WIRELESS NETWORKS

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Main Topics

- Architectures for wireless and/or mobile networks
- Research & Engineering challenges
- State of the art and IEEE Standards
- Practice in an open-source simulator: ns-2

Goals

- Familiarize with the state of the art in wireless and mobile networks
- Get to know the main technologies, standards and bodies that dominate the wireless industry
- Get to know the fundamental engineering challenges
- Get to know the solutions and their limitations
- Practice key concept on an open-source simulator

A quick poll -- live.voxvote.com PIN: 91758

- Does RTS/CTS solve the hidden terminal problem?
- Does RTS/CTS solve the exposed terminal problem?

Why Wi-Fi?

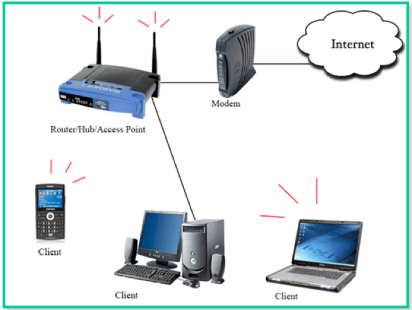
- Freedom from wires at home, campus, work, airport, café, etc. while being connected to the Internet at speeds up to 54 Mbps

- Wi-Fi is used by over 700 million people

- Over 4 million and counting Wi-Fi hotspots around the world

What is Wi-Fi?

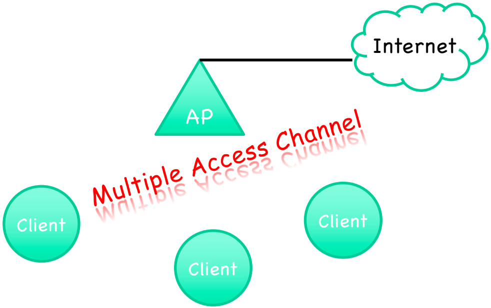
- Wi-Fi is the brand name for products using the IEEE 802.11 family of standards
- Supports two architectures:



WLAN Architecture

Ad-hoc (Peer-to-Peer) Architecture

WLAN Architecture

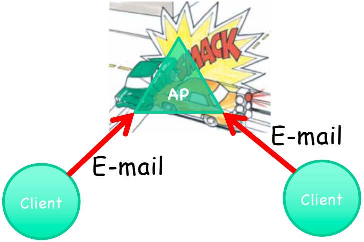


- A special station – Access Point – is static and connected to the internet through wires
- The other stations – the Clients – are free to move and connect to the Internet by giving their data to the Access Point
- All the clients communicate with the AP wirelessly on the same frequency/channel – *multiple access channel*

The Main Engineering Challenge in WLANs

- *How can multiple stations communicate efficiently with a single Access Point while using the same channel?*
  - *Formally defined as the problem of Medium Access Control*

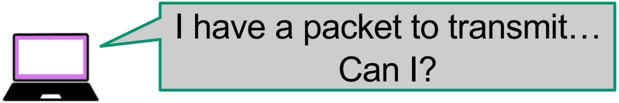
- Why is it challenging?
  1. The Access Point can only hear from one station at a time
     - If two stations transmit to the AP at the same time, the respective transmissions will collide and get destroyed



MAC for Wireless LANs

- They seem like LANs (except the medium is wireless), why not adopt the tried and proven Ethernet ?

Sharing a common medium



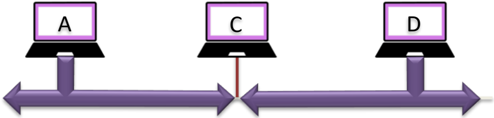
Ethernet ⇒ CSMA/CD

congestion at the receiver

= congestion at the transmitter

(*Just have to wait a little*)

Sharing a wired medium



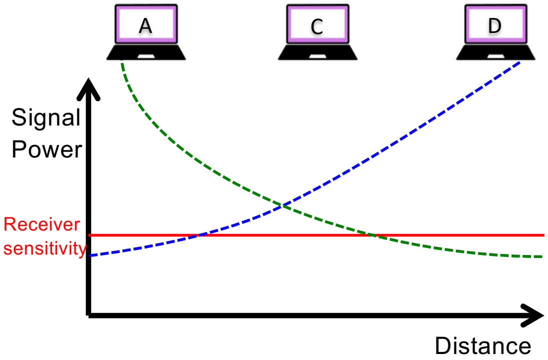
Collision ⇕ Collision at every other node

How do ***A*** and ***D*** know?

