Chapter 7 Medium Access Control in Cooperative Networks

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Why Multiple Access Control (MAC) Matters

So far we have focused on PHY. In this chapter, we discuss methods for multiple nodes (sources or relays) to access the channel $\Rightarrow$ MAC problem.

Key issues

- How MAC protocols can jointly work with PHY to enable cooperation?
- What are the advantages of cooperation from MAC layer perspective?

MAC parameters

- packet arrivals/departures
- queueing dynamics
- user interactions

Idea of Shared Medium

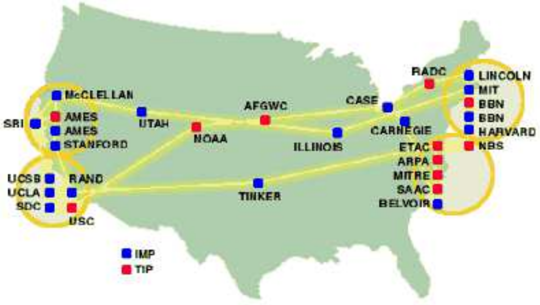


Figure: ARPANET, 1969.

Twenty Minute Pitch

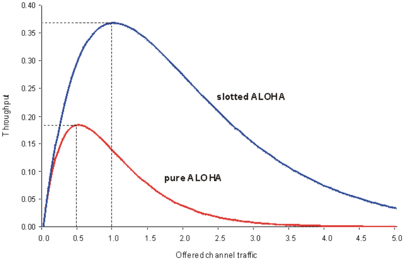
Bob Taylor

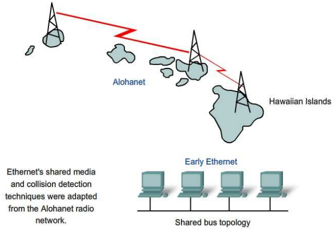
Larry Roberts

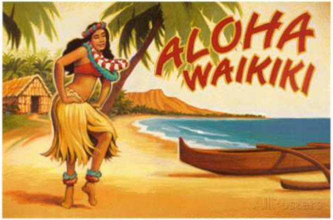
Charles Herzfeld

Taylor's proposal: *Cooperative Network of Time-Sharing Computers*

Surfing the Net







Slotted ALOHA

First wireless local area network - ALOHAnet designed by Norman Abramson, in June, 1971, at the University of Hawaii

- Time is slotted within which one packet is transmitted
- Each user decides whether to transmit in each slot based on the outcome of a local coin toss
- If collided, retry after a certain amount of time
- 9,600 bit/s island-wide over UHF, and 56,000 bit/s to the ARPANET in mainland USA via satellite
- Maximum normalized throughput $= e^{-1} = 0.368$

Spatial diversity can be easily exploited by applying slotted ALOHA in cooperative networks.

In the following, we introduce an improvement over slotted ALOHA based on repetition codes.

Network-Assisted Diversity Multiple Access (NDMA) [1]

Idea: instead of discarding the collided packets as in slotted Aloha, the collided packets are used to extract each individual user packet by leveraging temporal diversity.

System model

- A network with N users (i.e., source nodes) and one Access Point (AP) (i.e., destination node)

NDMA (cont'd)

Each user i attempts a transmission with probability p_i in the time slot whenever it has a packet $\mathbf{x}_i = [x_{i,0}, \cdots, x_{i,L-1}]$ with L symbols to transmit.

$\mathcal{I}[n]$: a set of users transmitting in the n-th slot. Let $|\mathcal{I}[n]| = K$. The received signal at AP:

$$\mathbf{y}[n] = \sum_{i \in \mathcal{I}[n]} \alpha_i[n]\mathbf{x}_i[n] + \mathbf{w}[n] \tag{1}$$

assuming the channel remains constant throughout each time slot but varies independently from slot to slot.

Can we separate packets of different users?

- MIMO theory: Yes, if we use $\hat{K}$ ($\hat{K} \geq K$) antennas to create $\hat{K}$ diversity paths (e.g., using $\hat{K}$ antennas).
- Can we create the necessary diversity without multiple antennas?

NDMA (cont'd)

Answer: Yes, it is possible to do so at the *protocol layer*.

Idea: The AP requests users in $\mathcal{I}$ to retransmit their data in the following $\hat{K}-1$ slots (so that the same data is repeated $\hat{K}$ times).

