Wireless Networks for Mobile Applications

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The Emergence of MACA, MACAW, & 802.11

- Wireless MAC proved to be non-trivial

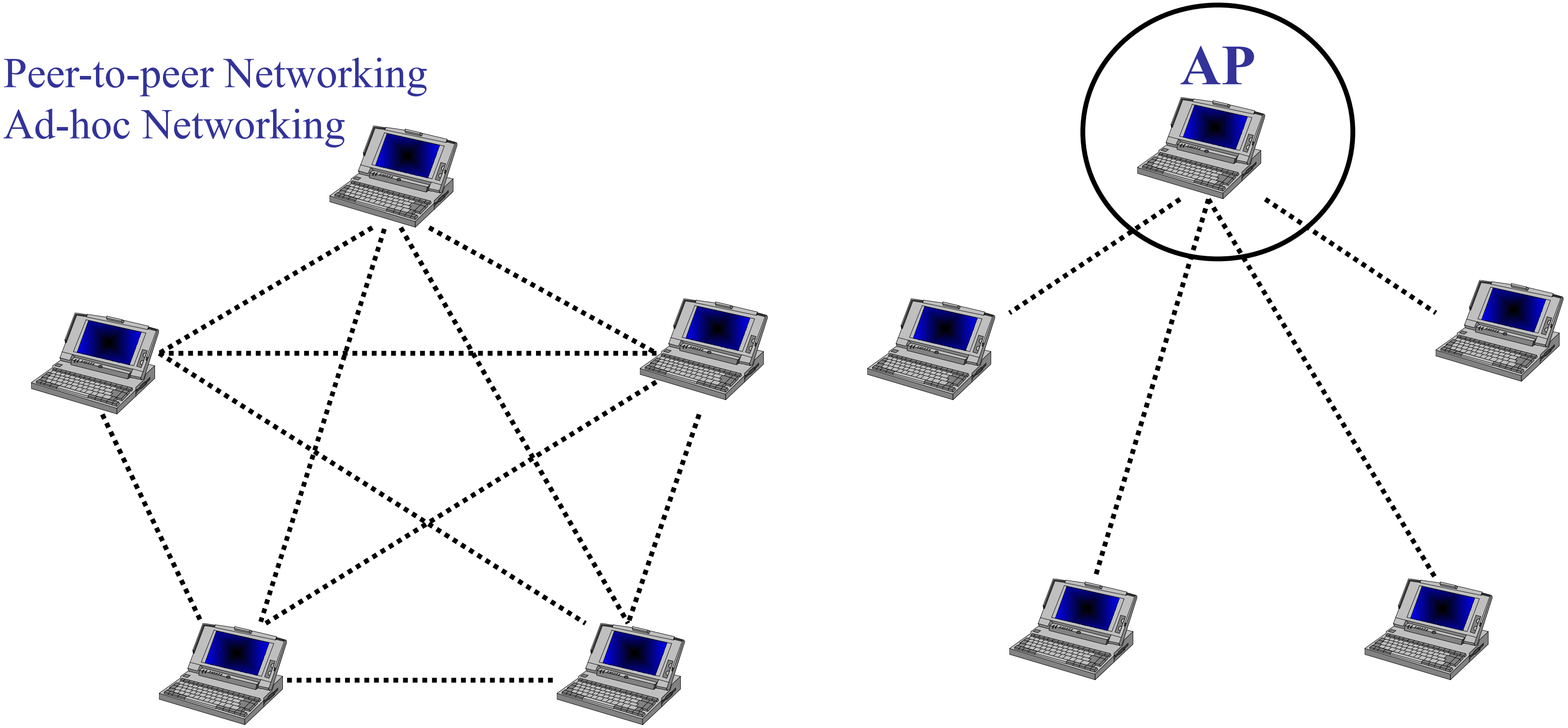
- 1992 - research by Karn (MACA)
- 1994 - research by Bhargavan (MACAW)
    - Multiple Access with Collision Avoidance for Wireless

- Led to IEEE 802.11 committee
    – The standard was ratified in 1999

IEEE 802.11 and Wireless LANs

- Wireless LANs
  - mostly indoor
  - base station (like cellular); or ad hoc networking (mostly point to point)
  - standards: IEEE 802.11 (various versions); HyperLAN (ETSI); Bluetooth
- Applications: nomadic Internet access, portable computing, ad hoc networking (multi-hopping)
- IEEE 802.11 standards define MAC protocol; unlicensed frequency spectrum bands: 900MHz, 2.4GHz, 5GHz

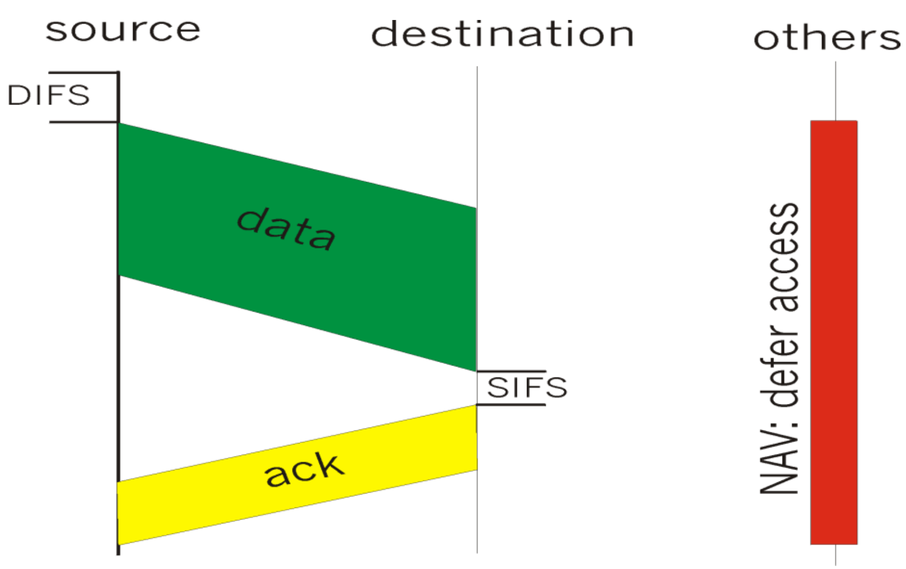
Wireless LAN Configuration



With or without control station (Access Point)

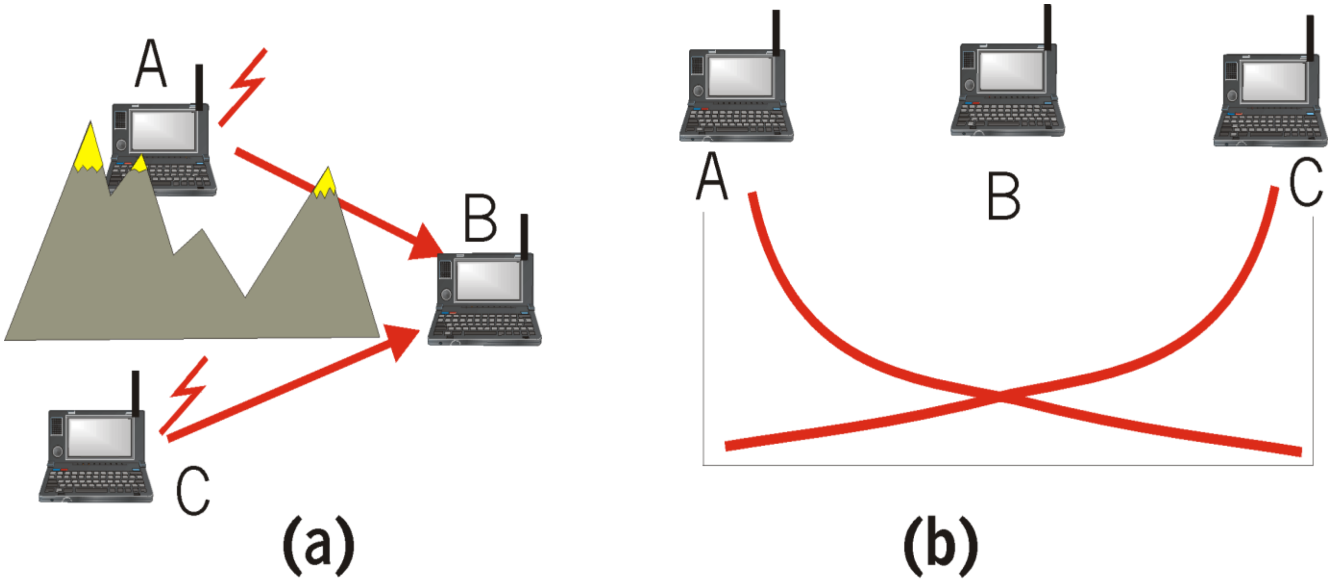
IEEE 802.11 MAC Protocol

- CSMA Version of the Protocol:
- sense channel idle for **DIFS** sec (Distributed Inter Frame Space)
  - transmit frame (no Collision Detection)
  - receiver returns ACK after **SIFS** (Short Inter Frame Space)
- if channel sensed busy => binary backoff
- **NAV**: Network Allocation Vector
  - min time of deferral even if no traffic is sensed
  - Time the sender declares to hold the medium (max 32,767 μs) so that other nodes can go to sleep
    - To spare energy



Hidden Terminal Effect

- CSMA inefficient in presence of hidden terminals
- Hidden terminals: A and C cannot hear each other because of obstacles or signal attenuation; but, if they transmit, their packets collide at B.
- Solution? **CSMA/CA**
- **CA** = Collision Avoidance

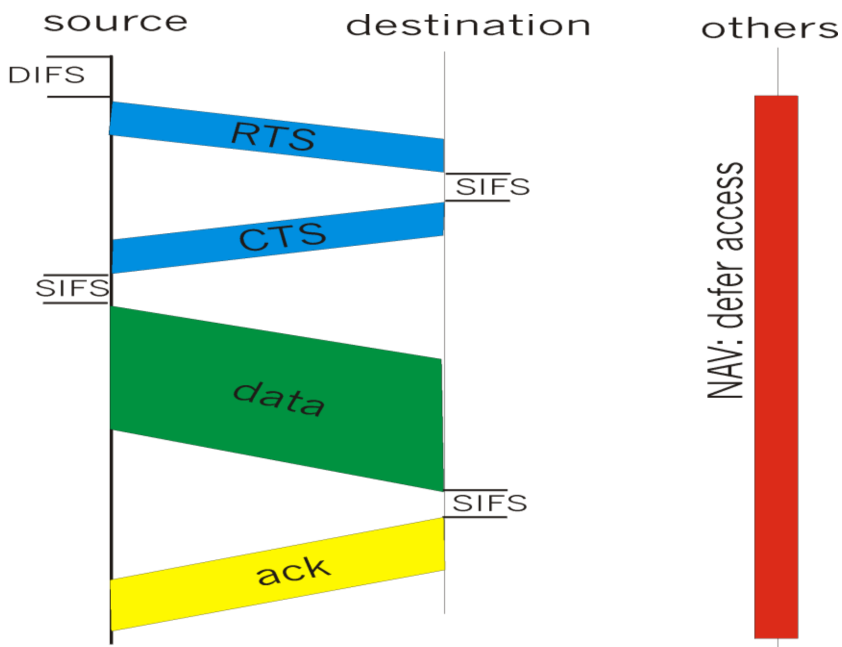


Collision Avoidance

- **RTS** freezes stations near the transmitter
- **CTS** "freezes" stations within range of receiver (but possibly hidden from transmitter); this prevents collisions by hidden station during data transfer
- **RTS** and **CTS** are very short: collisions during data phase are thus very unlikely (similar effect as Collision Detection)
- Note: IEEE 802.11 allows CSMA, CSMA/CA and "polling" from AP