- Signal power levels:
  everywhere almost the same
- Avoid/detect collisions:
  relying on what it is receiving (CSMA/CD)

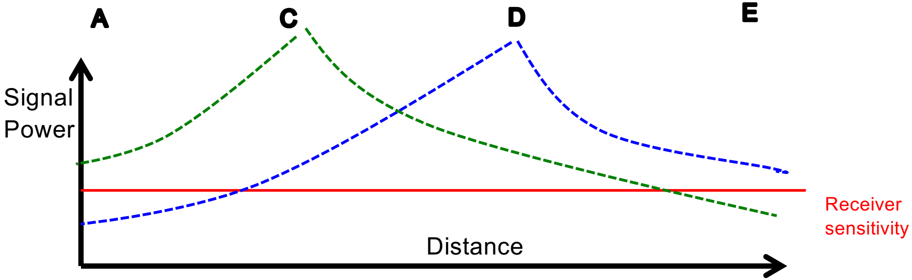
Sharing a wireless medium

Hidden terminal scenario



- Signal power levels not everywhere the same due to *pathloss*
- If A (D) does carrier sensing while D (A) is transmitting it will sense nothing and it will transmit – the wrong decision !

Exposed terminal scenario



- There is no collision at the receivers, A and E
- If C (D) does carrier sensing while D (C) is transmitting it will decide to defer --- the wrong decision (C&D are exposed terminals)

A Quick Conclusion

- CSMA in wireless networks:
  - Sometime it tells you to transmit when you should not (hidden terminal)
  - Sometime it tells you to not transmit when you should (exposed terminal)
- CD
  - Physically impossible

The Emergence of MACA, MACAW, & IEEE 802.11

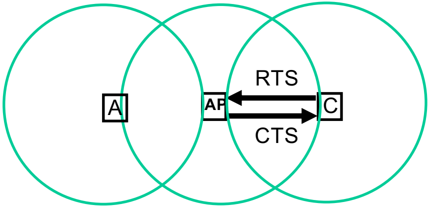
- Wireless MAC proved to be non-trivial

- 1992 - research by Karn (MACA)
- 1994 - research by Bhargavan (MACAW)

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

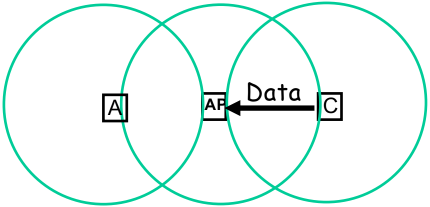
RTS/CTS: Addressing the Hidden Node

- MACA: Multiple Access with Collision Avoidance
- If node ***C*** has data to transmit, it first transmits a Request-to-Send (RTS) to the ***AP***. The RTS includes the duration of the pending data packet.
- The ***AP*** greenlights ***C*** by replying with a Clear-to-Send (CTS).
- ***A*** receives the CTS causing it to defer for the duration of the packet
-



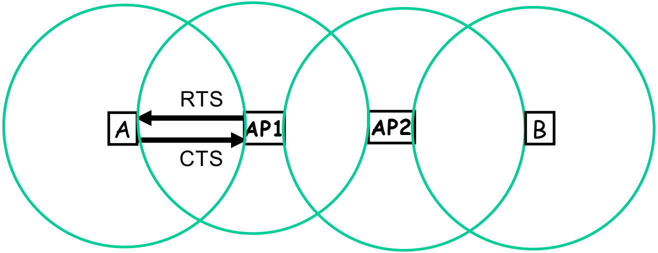
RTS/CTS: Addressing the Hidden Node

- MACA: Multiple Access with Collision Avoidance
- If node *C* has data to transmit, it first transmits a Request-to-Send (RTS) to the *AP*. The RTS includes the duration of the pending data packet.
- The *AP* greenlights *C* by replying with a Clear-to-Send (CTS).
- *A* receives the CTS causing it to defer for the duration of the packet
- *C* transmits the data safely to the access point (*AP*)