Assume the AP collects $\hat{K}$ copies of the collided packets as

$$\mathbf{Y} = \left[\mathbf{y}[n], \mathbf{y}[n+1], \cdots, \mathbf{y}[n+\hat{K}-1]\right]^T = \mathbf{H}\mathbf{X} + \mathbf{W}$$

where

$$\mathbf{H}_{\hat{K}\times K} = \begin{bmatrix} \alpha_{i_1}[n] & \cdots & \alpha_{i_K}[n] \\ \vdots & \cdots & \vdots \\ \alpha_{i_1}[n+\hat{K}-1] & \cdots & \alpha_{i_K}[n+\hat{K}-1] \end{bmatrix}$$

$$\mathbf{X}_{K\times L} = \left[\mathbf{x}_{i_1}[n], \cdots, \mathbf{x}_{i_K}[n]\right], \mathbf{W}_{\hat{K}\times L} = \left[\mathbf{w}_{i_1}[n], \cdots, \mathbf{w}_{\hat{K}}[n]\right]$$

NDMA (cont'd)

Given $\mathbf{H}$, estimate $\mathbf{X}$ based on $\mathbf{Y}$ using ML detector

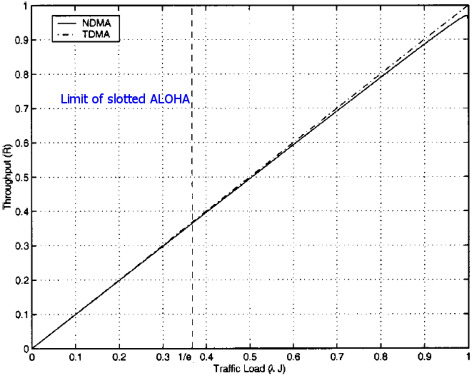
$$\arg\min_{\mathbf{X}} \|\mathbf{Y} - \mathbf{HX}\|_F^2 .$$

Less practically interesting because of exponentially increasing complexity with number of colliding users

Suboptimal linear receiver: $\hat{\mathbf{X}} = \mathbf{YH}^{-1}$

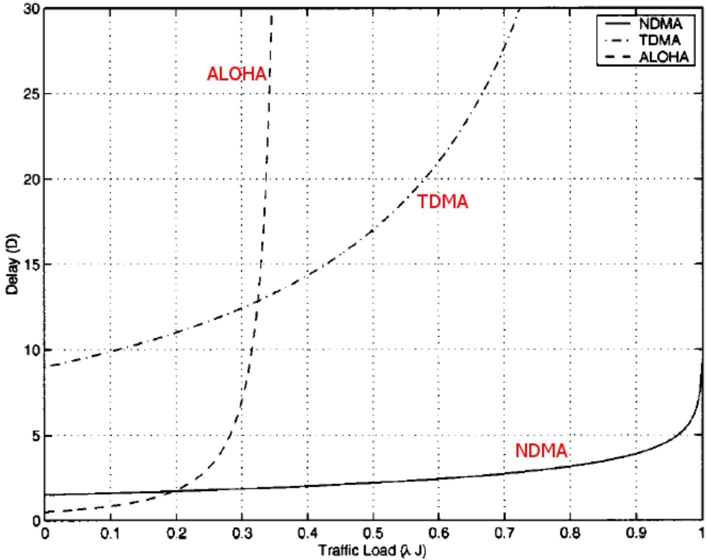
In a noiseless environment (ignoring $\mathbf{W}$) and with a full-rank $\mathbf{H}$, $\hat{K} = K$ is sufficient (no slot is wasted).

NDMA- throughput



- TDMA: assume infinite buffer.
- Slotted Aloha: max throughput $= e^{-1}$.

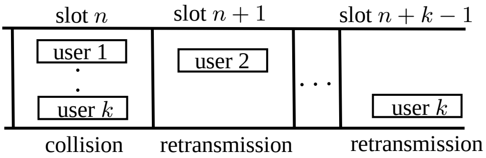
NDMA- average delay



NDMA (cont'd)

Implementation issues

- Users must be aware of collisions: each user transmits a unique signature sequence along with data packet that allows the AP to estimate $\mathcal{I}[n]$ by a bank of matched filters and then broadcasts the result.
- The parameter $\hat{K}$ can be chosen according to the delay tolerance, propagation conditions, and the desired reliability.
- If a certain control channel is available, the following protocol can simplifies the decoding complexity



Enhancements to NDMA with Relaying (NDMAr)

Some shortcomings of NDMA

- not able to overcome large-scale fading
- ineffective in slowly varying channels

Improvement over NDMA: leveraging spatial diversity by having another user forward the collided signal [2]

Recall (1) the received signal in the n-th slot at AP

$$\mathbf{y}_d[n] = \sum_{i \in \mathcal{I}[n]} \alpha_{s_i,d}[n]\mathbf{x}_i[n] + \mathbf{w}_d[n]$$

A set of users serves as relays in slot n denoted by $\mathcal{R}[n]$. The received signal at relay $r \in \mathcal{R}[n]$ is

$$\mathbf{y}_r[n] = \sum_{i \in \mathcal{I}[n]} \alpha_{s_i,r}[n]\mathbf{x}_i[n] + \mathbf{w}_r[n]$$

NDMAr (cont'd)

Let $|\mathcal{I}[n]| = K$, and use $\hat{K} - 1$ retransmissions to resolve collisions.

