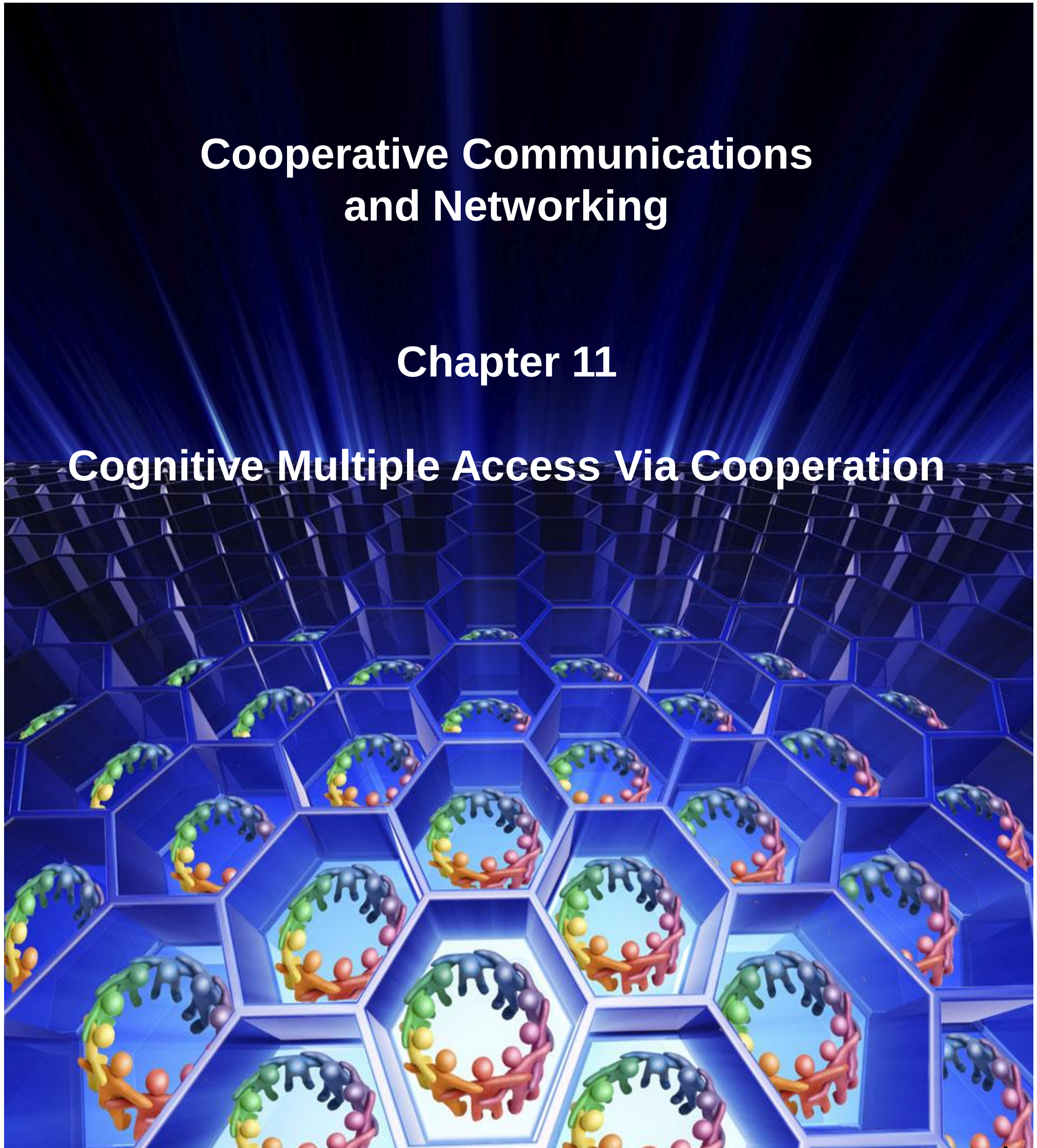
Cooperative Communications and Networking

Chapter 11

Cognitive Multiple Access Via Cooperation



Preview

- Motivations and Background
- Cooperative Cognitive Multiple Access (CCMA) Protocols
- Stability Analysis
- Delay Analysis
- Conclusion

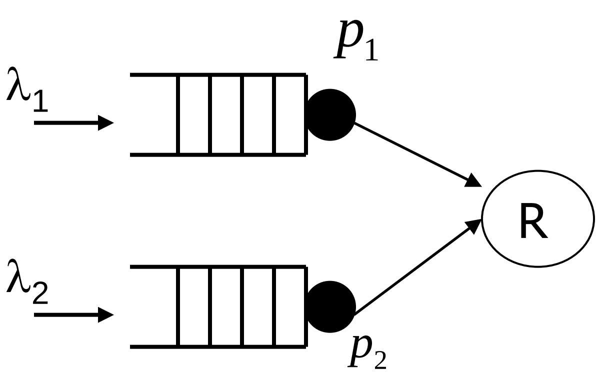
- Motivations, Background, and the Protocols

