MuCAR: A Greedy Multi-flow-based Coding-Aware Routing in Wireless Networks

Jing Chen[1], Quan Yuan[2], Ruiying Du[1], and Jie Wu[3]

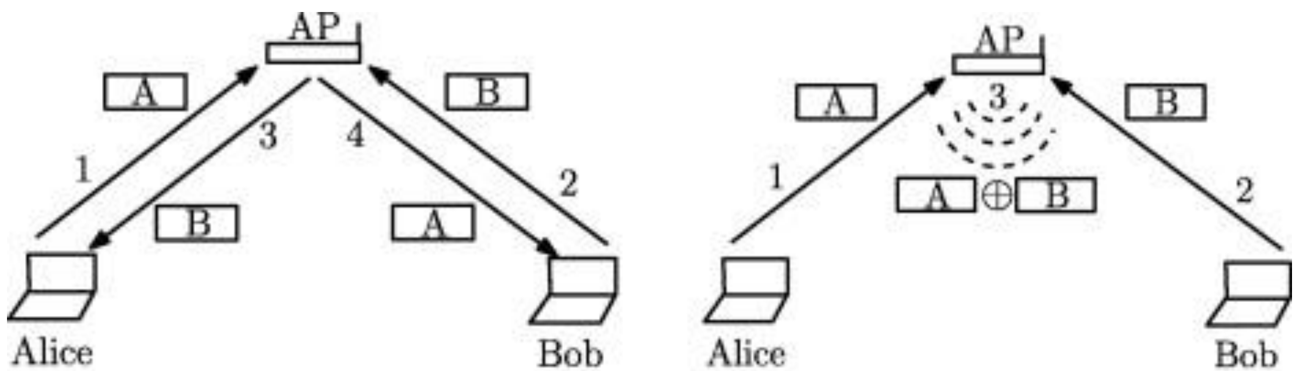
Wuhan University[1]
University of Texas-Permian Basin[2]
Temple University[3]

Outline

- Background & Motivation
- Decoding policy & Coding condition
- Implementation
- Simulation
- Conclusion

Background

- Network Coding



(a) Traditional Transmission (b) Network Coding

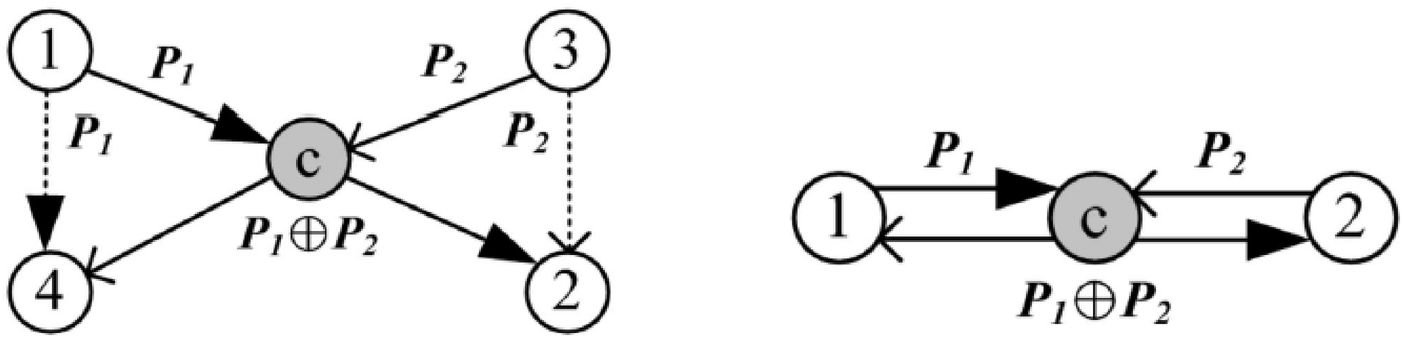
  - leverages the broadcast feature to augment a network's capacity
  - Inter-flow coding: encode the packets from different flows into one for transmission

Background

- Deterministic Code-aware Routing
  - Route determined before packet delivery
  - Code-aware
    - Evaluate coding opportunities
    - Use routes with more coding opportunities
  - Two options
    - Proactive
    - Reactive

Motivation

- Existing work on 2-flow coding



(a) (b)