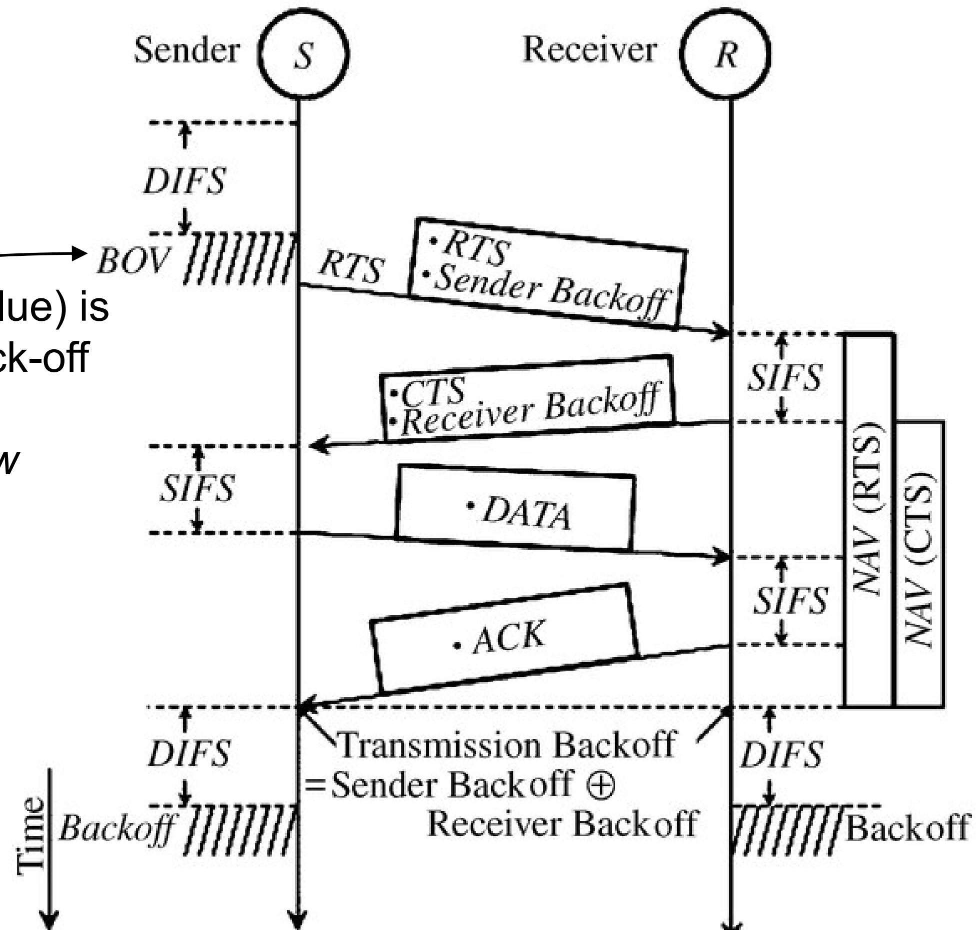
Retransmissions?

Also… there are backoff values after DIFS, before RTS (or DATA, if RTS is not used)
See next slide…



Data Sending Actual Procedure

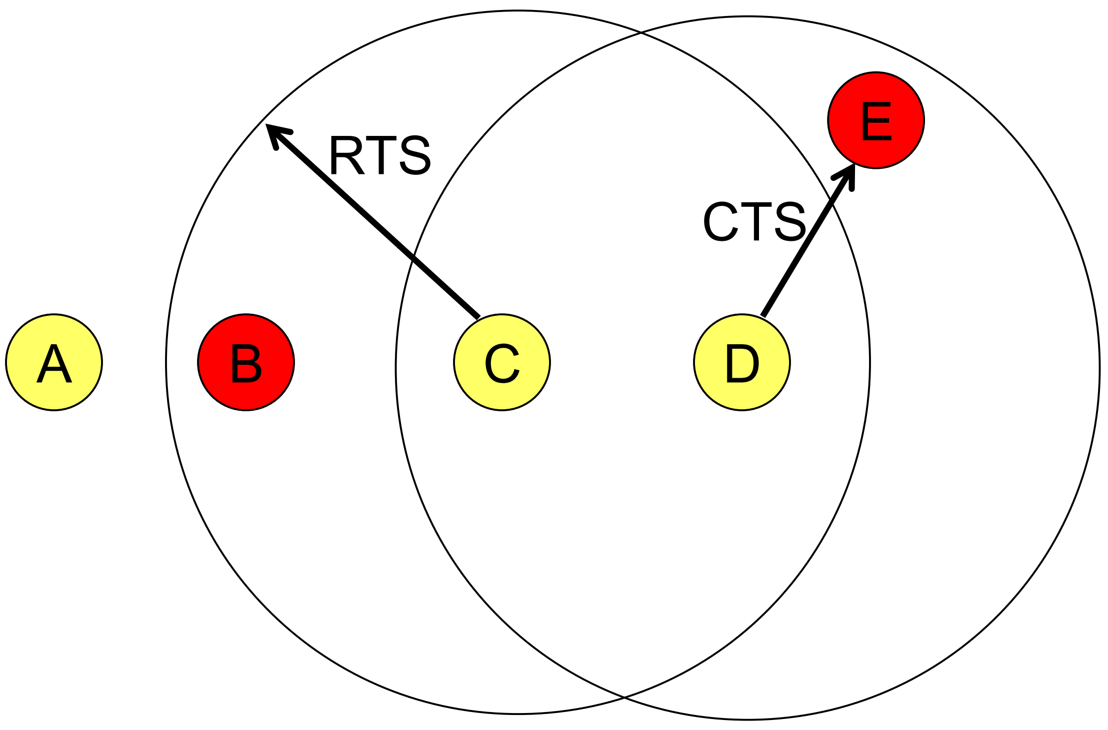
BOV (BackOff Value) is a randomized back-off mechanism, aka *contention window*



DIFS: Distributed Inter Frame Space
SIFS: Short Inter Frame Space
NAV: Network Allocation Vector
ACK: Acknowledgement
CW: Contention Window
RTS: Request to Send
CTS: Clear to Send
BOV: Backoff Value

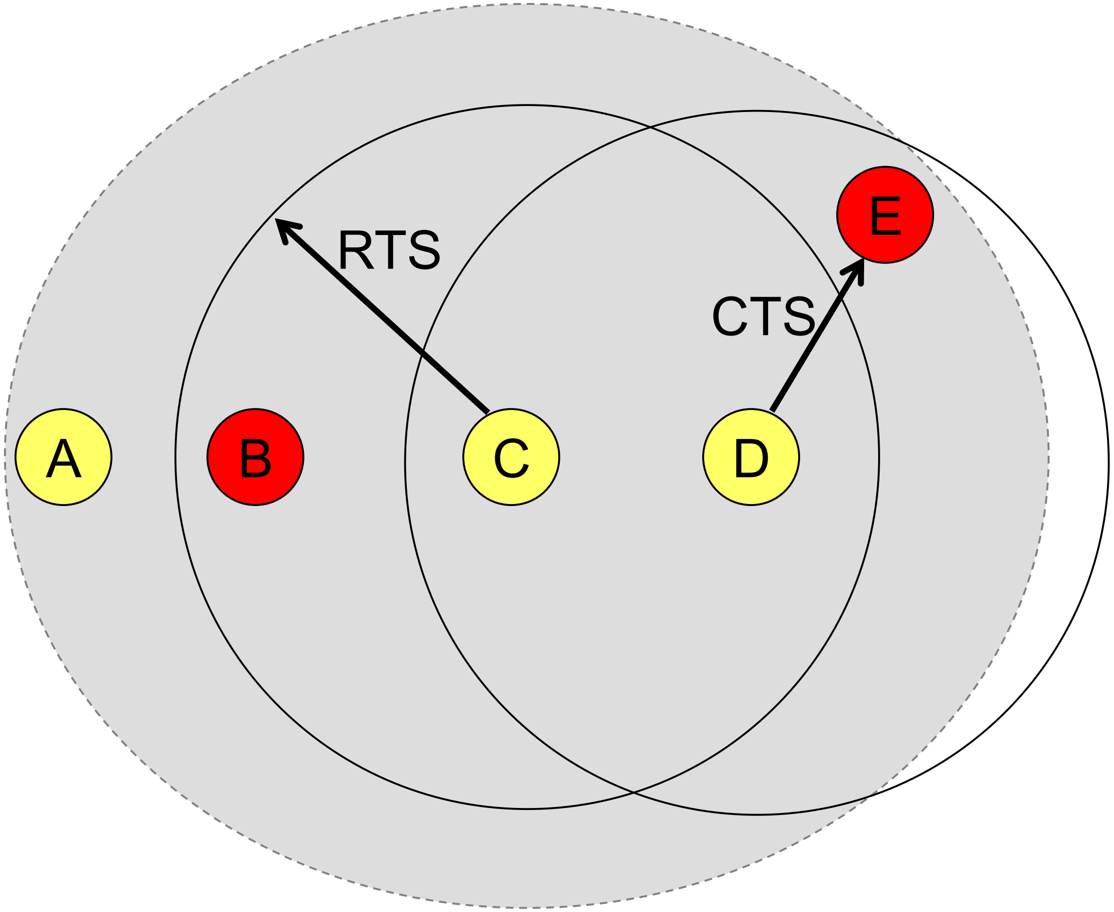
Exposed Terminal

- B should be able to transmit to A
  - RTS prevents this



Exposed Terminal

- B should be able to transmit to A
  - Carrier sensing makes the situation worse



Thoughts !