$(n + j)$-th slot: choose a node r from $\mathcal{I}[n]$ or $\mathcal{R}[n]$ for retransmission

- $r \in \mathcal{I}[n]$: retransmits its own packet
- $r \in \mathcal{R}[n] \backslash \mathcal{I}[n]$: perform AF (why AF?)

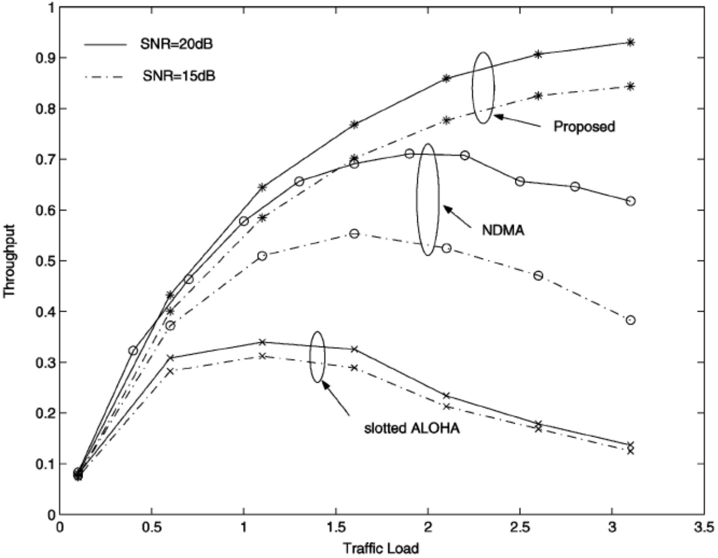
The received signal at AP in the $(n + j)$-th slot

$$\begin{aligned} \mathbf{y}_d[n+j] &= \begin{cases} \alpha_{r,d}[n+j]\mathbf{x}_r[n] + \mathbf{w}_d[n+j], & \text{if } r \in \mathcal{I}[n] \\ \alpha_{r,d}[n+j]G[n+j]\mathbf{y}_r[n] + \mathbf{w}_d[n+j], & \text{if } r \in \mathcal{R}[n] \backslash \mathcal{I}[n] \end{cases} \\ &= \mathbf{HX} + \mathbf{W} \end{aligned}$$

where $G[n + j]$ is the amplifying gain, $\mathbf{w}_d[n + j]$ is the noise vector.

NDMAr- throughput

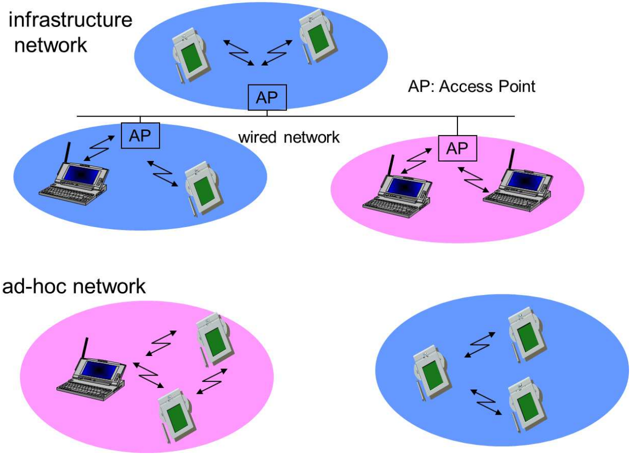
32 nodes



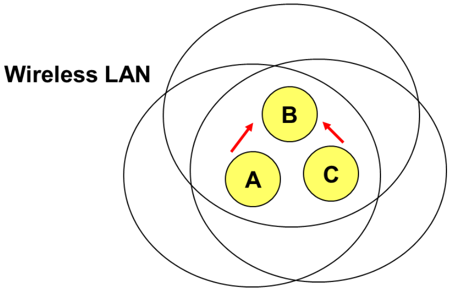
Cooperation in WLAN

The concept of "cooperation" can be incorporated in practical WLANs, where multiple nodes share the same channel without coordination.

Each node first *listens* ro the channel before *talking*.



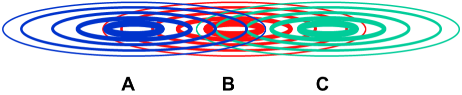
Problems in WLANs: Hidden/Exposed Terminals



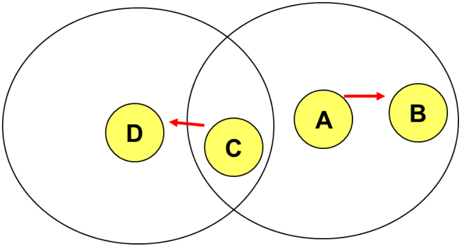
- If both A and C sense the channel to be idle at the same time, they send at the same time.
- Collision can be detected at sender in fixed LANs.
- Half-duplex radios in wireless cannot detect collision at sender.

