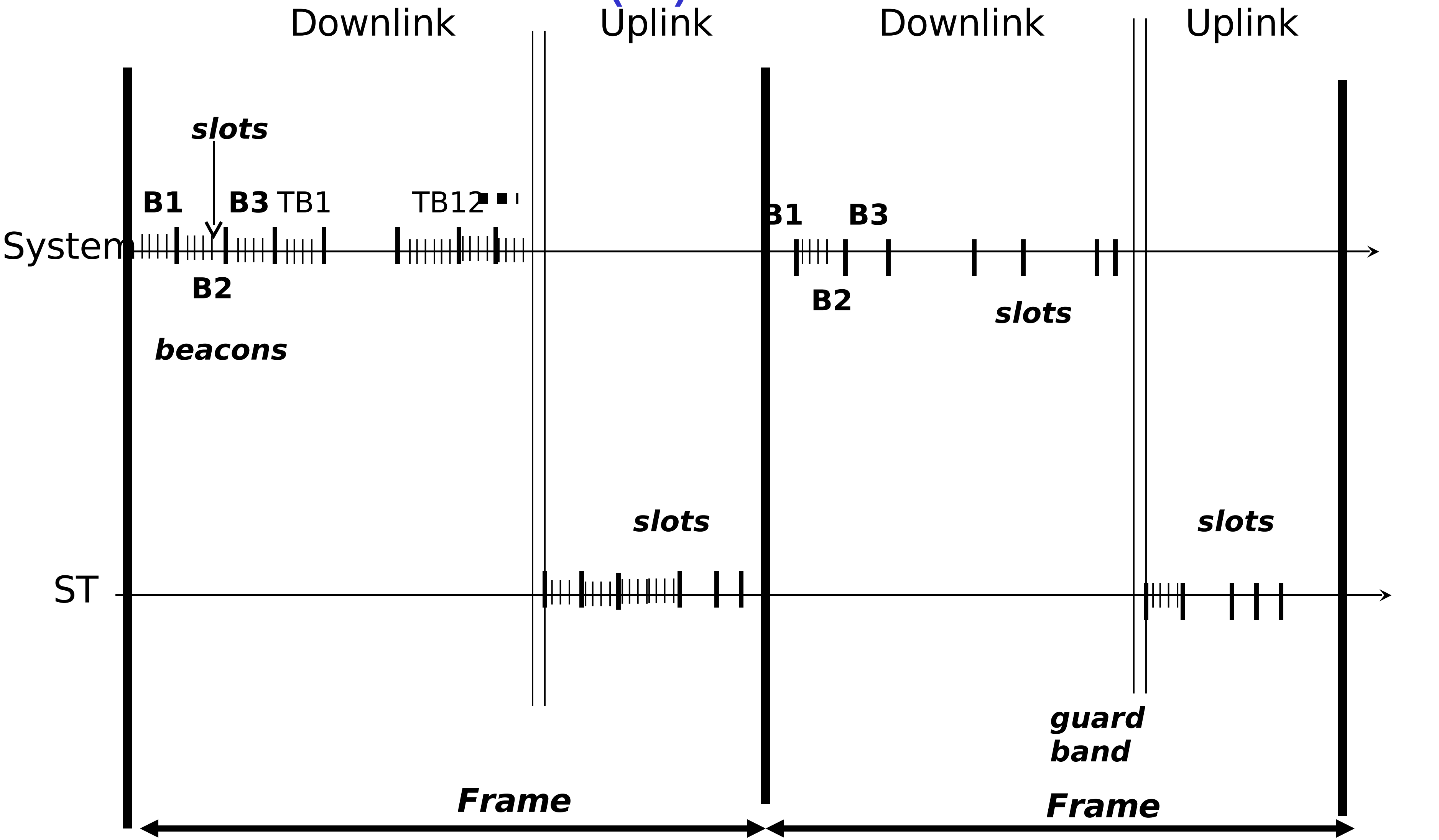
WiFiRe MAC

- Single WiFi channel used by all the sectors.
- No multi-path issues but antennas may interfere.
- One MAC controls all the sectors in a BS.

- Slotted system – 32 μSec slot; 10 mSec frame.
- TDD – No interleaving of downlink and uplink transmissions.
- MSTDM scheduling –Non interfering transmissions across multiple sectors may happen in parallel (within the TDD).

- Within each sector, the WiFiRe MAC is somewhat similar to the WiMAX MAC.

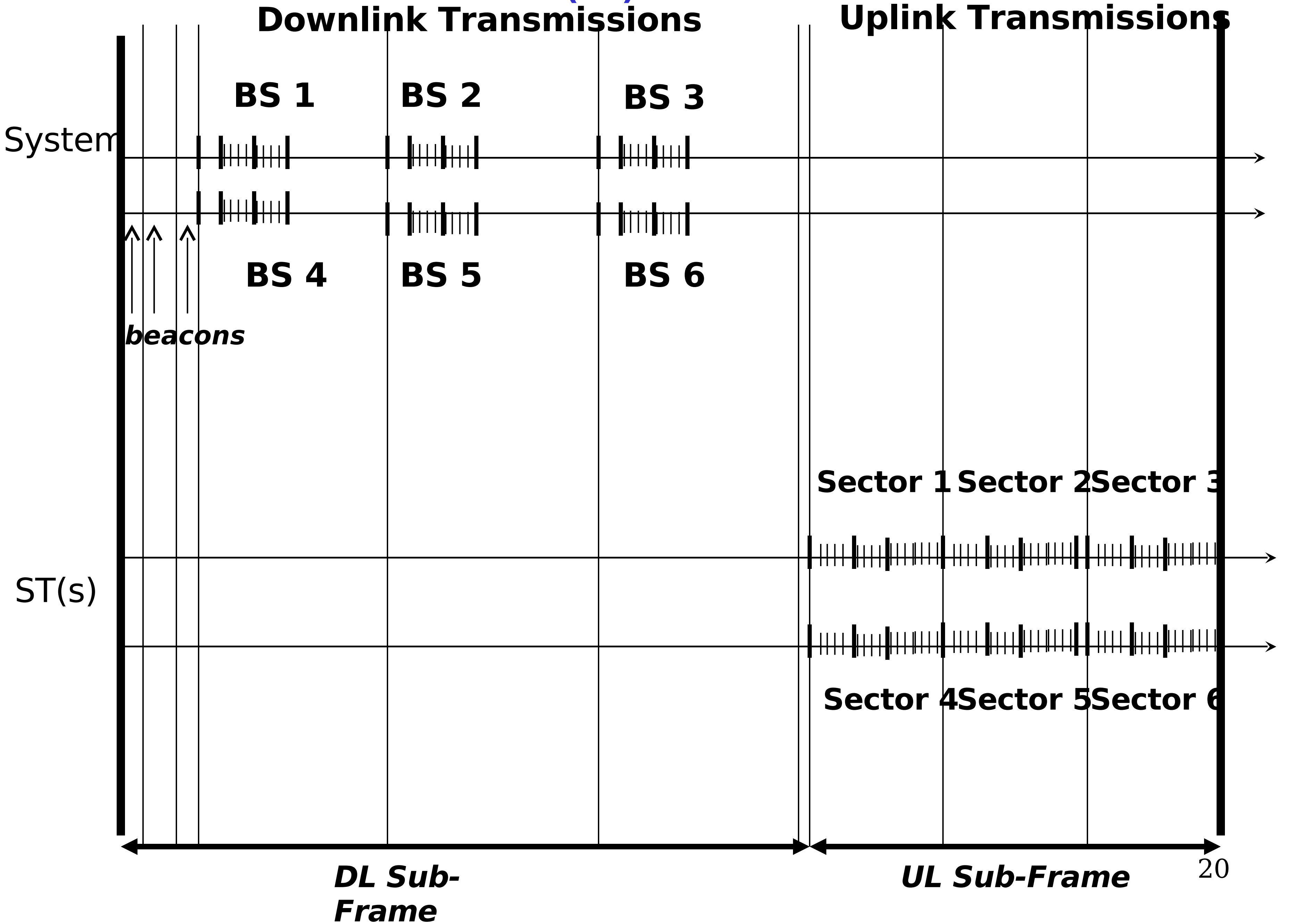
Frame structure –(1)



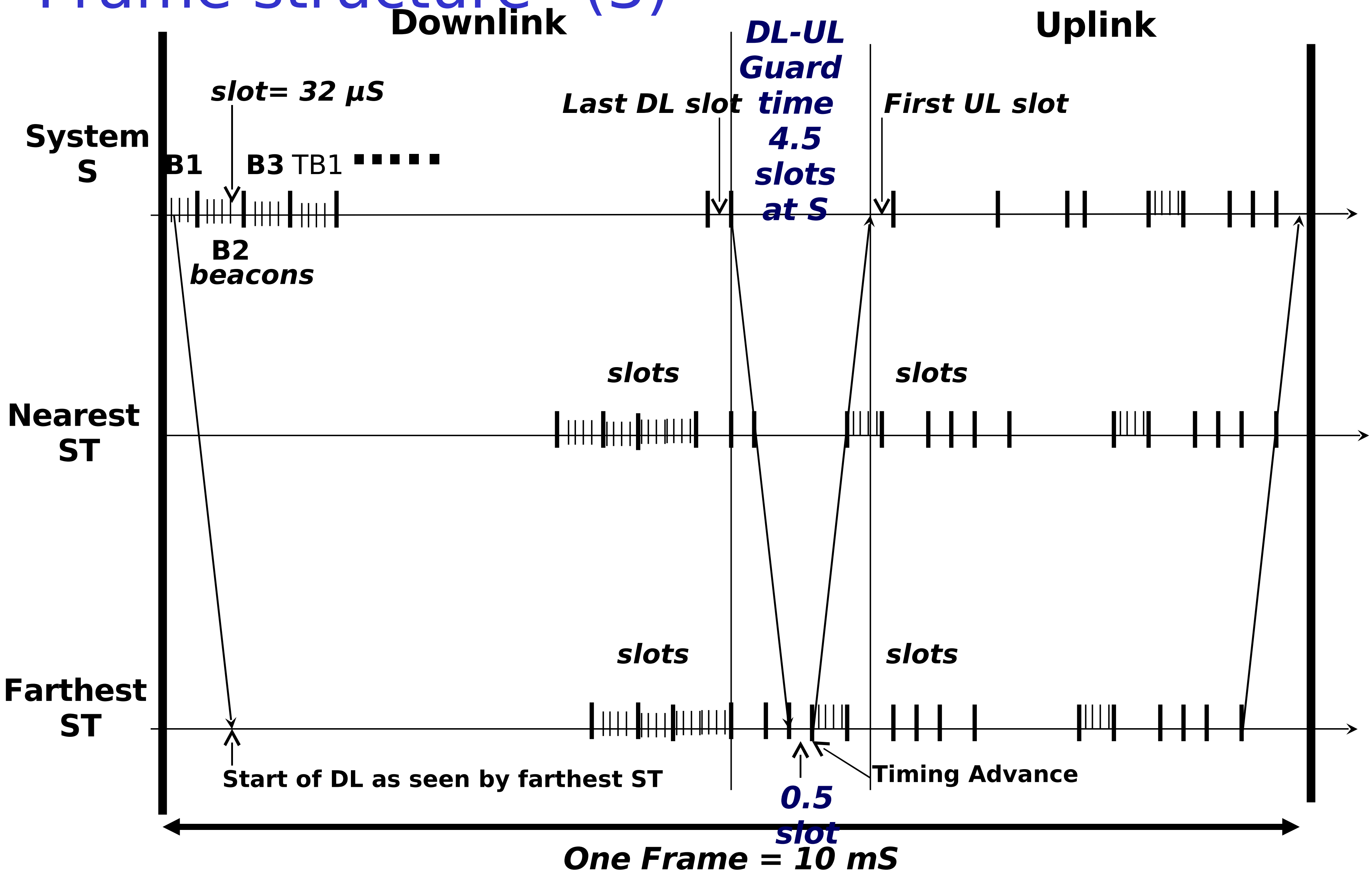
B1, B2, B3 – Beacons; contain MAP(s) on DL and UL allocation.

TB - Transmit Block; can be of unequal durations. Slots are of equal duration.