- 802.11 does not solve HT/ET completely
  - Only alleviates the problem through RTS/CTS and recommends larger CS zone

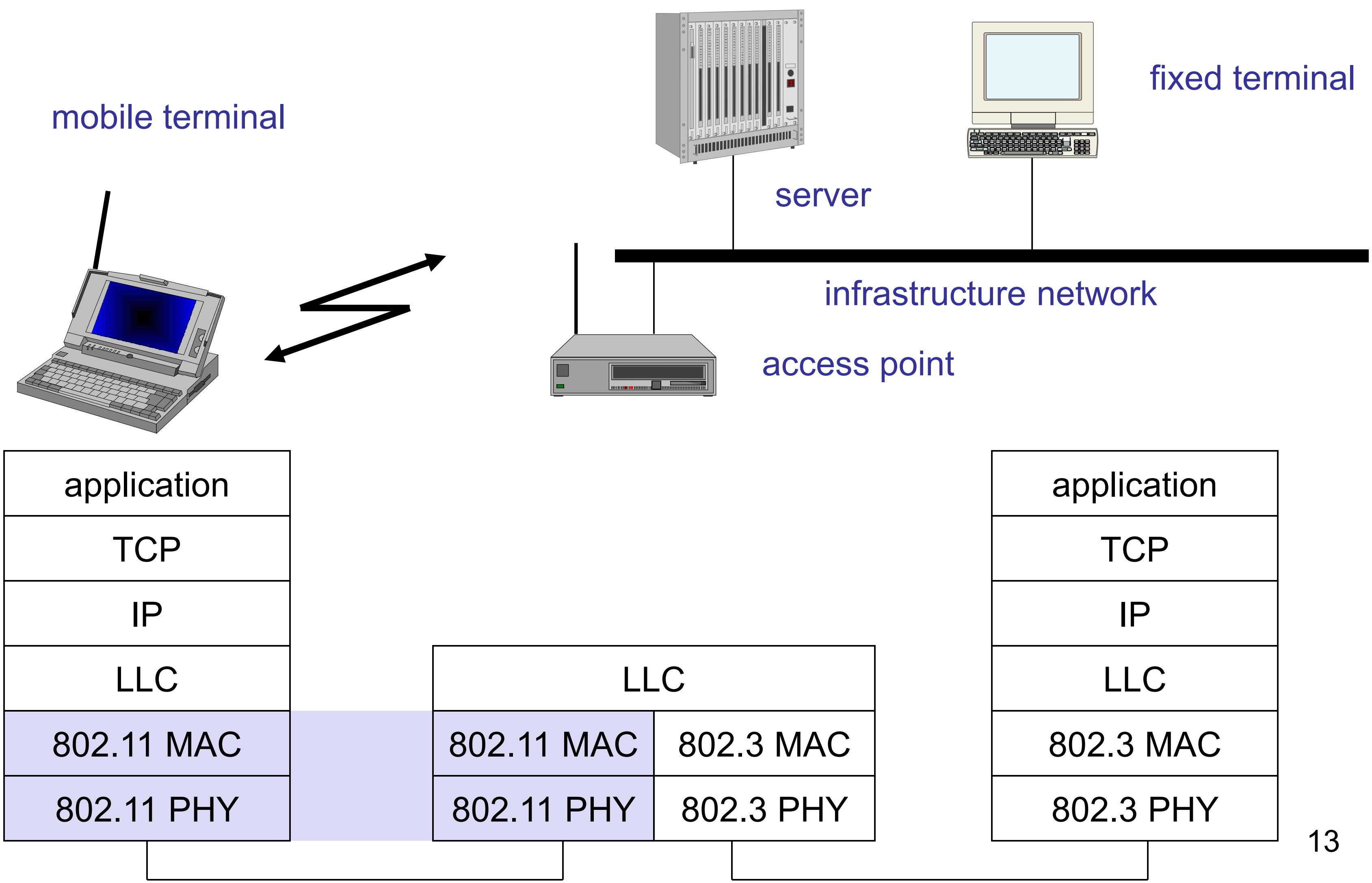
- Large CS zone aggravates exposed terminals
  - Spatial reuse reduces → A tradeoff
  - RTS/CTS packets also consume bandwidth
  - Moreover, backing off mechanism is also wasteful

The search for the best MAC protocol is still on.
However, 802.11 is being optimized too.
Thus, wireless MAC research still alive

To RTS/CTS or Not to RTS/CTS?

- 802.11 does addresses the hidden terminal problem to RTS/CTS
- Two simultaneous RTS messages sent by two different nodes may result in a collision; so no improvement with respect sending directly the two data messages?
  - Actually RTS messages are much smaller (few bytes) than a data message. So the probability of a collision is smaller (even if not zero). This is way they are an improvement at the cost of the limited overhead of their transmission.
  - If data messages sent are very small (e.g., VoIP or gaming messages), then there is no point in using RTS/CTS and actually they slow down (a little bit) the transmission of data messages and represent an overhead that, although little, is comparable to the amount of traffic generate by the application.

IEEE 802.11 Positioning



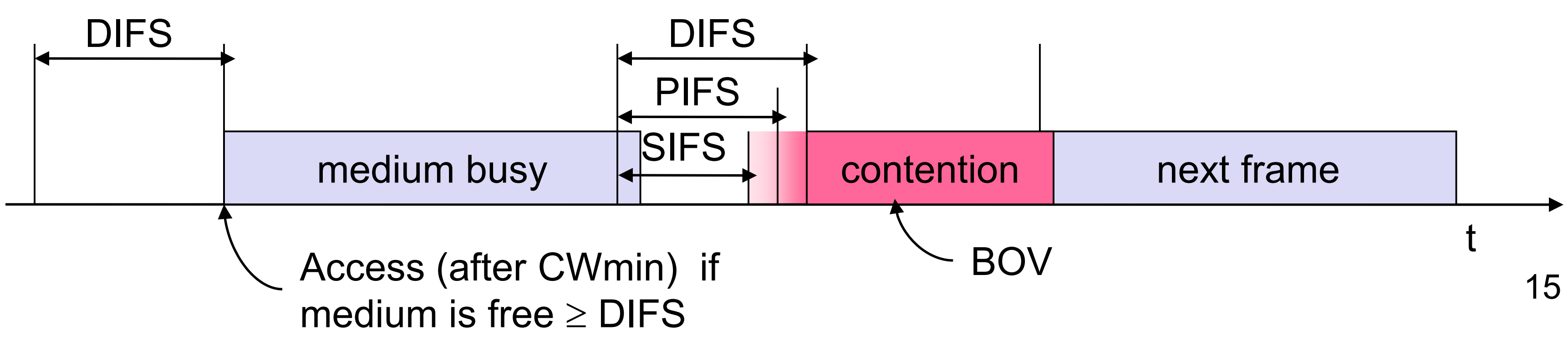
IEEE 802.11 MAC Layer

- Access methods:
  - MAC-DCF CSMA/CA (mandatory)
    - collision avoidance via randomized back-off mechanism
    - minimum distance between consecutive packets
    - **ACK** packet for acknowledgements (not for broadcasts)
  - MAC-DCF w/ RTS/CTS (optional)
    - Distributed Foundation Wireless MAC
    - avoids hidden terminal problem
  - MAC- PCF (optional)
    - access point polls terminals according to a list

DCF: Distributed Control Function
PCF: Point Control Function

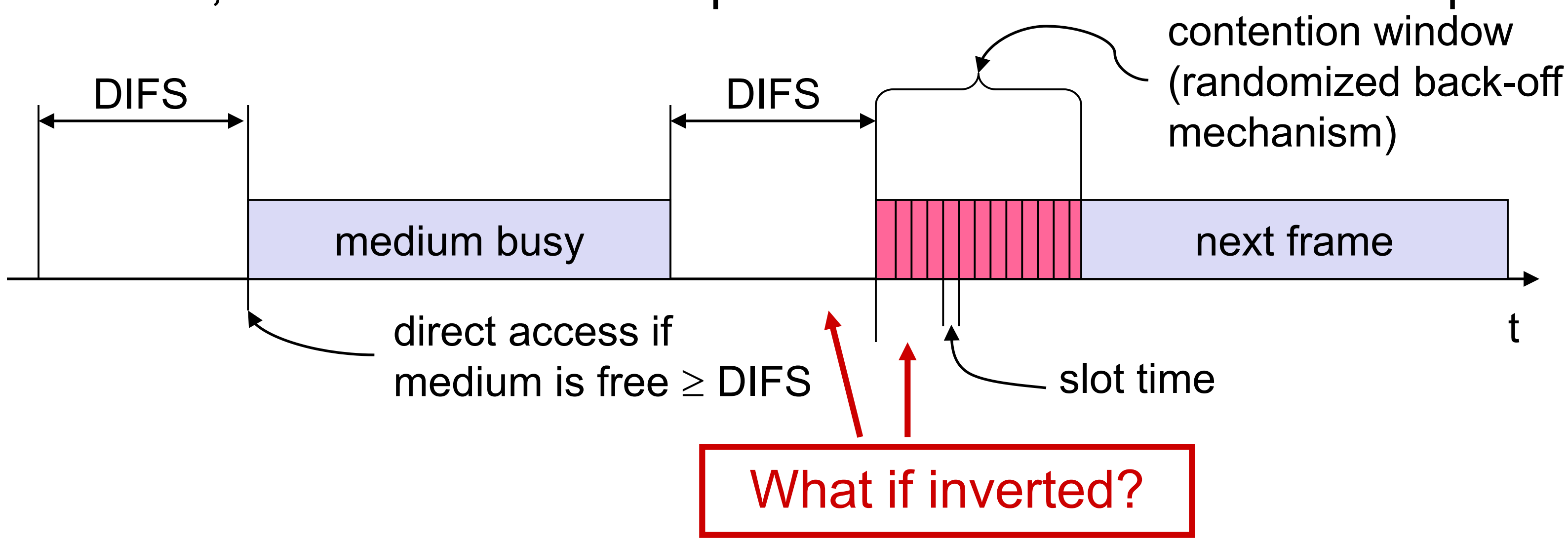
IEEE 802.11 MAC Layer

- Priorities
  - defined through different inter frame spaces
  - no guaranteed, hard priorities
  - SIFS (Short Inter Frame Spacing)
    - highest priority, for ACK, CTS, polling response
  - PIFS (PCF IFS)
    - medium priority, for time-bounded service using PCF
  - DIFS (DCF IFS)
    - lowest priority, for asynchronous data service