Problems in WLANs (cont'd)

Hidden terminal problems



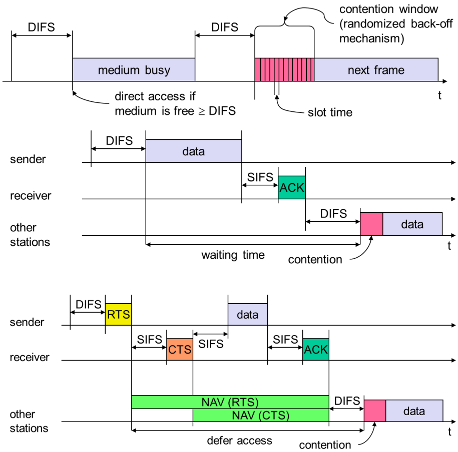
Exposed terminal problems



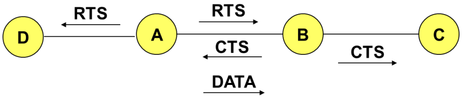
Solution to Hidden/Exposed Terminals

WLAN standard IEEE 802.11 uses two approaches

- CSMA/CA (mandatory): collision avoidance via randomized back-off
- RTS/CTS (optional): avoid hidden/exposed terminal problem



Solution to Hidden/Exposed Terminals

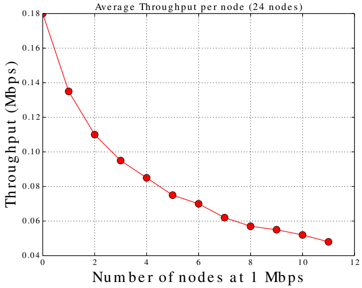


- A first sends a *Request-to-Send (RTS)* to B
- On receiving RTS, B responds *Clear-to-Send (CTS)*
- Hidden node C overhears CTS and keeps quiet
  - Transfer duration is included in both RTS and CTS
- Exposed node overhears a RTS but not the CTS
  - D's transmission cannot interfere at B

Problems in WLANs: Low Rate Stations

- 802.11 supports multiple data rates.
- Low rate stations occupy channel, degrading overall throughput.

Data Rate	Code Length	Modulation	Symbol Rate	Bits/Symbol
1 Mbps	11 (Barker Sequence)	BPSK	1 MSps	1
2 Mbps	11 (Barker Sequence)	QPSK	1 MSps	2
5.5 Mbps	8 (CCK)	QPSK	1.375 MSps	4
11 Mbps	8 (CCK)	QPSK	1.375 MSps	8



CoopMAC

Idea: let high rate stations assist low rate stations [3]

- low rate stations keep tracking potential helpers via a table

ID	Time	$R_{h,d}$	$R_{s,h}$	NumOfFailure

  - ID: MAC address of helper $h \in [1, \cdots, N]$
  - Time: Time the last packet heard from helper h
  - $R_{h,d}$: Tx rate from helper h to D
  - $R_{s,h}$: Tx rate from helper D to h
  - NumofFailure: Count for sequential Tx failures of helper h
- A station satisfying $\frac{1}{R_{sh}} + \frac{1}{R_{hd}} > \frac{1}{R_{sd}}$ becomes a helper.
- NumOfFailure > 3: remove from the table
- The station with the minimum Time value is chosen first
- Either direct or two-hop transmission whichever minimizes total transmission time.