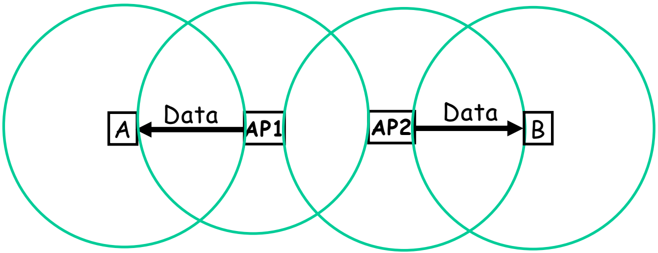
RTS/CTS: Addressing the Exposed Node

- If the ***AP1*** has data to transmit, it first sends a Request-to-Send (RTS) to ***A***.
- ***AP2*** receiving an RTS not addressed at him, defers from transmitting enough for the recipient to send a CTS.
- Node ***A*** transmits a Clear-to-Send (CTS). The CTS echoes the data packet duration ***B*** intends to transmit
-



RTS/CTS: Addressing the Exposed Node (?)

- If the ***AP1*** has data to transmit, it first sends a Request-to-Send (RTS) to ***A***.
- ***AP2*** receiving an RTS not addressed at him, defers from transmitting enough for the recipient to send a CTS.
- Node ***A*** transmits a Clear-to-Send (CTS). The CTS echoes the data packet duration ***B*** intends to transmit
- ***AP2*** receives the RTS but did not receive the CTS- it cannot cause a collision - and therefore it's free to transmit to node ***B***



IEEE 802.11 MAC: CSMA/CA

- Combination of carrier sensing with collision avoidance
  - CSMA before transmitting an RTS (or data if no RTS/CTs)
- ARQ: Automatic Request Acknowledgment
  - The recipient of data packet sends an ACK to the sender
  - Unlike Ethernet
- Truncated binary exponential backoff for handling congestion
  - Just like Ethernet

Answer on live.voxvote.com PIN: 91758

- ARQ in IEEE 802.11 is unnecessary -- Etherenet does no include one
  - Agree
  - Strongly agree
  - Disagree
  - Strongly disagree

Answer on live.voxvote.com PIN: 91758

- ARQ in IEEE 802.11 is unnecessary – TCP can take care of reliability
  - Agree
  - Strongly agree
  - Disagree
  - Strongly disagree

IEEE 802.11 MAC

- Before transmitting an RTS, a node invokes the ***CS mechanism*** to determine the busy/idle state of the medium
- A node will defer until the channel is sensed free period of time equal to DIFS
- After DIFS idle time, the node generates a random backoff counter
- For every time slot for which the channel is free the backoff counter is reduced by 1, otherwise it stays unchanged
- Once the backoff counter reaches 0 the node is free to transmit

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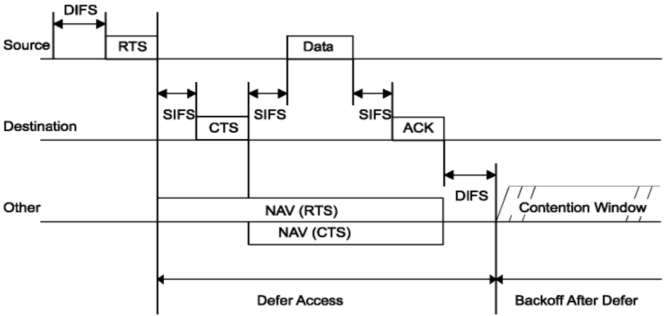
- Is RTS/CTS Always Beneficiary?
  - Yes
  - No

Frame Spacing in IEEE 802.11



- **SIFS** (Short Interframe Space)= RxRFDelay + RxPLCPDelay + MACProcessingDelay + RxTxTurnaroundTime
- **SlotTime** = aCCATime + aRxTxTurnaroundTime + aAirPropagationTime + aMACProcessingDelay
- **DIFS**(DCF Interframe Space) = SIFS + 2 x SlotTime