Frame structure – (2)



Frame structure –(3)

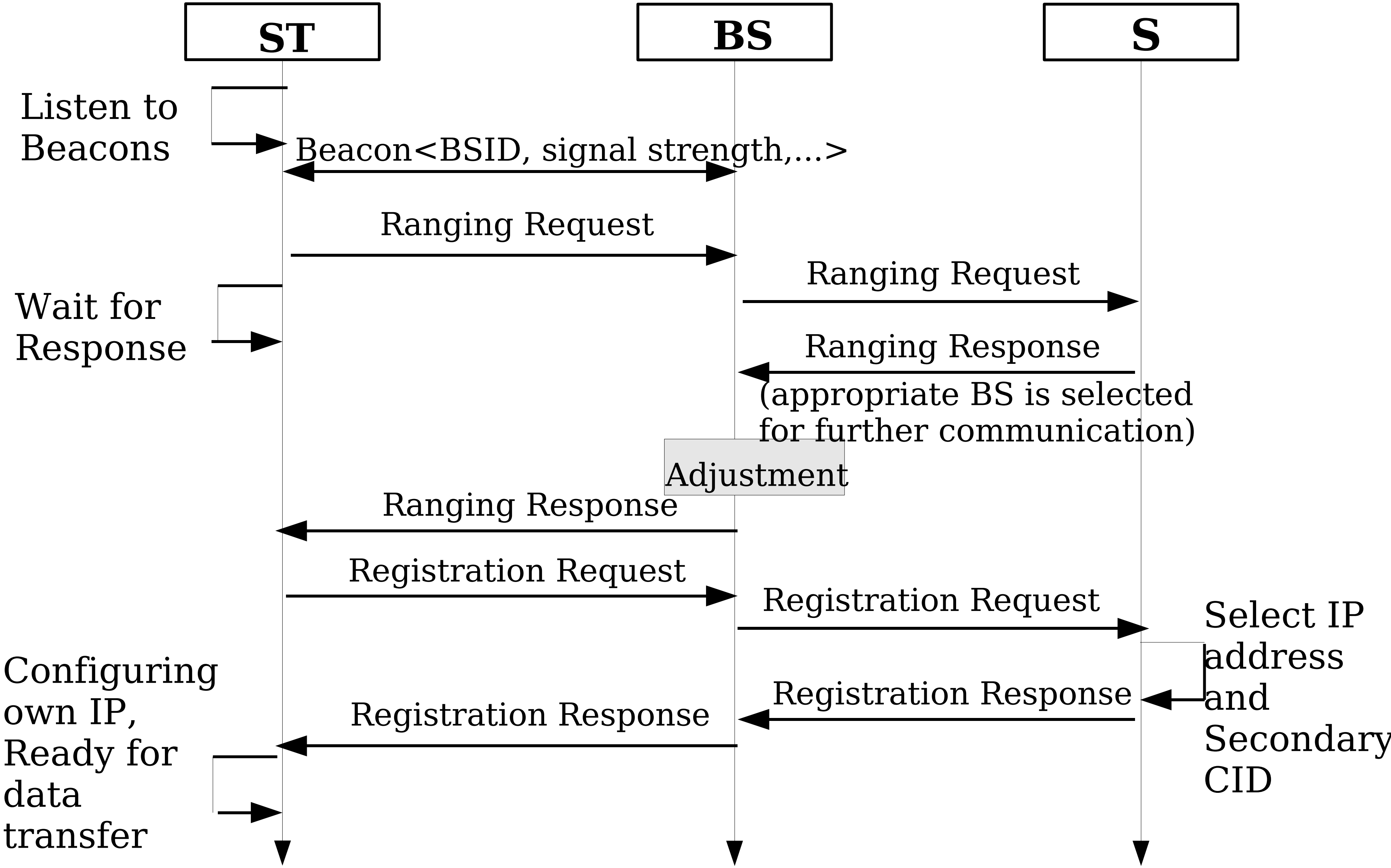


Showing 4.5 slots DL-UL guard time at S. Not to scale.
The timings are exaggerated for the purpose of illustration.

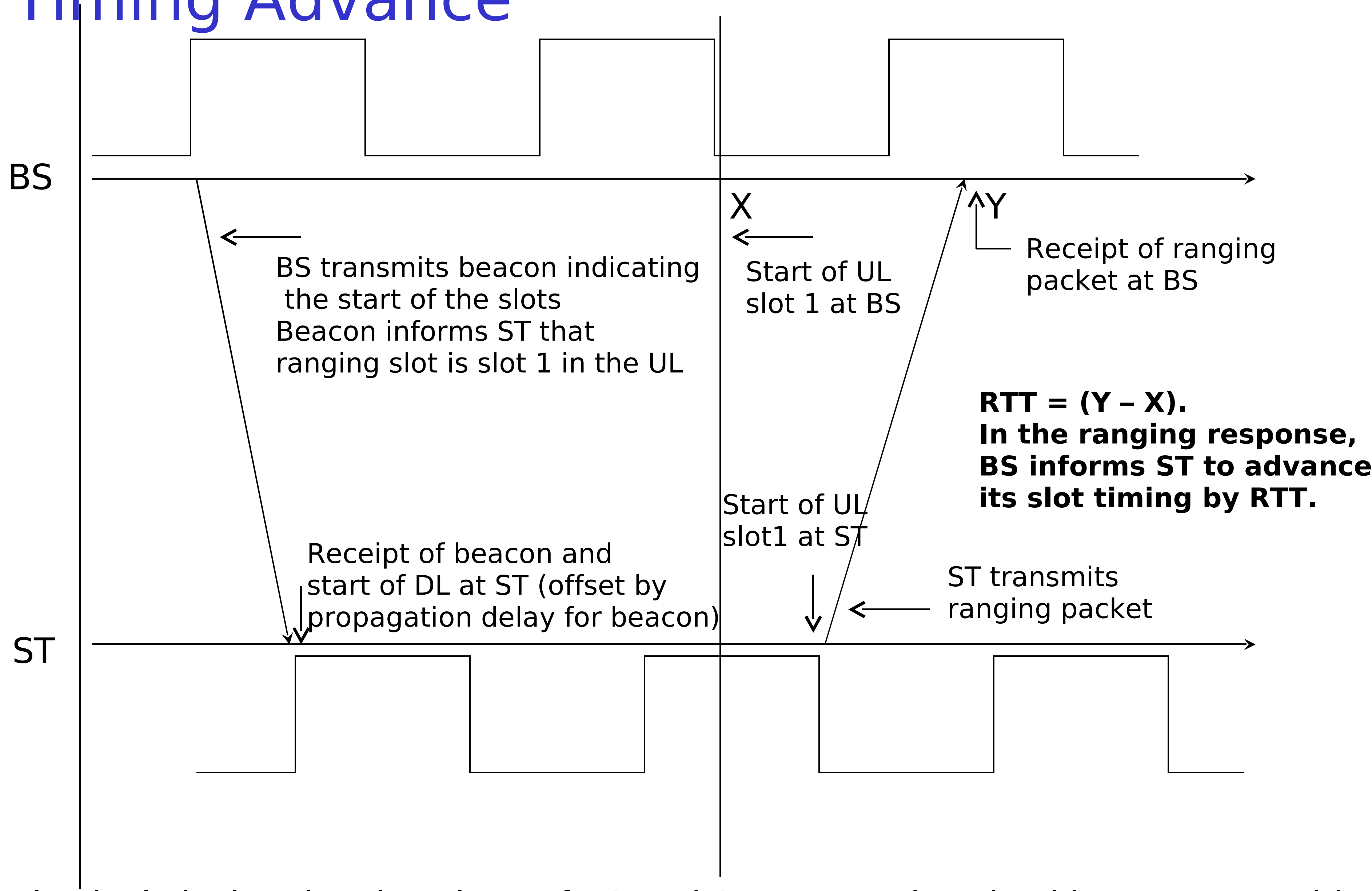
Protocol Phases – (1)

1. BS Power Up – Initialize values of channel id, TDD duration etc.
2. Beaconing – As per TDD frame structure for parallel transmission.
3. ST Power Up – Get values of fixed parameters (Sys ID, Opr ID).
    1. Listen for beacons
    2. PHY synchronization takes place
    3. Read beacon, Determine Ranging Slots
4. Ranging – The ST makes its presence known to the BS
    1. ST transmits packet in Ranging slot
    2. Suitable BS is chosen and basic connection ID is created
    3. BS to ST delay is calculated and ST is informed of timing advance
5. Authentication – MAC address used for authentication
    1. Packet transmitted in Contention Slot
    2. Security parameters exchanged
6. Registration - Each ST registers with S and acquires an IP address
    1. Packet transmitted in pre-allocated slot (or contention slot).
    2. Primary CID is obtained. This is used for making allocation requests.

Network Initialization



Timing Advance



Physical clock pulse durations of BS and ST are synchronized by PHY preamble

TDD frame for a sector - Logical view

Beacon (BS ID DL-MAP UL-MAP)	**DL-TB 1 (Min 4 slots)**	......	**DL-TB N (Min 4 slots)**	**DL-UL Guard Time (4.5 slots)**	**Ranging Block (8.5 slots) (optional)**	**UL-TB 1 (Min 4 slots)**	......	**UL-TB N (Min 4 slots)**	**Contention Block (Min 4 slots) (optional)**

- DL-MAP and UL-MAP represent the schedule.
- 3 slot PHY overhead per MAC PDU.
- Ranging and contention slots in the UL.

Beacon Message

Header (2 bytes)	**Opr ID (1 byte)**	**Sys ID (1 byte)**	**BS ID (7 bits)**	**Rng Slot (1 bit)**	**DL MAP (50 bytes)**	**UL MAP (50 bytes)**

- <u>Beacon</u>

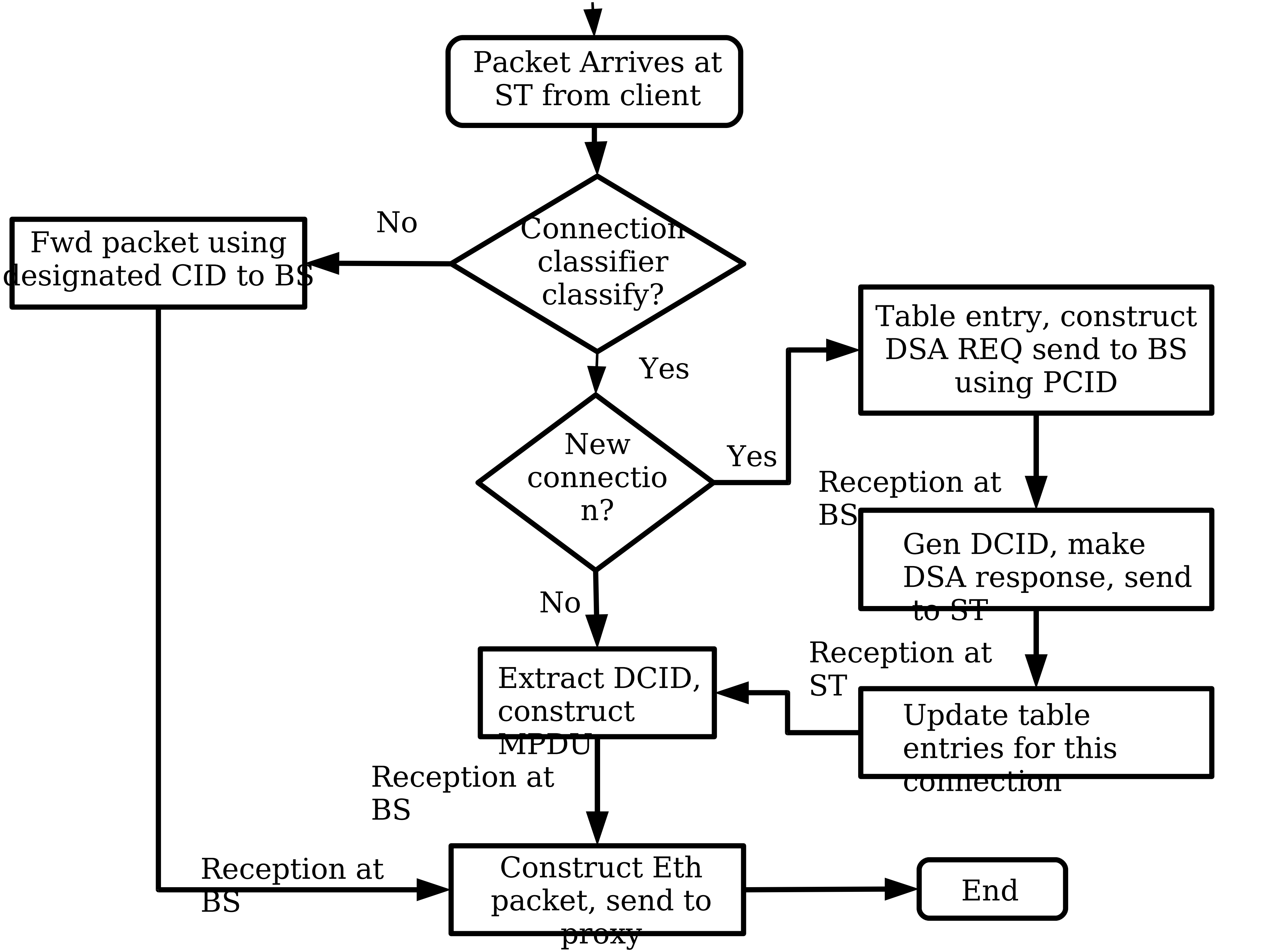
2. Header is the 2 bytes defined earlier.
3. Opr ID is a 1 byte value identifying the Operator of the network.
4. Sys ID is a 1 byte a value identifying the System (S).
5. BS ID is a 7 bits value identifying the BS in the System that is transmitting this Beacon.

7. DL-MAP is 50 bytes. It is a 25 element vector of <ST ID = (1 byte), Slot id = (1 byte)>. ST ID = 0x11 value implies that the message in the corresponding DL slot is a broadcast message for all ST(s).
8. UL-MAP is 50 bytes. It is a 25 element vector of <ST ID = (1 byte), Slot id= (1 byte)>.