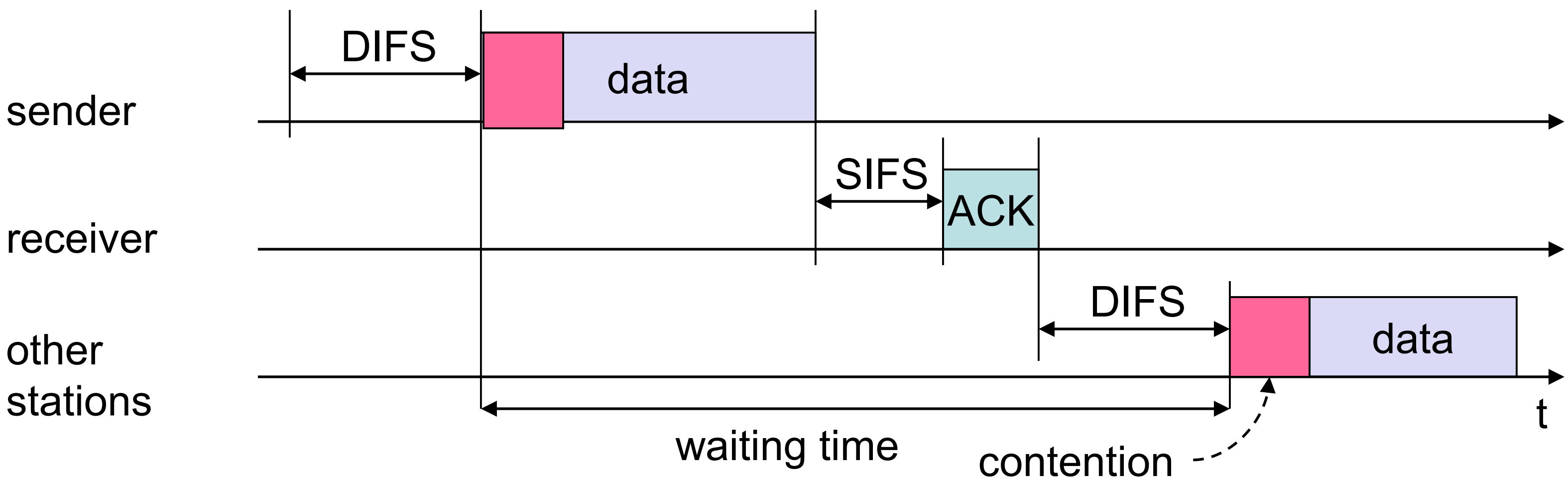
802.11 CSMA/CA Basic Access Method

- station ready to send starts sensing the medium (Carrier Sense based on CCA, Clear Channel Assessment)
- if the medium is free for the duration of an Inter-Frame Space (IFS), the station can start sending after CWmin (IFS depends on packet type)
- if the medium is busy, the station has to wait for a free IFS, then the station must additionally wait a random back-off time (collision avoidance, multiple of slot-time)
- if another station occupies the medium during the back-off time of the station, the back-off timer is paused and then resume when possible



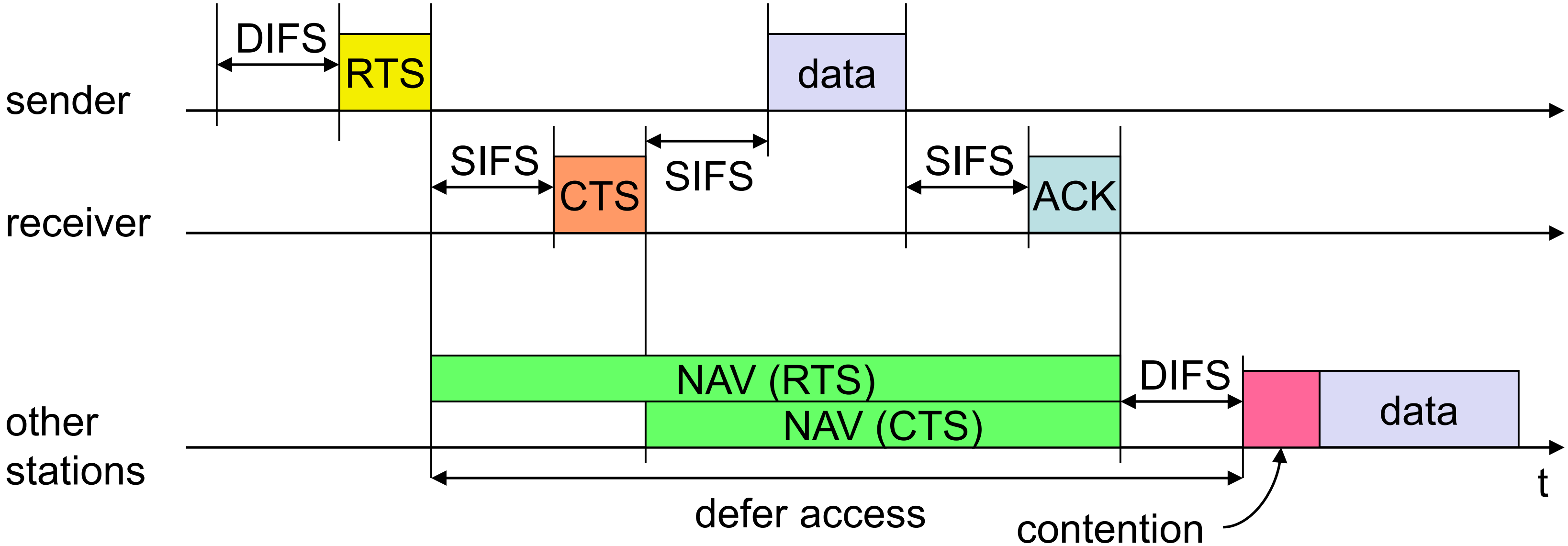
802.11 - CSMA/CA

- Sending unicast packets
  - station has to wait for DIFS (and CWmin) before sending data
  - receivers acknowledge at once (after waiting for SIFS) if the packet was received correctly (CRC)
  - automatic retransmission of data packets in case of transmission errors

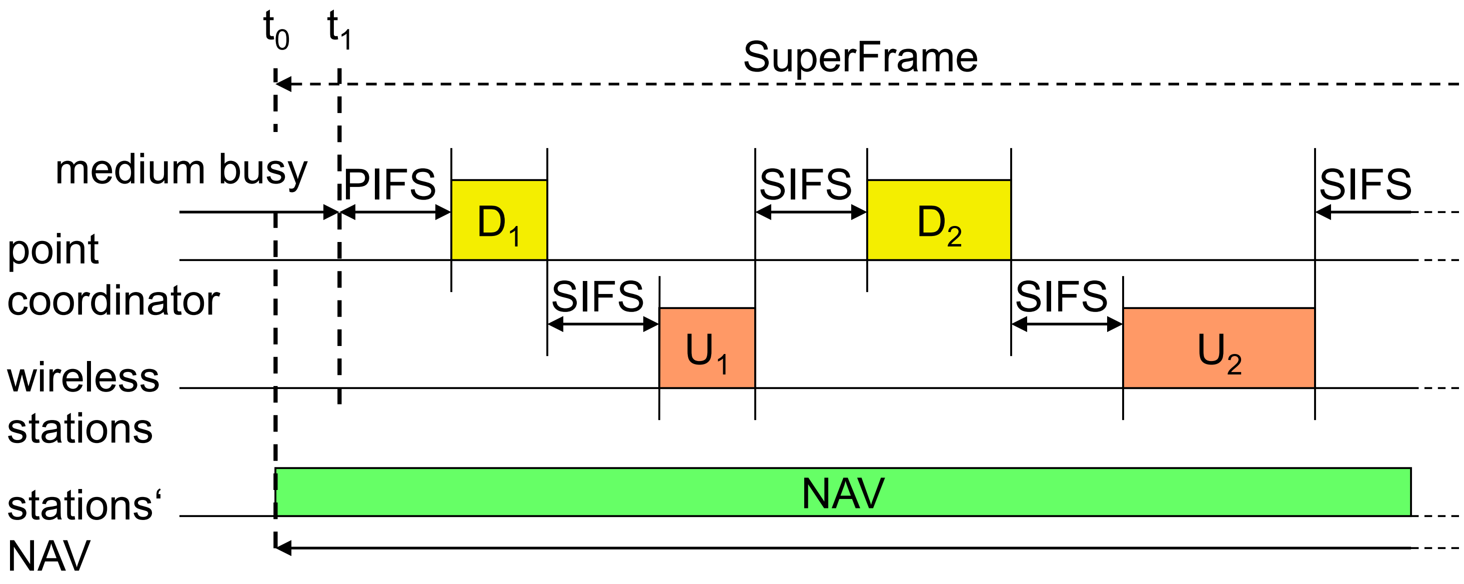


802.11 - CSMA/CA with RTS/CTS

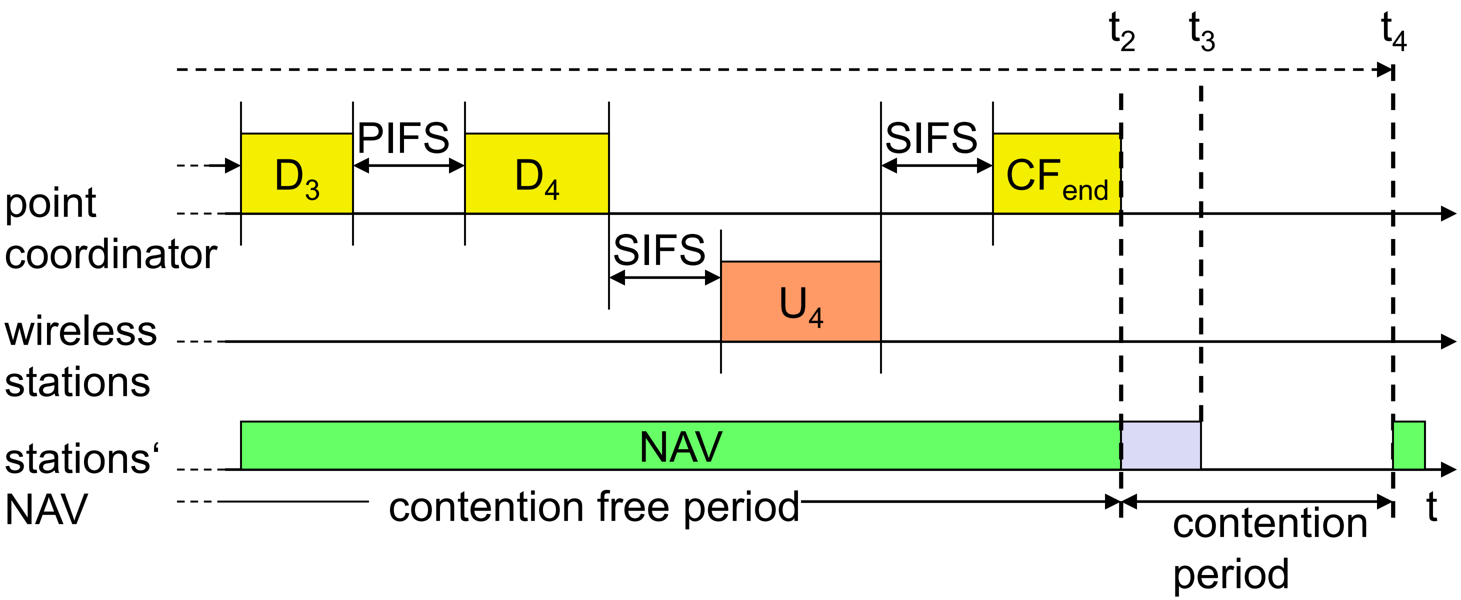
- Sending unicast packets
  - station can send RTS with reservation parameter after waiting for DIFS (reservation declares amount of time the data packet needs the medium)
  - acknowledgement via CTS after SIFS by receiver (if ready to receive)
  - sender can now send data at once, acknowledgement via ACK
  - other stations store medium reservations distributed via RTS and CTS