CoopMAC: RTS/CTS Mode

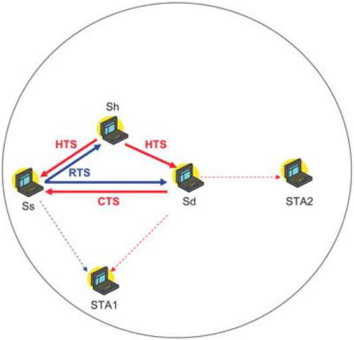


Figure: Control frame exchange

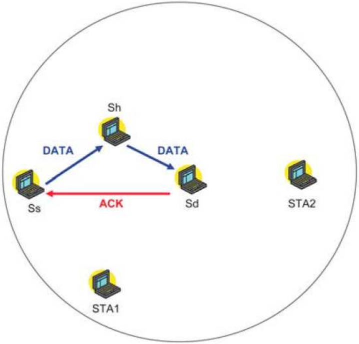
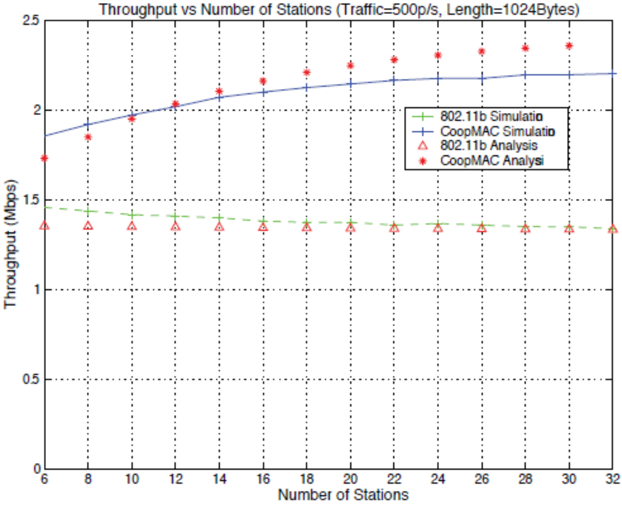
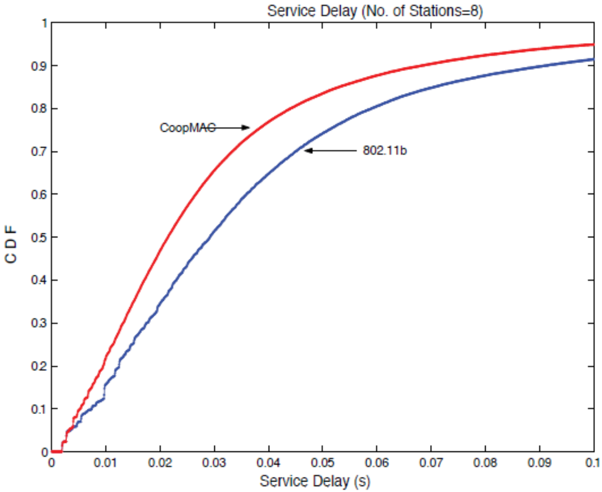


Figure: Data frame exchange

CoopMAC: Throughput



CoopMAC: Delay



Timer-based Distributed Cooperation

We have introduced a family of time-orthogonal cooperative relaying protocols: OR, and CoopMAC.

Without centralized coordination, random backoff has been used to allow distributed channel access.

- OR uses a continuous-time backoff timer based on CSI
- CoopMAC users a discrete-time backoff timer

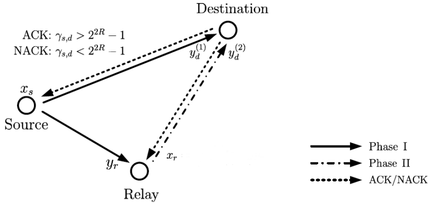
In the following, we introduce another example of realizing distributed cooperation.

Incremental Relaying (IR)

In Chapter 4, we have seen that full diversity order of two can be achieved if signals received in both Phase I and Phase II are combined for detection at the destination.

However, basic AF and DF schemes is bandwidth inefficient, compared to direct transmission, since the same information is repeated over two slots.

Idea of IR: If the direction link is good enough, then do not need to activate relays in Phase II $\Rightarrow$ saving bandwidth consumption.



How do relays know if they should help or not? $\Rightarrow$ 1-bit feedback can do.

IR (cont'd)

System Model: A single S-D pair with the aid of a set of AF relays $\mathcal{R} = \{R_1, \cdots, R_M\}$. TDMA is used to achieve orthogonal transmissions.

1) If D is able to successfully receive the source signal in phase I, D will broadcast an acknowledgement (ACK) message to inform S and R of this success, which occurs when

$$\frac{1}{2}\log_2(1+\gamma_0) \geq \mathtt{R}.$$

2) If direct transmission fails, D will broadcast a negative acknowledge (NACK) message to inform both S and R of this failure, and R is activated in phase II. Assuming VAF, the effective SNR at the output of the MRC is $\gamma_0 + \gamma_{\textsf{eq}}^{\textsf{VAF}}$ with $\gamma_{\textsf{eq}}^{\textsf{VAF}}$ given by Eq. (6) (page 14, Ch. 4).

$$\begin{aligned} P_{out} &= \Pr[\log_2(1+\gamma_0) < \mathtt{R}] \Pr[\frac{1}{2}\log(1+\gamma_0+\gamma_{\textsf{eq}}^{\textsf{VAF}}) < \mathtt{R} \,\Big|\, \log_2(1+\gamma_0) < \mathtt{R}] \\ &= \Pr[\frac{1}{2}\log(1+\gamma_0+\gamma_{\textsf{eq}}^{\textsf{VAF}}) < \mathtt{R}], \qquad (2) \end{aligned}$$

which is the same result as VAF with diversity combining (Eq. (11), page 20, Ch. 4).

Rate Improvement of IR

The transmission rate of IR varies depending on the quality of the direct link.