IEEE 802.11 MAC

- The Carrier Sensing mechanism is not invoked for the the following packets:
  - CTS
  - DATA-ACK
  - DATA packet when RTS/CTS is enabled

- All these packets are sent as soon as physically possible (SIFS time from receiving a respective packet)

Packet Exchange In Detail

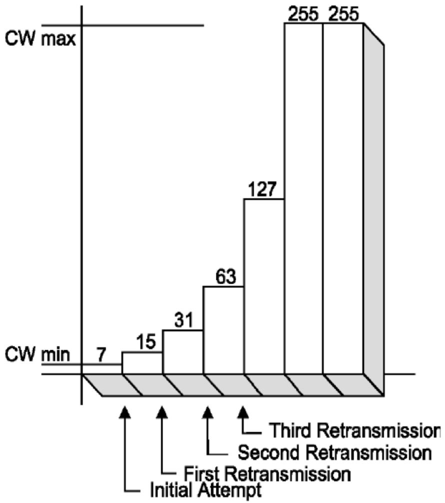
1. A node wanting to transmit a data, invokes the CS mechanism and transmits an RTS
2. If it receives a CTS it sends the Data packet
3. Otherwise it backs off and goes back to step 1. up to a limited number of times
4. Upon receiving a CTS a node sends a Data
5. If the data is acknowledged - > success!
6. Otherwise it goes back to step 1. for up to a limited number of times

- If the limit on the RTS or DATA retries is reached the MAC gives up and drops the packet
- After the successful transmission of a data packet the node has to backoff before transmitting another packet

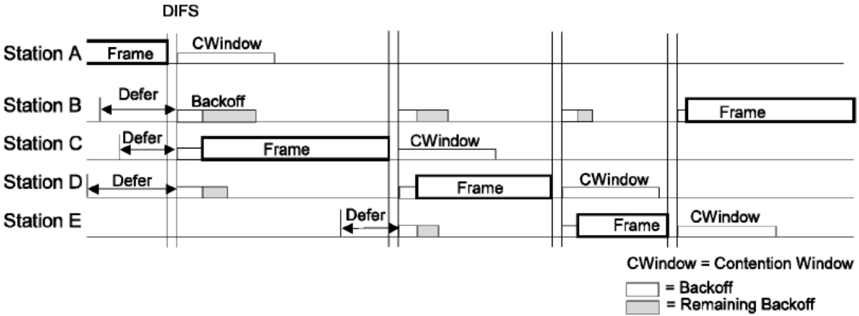
What about Multicast/broadcast?

Backoff in IEEE 802.11

- Backoff Time = Random() x SlotTime
- Random() = Pseudo-random integer drawn from [0,CW], where CWmin ≤ CW ≤ Cwmax
- The CW is initialized at CWMin and is doubled every time there is no CTS for an RTS or there is no ACK for a DATA -> Why?
- Once it reaches CWmax the CW does not increase anymore
- The CW is reset to CWmin after receiving a CTS or ACK or a packet is dropped.



Example of a Backoff Race



1. The node drawing the smallest Contention Window wins the race and gets to transmit first

What about Multicast/broadcast?

QOS IN IEEE 802.11 (WI-FI)

What is QoS ?

- Quality of service is the ability to:

1. Provide ***different*** priorities to different applications, users, or data flows

   or

2. To ***guarantee*** a certain level of performance to a data flow

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- Can IEEE 802.11:

1. Provide different priorities to different applications, users, or data flows ?

2. Guarantee a certain level of performance to a data flow ?

IEEE 802.11e: QoS Amendment

- An approved amendment that defines QoS enhancements through modifications to the MAC layer

- DCF -> Enhanced distributed channel access (EDCA)
  - Use shorter CW counter for higher priority traffic
  - Transmit opportunity (TXOP): a node winning the backoff race is free to transmit frames continuously for a up to a TXOP period
    - No need for a backoff between packet transmissions