MAC-PCF (Point Coordination Function) like polling



MAC-PCF (Point Coordination Function) like polling



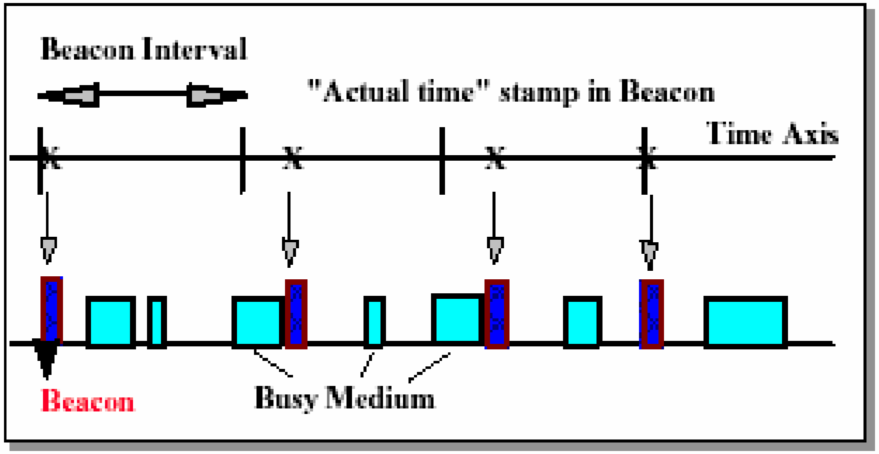
Learning whether PCF is Supported

- The AP announces whether it supports PCF in the beacon, and in other control messages
  - The AP periodically broadcasts beacons
  - Nodes use these beacons to learn about APs
  - The node and the AP authenticate each other
    - Then the node associates with that AP
    - The node sends an association request management frame
    - The AP replies with an association response
    - In the association/reassociation frames the node announces to the AP whether it is pollable and capable to transmit during the contention free period (CFP)

Synchronization in 802.11 (READ)

- Timing Synchronization Function (TSF)
- Used for Power Management
  - Beacons sent at well known intervals
  - All station timers in BSS are synchronized
- Used for Point Coordination Timing
  - TSF Timer used to predict start of Contention Free burst
- Used for Hop Timing for FH PHY
  - TSF Timer used to time Dwell Interval
  - All Stations are synchronized, so they hop at same time.

Infrastructure Beacon Generation

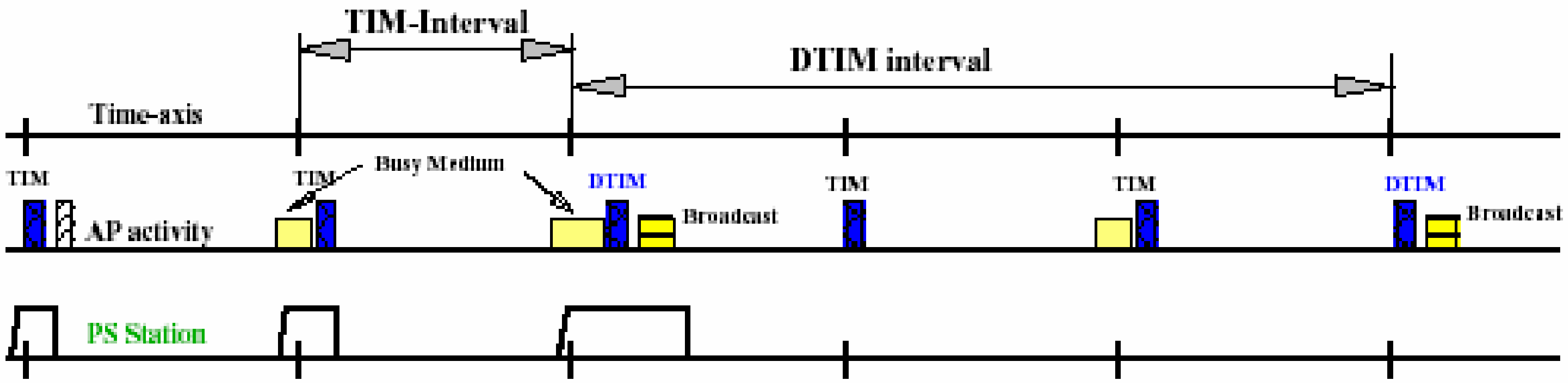


- **APs send Beacons in infrastructure networks.**
- **Beacons scheduled at Beacon Interval.**
- **Transmission may be delayed by CSMA deferral.**
  - subsequent transmissions at expected Beacon Interval
  - not relative to last Beacon transmission
  - next Beacon sent at Target Beacon Transmission Time
- **Timestamp contains timer value at transmit time.**

Power Management Approach

- **Allow idle stations to go to sleep**
  - station's power save mode stored in AP
- **APs buffer packets for sleeping stations.**
  - AP announces which stations have frames buffered
  - Traffic Indication Map (TIM) sent with every Beacon
- **Power Saving stations wake up periodically**
  - listen for Beacons
- **TSF assures AP and Power Save stations are synchronized**
  - stations will wake up to hear a Beacon
  - TSF timer keeps running when stations are sleeping
  - synchronization allows extreme low power operation
- **Independent BSS also have Power Management**
  - similar in concept, distributed approach

Infrastructure Power Management



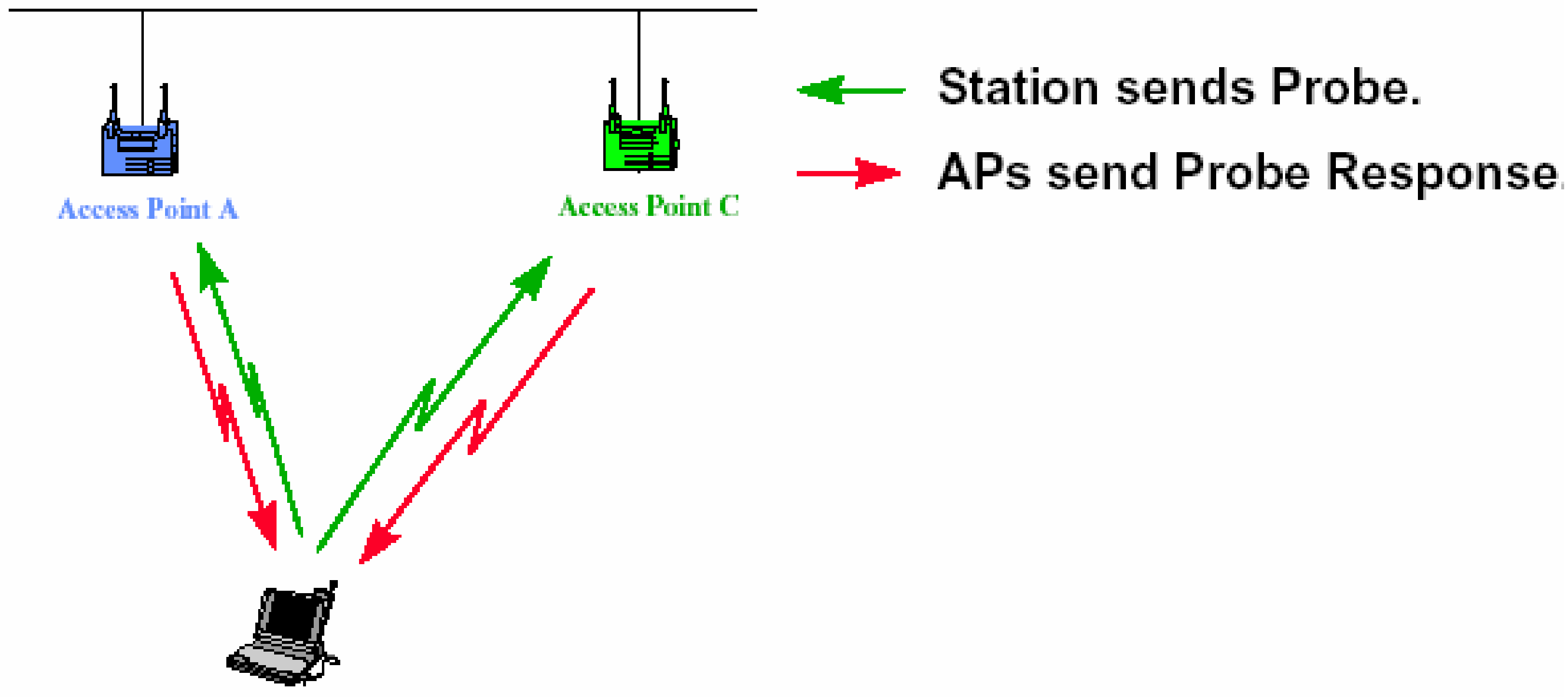
- **Broadcast frames are also buffered in AP.**
  - all broadcasts/multicasts are buffered
  - broadcasts/multicasts are only sent after DTIM
  - DTIM interval is a multiple of TIM interval
- **Stations wake up prior to an expected (D)TIM.**

Scanning

- **Scanning required for many functions.**
  - finding and joining a network
  - finding a new AP while roaming
  - initializing an Independent BSS (ad hoc) network
- **802.11 MAC uses a common mechanism for all PHY.**
  - single or multi channel
  - passive or active scanning
- **Passive Scanning**
  - Find networks simply by listening for Beacons
- **Active Scanning**
  - On each channel
    - » Send a Probe, Wait for a Probe Response
- **Beacon or Probe Response contains information necessary to join new network.**