If $\gamma_0 \geq 2^{\mathtt{R}} - 1$, the transmission rate can reach $\mathtt{R}$. Otherwise, it is reduced to $\mathtt{R}/2$. Hence, the average transmission rate is

$$\begin{aligned}
\bar{\mathtt{R}} &= \mathtt{R} \cdot \Pr[\gamma_0 \geq 2^{\mathtt{R}} - 1] + \frac{\mathtt{R}}{2} \cdot \Pr[\gamma_0 < 2^{\mathtt{R}} - 1] \\
&= \mathtt{R} \cdot \Pr[\alpha_0^2 \geq \frac{2^{\mathtt{R}} - 1}{\mathtt{SNR}}] + \frac{\mathtt{R}}{2} \cdot \Pr[\alpha_0^2 < \frac{2^{\mathtt{R}} - 1}{\mathtt{SNR}}] \\
&= \mathtt{R} \cdot \exp\left(-\frac{2^{\mathtt{R}} - 1}{\mathtt{SNR}\sigma_0^2}\right) + \frac{\mathtt{R}}{2} \cdot \left[1 - \exp\left(-\frac{2^{\mathtt{R}} - 1}{\mathtt{SNR}\sigma_0^2}\right)\right] \\
&= \frac{\mathtt{R}}{2}\Big[1 + \exp\big(-\frac{2^{\mathtt{R}} - 1}{\mathtt{SNR}\sigma_0^2}\big)\Big]. \qquad (3)
\end{aligned}$$

Comparing with the basic AF schemes, the transmission rate of IR is increased by a factor of $\exp\big(-\frac{2^{\mathtt{R}}-1}{\mathtt{SNR}\sigma_0^2}\big)$.

Problem: If multiple relays are eligible to help, using all of them to repeat the source message is fairly inefficient.

Time-Orthogonal IR with Distributed MAC

Idea: Instead of calling all relays for help, activate those relays with a stronger end-to-end channel quality than the direct link only

- r_i is activated if $\min(\gamma_{s,r_i}, \gamma_{r_i,d}) \geq \gamma_{s,d}$.
  - γ_{s,r_i} can be learned from source broadcasting
  - $\gamma_{r_i,d}$ can be learned from `NACK`.
  - $\gamma_{s,d}$ needs to be inserted in `NACK` (how to send a continuous number using finite bits?).
- Adaptive nature: more relays will be invoked to assist source transmission when the s-d channel is weaker.

Quantized Feedback

To reduce the feedback load, use the quantized $\gamma_{s,d}$ instead of the real value.

Using L quantization levels results in additional overhead of $\lceil \log_2 L \rceil$ bits only.

Given $\gamma_{s,d} \in [q_l, q_{l+1})$, $l = 0, \cdots, L-1$, relay decision on cooperation is

$$\min(\gamma_{s,r_i}, \gamma_{r_i,d}) := \gamma_{\mathsf{eq},i} \geq q_l. \tag{4}$$

Only those relays satisfying (4) would participate in cooperation. Defined the *forwarding* set as

$$\mathcal{F}_l = \{r_i \in \mathcal{R} : \gamma_{\mathsf{eq},i} \geq q_l\}.$$

When $\mathcal{F}_l \neq \emptyset$, cooperative relaying can be performed by either a single best relay or multiple relays.

Two Variants of Distributed IR [4]

Selective IR (S-IR)

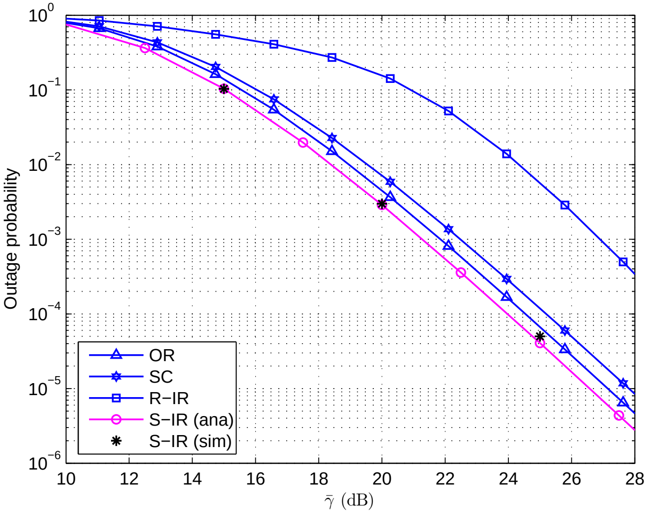
- relay r_i in $\mathcal{F}_l$ sets a backoff timer $\delta_i = \frac{1}{\gamma_{\text{eq},i}}$
- Bandwidth efficient because only one best relay is used
- Continuous-time backoff timer $\Rightarrow$ unbounded delay

Randomized IR (R-IR)

- Each relay sets a backoff timer uniformly selected from $[0, CW]$, where CW is the contention window size.
- Use as many relays as possible until success
- Discrete-time back off timer $\Rightarrow$ bounded backoff delay, but collisions might occur
- Indicate "collision" or "decoding failure" in NACK
  - Collided relays keep activated
  - Deactivate transmitted relays that do not yield successful decoding