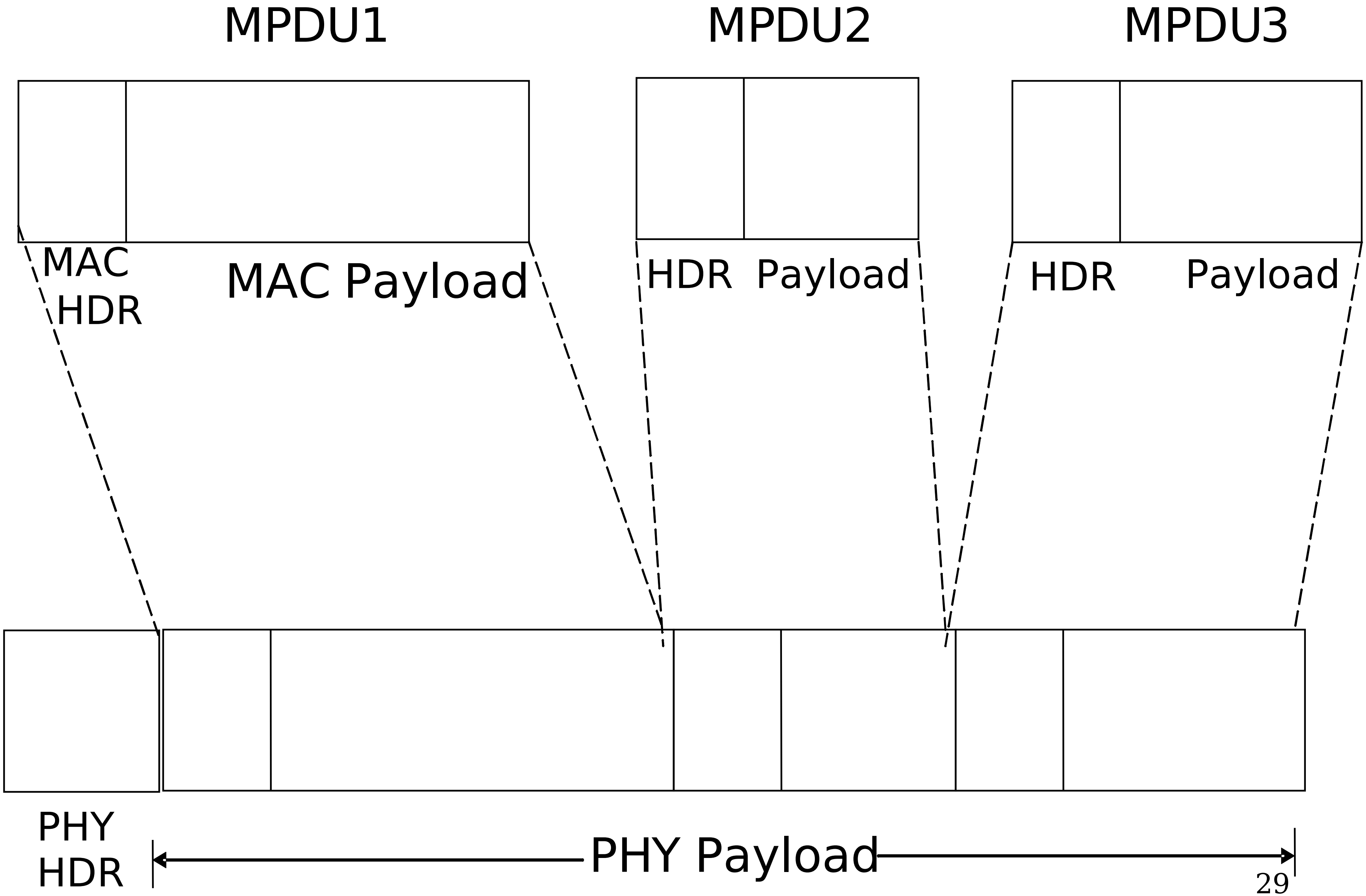
10. Rng Slot is a 1 bit indicating if there are any ranging slots allocated in the UL-MAP. The value is set to 1 if any ranging slot is present in the UL sub-frame, 0 otherwise.

Protocol Phases – (2)

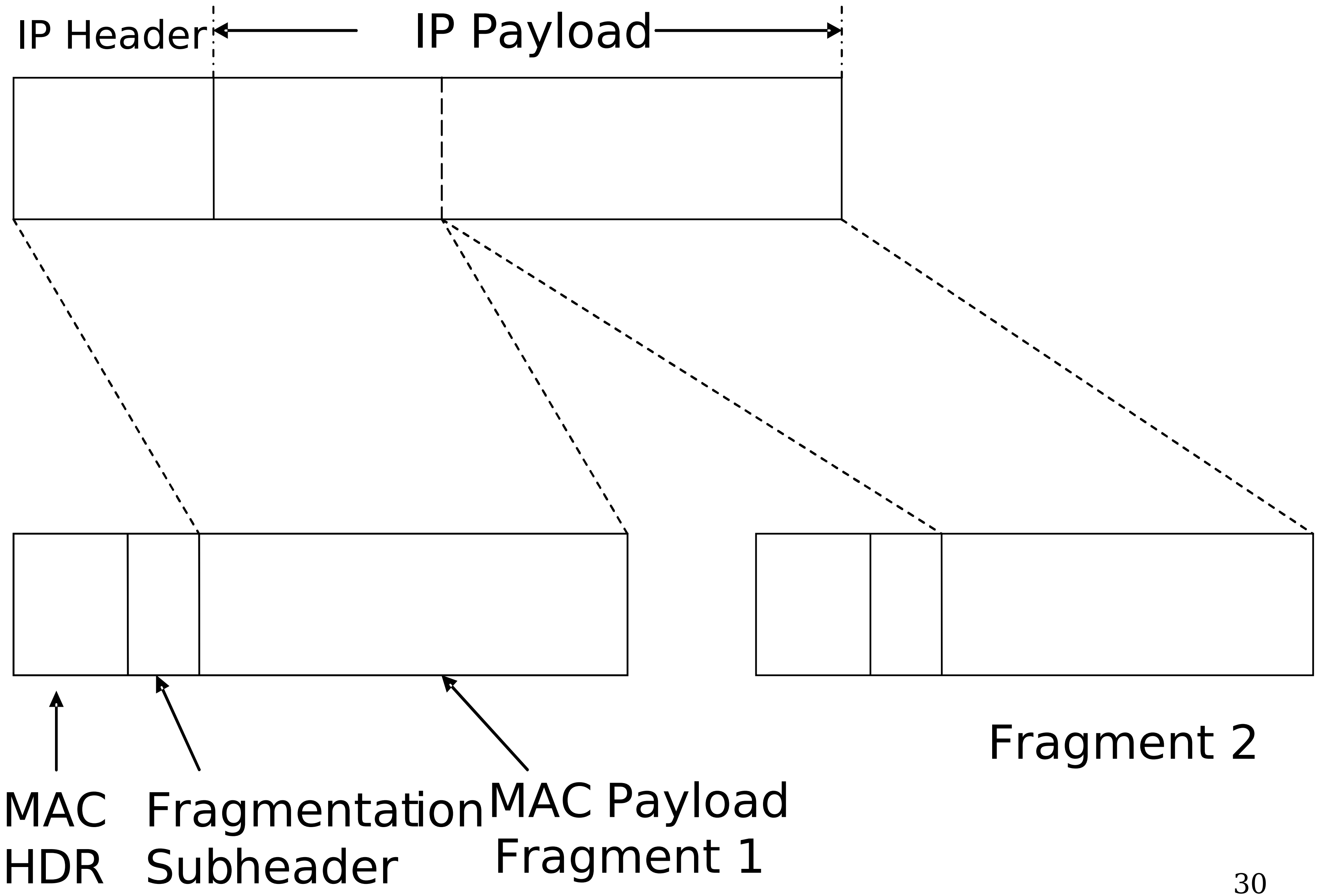
1. Connection Set Up
   1. S schedules request slots periodically for ST to send connection setup messages.
   2. Upon receipt of higher layer PDU, the SSS layer determines and classifies the type of connection – implicitly or explicitly.
   3. ST sends a connection creation message in the request slot. The QoS requirement of the connection are specified.
   4. BS grants the request and a data Connection Id is set up.
2. Data Transfer
   1. UGS (VoIP) – periodic slots allocated in UL-MAP.
   2. rtPS (Video) – initial parameters are specified at connection setup. For modification or extension of connection, either piggyback or request slot or contention slot is used.
   3. nrtPS (burst ftp) – Similar mechanism as rtPS.
   4. BE (http) – use contention slot(s).
3. Transfer data using Connection id.
4. Terminate connection, release resources.


Packet Arrives at ST from client
Connection classifier classify?
No
Fwd packet using designated CID to BS
Yes
New connection?
Yes
Table entry, construct DSA REQ send to BS using PCID
Reception at BS
Gen DCID, make DSA response, send to ST
No
Reception at ST
Extract DCID, construct MPDU
Update table entries for this connection
Reception at BS
Reception at BS
Construct Eth packet, send to proxy
End

Concatenation



Fragmentation



Protocol Phases

1. BS Power Up – Get values of channel id, TDD duration etc. – Hard-code into driver.
2. Beaconing – See beacon format. See TDD frame structure for parallel transmission.
3. ST Power Up – Get values of parameters – hard-code into driver.
    1. Listen for beacons
    2. PHY Physical synchronization takes place, Reads beacon, Find out Ranging Slots
4. Ranging - S to ST delay is calculated ST is informed
    1. Sends MAC id – pkt transmitted in Ranging slot – scheduler directive for periodic slots.
    2. Basic connection ID is created
5. Authentication – MAC addr for authentication and Security parameters xchg
    1. Pkt txd in Contention slot – scheduler directive for min # contention slots per frame?
    2. Primary CID is used is obtained.
6. Registration - Each ST registers with S and acquires an IP address
    1. Pkt txd in pre-allocated slot (or contention slot) – scheduler directive.
7. Connection Set Up
    1. S schedules request slots periodically for ST to send conn setup msgs – scheduler directive
    2. Upon receipt of higher layer PDU, SSS classifies the type of connection and sends connection request message in request slot, with QoS requirement specified
    3. Request granted with appropriate conditions – duration of the connection.
    4. Data connection id is set up.
8. Data Transfer
    1. UGS (VoIP) – periodic slots allocated in UL-MAP. When duration of connection is to expire, an ‘extension’ request is piggybacked on data (or sent in the UL allocation).
    2. rtPS (Video) – piggyback extension requests or use request slot or use contention slot.
    3. nrtPS (burst ftp) – piggyback requests or use contention slot.
    4. BE (web) – use contention slot
9. Transfer Data using Connection id
10. Terminate connection, release resources.

WiFiRe MAC functions - Summary

- One MAC controls all the sectors in a BS; Single channel.

- Slotted system – 32 μSec slot; 10 mSec frame.
- TDD – No interleaving of downlink and uplink transmissions.
- MS-TDM scheduling –Non interfering transmissions across multiple sectors may happen in parallel (within the TDD).

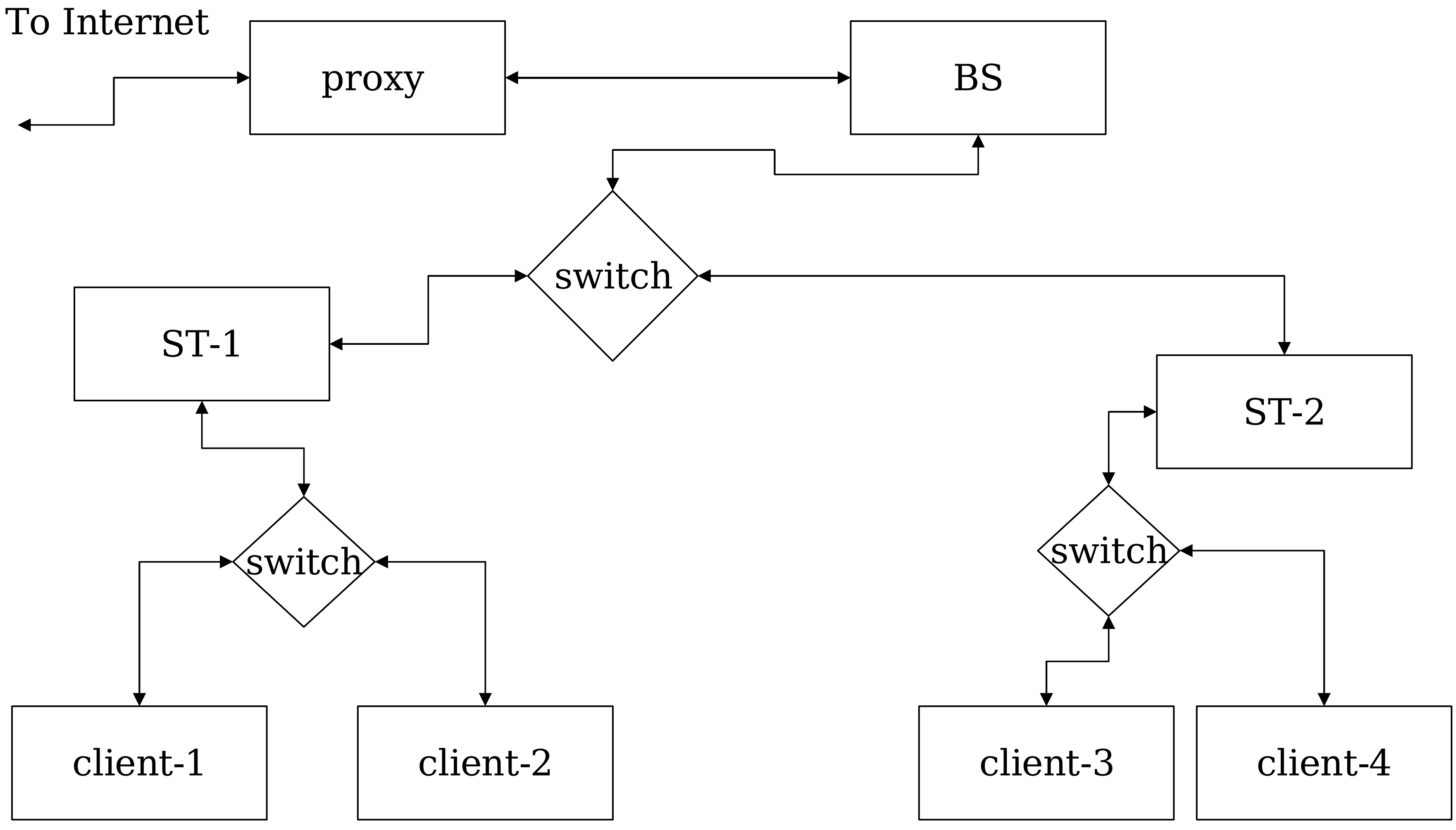
- Connection oriented MAC.
- QoS levels – UGS; rtPS; nrtPS; BE
- Grant levels – GPC; GPST; GPSF
- Scheduler creates the DL-MAP and UL-MAP, which are broadcast with the Beacon(s).