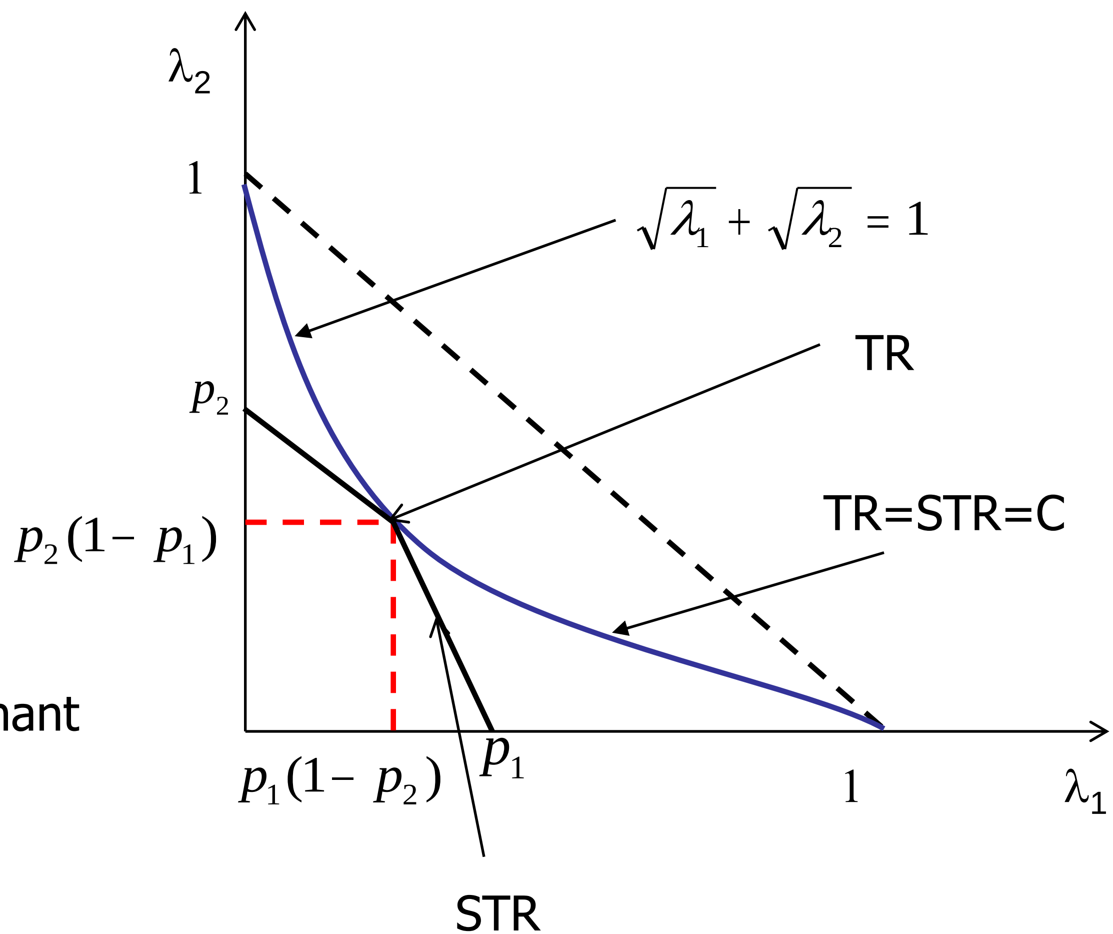
Background

- Important performance measures
  - At the PHY layer,
    - Capacity Region (bits/s) (reliable communication limits)-**C**
  - At the MAC layer,
    - Maximum Throughput Region (packets/slot) (saturated queues)-**TR**
    - Maximum <u>Stable</u> Throughput Region (packets/slot) (finite delays)-**STR**

Background

- Example: 2-users in random access collision channel



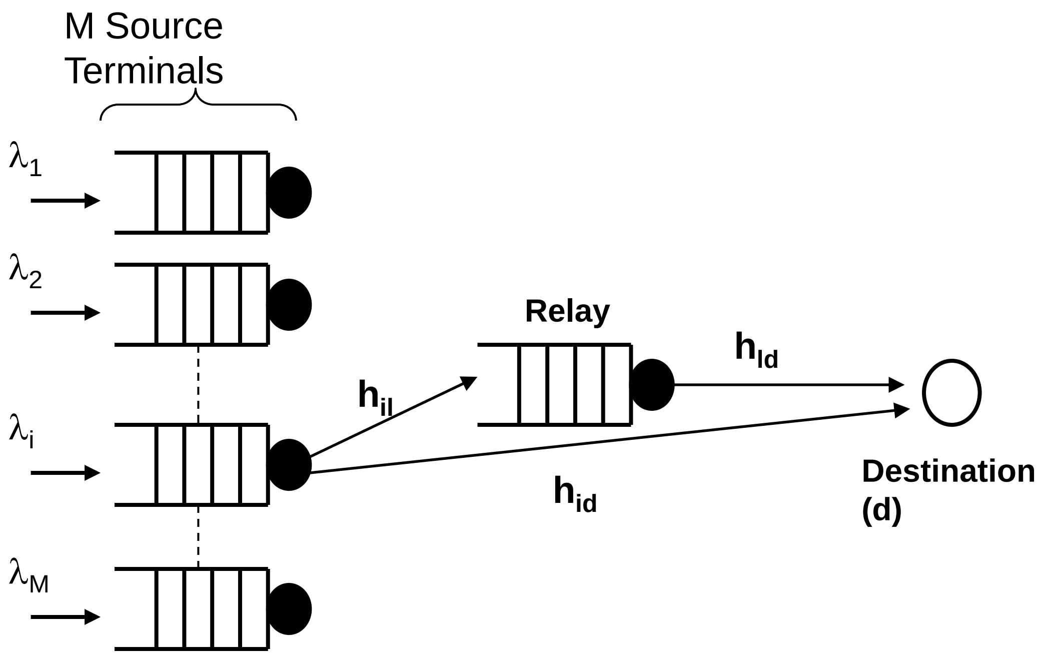


•Interacting Queues-Dominant Systems

Motivations

- "*Cooperation in a Network can occur at different levels*"!
  - Most of previous work on cooperation focused on PHY layer issues such as capacity regions and diversity-gains and so on.
  - Can we leverage cooperation to improve MAC performance?
  - In a network layer, source burstiness and the stability of the queueing system need to be considered.

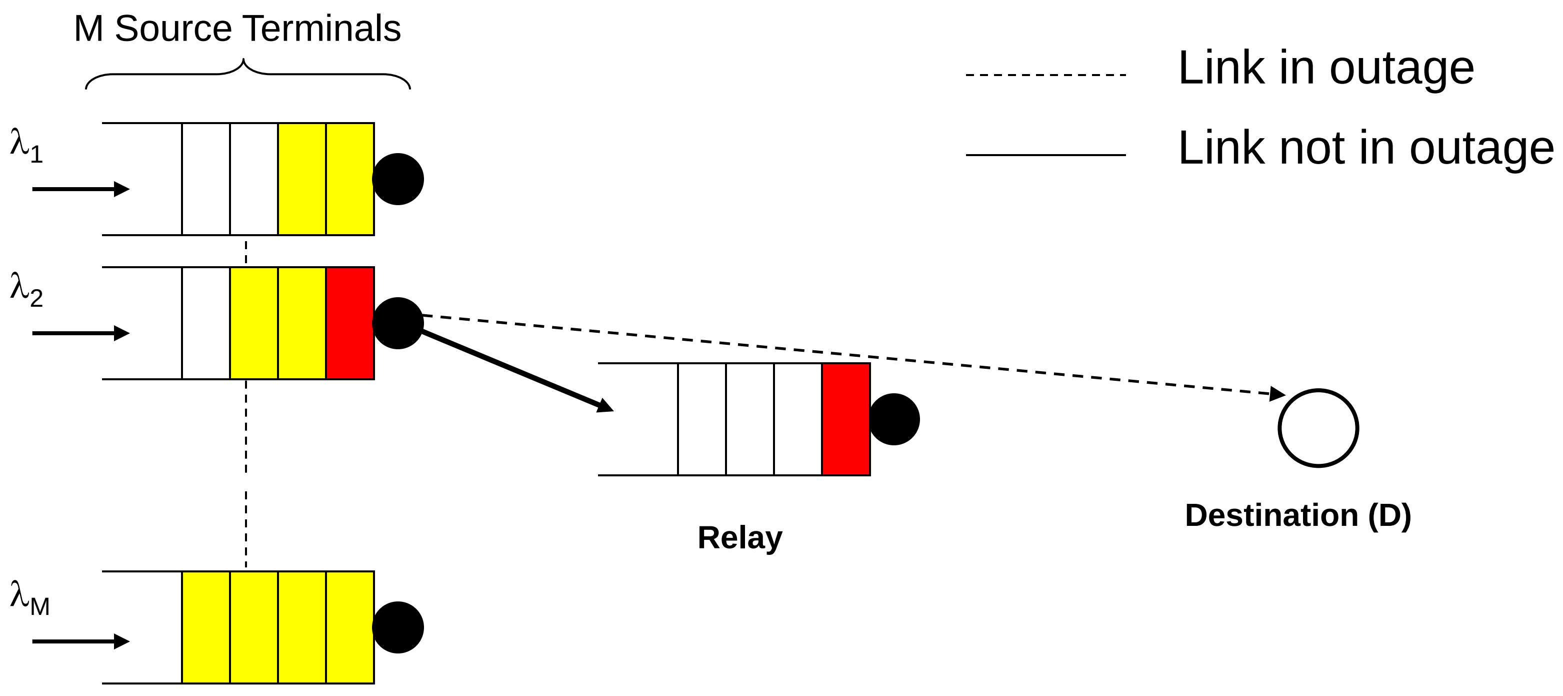
System Model



- TDMA underlying structure (ω_i): i^{th}-user's portion (interference-free)
- Success if SNR>β
- Assumptions
  - Channel sensing is possible
  - Feedback ACK is perfect