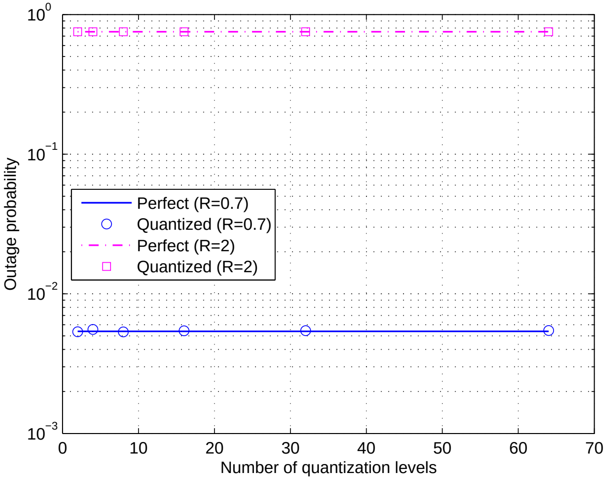
Outage Performance

$\mathtt{R} = 2$ b/s/Hz.



Impact of Quantization Levels

$M = 3$, $\bar{\gamma} = 10$ dB



Delay Performance

$M = 10$, $\mathtt{R} = 0.7$ b/s/Hz

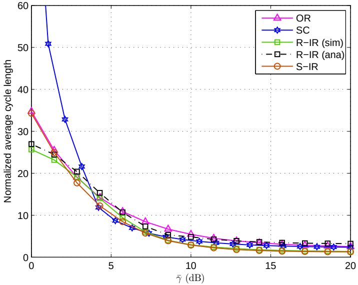


Figure: Mean.

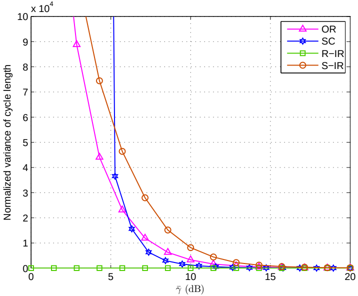
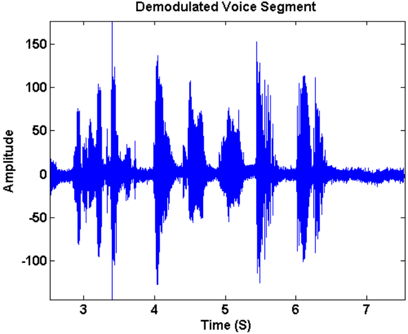


Figure: Variance.

Content-aware Cooperative Multiple Access

In previous chapters, relays are used to assist source transmission without considering the characteristics of source data.

Speech sources are characterized by periods of silence in between talk spurts.

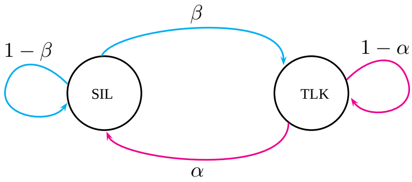


Idea: The **On-Off** pattern of voice signal can be used to increase network capacity and cooperation efficiency.

System Model

Speech source model

A continuous-time Markov chain with two states: talk (TLK) and silence (SIL).

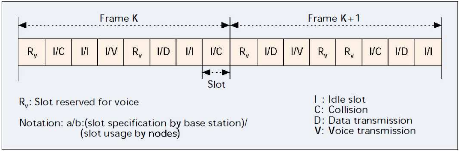


Steady-state probabilities:

$$p_{\mathsf{SIL}} = \frac{\alpha}{\alpha+\beta}, \quad p_{\mathsf{TLK}} = \frac{\beta}{\alpha+\beta}$$

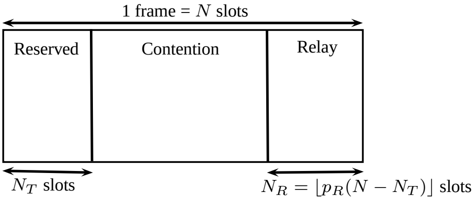
Packet reservation multiple access (PRMA)

The best known MAC protocol considering the traffic characteristics of packet speech



- Combining TDMA and slotted ALOHA
- Time is divided into *slots* as the transmission unit
- Several slots form a scheduling unit called *frame*
- User classified in two types
  - Voice user: contend for slots and reserve slots only for calls in a talk spurt
  - Data user: contend for every slot it would like to use
- Unstable when a large number of nodes are contending and a large number of slots are reserved $\Rightarrow$ little bandwidth is left for contention
- Solution: separate the request and data channels.