WiFiRe: Implementation

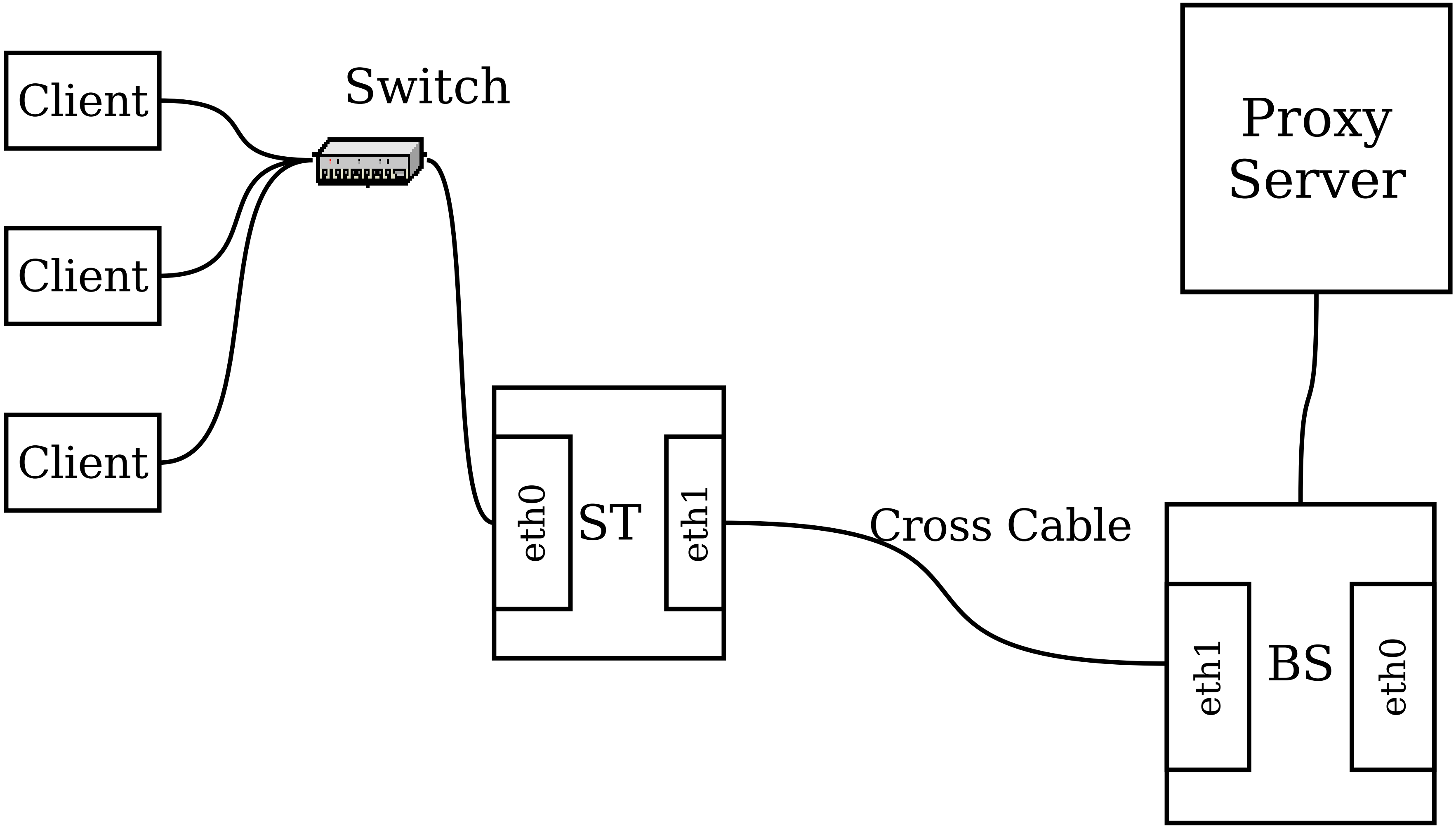
Prototype development

- PHY board (IIT M)
- LAN Emulation for MAC (IIT B)
  - Single Sector, 1 BS, multiple ST and clients
  - Single proxy server to handle web and VoIP requests
  - All machines connected using 802.3 or 802.11 based LAN
  - MAC code in user space with Ethernet Sockets
- Integration
- Deployment