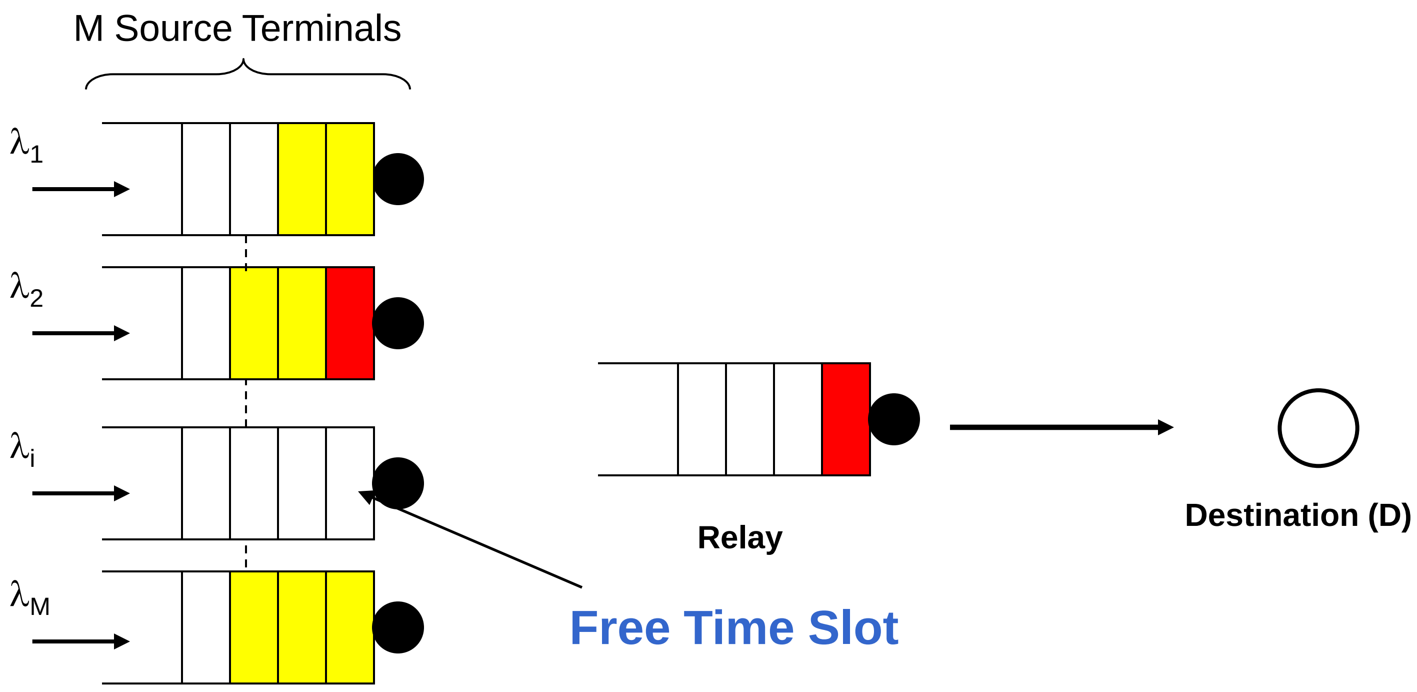
Objective: Exploit the capabilities of the relay

CCMA-S (1)



- Each terminal transmits a packet in its assigned slot (if empty, slot is free)
- If D receives successfully, it sends ACK (heard by the relay and the user)
- If not, relay stores the packet if received successfully
- Note that the user does NOT remove the packet from his queue.

CCMA-S (2)



- If the relay senses an empty time slot, it transmits the packet
- The packet is kept in the relay’s queue for only M consecutive time slots
- The responsibility of delivering a packet is in the corresponding user

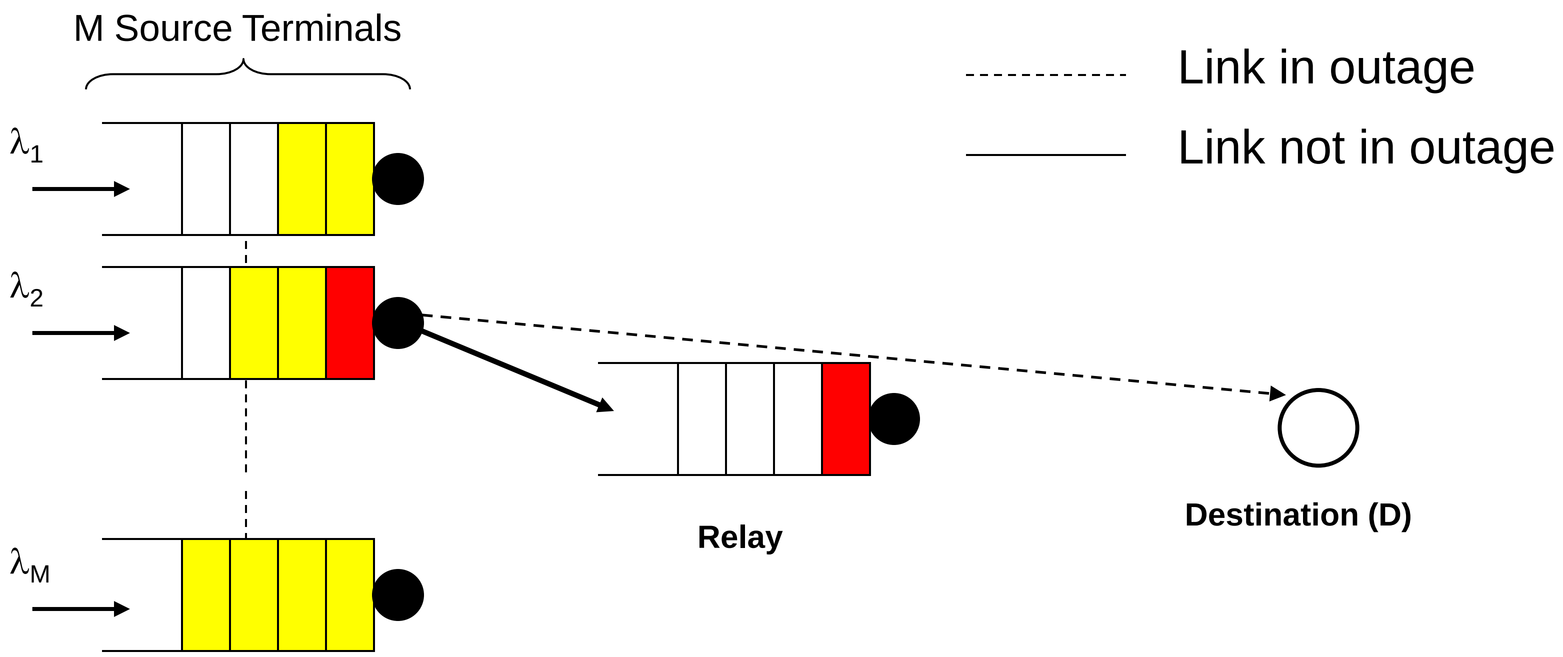
CCMA-S (3)