IEEE 802.11e Parameters

AC	CWmin	CWmax	AIFSN	Max TXOP
Background (AC_BK)	31	1023	7	0
Best Effort (AC_BE)	31	1023	3	0
Video (AC_VI)	15	31	2	3.008ms
Voice (AC_VO)	7	15	2	1.504ms
Legacy DCF	15	1023	2	0

IEEE 802.11 RATE CONTROL

Wi-Fi PHY

802.11 protocol	Release[1]	Freq. (GHz)	Bandwidth (MHz)	Data rate per stream (Mbit/s)[2]	Allowable MIMO streams	Modulation
—	Jun 1997	2.4	20	1, 2	1	DSSS, FHSS
a	Sep 1999	5	20	6, 9, 12, 18, 24, 36, 48, 54	1	OFDM
		3.7[A]				
b	Sep 1999	2.4	20	1, 2, 5.5, 11	1	DSSS
g	Jun 2003	2.4	20	6, 9, 12, 18, 24, 36, 48, 54	1	OFDM, DSSS
n	Oct 2009	2.4/5	20	7.2, 14.4, 21.7, 28.9, 43.3, 57.8, 65, 72.2[B]	4	OFDM
			40	15, 30, 45, 60, 90, 120, 135, 150[B]		
ac	Dec 2012	5	20	up to 87.6[4]	8	
			40	up to 200[4]		
			80	up to 433.3[4]		
			160	up to 866.7[4]		
ad	~Feb 2014	2.4/5/60		up to 6912 (6.75Gb/s) [5]		

Questions on the PHY

1. Why so many rates?

2. Which rate do the stations use?

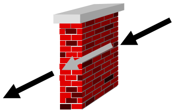
Radio Channel

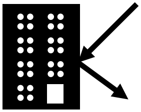
- The radio channel is different
  - Extremely harsh environment compared to "wired" or guided media
  - Channel is time variant because of
    - Movement of people changes reflection
    - Switching off and on of interference
    - Movement of mobile terminals changes the distance
    - Sensitivity to a variety of other factors like "Fading" and "Multipath"

Radio Channel

- Path loss
- Interference
- Shadowing
- Multipath – receiving multiple reflections of the original signal that will interfere with each other
- Interference from other operators on the same frequency (microwaves use the same frequency as wi-fi)

- All of these can change fast when the nodes are mobile!


shadowing


reflection

scattering

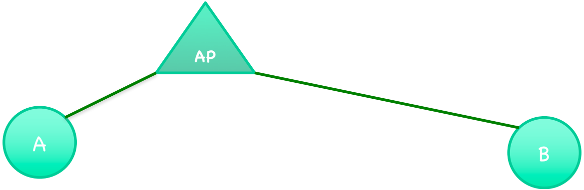

diffraction

Why so many rates in Wi-Fi

- The quality of the signal between any pair of Wi-Fi stations can vary greatly
  - Distance
  - Environment (shadowing, multipath)
- The better the signal the higher a rate can be used

Rate Control

- Problem: The access point wants to transmit to A and B.
  - What rate should it use with A?
  - What rate should it use with B?
- Why is it challenging
  - The AP does not know the conditions of the links to A and B
  - A and B may be moving, which would change the channel conditions and therefore the right bit-rate to use



Auto Rate Fallback (ARF)

- When the ARF algorithm starts for a new destination, it selects the initial bit-rate to be the highest possible bit-rate.
- ARF adjusts the bit-rate for the destination based on the following criteria:
  - Move to the next lowest bit-rate if a packet was dropped (i.e., never ACKed)
  - Move to the next highest bit-rate if 10 successive transmissions have occurred without any retransmissions.
  - Otherwise, continue at the current bit-rate.
- Weakness: only reacts to packet drops not retries!