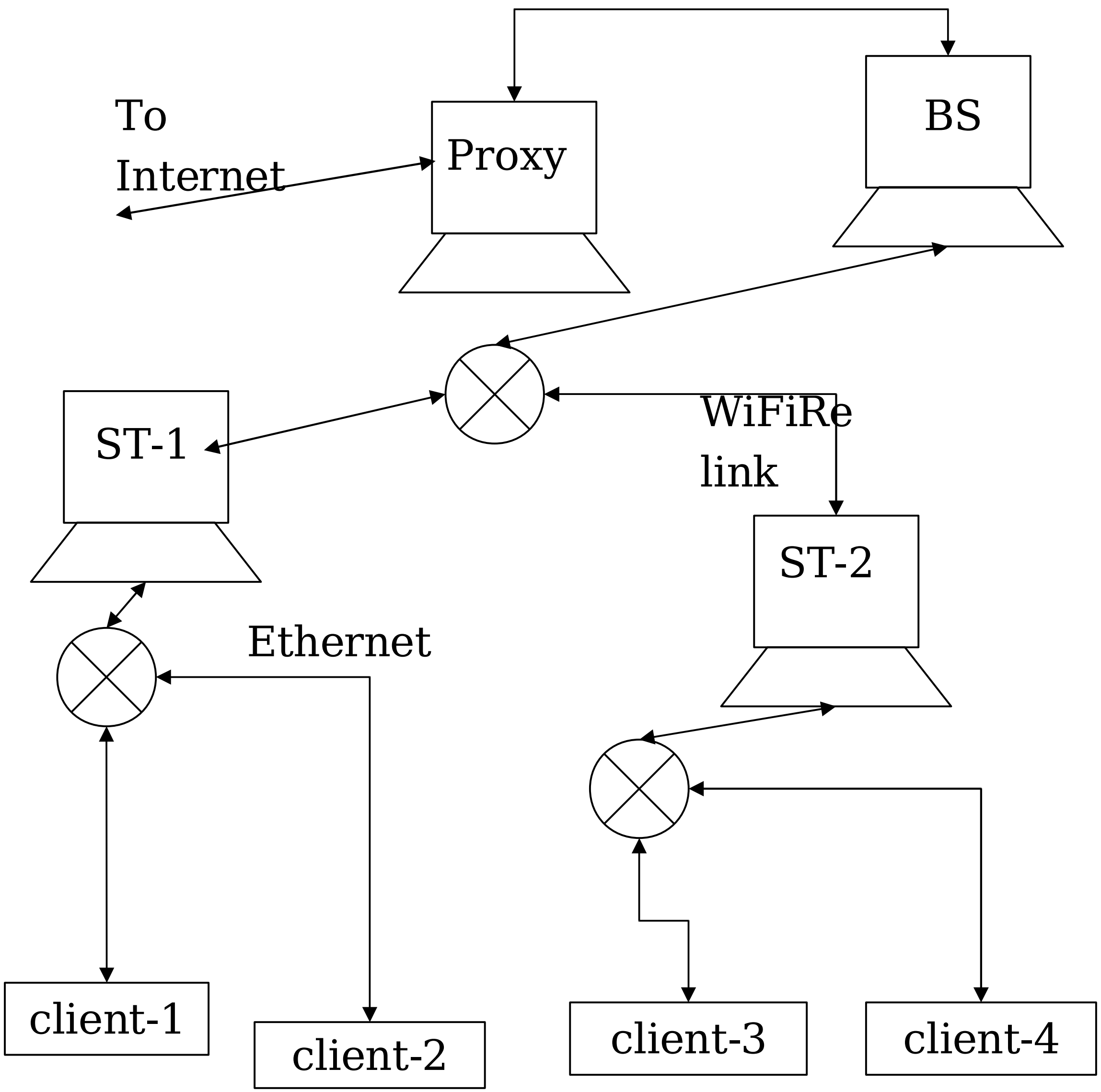
TestBed Setup



Basic Testbed setup

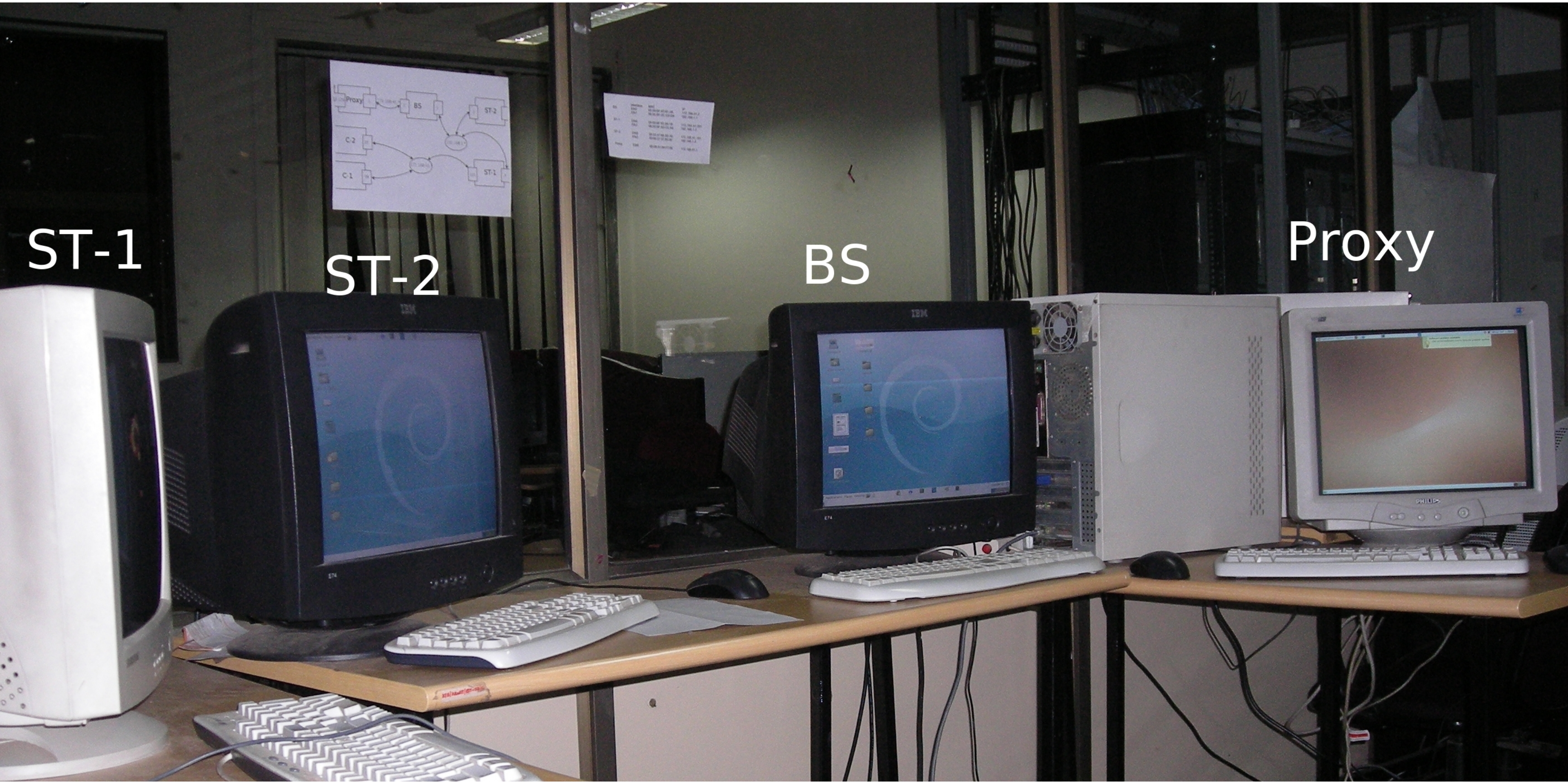


Ethernet TestBed



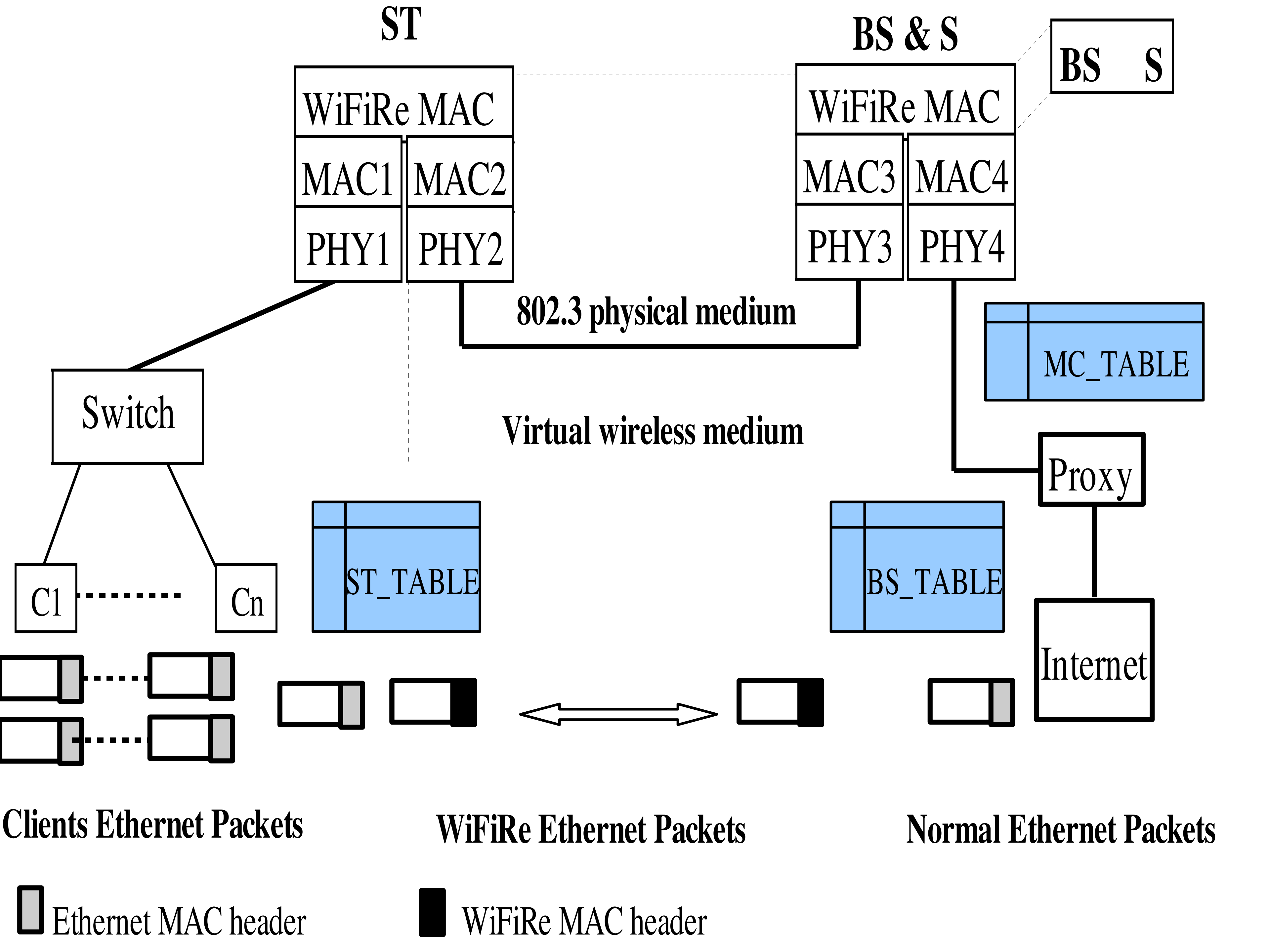
- Single Sector, 1 BS, multiple ST and clients
- Single proxy server to handle web and VoIP requests
- All machines connected to ST using 802.3
- MAC code in user space with Ethernet Sockets
- Emulate Ethernet as WiFiRe 802.11b PHY

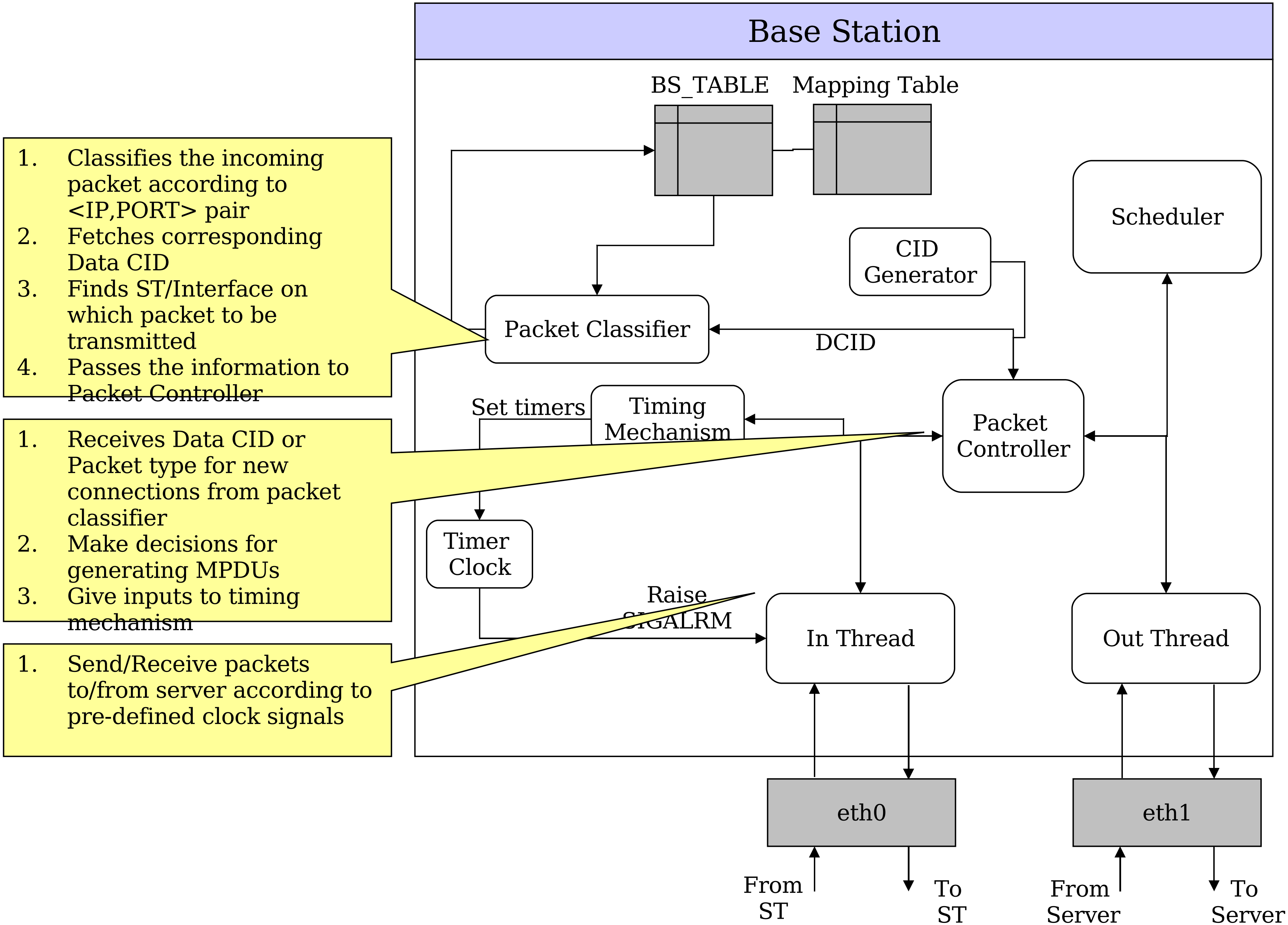
TestBed (cont.)



Ethernet sockets

- Using PF_SOCK in C
- Byte level access, Binding with particular NIC
- Send/receive data using sockets on MAC layer
- Allows non-Ethernet packets (like WiFiRe frame); Eth switch broadcast those packets, Eth MAC header not mandatory


ST
BS & S
BS S
WiFiRe MAC
MAC1
MAC2
PHY1
PHY2
WiFiRe MAC
MAC3
MAC4
PHY3
PHY4
802.3 physical medium
MC_TABLE
Switch
Virtual wireless medium
Proxy
C1
Cn
ST_TABLE
BS_TABLE
Internet
Clients Ethernet Packets
WiFiRe Ethernet Packets
Normal Ethernet Packets
Ethernet MAC header
WiFiRe MAC header


Base Station
BS_TABLE
Mapping Table
Scheduler
CID Generator
Packet Classifier
DCID
Set timers
Timing Mechanism
Packet Controller
Timer Clock
Raise SIGALRM
In Thread
Out Thread
eth0
eth1
From ST
To ST
From Server
To Server
1. Classifies the incoming packet according to <IP,PORT> pair
2. Fetches corresponding Data CID
3. Finds ST/Interface on which packet to be transmitted
4. Passes the information to Packet Controller
1. Receives Data CID or Packet type for new connections from packet classifier
2. Make decisions for generating MPDUs
3. Give inputs to timing mechanism
1. Send/Receive packets to/from server according to pre-defined clock signals

Ethernet sockets

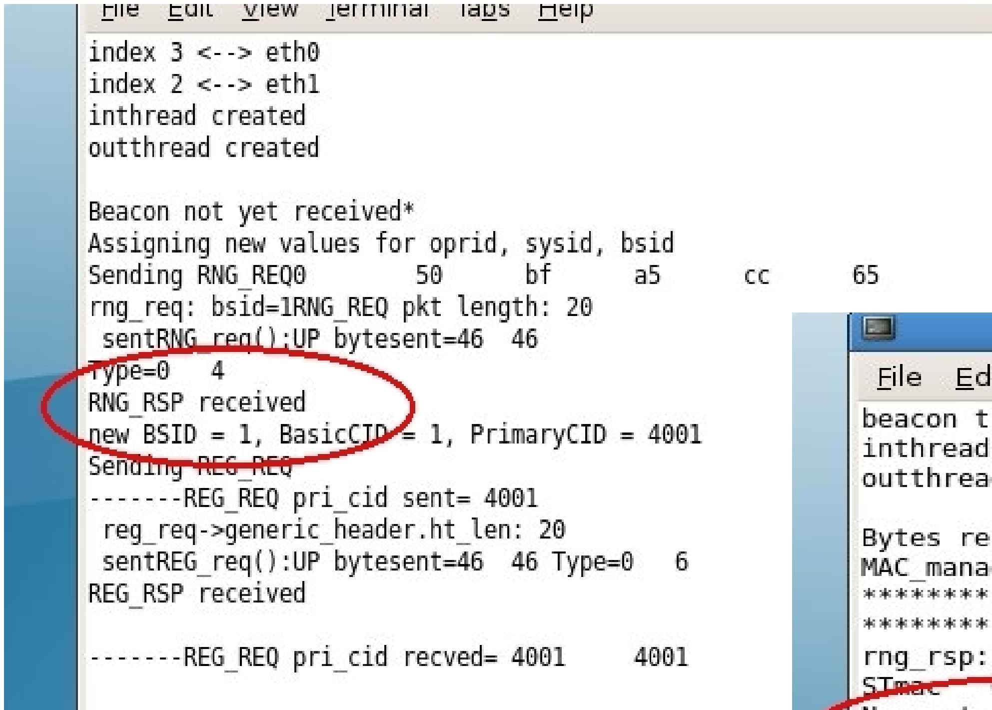
- Using PF_SOCK in C
- Byte level access
- Binding with particular NIC
- Send/receive data using sockets on MAC layer
- Allows non-Ethernet packets (like WiFiRe frame); Eth switch broadcast those packets

```
/* Socket creation */
if ( (in_sock=socket(PF_PACKET, SOCK_RAW, htons
                perror("socket");
                exit(1);
}

memset(&in_addr, 0, sizeof(struct sockaddr_ll))
memset(&ifr, 0, sizeof(struct ifreq));

strncpy(ifr.ifr_name, "eth1", sizeof(ifr.ifr_na
dummy = socket(AF_INET, SOCK_DGRAM, 0);
if (dummy == -1) {
                perror("dummy");
                exit(1);
}
ret = ioctl(dummy, SIOCGIFINDEX, &ifr);
```