- How about multi-flow coding?
  - Benefits
  - Challenges

Motivation

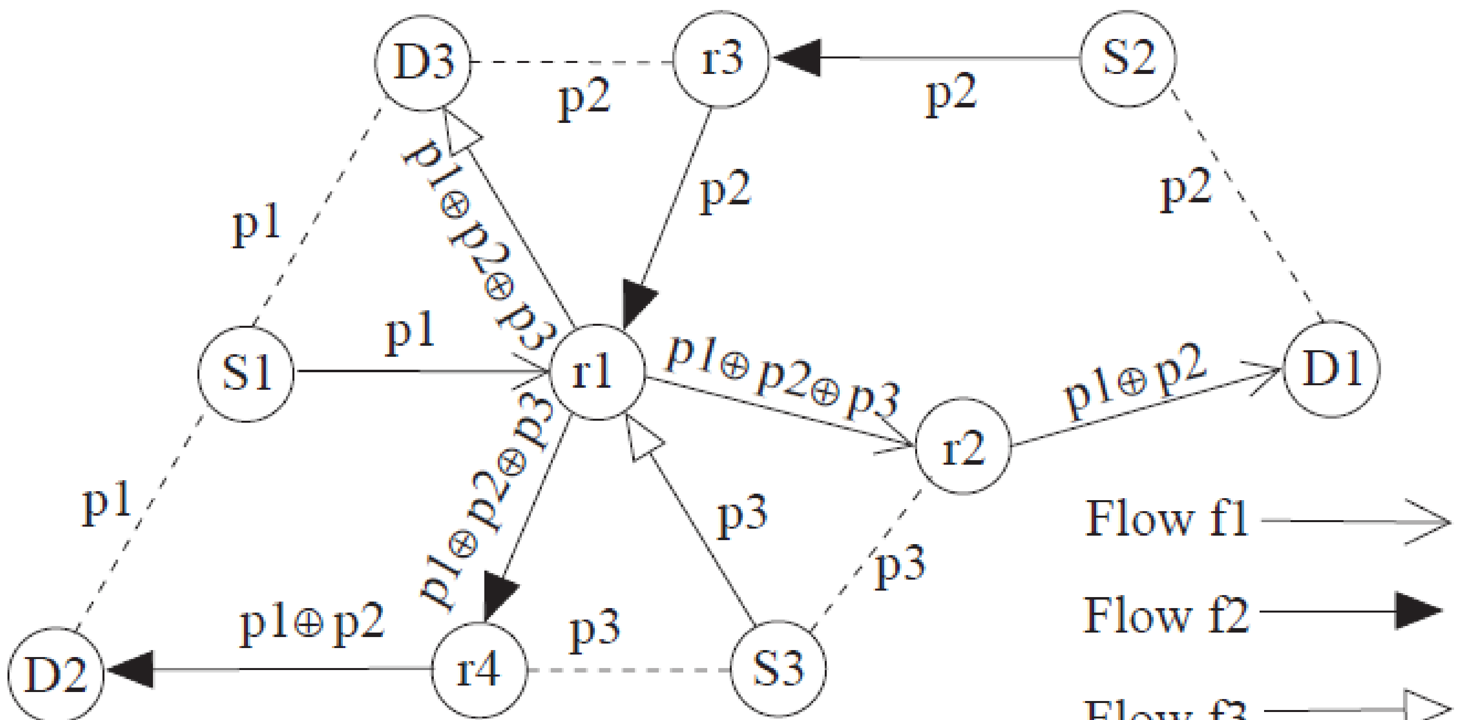


Fig. 1. Decoding at intermediate nodes example in a multi-flow network

Motivation

- System Model
  - Multi-hop wireless network
  - Multiple flows with flow rate varying
  - Nodes can encode multiple flows at once
  - Nodes decode packets cooperatively
  - Link quality changes unpredictably
- Key challenges
  - Coding condition and decoding policy
  - Multi-flow interference
  - Backward compatibility to 2-flow coding
  - Influence of flow rate difference

Greedy Decoding Policy

- 2-flow coding only focus on finding a single node for decoding to define coding conditions,
- In the multi-flow coding, early decoding is encouraged.