1. Relay has always a finite queue (M packets Max)
2. Successful service of a packet in a frame depends on whether the other terminals are idle or not
3. Individual terminals interact

Idle slots are utilized!

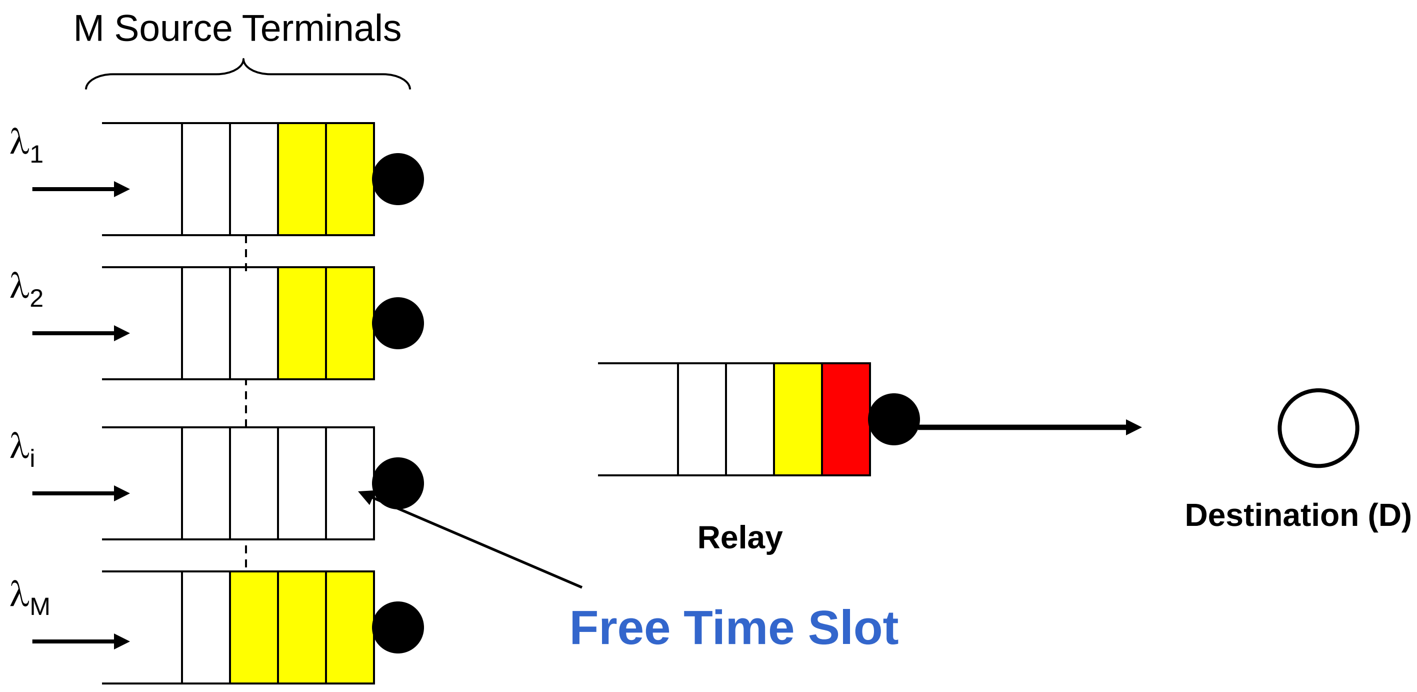
Stable throughput for the M terminals

CCMA-M (1)



- Each terminal transmits a packet in its assigned slot (if empty, slot is free)
- If D receives successfully, it sends ACK (heard by the relay and the user)
- If not, relay stores the packet if received successfully
- Note that the user DOES remove the packet from his queue, if either D or the relay receives it

CCMA-M (2)



- If the relay senses an empty time slot, it transmits the packet
- Now the relay is responsible for delivering the packet

CCMA-M (3)

1. Relay has a possibly growing queue
2. Individual terminals do not interact
3. They release the unsuccessful packets to the relay
4. Enhanced version: Relay retransmits only packets of terminals with inferior channels

Again: Idle slots are utilized!

Stable throughput for the M terminals and the Relay

-**Performance Analysis**

- -**Stability Analysis**
- -**Delay Analysis**

Stability Analysis: CCMA-S (2-users case)

- "*Note that the queues are interacting*"!
- Decouple the interaction of the queues by introducing the dominant system [Rao88]
  - The queues in the dominant system stochastically dominate the queues in the original systems.
  - Define the dominant system $S_j, j \in \{1, 2\}$ as
    - S_j and CCMA-S are identical, except that, the packets successfully transmitted by the relay for user *j* are not removed form user *j*'s queue.

[Rao88] R. Rao and A. Ephremides, "On the stability of interacting queues in a multiple-access system", IEEE Transactions on Information Theory, Vol. 34, No. 5, Sep. 1988

Stability Analysis: CCMA-S (2-users case)

- Consider system S_1 (relay only helps user 2),
  - Queue dynamics: $Q_i^{t+1}(S_1) = \left(Q_i^t(S_1) - Y_i^t(S_1)\right)^+ + X_i^t(S_1)$
  - For user 1 (identical with TDMA system),

$$Y_1^t(S_1) = 1[A_1^t \cap \overline{O_{1,d}^t}] \to \lambda_1 < \omega_1 f_{1d}.$$

  - For user 2,

$$Y_2^t(S_1) = 1[A_2^t \cap \overline{O_{2,d}^t}] + 1[A_1^t \cap \{Q_1^t(S_1) = 0\} \cap A_2^{t-1} \cap \overline{O_{2,l}^{t-1}} \cap O_{2,d}^{t-1} \cap \overline{O_{l,d}^t}],$$