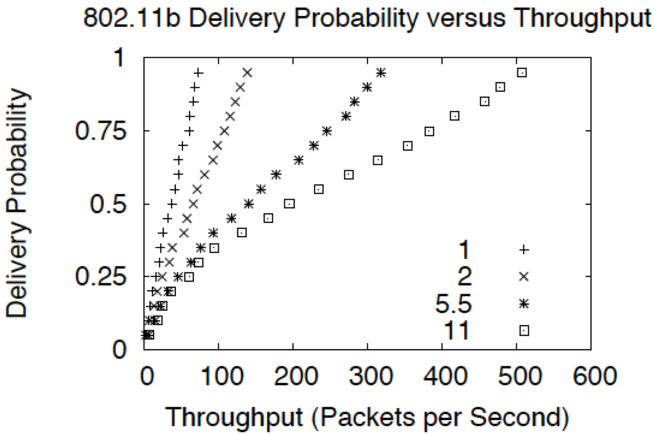
Onoe

- The first open source bit-rate selection algorithm designed to work with 802.11b, 802.11g, and 802.11a devices
- Tries to find the highest bit-rate that has less than 50% loss rate
- For each individual destination, the Onoe algorithm keeps track of the current bit-rate for the link and the number of credits that bit-rate has accumulated
  - It only keeps track of these credits for the current bit-rate and increments the credit if it is performing with very little packet loss
- Once a bit-rate has accumulated a threshold value of credits, Onoe will increase the bit-rate
- If a few error conditions occur, the credits will be reset and the bit-rate will decrease

Onoe

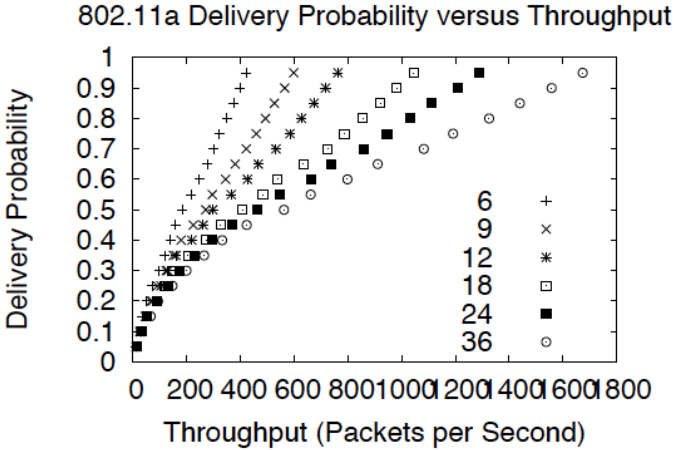
- Initially, set the rate to a destination to the highest. It also sets the number of credits for that bit-rate to 0.
- Periodically (1/sec by defaul) perform the following for every destination
  - Move to the next lower rate if:
    - No packets have succeeded
    - If 10 or more packets have been sent and the average number of retries per packet was greater than one
  - If the current bit-rate has 10 or more credits, increase the bit-rate
    - If more than 10% of the packets needed a retry, decrement the number of credits (minimum 0)
    - If less than 10% of the packets needed a retry, increment the number of credits
  - Otherwise continue at the current rate.

Onoe Performance



- Customized for 802.11b where the throughput of the next lowest bit-rate is usually half the current bit-rate

Onoe Performance



- It won't work well for 802.11a: perfect 24 Mbps is better than 70% 36 Mbps

Onoe Performance

- Onoe is conservative: once it decides a bit-rate will not work, it will not attempt to step up again until at least 10 seconds have gone by
- It can take time to stabilize: It will only step down one bit-rate during each period
  - It can take a few seconds before the Onoe algorithm can send packets if it starts at a bit-rate that is too high for a given link.

Receiver Based Auto-Rate (RBAR)

- Chooses the bit-rate based on SNR measurements at the receiver
- When a receiver gets an RTS packet, it calculates the highest bit-rate that would achieve a BER less than 10^{-5} based on the SNR of the RTS packet
- The receiver piggybacks on the CTS packet the rate the sender should use to send the data packet
- Weakness: It may not be possible to compute the best rate based on the SNR

Opportunistic Auto-Rate (OAR)
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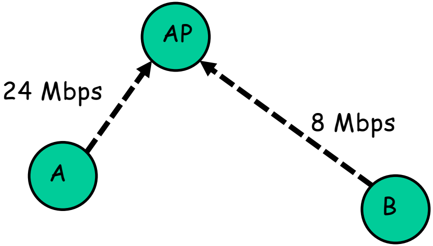
- Approximately, how many Mbps is the AP receiving, on average?