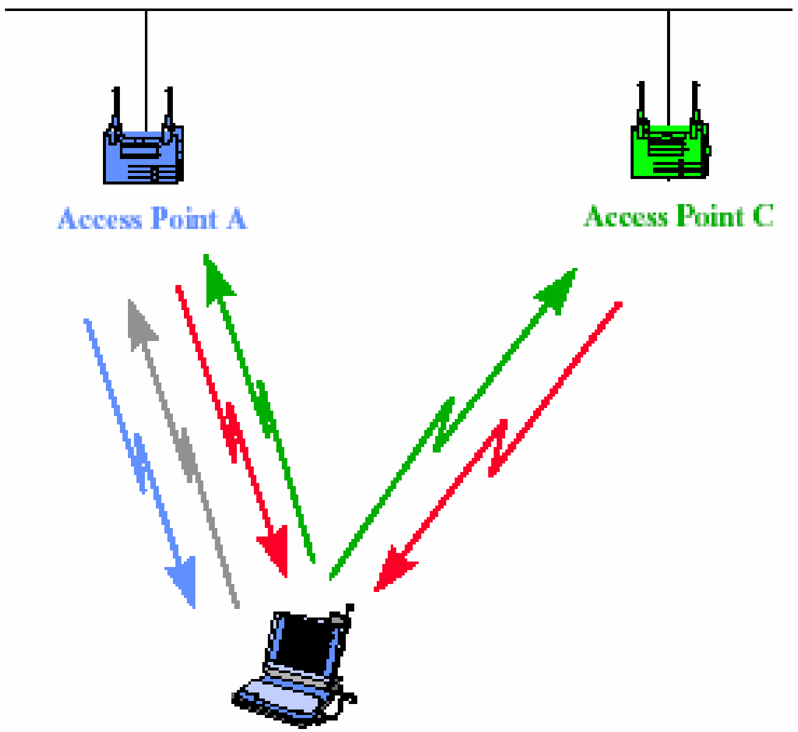
Active Scanning Example 1/2

Steps to Association:



Initial connection to an Access Point

Active Scanning Example 2/2



Steps to Association:

- Station sends Probe.
- APs send Probe Response.
- Station selects best AP.
- Station sends Association Request to selected AP.
- AP sends Association Response.

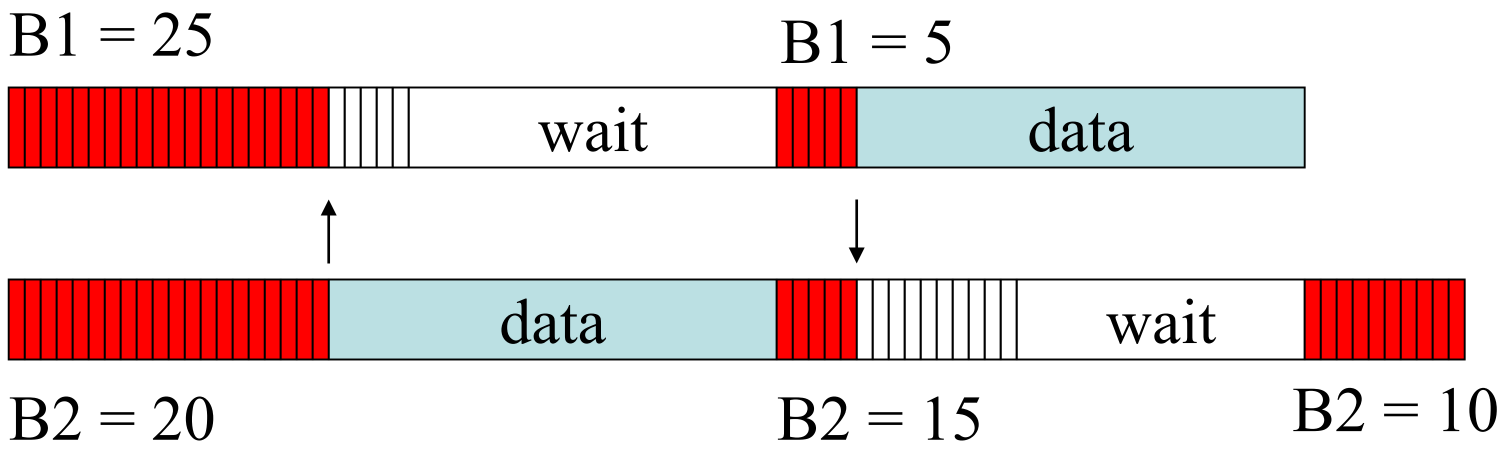
Initial connection to an Access Point
- ReAssociation follows a similar process

Congestion Avoidance: IEEE 802.11 DCF (some more info)

- Before transmitting a packet, randomly choose a backoff interval in the range [0,cw]
  - cw is the contention window
- “Count down” the backoff interval when medium is idle
  - Count-down is suspended if medium becomes busy
- When backoff interval reaches 0, transmit packet (or RTS)

DCF Example

Let cw = 31



B1 and B2 are backoff intervals at nodes 1 and 2

Congestion Avoidance Control

- Since the number of nodes attempting to transmit simultaneously may change with time, some mechanism to manage congestion is needed
- IEEE 802.11 DCF: Congestion control achieved by dynamically adjusting the contention window ***cw***

Congestion Avoidance: CONTENTION Window Tradeoff

- The time spent counting down backoff intervals contributes to MAC overhead
- Choosing a *large cw* leads to large backoff intervals and can result in larger overhead
- Choosing a *small cw* leads to a larger number of collisions (more likely that two nodes count down to 0 simultaneously)

Binary Exponential Backoff in DCF

- When a node fails to receive CTS in response to its RTS, it increases the contention window
  - *cw* is doubled (up to an upper bound – typically 5 times)
- When a node successfully completes a data transfer, it restores *cw* to *CWmin*

MILD Algorithm in MACAW

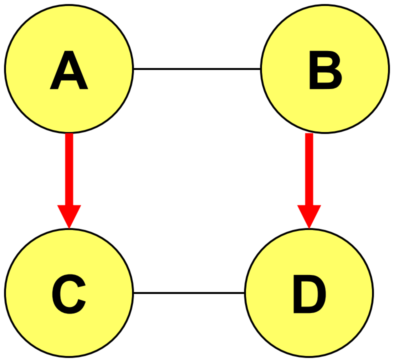
- When a node fails to receive CTS in response to its RTS, it multiplies *cw* by **1.5**
  - Less aggressive than 802.11, which multiplies by 2

- When a node successfully completes a transfer, it reduces *cw* by 1
  - More conservative than 802.11, where cw is restored to Cwmin
  - 802.11 reduces cw much faster than it increases it
  - MACAW: cw reduction slower than the increase
  - Exponential Increase Linear Decrease

- MACAW can avoid wild oscillations of cw when congestion is high

Fairness Issue

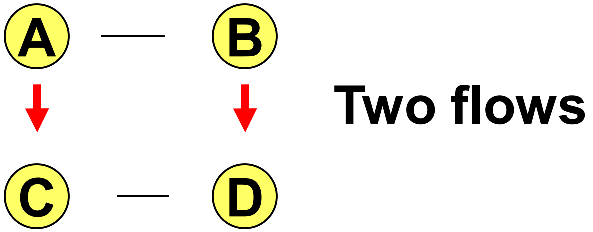
- Many definitions of fairness plausible
- Simplest definition: All nodes should receive *equal* bandwidth



Two flows

Fairness Issue

- Assume that initially, A and B both choose a backoff interval in range [0,31] but their RTSs collide
- Nodes A and B then choose from range [0,63]
  - Node A chooses 4 slots and B chooses 60 slots
  - After A transmits a packet, it next chooses from range [0,31]
  - It is possible that A may transmit several packets before B transmits its first packet
- Observation: unfairness occurs when one node has backed off much more than some other node



MACAW Solution for Fairness

- MACAW
  - (Multiple Access with Collision Avoidance for Wireless)

- When a node transmits a packet, it appends its current *cw* value to the packet

- All nodes hearing that *cw* value use it for their future transmission attempts

- The effect is to reset all competing nodes to the same ground rule

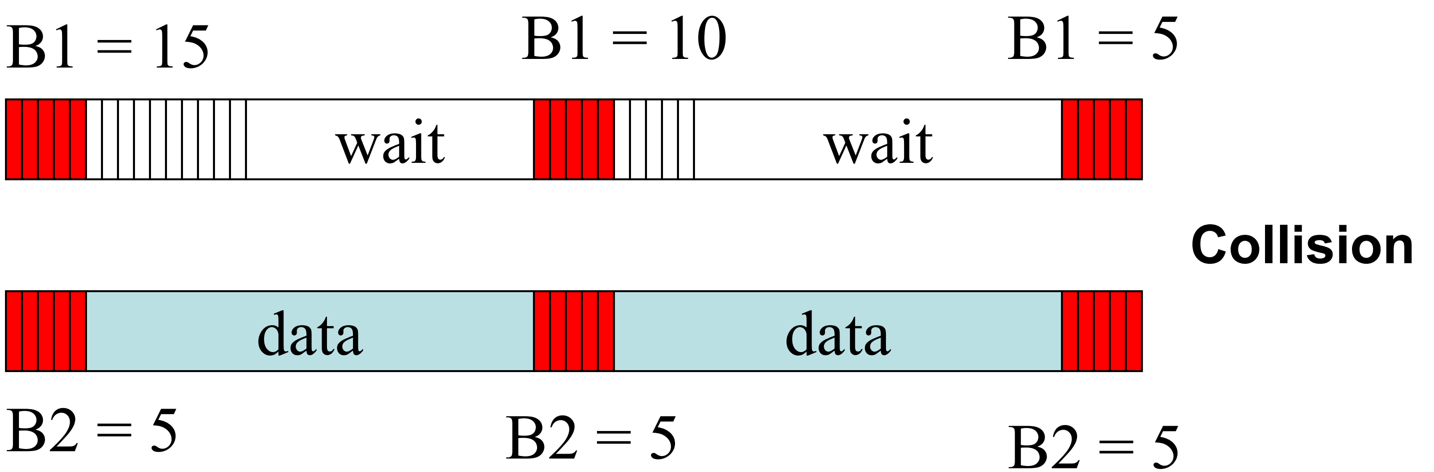
Weighted Fair Queuing

- Assign a weight to each node
- Goal: bandwidth used by each node should be proportional to the weight assigned to the node

Distributed Fair Scheduling (DFS)

- A fully distributed algorithm for achieving weighted fair queueing
- Chooses backoff intervals proportional to *(packet size / weight)*
- DFS attempts to mimic the centralized Self-Clocked Fair Queueing algorithm
- Works well on a LAN

Distributed Fair Scheduling (DFS)