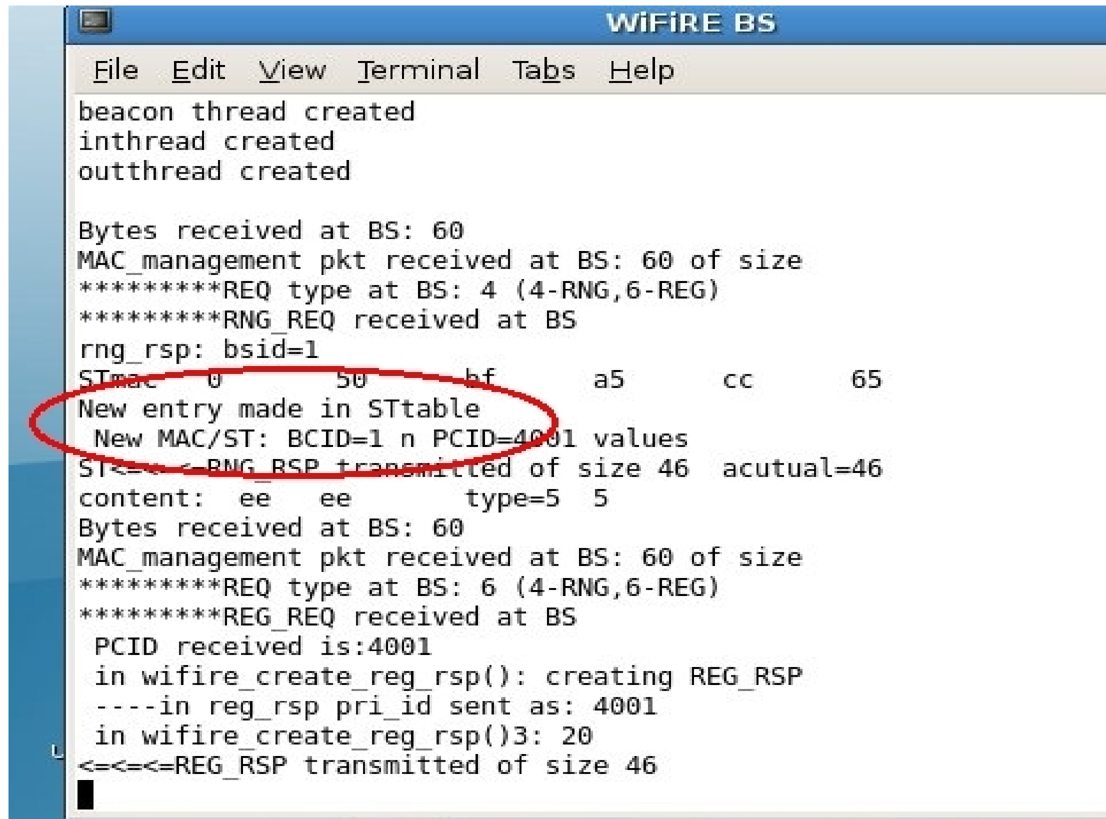
Beacon, Registration etc.

- BS sends periodic beacons
- ST sends registration request
- BS adds ST in list, allow access
- ST starts transmission
- client can not start communication before registration
- BS and ST shut down/ restart condition handled

Beacon, Registration etc.



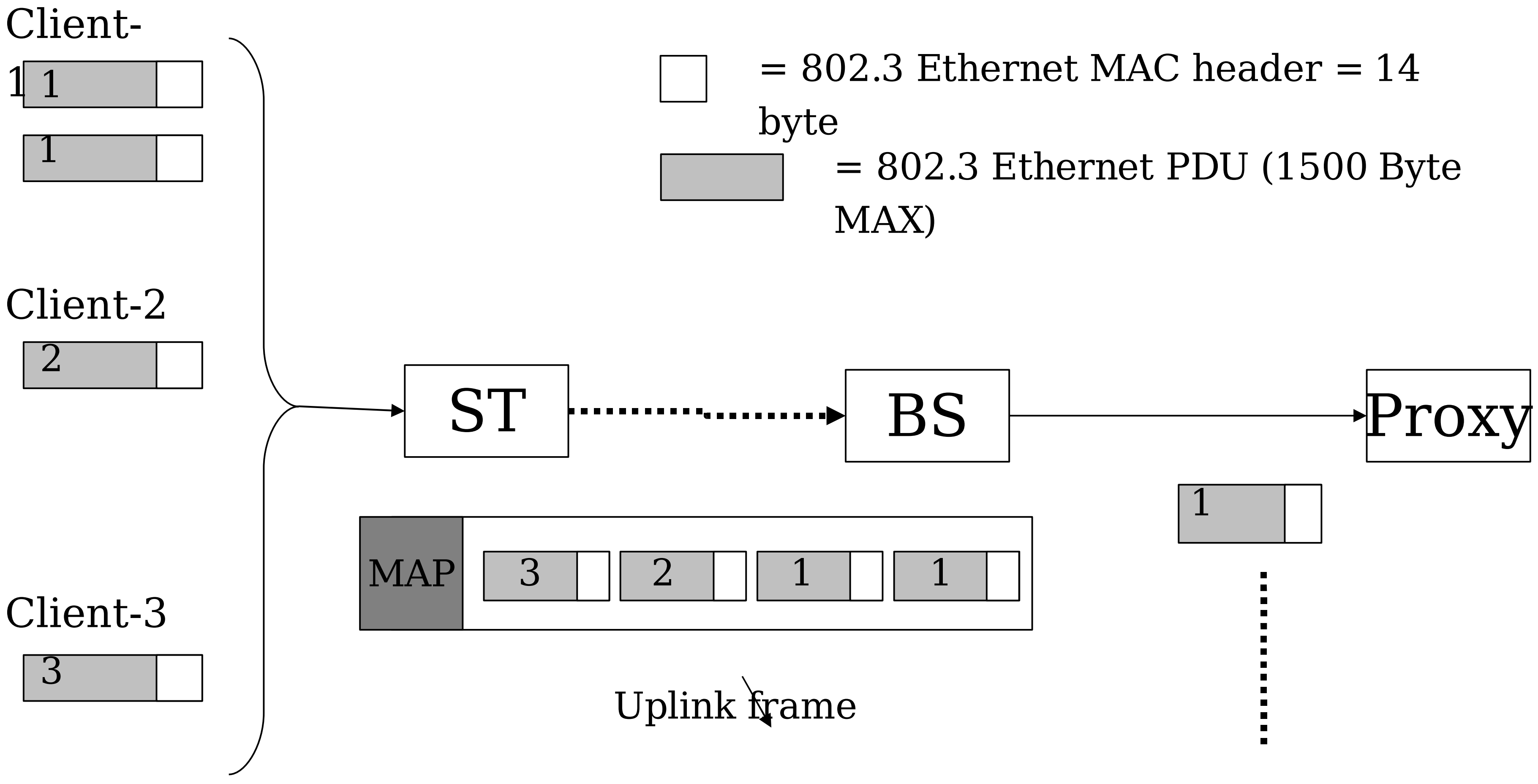
ST sends request



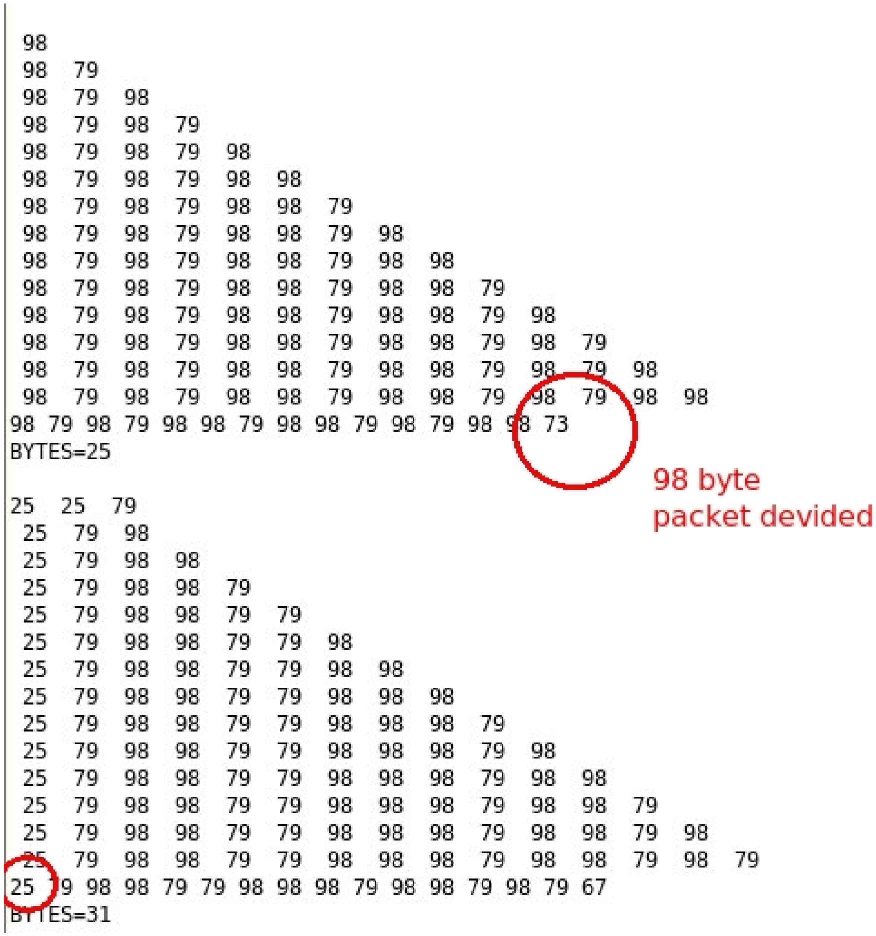
Encapsulation and Fragmentation

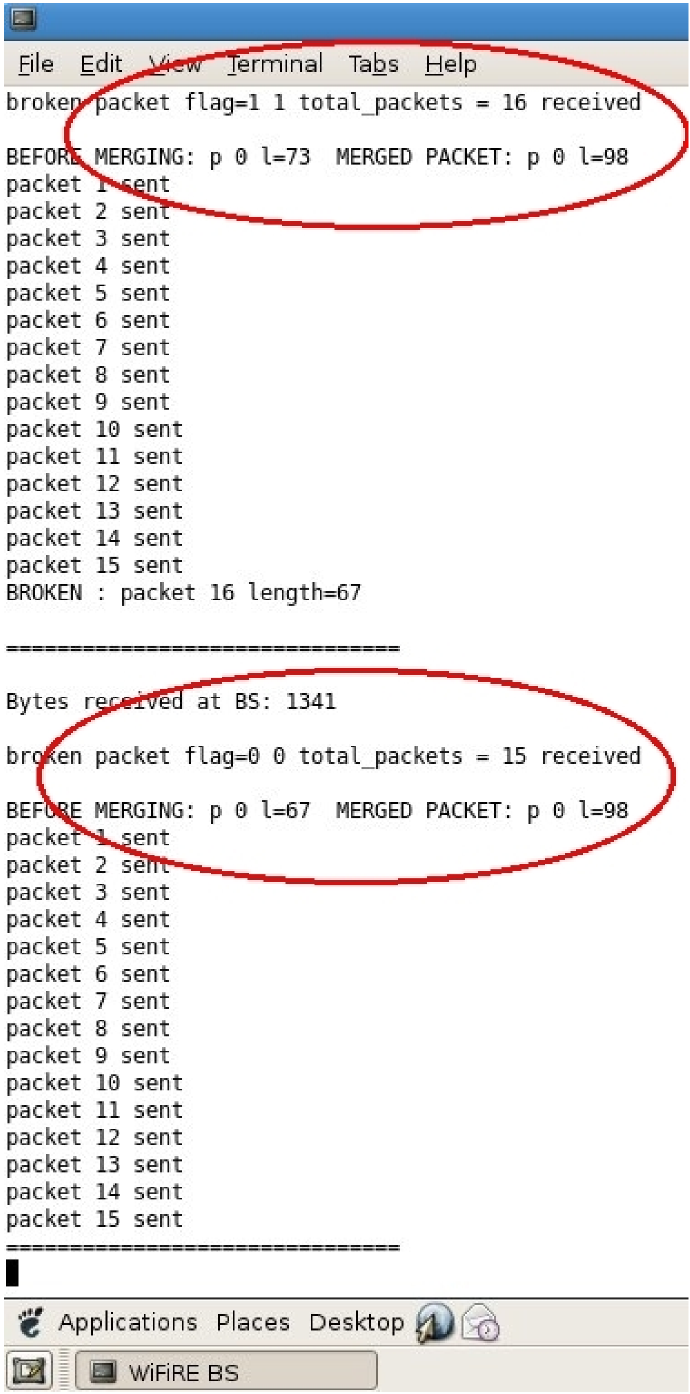
- ST will receive packets from client, keep them in buffer
- Encapsulate multiple MAC packets and make packets of 1450 bytes
- Fragment MAC packets if larger
- Takes care of Ethernet MTU
- see next slide