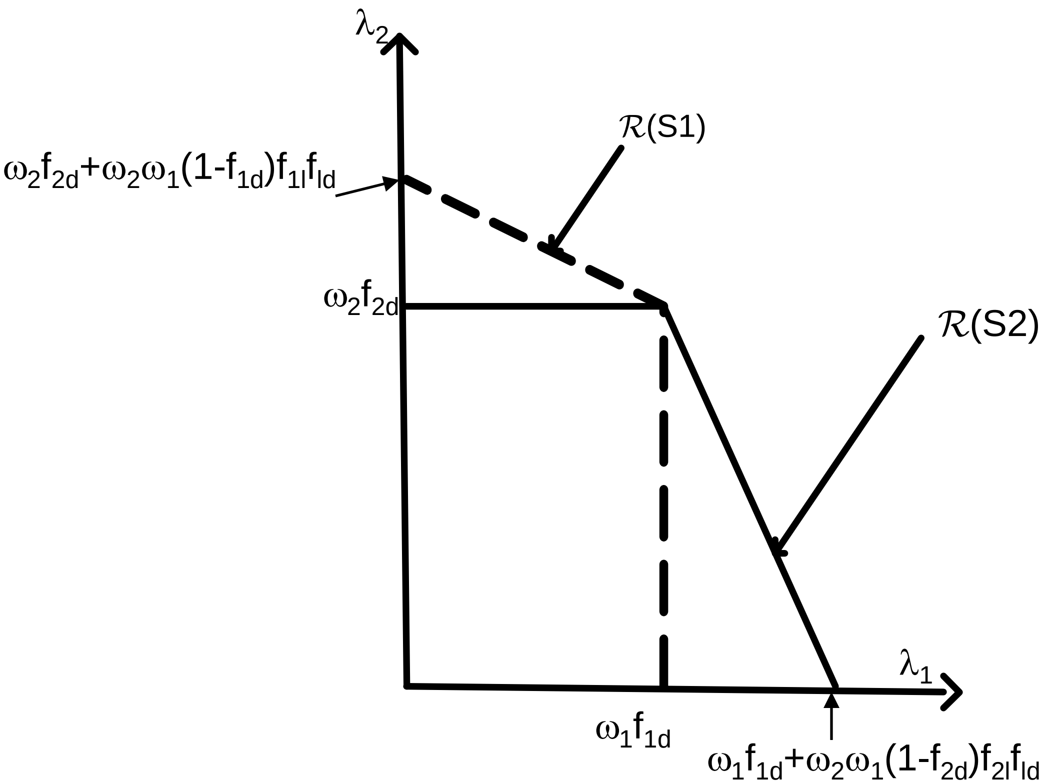
$$\lambda_2 < \omega_2 f_{2d} + \omega_1 \omega_2 \left(1 - \frac{\lambda_1}{\omega_1 f_{1d}}\right)(1 - f_{2d}) f_{2l} f_{ld}.$$

  - Denote the region specified by the above inequalities as $\mathrm{R}(S_1)$ and $\mathrm{R}(S_2)$ can be similarly obtained by considering dominant system S_2 .

Stability Analysis: CCMA-S (2-users case)

- Stability region at a fixed resource sharing vector:

$$\mathrm{R}_{\Omega}(\text{CCMA-S}) = \mathrm{R}(S_1) \bigcup \mathrm{R}(S_2), \Omega = [\omega_1, \omega_2].$$



Stability Analysis: CCMA-S (2-users case)

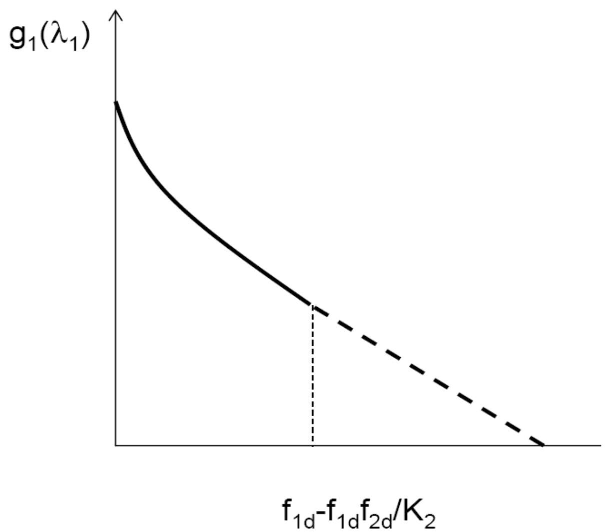
- The whole stability region can be found by

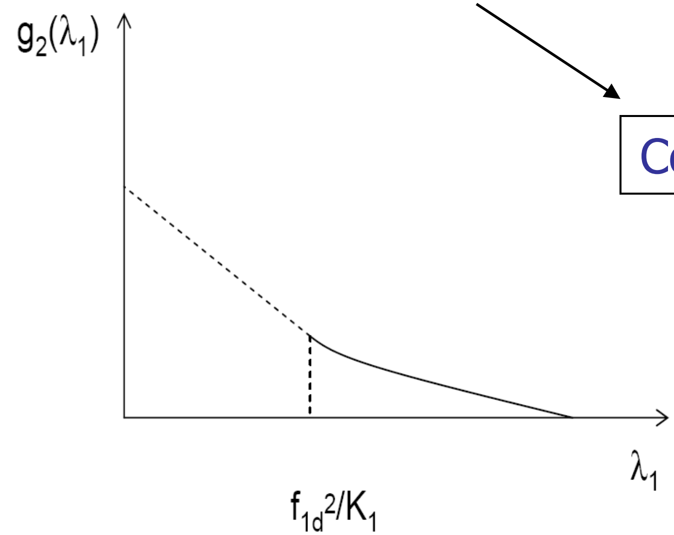
$$\mathcal{R}(\text{CCMA-S}) = \bigcup_{\vec{\omega}\in \mathrm{F}} \{\mathcal{R}(S_1) \cup \mathcal{R}(S_2)\},$$

- And is specified as

$$\mathcal{R}(\text{CCMA-S}) = \{[\lambda_1, \lambda_2] \in R_+^2 : \lambda_2 < \underbrace{\max[g_1(\lambda_1), g_2(\lambda_1)]}\}.$$

Convex!

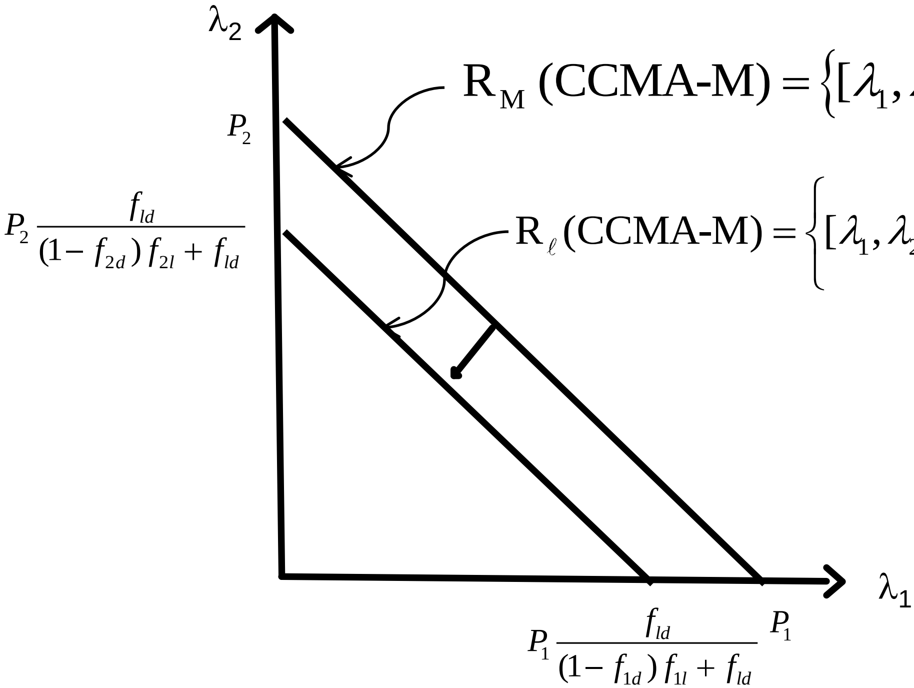




Stability Analysis: CCMA-M (2-users case)