C-PRMA



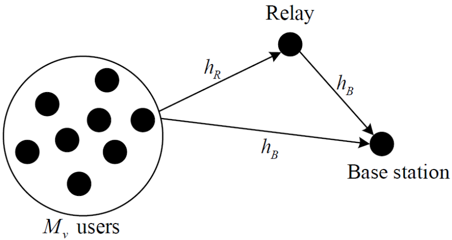
To incorporate relay operation, modify the frame structure as follows [5]

- N_T out of N slots are reserved for talking users
- In the remaining $N - N_T$ slots, a fraction p_R is assigned to the relay and the rest is available for contention.
- The parameter p_R determines the tradeoff between the amount of help from the relay to the existing users and the ability to admit new users.

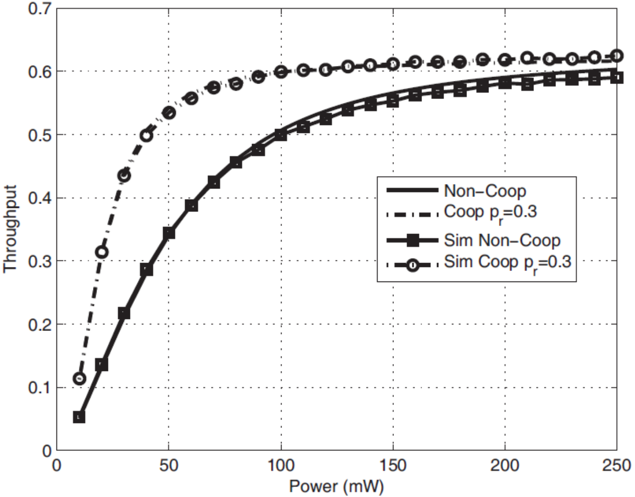
Performance of C-PRMA

Simulation setting

- $N = 10$ slots per frame
- Mean talk spurt $t_1 = 1$ s and mean silence period $t_2 = 1.35$ s.
- 25 users, one relay performs incremental DF
- $d_{sd} = 100$ m, $d_{sr} = 50$ m, pathloss exponent of 3.7

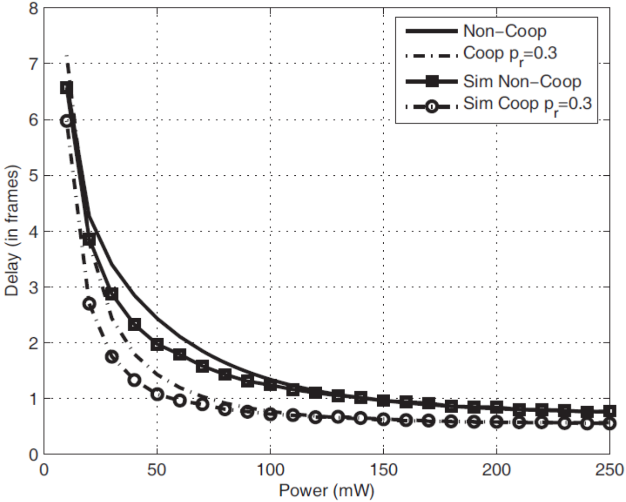


Performance of C-PRMA (cont'd)



At 100 mW of power level, cooperative throughput with $p_R = 0.3$ improves throughput by 128%

Performance of C-PRMA (cont'd)



- At low power level, delay is dominated by outage probability
- At high power level, delay is primarily caused by failed contention

Performance of C-PRMA (cont'd)

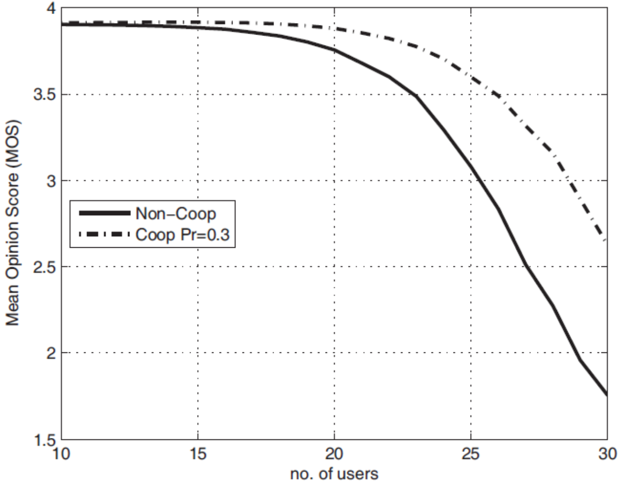
Subjective voice quality: how the speech is subjectively perceived at the receiver

Mean opinion score (MOS) test: a group of listeners are polled to grade a number of speech sequences.

ITU-T PESQ quality measure standard: from 1 (bad quality) to 5 (excellent quality)

MOS	Quality	Impairment
5	Excellent	Imperceptible
4	Good	Perceptible but not annoying
3	Fair	Slightly annoying
2	Poor	Annoying
1	Bad	Very annoying

Performance of C-PRMA (cont'd)



GSM AMR voice codec with coding rate 12.2 kbps (MOS=4.14)

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