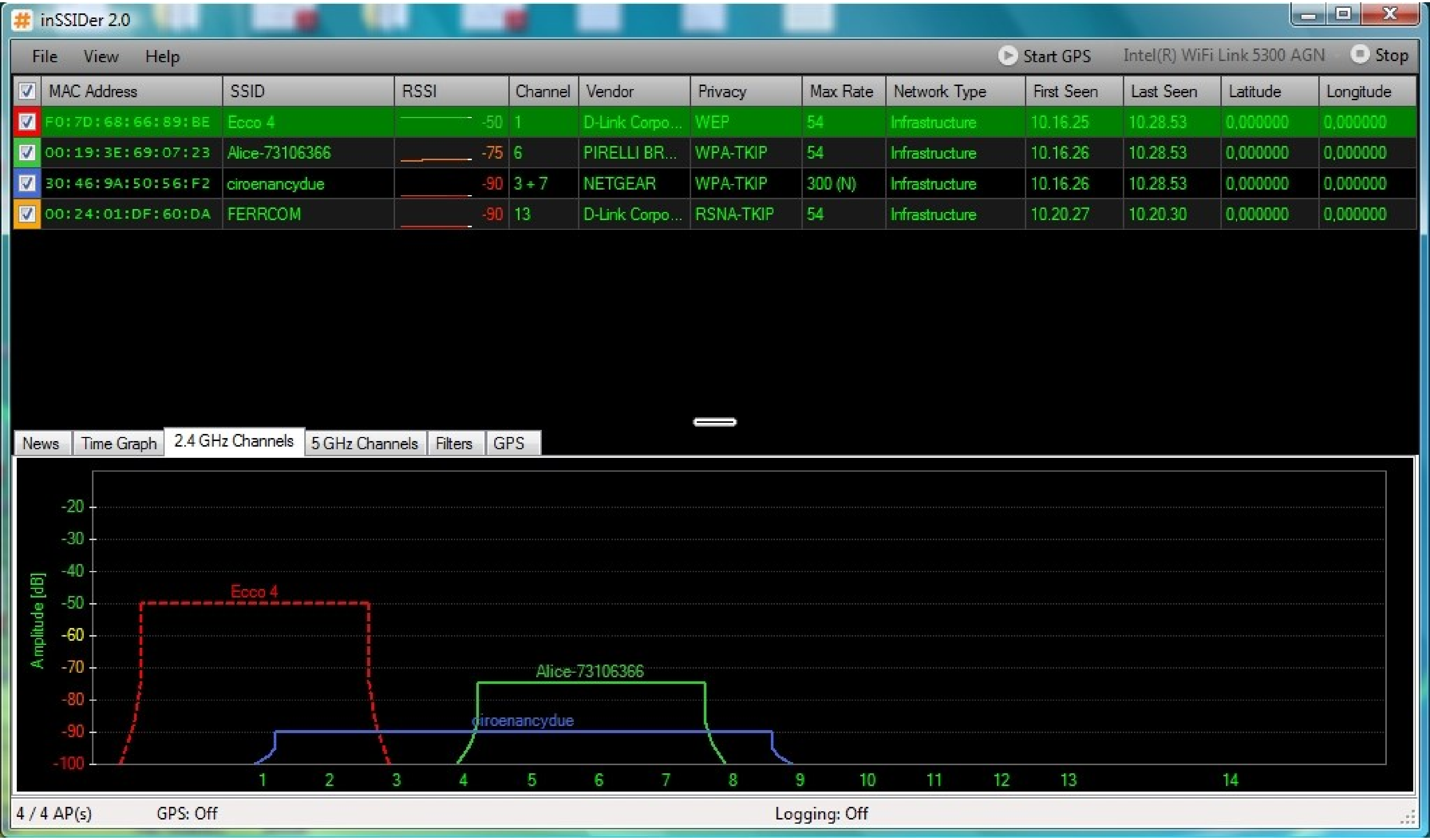
Weight of node 1 = 1
Weight of node 2 = 3

Assume equal packet size

B1 = 15 **(DFS actually picks a random value with mean 15)**

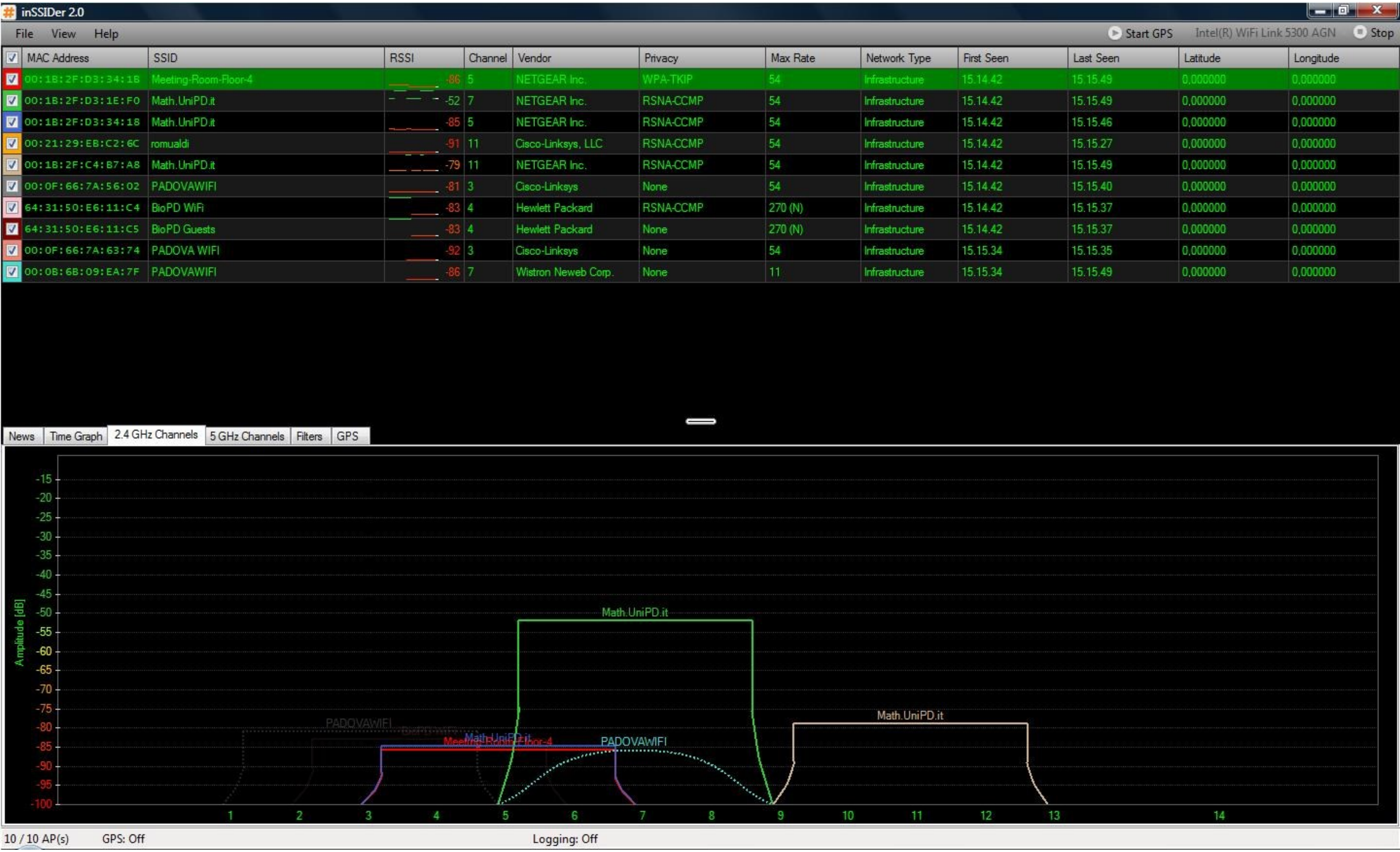
B2 = 5 **(DFS picks a value with mean 5)**

Channel Monitoring (1/6)

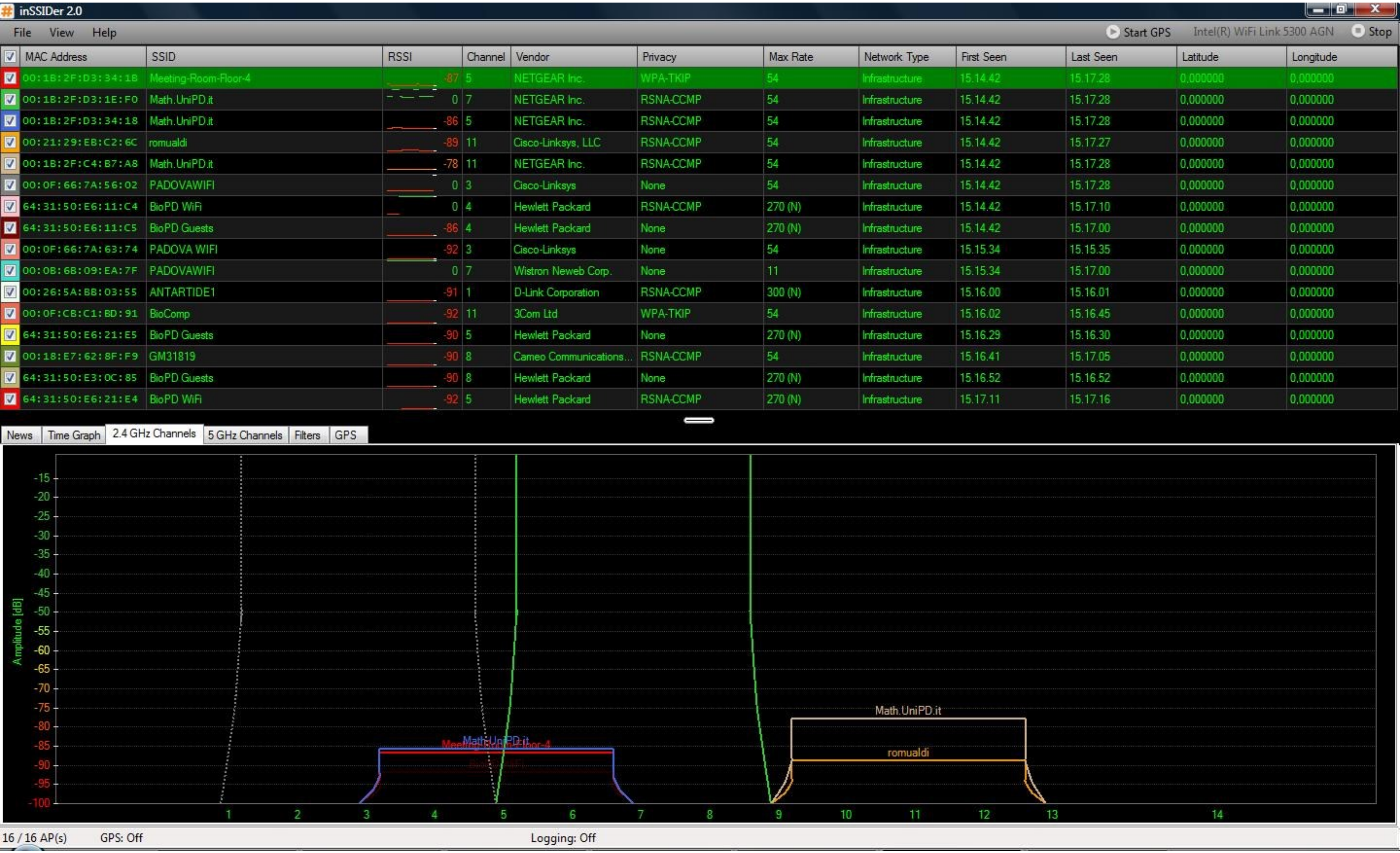


Channel Monitoring (2/6)