Encapsulation and Fragmentation



Encapsulation and Fragmentation





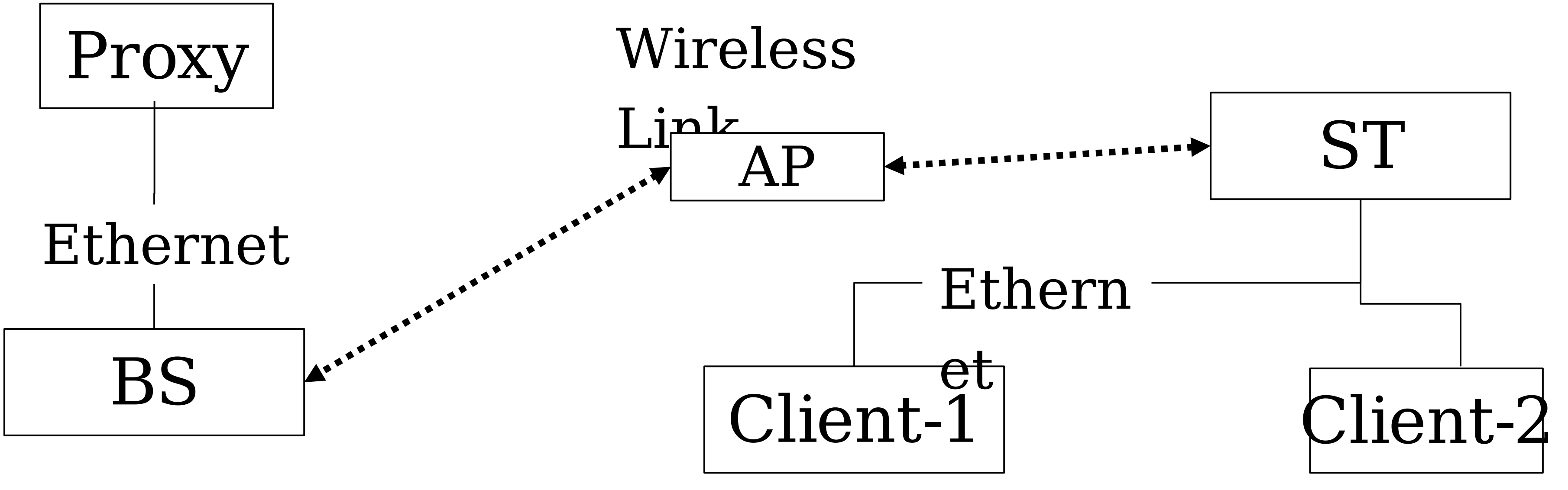
ST collects packet and send them in single frame to BS

Communication using 802.11

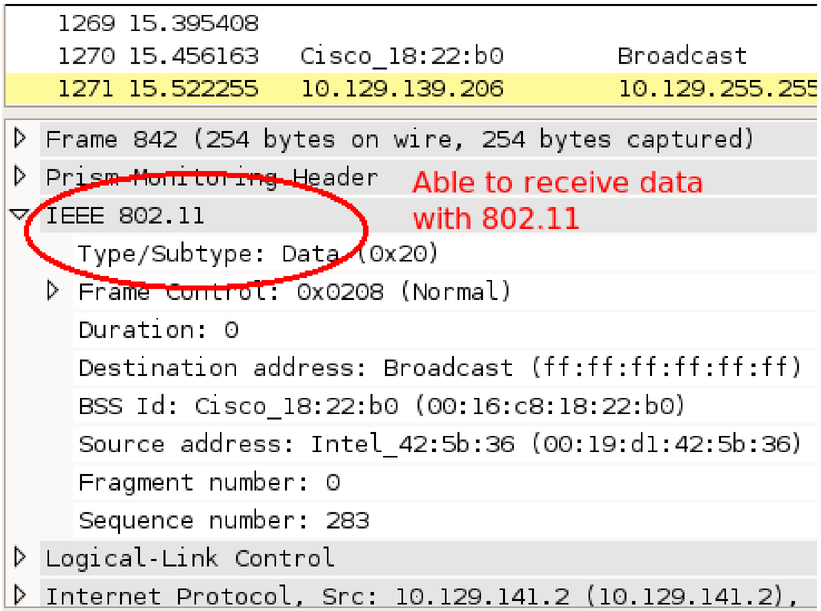
- Ethernet socket replaced with WiFi socket
- Works with pseudo interface
- Using madwifi driver
- Transparent to BS/ST code
- Client can be connected via wired/wireless LAN

Communication using 802.11

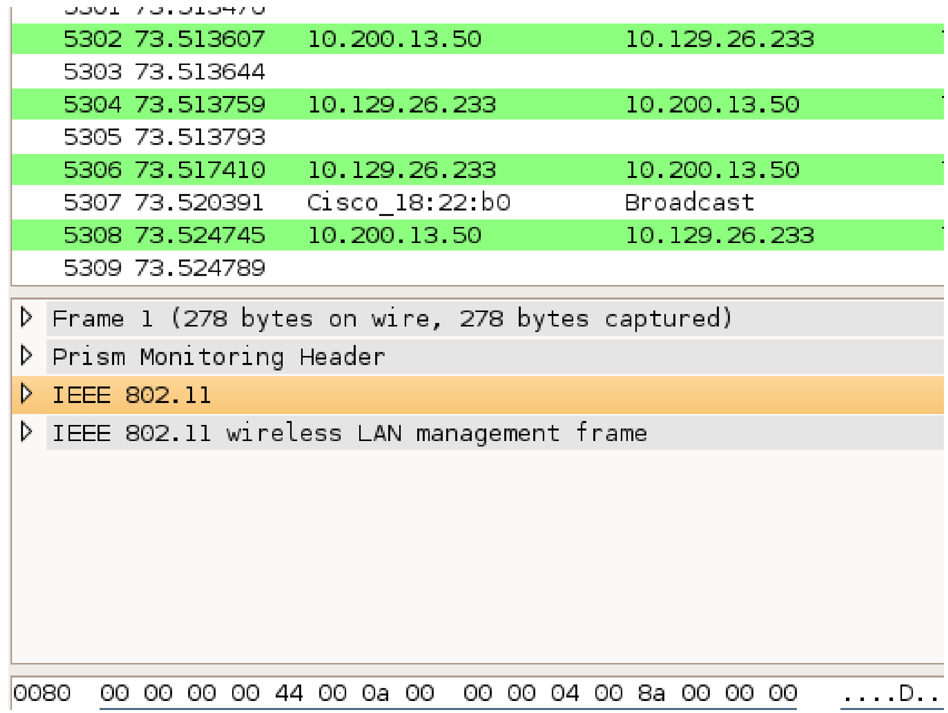
- WiFiRe actual deployment will have BS-ST link as wireless 802.11b link
- MAC is transparent to PHY
- Ethernet socket replaced with WiFi socket
- Works with pseudo interface
- Using Atheros + D-link + madwifi driver



Communication with 802.11



Able to send / receive packets on 802.11



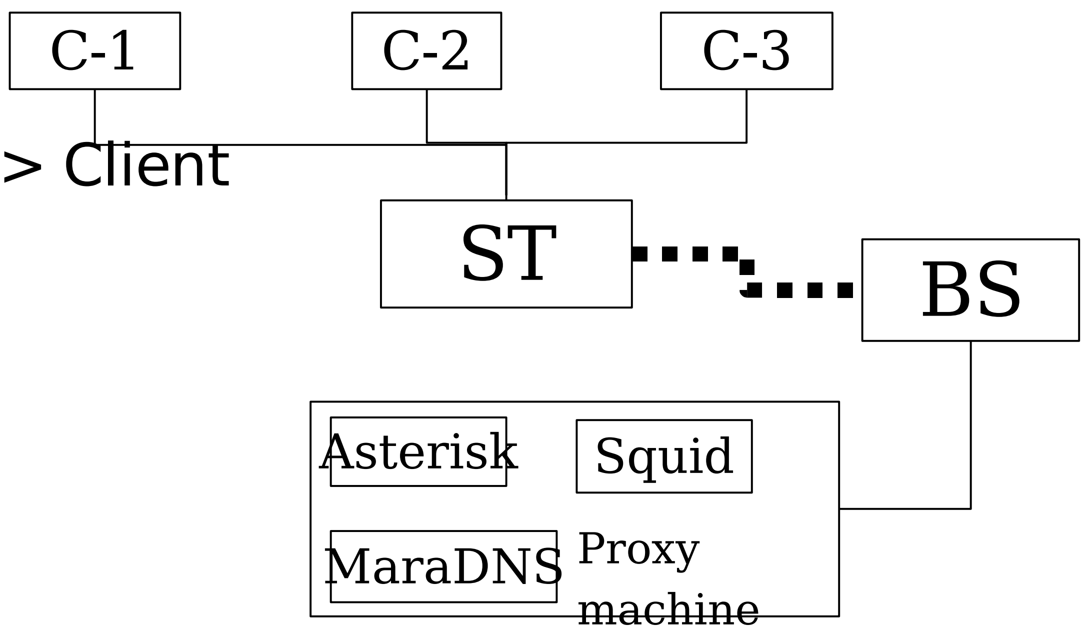
TCP session using 802.11

GPSS and GPC mode

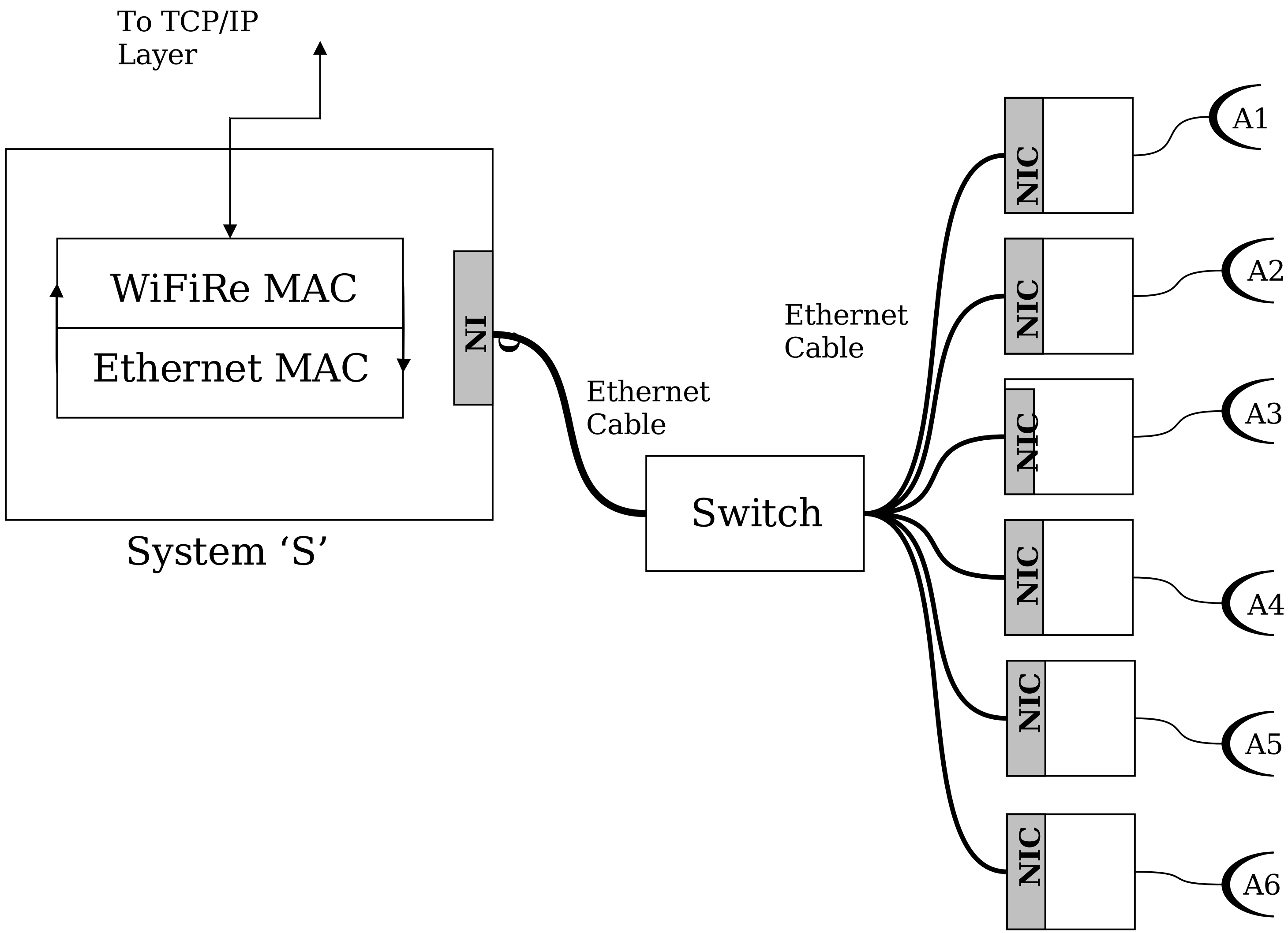
- Grant per Subscriber station model followed
- BS gives slots per ST
- ST handles client level fairness
- SSID, CID on ST level
- GPC mode – work in progress