- In CCMA-M, the relay's queue can possibly grow.
- The stability region of the whole system is

$$\mathrm{R}_{\mathrm{M}}(\text{CCMA-M}) \bigcap \mathrm{R}_{\ell}(\text{CCMA-M})$$



$$\mathrm{R}_{\mathrm{M}}(\text{CCMA-M}) = \left\{[\lambda_1, \lambda_2] \in R_+^2 : \lambda_i < \omega_i P_i, \forall i \in \mathrm{M}, \forall \Omega \in \mathrm{F} \right\}$$

$$\mathrm{R}_{\ell}(\text{CCMA-M}) = \left\{[\lambda_1, \lambda_2] \in R_+^2 : \frac{\lambda_1}{P_1}\left((1-f_{1d})f_{1l}+f_{ld}\right) + \frac{\lambda_2}{P_2}\left((1-f_{2d})f_{2l}+f_{ld}\right) < f_{ld} \right\}$$

$$P_i = f_{id} + f_{il} - f_{id} f_{il}$$

Enhanced Protocol CCMA-Me

- When is the CCMA-M better than the TDMA?
  - Let's compare the intersection with the axes!
  - CCMA-M:

$$\lambda_1^*(\text{CCMA-M}) = P_1 \frac{f_{ld}}{(1-f_{1d})f_{1l} + f_{ld}}, \quad \lambda_2^*(\text{CCMA-M}) = P_2 \frac{f_{ld}}{(1-f_{2d})f_{2l} + f_{ld}}$$

  - TDMA:

$$\lambda_1^*(\text{TDMA}) = f_{1d}, \quad \lambda_2^*(\text{TDMA}) = f_{2d}.$$

  - Stability region of TDMA is a subset of CCMA-M if

$$f_{ld} > f_{1d}, \quad f_{ld} > f_{2d}.$$

Enhanced Protocol CCMA-Me

- A natural way to enhance the CCMA-M
  - The relay helps the terminal only if $f_{ld} > f_{id}, \ \forall i \in \mathrm{M}$.
  - Other terminals operate as in TDMA.
  - Assume that the relay only helps terminal 1. Then,

$$\mathrm{R}\,(\text{CCMA-Me}) = \left\{ [\lambda_1, \lambda_2] \in R_+^2 : \frac{\lambda_1}{P_1}\Big((1 - f_{1d})\, f_{1l} + f_{ld}\Big) + \lambda_2 \frac{f_{ld}}{f_{2d}} < f_{ld} \right\}$$

- Theorem on the STR:

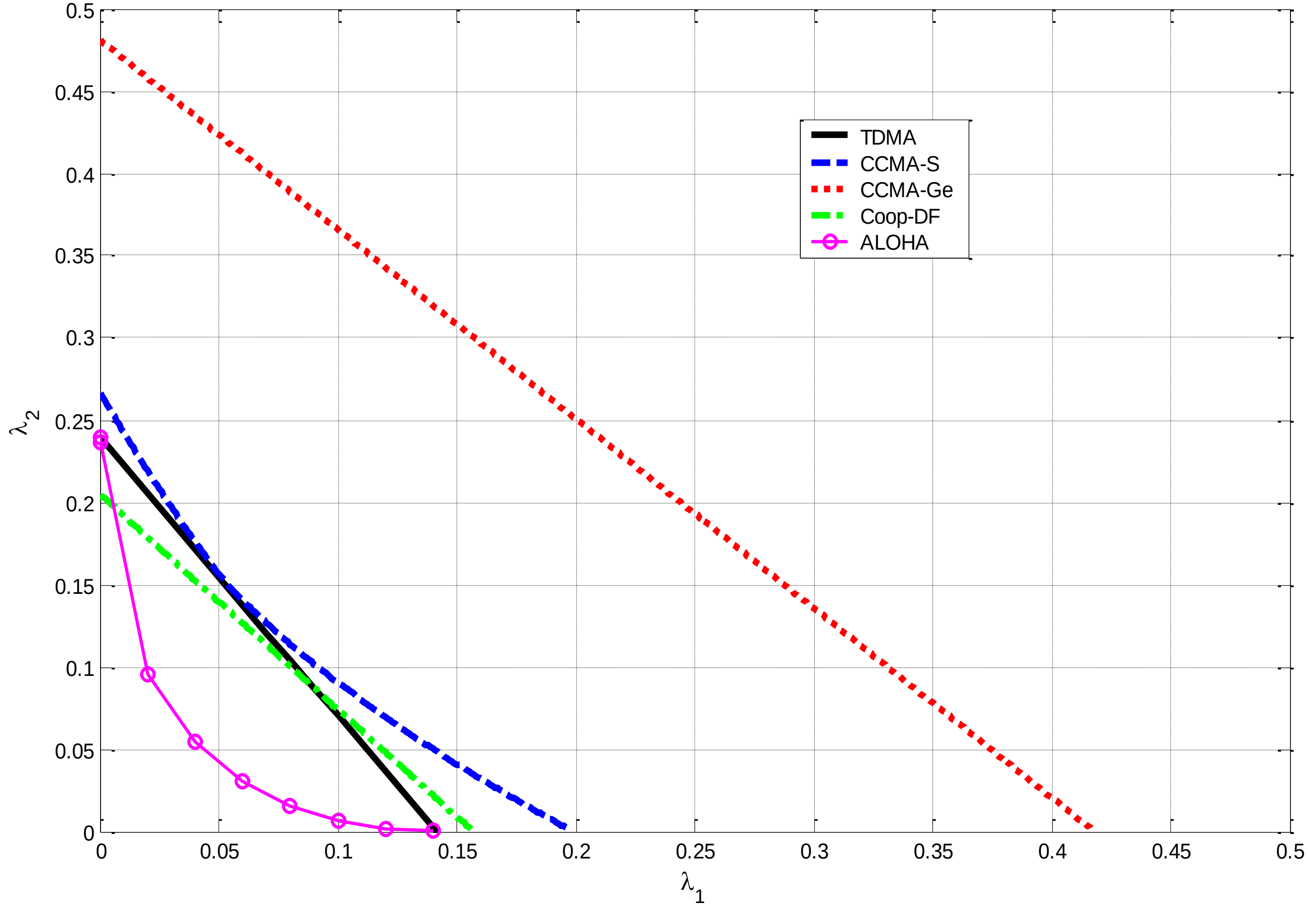
$$\mathrm{R}\,(\text{TDMA}) \subseteq \mathrm{R}\,(\text{CCMA-S}) \subseteq \mathrm{R}\,(\text{CCMA-Me})$$