- 32
- 24
- 8
- 12
- 16
- 18

Conditions:
- All stations are using IEEE 802.11 (no QoS)
- A and B transmit as possible as the MAC allows packets of equal size
- AP, A and B are all in each other's range (no hidden terminals)
- Ignore overhead due to bakcoff, RTS/CTS, ACK

Opportunistic Auto-Rate (OAR)

- The intuition behind OAR is that channel coherence times typically exceed multiple packet transmission times
  - By taking advantage of high link qualities when they appear, channel throughput can be increased
- OAR uses the RTS/CTS exchange for rate control purposes (like RBAR)
- Grant each sender the same amount of time in the CTS as the transmission time of a packet at the base rate
  - The sender can send multiple packets at a high bit-rate in the same time that one transmission would take at a lower bit-rate.

SAMPLERATE

Design Principles

- A bit-rate selection algorithm cannot conclude that higher bit-rates will perform poorly just because lower bit-rates perform poorly
- The bit-rate that achieves the most throughput may suffer from a significant amount of loss. Algorithms that only use bit-rates with high delivery probability may not find the bit-rate that achieves the highest throughput
- Link conditions may change. Failing to react to changes in link conditions could result in needlessly low throughput
- A bit-rate selection algorithm that constantly measured the throughput of every bit-rate would likely achieve low throughput.

General Approach

- SampleRate sends data at the bit-rate that has the smallest predicted average packet transmission time, including time required to recover from losses
  - Predicts the estimated packet transmission time by averaging the transmission times of previous packet transmissions at a particular bit-rate

- Periodically send packets at a bit-rate other than the current bit-rate to gather information about other bit-rates

- Reduce the number of bit-rates to sample by eliminating bit-rates that could never send at higher rates than the current bit-rate that is being used.

SampleRate

- Start at the highest possible rate
- Stop using a bit-rate after four successive drops
- Every tenth data packet pick a random bit-rate from the set of bit-rates that *may* do better than the current one and sends the packet using that bit-rate instead of the current one
- A bit-rate is not eligible to be sampled if
  - Four recent successive packets at that bit-rate have been unacknowledged or
  - Its lossless transmission time (without any retries) is greater than the average transmission time of the current bit-rate
  - Calculate the average transmission time over packets that were sent within the last 10 seconds

SampleRate: Example in Practice

Destination	Bit-rate	Tries	Packets Ack'ed	Succ. Fails	Total TX Time	Avg TX Time	Lossless TX Time
00:05:4e:46:97:28	11	16	0	4	250404	∞	1873
00:05:4e:46:97:28	5.5	100	100	0	297600	2976	2976
00:05:4e:46:97:28	2	0	0	0	0	-	6834
00:05:4e:46:97:28	1	0	0	0	0	-	12995
00:0e:84:97:07:50	11	28	14	0	52654	3761	1873
00:0e:84:97:07:50	5.5	50	46	0	148814	3235	2976
00:0e:84:97:07:50	2	0	0	0	0	-	6834
00:0e:84:97:07:50	1	0	0	0	0	-	12995

- Destination **00:05:4e:46:97:28** has the properties that 11 megabits delivers no packets and all packets sent at 5.5 megabits are acknowledged successfully without retries
- The first few packets sent on this link at 11 megabits failed, and once the Successive-Failures column reached 4 it stopped sending packets at 11 megabits. It then proceeded to send 100 packets at 5.5 megabits
- Packets were never sent at 1 or 2 megabits because their lossless transmission time is higher than the average transmission time for 5.5 megabits

SampleRate: Example in Practice

Destination	Bit-rate	Tries	Packets Ack'ed	Succ. Fails	Total TX Time	Avg TX Time	Lossless TX Time
00:05:4e:46:97:28	11	16	0	4	250404	∞	1873
00:05:4e:46:97:28	5.5	100	100	0	297600	2976	2976
00:05:4e:46:97:28	2	0	0	0	0	-	6834
00:05:4e:46:97:28	1	0	0	0	0	-	12995
00:0e:84:97:07:50	11	28	14	0	52654	3761	1873
00:0e:84:97:07:50	5.5	50	46	0	148814	3235	2976
00:0e:84:97:07:50	2	0	0	0	0	-	6834
00:0e:84:97:07:50	1	0	0	0	0	-	12995