Channel Monitoring (3/6)

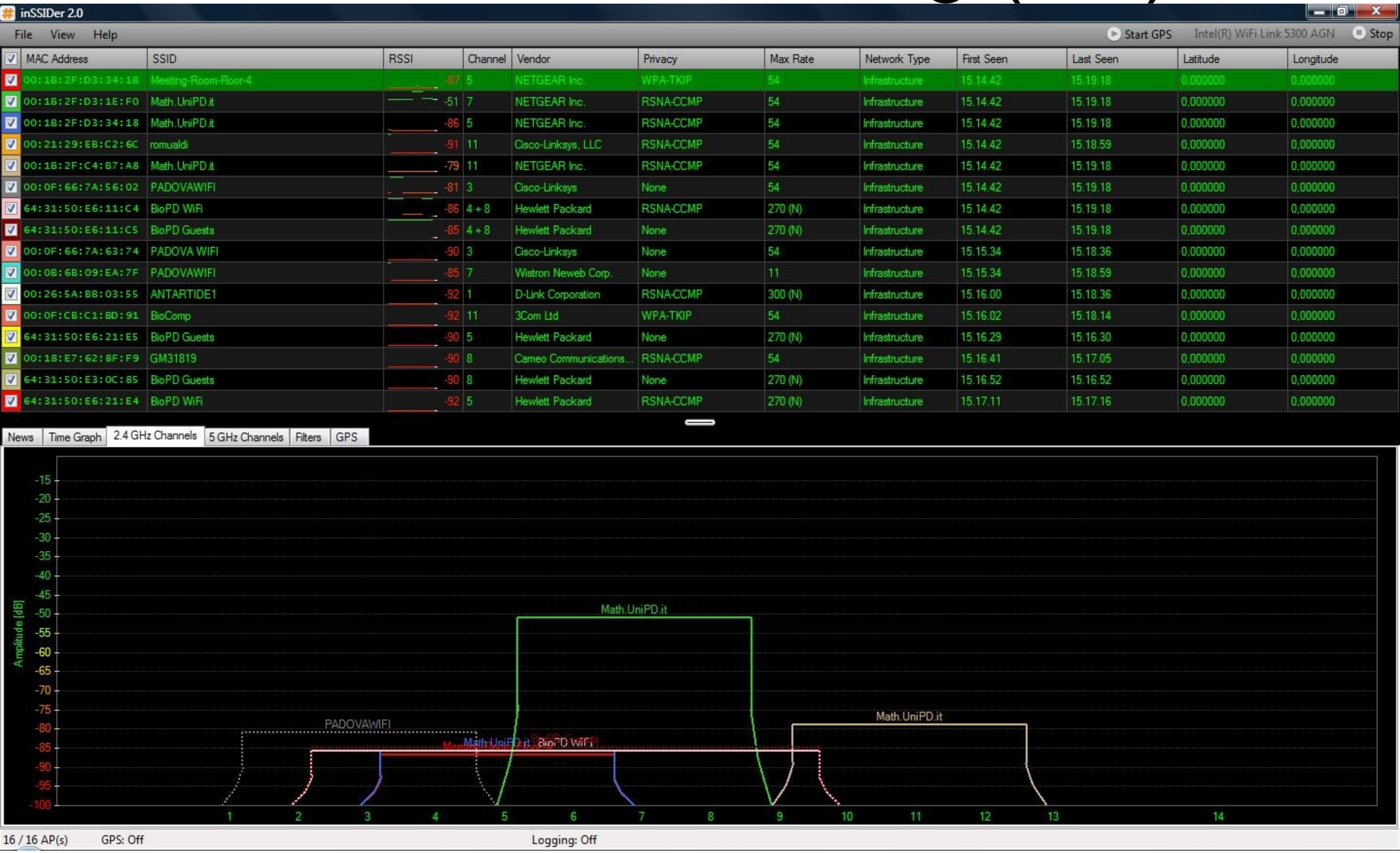


Channel Monitoring (4/6)



MAC Address	SSID	RSSI	Channel	Vendor	Privacy	Max Rate	Network Type	First Seen	Last Seen	Latitude	Longitude
00:1B:2F:D3:34:1B	Meeting-Room-Floor-4	-87	5	NETGEAR Inc.	WPA-TKIP	54	Infrastructure	15.14.42	15.17.28	0,000000	0,000000
00:1B:2F:D3:1E:F0	Math.UniPD.it	0	7	NETGEAR Inc.	RSNA-CCMP	54	Infrastructure	15.14.42	15.17.28	0,000000	0,000000
00:1B:2F:D3:34:18	Math.UniPD.it	-86	5	NETGEAR Inc.	RSNA-CCMP	54	Infrastructure	15.14.42	15.17.28	0,000000	0,000000
00:21:29:EB:C2:6C	romualdi	-89	11	Cisco-Linksys, LLC	RSNA-CCMP	54	Infrastructure	15.14.42	15.17.27	0,000000	0,000000
00:1B:2F:C4:B7:A8	Math.UniPD.it	-78	11	NETGEAR Inc.	RSNA-CCMP	54	Infrastructure	15.14.42	15.17.28	0,000000	0,000000
00:0F:66:7A:56:02	PADOVAWIFI	0	3	Cisco-Linksys	None	54	Infrastructure	15.14.42	15.17.28	0,000000	0,000000
64:31:50:E6:11:C4	BioPD WiFi	0	4	Hewlett Packard	RSNA-CCMP	270 (N)	Infrastructure	15.14.42	15.17.10	0,000000	0,000000
64:31:50:E6:11:C5	BioPD Guests	-86	4	Hewlett Packard	None	270 (N)	Infrastructure	15.14.42	15.17.00	0,000000	0,000000
00:0F:66:7A:63:74	PADOVA WIFI	-92	3	Cisco-Linksys	None	54	Infrastructure	15.15.34	15.15.35	0,000000	0,000000
00:0B:6B:09:EA:7F	PADOVAWIFI	0	7	Wistron Neweb Corp.	None	11	Infrastructure	15.15.34	15.17.00	0,000000	0,000000
00:26:5A:BB:03:55	ANTARTIDE1	-91	1	D-Link Corporation	RSNA-CCMP	300 (N)	Infrastructure	15.16.00	15.16.01	0,000000	0,000000
00:0F:CB:C1:BD:91	BioComp	-92	11	3Com Ltd	WPA-TKIP	54	Infrastructure	15.16.02	15.16.45	0,000000	0,000000
64:31:50:E6:21:E5	BioPD Guests	-90	5	Hewlett Packard	None	270 (N)	Infrastructure	15.16.29	15.16.30	0,000000	0,000000
00:18:E7:62:8F:F9	GM31819	-90	8	Cameo Communications...	RSNA-CCMP	54	Infrastructure	15.16.41	15.17.05	0,000000	0,000000
64:31:50:E3:0C:85	BioPD Guests	-90	8	Hewlett Packard	None	270 (N)	Infrastructure	15.16.52	15.16.52	0,000000	0,000000
64:31:50:E6:21:E4	BioPD WiFi	-92	5	Hewlett Packard	RSNA-CCMP	270 (N)	Infrastructure	15.17.11	15.17.16	0,000000	0,000000

Channel Monitoring (5/6)



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00:1B:2F:D3:1E:F0	Math.UniPD.it	-51	7	NETGEAR Inc.	RSNA-CCMP	54	Infrastructure	15.14.42	15.19.18	0,000000	0,000000
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00:1B:2F:C4:B7:A8	Math.UniPD.it	-79	11	NETGEAR Inc.	RSNA-CCMP	54	Infrastructure	15.14.42	15.19.18	0,000000	0,000000
00:0F:66:7A:56:02	PADOVAWIFI	-81	3	Cisco-Linksys	None	54	Infrastructure	15.14.42	15.19.18	0,000000	0,000000
64:31:50:E6:11:C4	BioPD WiFi	-86	4 + 8	Hewlett Packard	RSNA-CCMP	270 (N)	Infrastructure	15.14.42	15.19.18	0,000000	0,000000
64:31:50:E6:11:C5	BioPD Guests	-85	4 + 8	Hewlett Packard	None	270 (N)	Infrastructure	15.14.42	15.19.18	0,000000	0,000000
00:0F:66:7A:63:74	PADOVA WIFI	-90	3	Cisco-Linksys	None	54	Infrastructure	15.15.34	15.18.36	0,000000	0,000000
00:0B:6B:09:EA:7F	PADOVAWIFI	-85	7	Wistron Neweb Corp.	None	11	Infrastructure	15.15.34	15.18.59	0,000000	0,000000
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00:0F:CB:C1:BD:91	BioComp	-92	11	3Com Ltd	WPA-TKIP	54	Infrastructure	15.16.02	15.18.14	0,000000	0,000000
64:31:50:E6:21:E5	BioPD Guests	-90	5	Hewlett Packard	None	270 (N)	Infrastructure	15.16.29	15.16.30	0,000000	0,000000
00:18:E7:62:8F:F9	GM31819	-90	8	Cameo Communications...	RSNA-CCMP	54	Infrastructure	15.16.41	15.17.05	0,000000	0,000000
64:31:50:E3:0C:85	BioPD Guests	-90	8	Hewlett Packard	None	270 (N)	Infrastructure	15.16.52	15.16.52	0,000000	0,000000
64:31:50:E6:21:E4	BioPD WiFi	-92	5	Hewlett Packard	RSNA-CCMP	270 (N)	Infrastructure	15.17.11	15.17.16	0,000000	0,000000

Channel Monitoring (6/6)