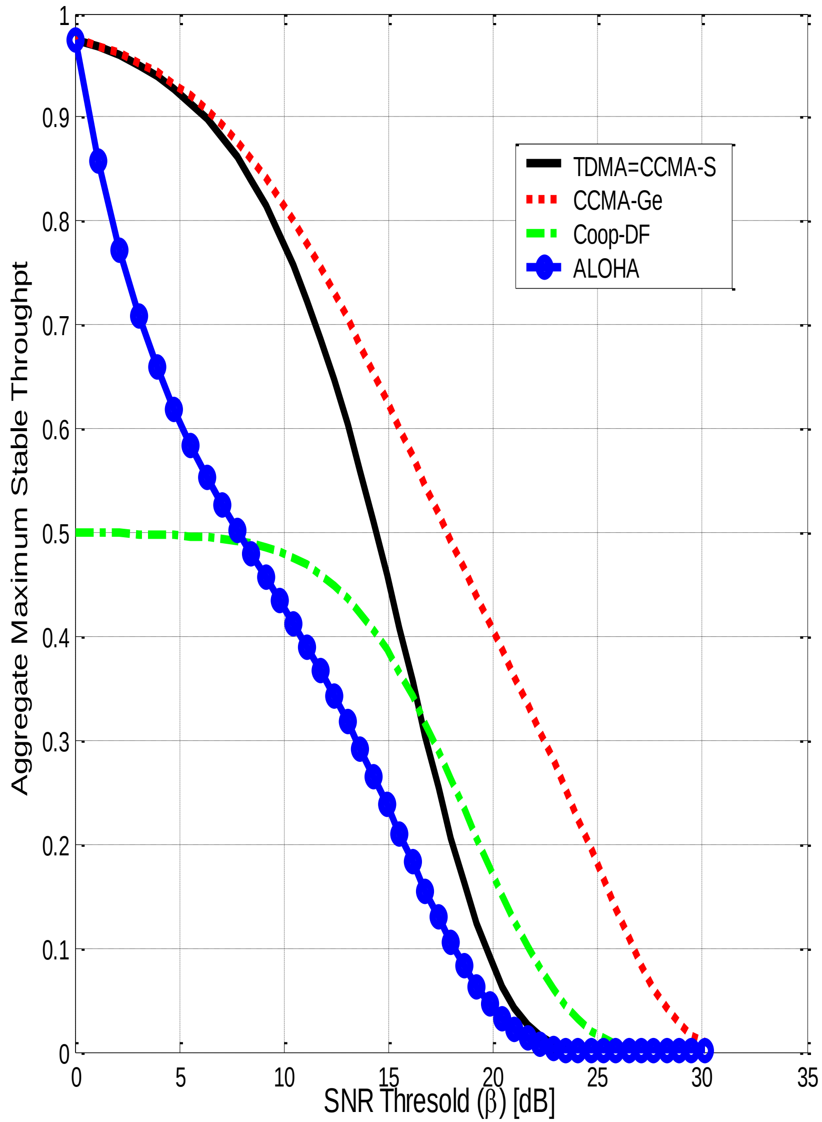
Performance Comparison

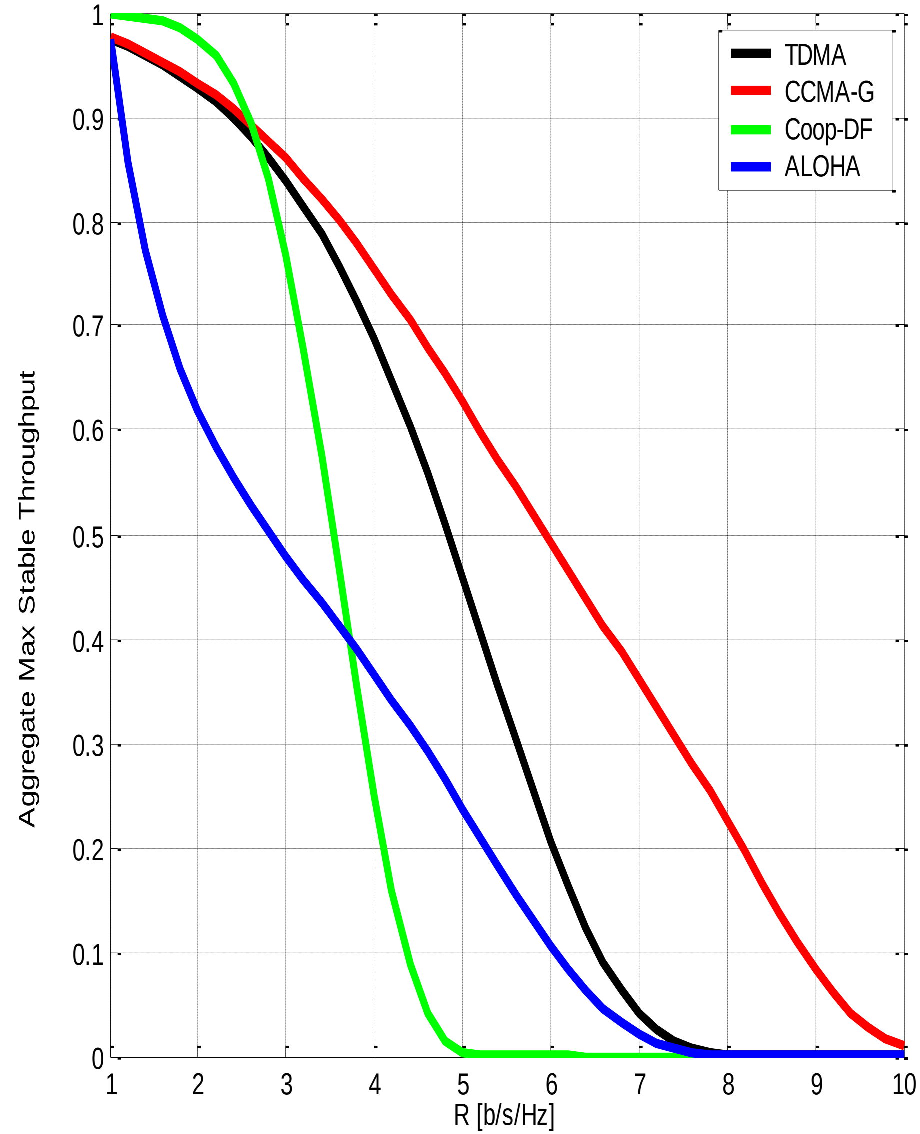
- Existing cooperation protocols
  - Selection Decode-and-Forward (SDF):
    - In the first phase, the source transmits and both the relay and the destination listen.
    - In the second phase, if the relay is able to decode the signal, then forwards. Otherwise, the source retransmits.
  - Selection Incremental Decode-and-Forward(SIDF):
    - The first phase is the same as amplify-and-forward incremental relaying.
    - In the second phase, if the destination does not receive correctly and the relay does, then the relay forwards the packet. Otherwise, the source retransmits.