- Destination **00:0e:84:97:07:50** has the properties that packets sent at 11 megabits require a retry before being acknowledged, and packets sent at 5.5 megabits require no retries 90% of the time and one retry otherwise.
- SampleRate starts at 11 megabits and then sends the 10th packet at 5.5 megabits
- After the first 5.5 megabit packet required no retries, SampleRate determined that 5.5 megabits is the better rate
- It still sent at 11 megabits once every 10 packets to see if performance has improved at that bit-rate.

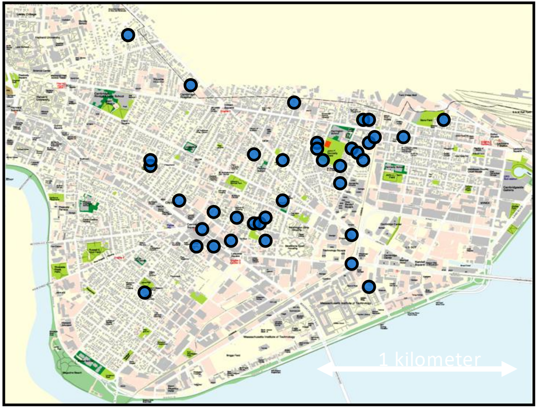
Computing the Transmission Time

Attempt	Average Back-off
1	155
2	315
3	635
4	1275
5	2555
6	5115
7	5115
8	5115

$$tx\_time(b, r, n) = difs + backoff(r) + (r + 1) * (sifs + ack + header + (n * 8/b)$$

b: bit-rate, r: number of retries, n: packet size

Evaluation – RoofNet Project

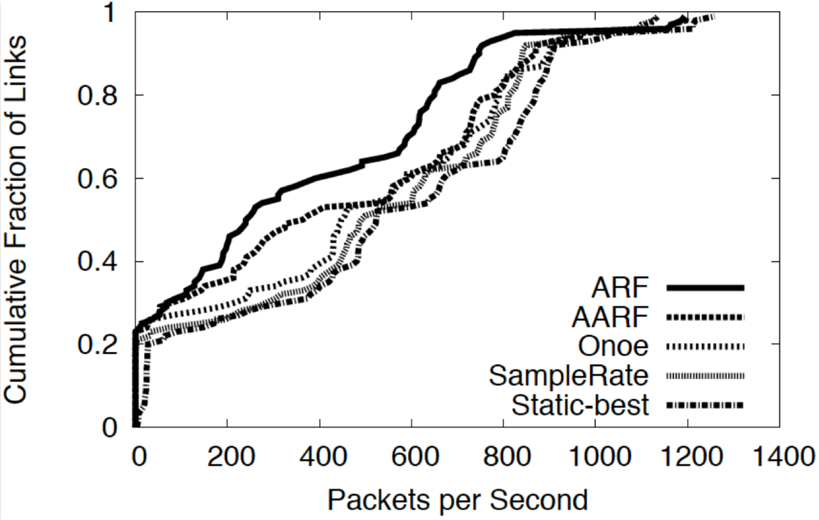


- 38 nodes distributed over 6 km^2
- Each node consists of a PC with an 802.11b card connected to an omni antenna mounted on the roof
  - Intersil Prism 2.5 chip-set
- The cards use 802.11b channel 3 with transmission power +23dBm(200mV)
- The antenna provides 8dBi of gain with 20-degree -3dB vertical beam-width

Evaluation – RoofNet Project

- Each bit-rate selection algorithm runs for 30 sec on every link on the testbed
- During the 30 sec the transmitters sends 1500-byte unicast packets as fast as it could
- To have a basis of comparison, the unicast throughput for each bit-rate was measured over every link
- The maximum throughput achieved for all the bit-rates on a link is referred to as best-static throughput

Evaluation - RoofNet Project



Rate Control

- All the rates control algorithms are for unicast traffic
  - They all require feedback from the receiver

- What about the broadcast traffic?