Web and VoIP connectivity

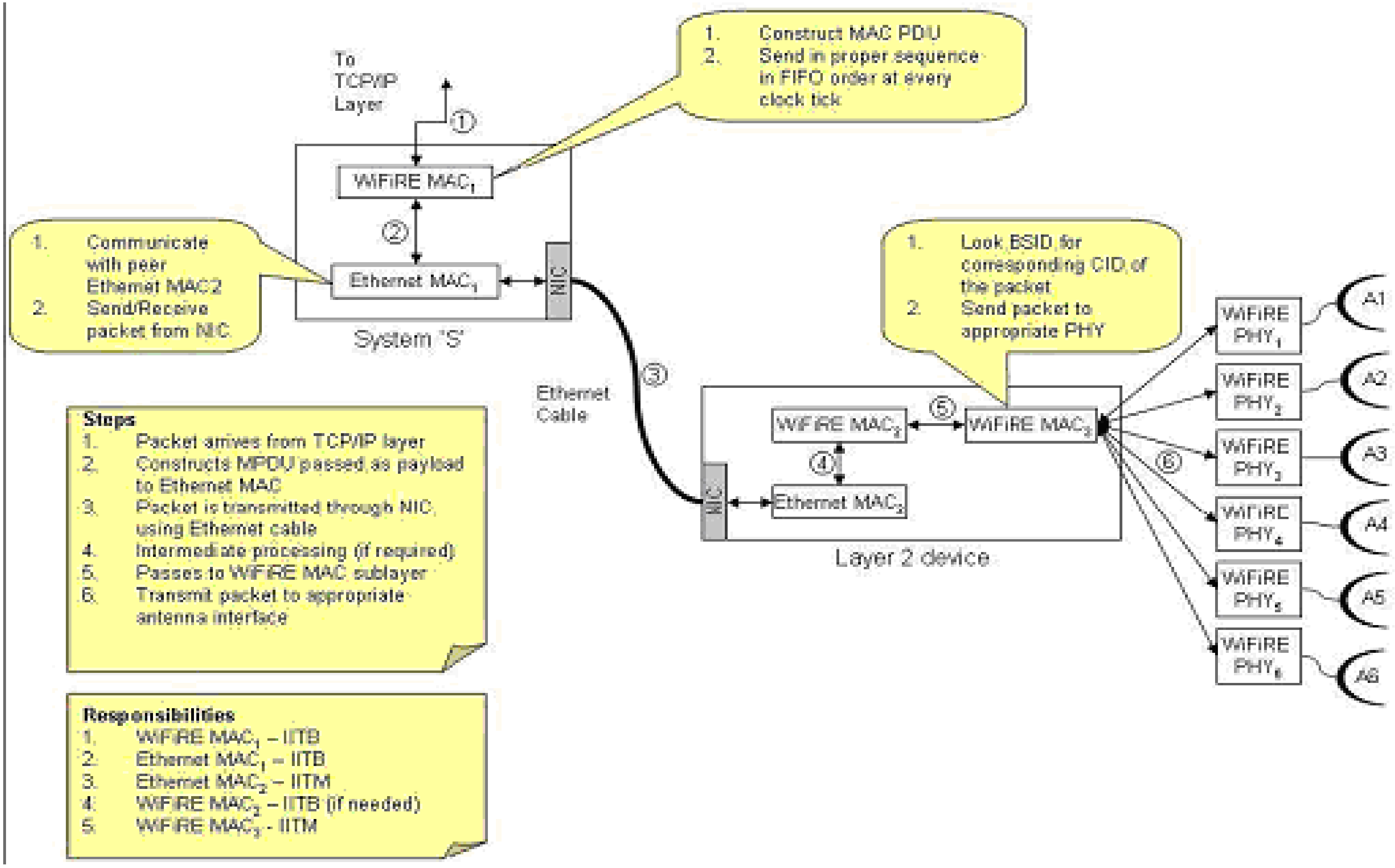
- Proxy machine runs squid server for web traffic
- Asterisk server for VoIP connectivity
- Clients send request to proxy using WiFiRe MAC protocol
- Client --> ST --> BS --> proxy
- Proxy replies back
- Proxy --> BS --> ST --> Client



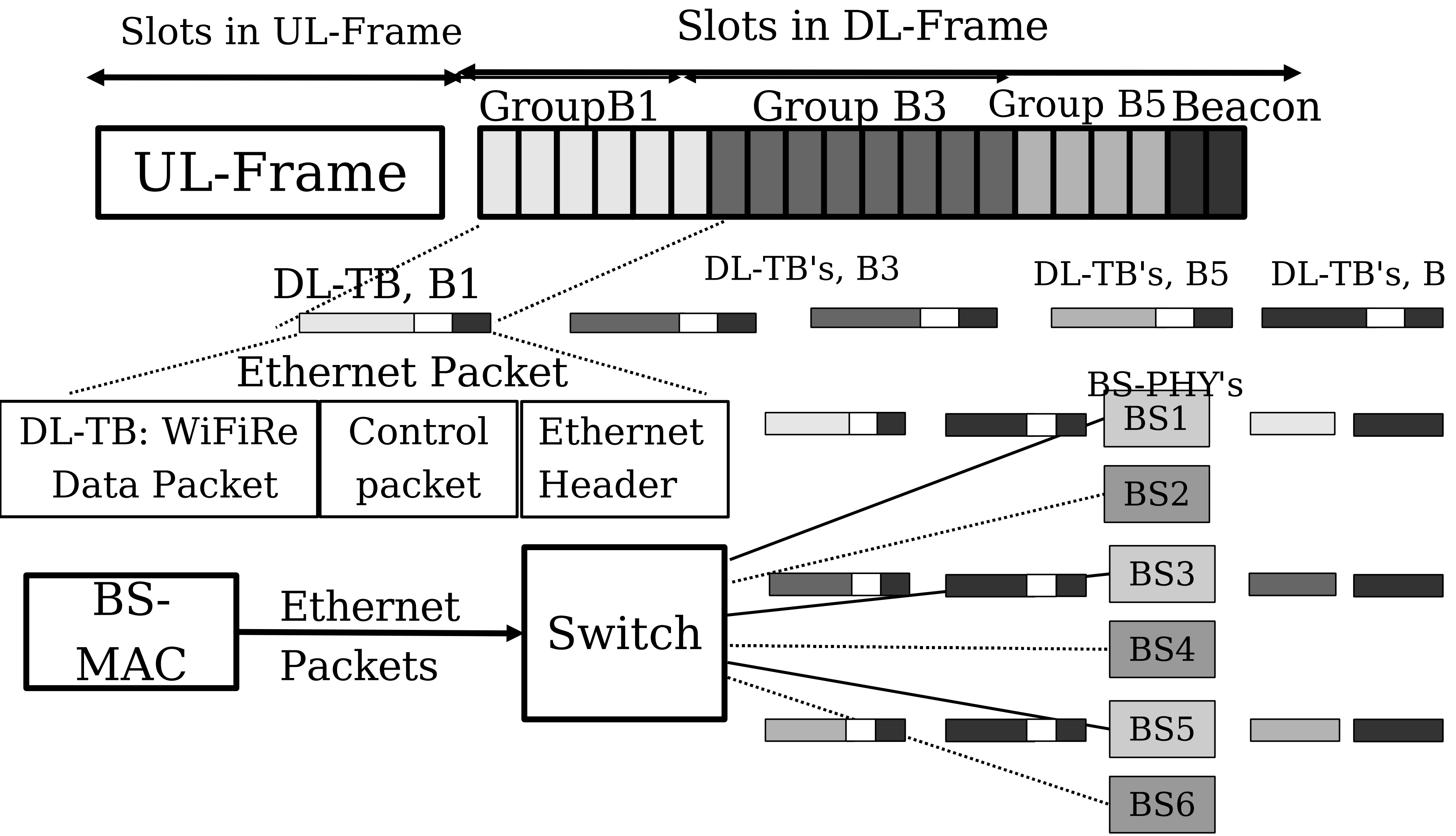
Integration with IITM-PHY board



Integration with IITM-PHY board



WiFiRe meta-frame



Work in Progress

- Basic Scheduler
- Traffic Diversion at BS
- Soft timer and ST synchronisation
- DL-MAP and UL-MAP for GPC
- Generic MAC PDU

WiFiRe: Performance

WiFiRe – Capacity analysis and scheduling

- Given that 1 VoIP call generates 40 bytes every 20 mSec.
- Given that a TDD frame, of length N slots (e.g., 300~slots), is partitioned into N_D (contiguous) downlink slots (e.g., 200~slots), and N_U uplink slots (e.g., 100~slots).
- Given n sectors (e.g., n=6) and m STs (e.g., m=60).

- The association of the n BS(s) and the m ST(s) forms a bipartite graph.
- During each slot time, a schedule comprises a matching on the above bipartite graph.
- Not all matchings are feasible, since transmissions in a sector can interfere with links near the boundaries of the neighbouring sectors.

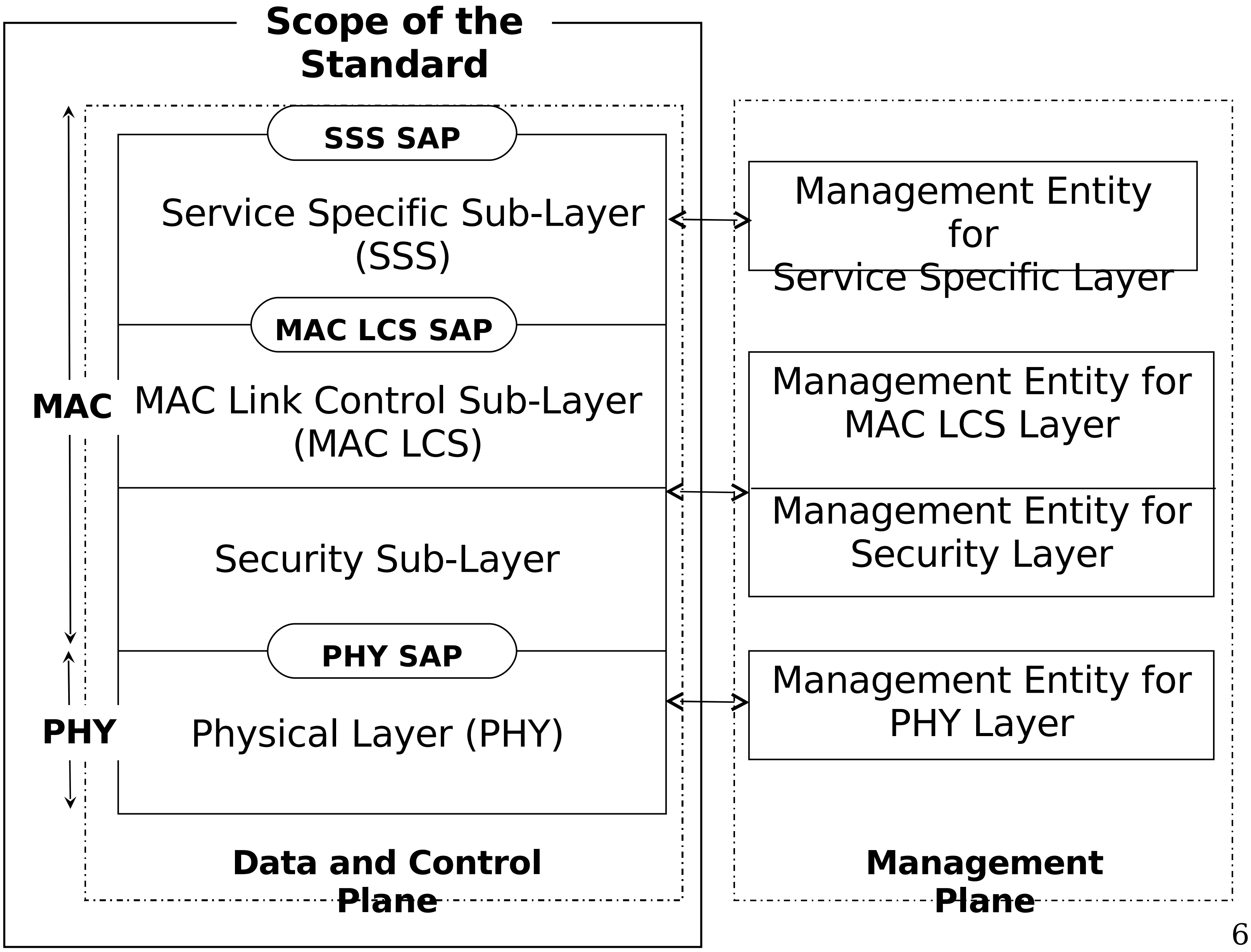
- Objective: For each of the N slots in each frame, determine a feasible matching so that the QoS objectives of various traffic flows being carried are met, and the system capacity is maximised.

Capacity and scheduling – Results

- Raw data rate - 11 Mbps, per sector.
  - When the maximum number of simultaneous transmissions is 3, and a 2:1 Downlink to Uplink ratio, we have an aggregate of 22 Mbps in the DL and 11 Mbps in the UL.
- Each voice call requires a slot every alternate frame.

- Simulation results for a greedy heuristic sheduler:
- For a 6 sector system, with a taboo region of 10đ,
  - For 40 ST(s), one voice call per ST, each ST gets about 370 Kbps.
  - For 40 ST(s), two voice calls per ST, each ST gets about 369 Kbps.
  - For 80 ST(s), one voice call per ST, each ST gets about 164 Kbps.
  - For 80 ST(s), two voice calls per ST, packet drop probability is 2%.
- Typical utilization
  - For downlink, is about 15.1 Mbps (out of 22 Mbps).
  - For uplink, is about 5.2 Mbps (out of 11 Mbps).

More details – www.cewit.org.in



Thanks

Sridhar Iyer

IIT Bombay

www.it.iitb.ac.in/~sri