Performance Comparison

- Stability regions







Coop-DF: Relay transmits at the same rate and utilizes two time slots.

Coop-DF: Relay transmits at twice the rate and utilizes one time slots. (Rate and SNR-threshold are related through the Gaussian mutual information formula

-Performance Analysis

-Stability Analysis

-Delay Analysis

Delay Analysis: CCMA-S (2-users case)

- It is very difficult problem if the queues are interacting! -> 2-users symmetric case.
- Moment generating function approach:

$$G(u,v) = \lim_{t\to\infty} E\left[u^{Q_1^t} v^{Q_2^t}\right], \text{ where}$$

$$E\left[u^{Q_1^{t+1}} v^{Q_2^{t+1}}\right] = E\left[u^{X_1^t} v^{X_2^t}\right] E\left[u^{\left(Q_1^t - Y_1^t\right)^+} v^{\left(Q_2^t - Y_2^t\right)^+}\right].$$

- The average queue size is given by

$$G_1(1,1), \text{ where } G_1(u,v) = \frac{\partial \mathrm{G(u,v)}}{\partial \mathrm{u}}.$$

Delay Analysis: CCMA-S (2-users case)

- We obtain $G_1(1,1)$ which is of the form:

$$G_1(1,1) = \frac{-\left(2\omega f_{1d} + \omega^2 f_{1l} f_{ld}(1 - f_{1d})\lambda^2 + 2\omega f_{1d}\lambda\right)}{2\left(\omega f_{1d} + \omega^2 f_{1l} f_{ld}(1 - f_{1d})\right)\left(\omega f_{1d} - \lambda\right)}.$$

- Consequently, the average queueing delay is given by

$$\mathrm{D}\left(\text{CCMA-S}\right) = \frac{\mathrm{G}_1(1,1)}{\lambda} \qquad \leftarrow N = \lambda s; \quad \text{Little's Formula}$$

  - At $\lambda = \omega f_{1d}$, the delay of the system becomes unbounded. Since it the maximum stable throughput that the system can support with finite delay.

Delay Analysis: CCMA-Me (2-users case)

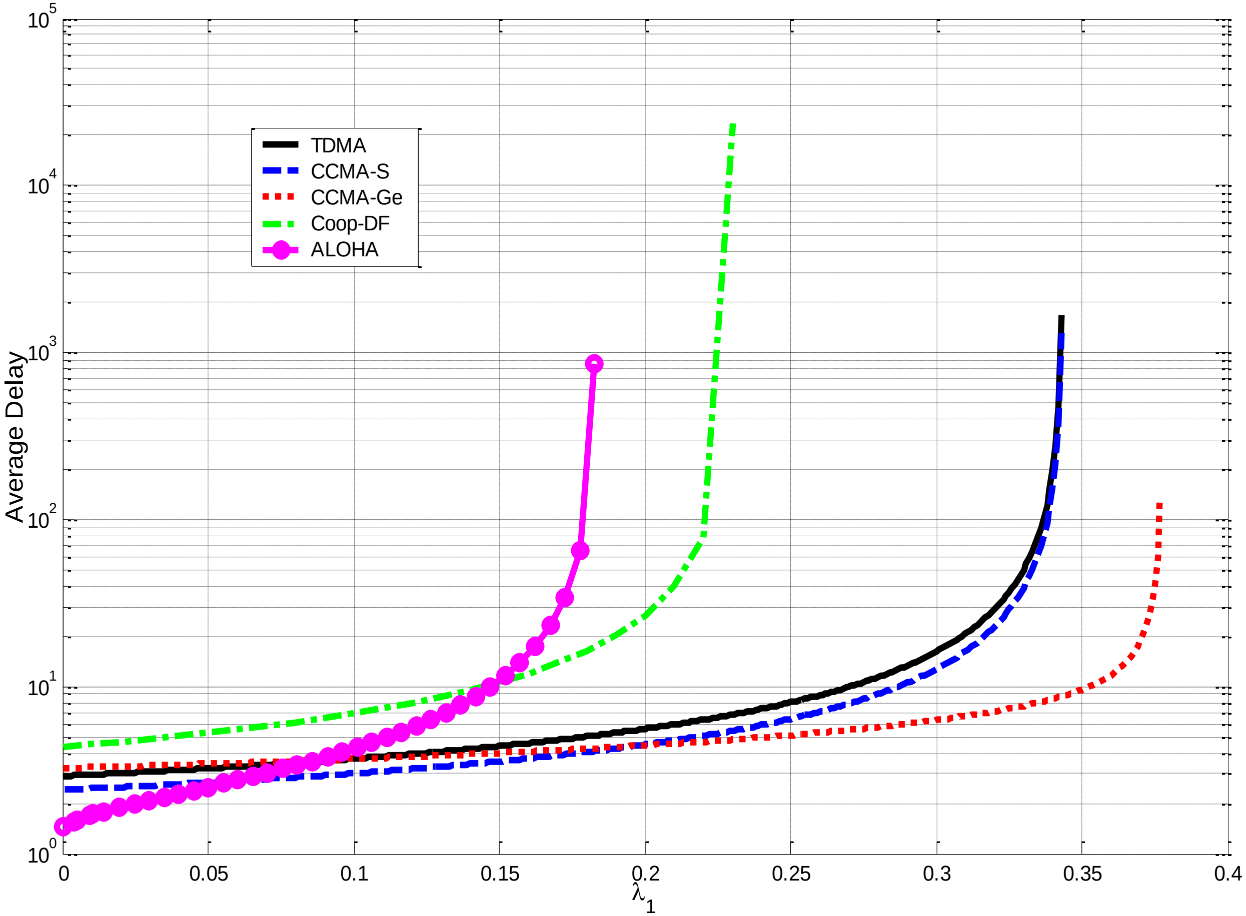
- In CCMA-M, a packet can encounter two queueing delays; the first in the terminal's queue and the second in the relay's queue.

$$T\left(\text{CCMA-M}\right)=\begin{cases} T_t, & \xi \\ T_t+T_l, & \overline{\xi} \end{cases}$$

- The average queueing delay is

$$\mathrm{D}\left(\text{CCMA-M}\right)=\frac{f_{1d}}{P_1}\frac{1-\lambda}{\omega P_1-\lambda}+\frac{f_{1l}(1-f_{1d})}{P_1}\left(\frac{1-\lambda}{\omega P_1-\lambda}+\frac{1-\lambda_l}{\mu_l-\lambda_l}\right).$$

Performance Comparison



Conclusions

- Cognitive relays can utilize idle channel resources for cooperation!
- We can leverage cooperation to improve MAC layer performance by introducing the two novel protocols!
- Significant increases in the stable throughput regions and better delay performance!