Definition 1. *(Greedy decoding policy). For the n native packets $p_1, p_2, ..., p_n$ which respectively come from the flows $f_1, f_2, ..., f_n$, node c generates the coded packet $p_1 \oplus p_2 ... \oplus p_n$. If $r_k \in F(c, f_i)$ $(1 \leq i \leq n)$ can be aware of the native packet p_j of flow f_j($1 \leq j \leq n, j \neq i$), r_k partially decodes the coded packet by removing p_j from it.*

- *F(a, f)* denotes the forward nodes set of node *a* on the route of flow *f*
- r_k(k > 0) represent the intermediate nodes on the route

Coding Condition

- Identify potential coding nodes based on our greedy decoding

Definition 2. *(Coding condition). For n flows f_1, f_2, ..., f_n intersecting at node c, if any two flows f_i and f_j satisfy the following condition, the node c can be a potential coding node:*

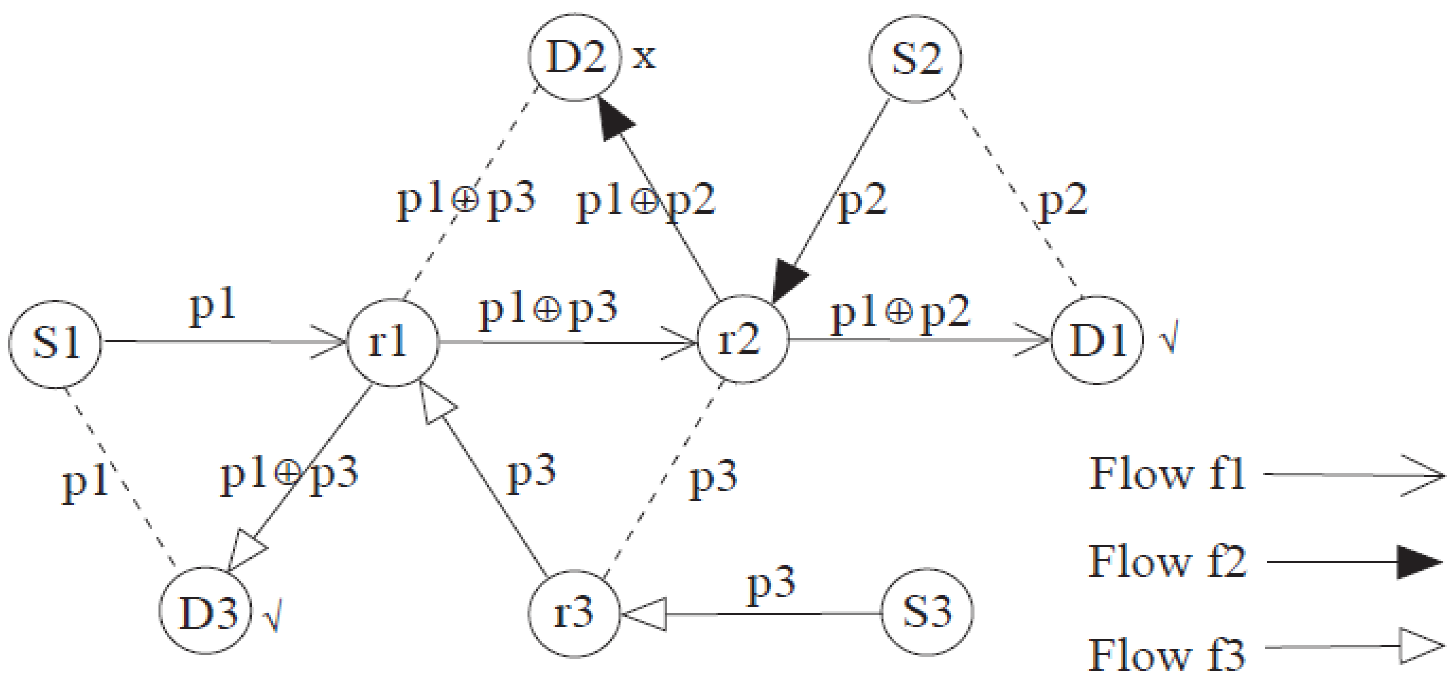
- *There exists node $q \in B(c, f_i)$ and node $t \in F(c, f_j)$, such that $q = t$ or $q \in N(t)$ or $t \in N(q)$, $(1 \leq i, j \leq n$, $i \neq j)$*

Theorem III.1. *The coding condition in Definition 2 is only a necessary condition of greedy coding awareness.*

- *N(a)* is the single-hop neighbor set of node *a*.
- *B(a, f)* indicates the backward nodes set of node *a* on the route of flow *f*

Multi-flow Interference

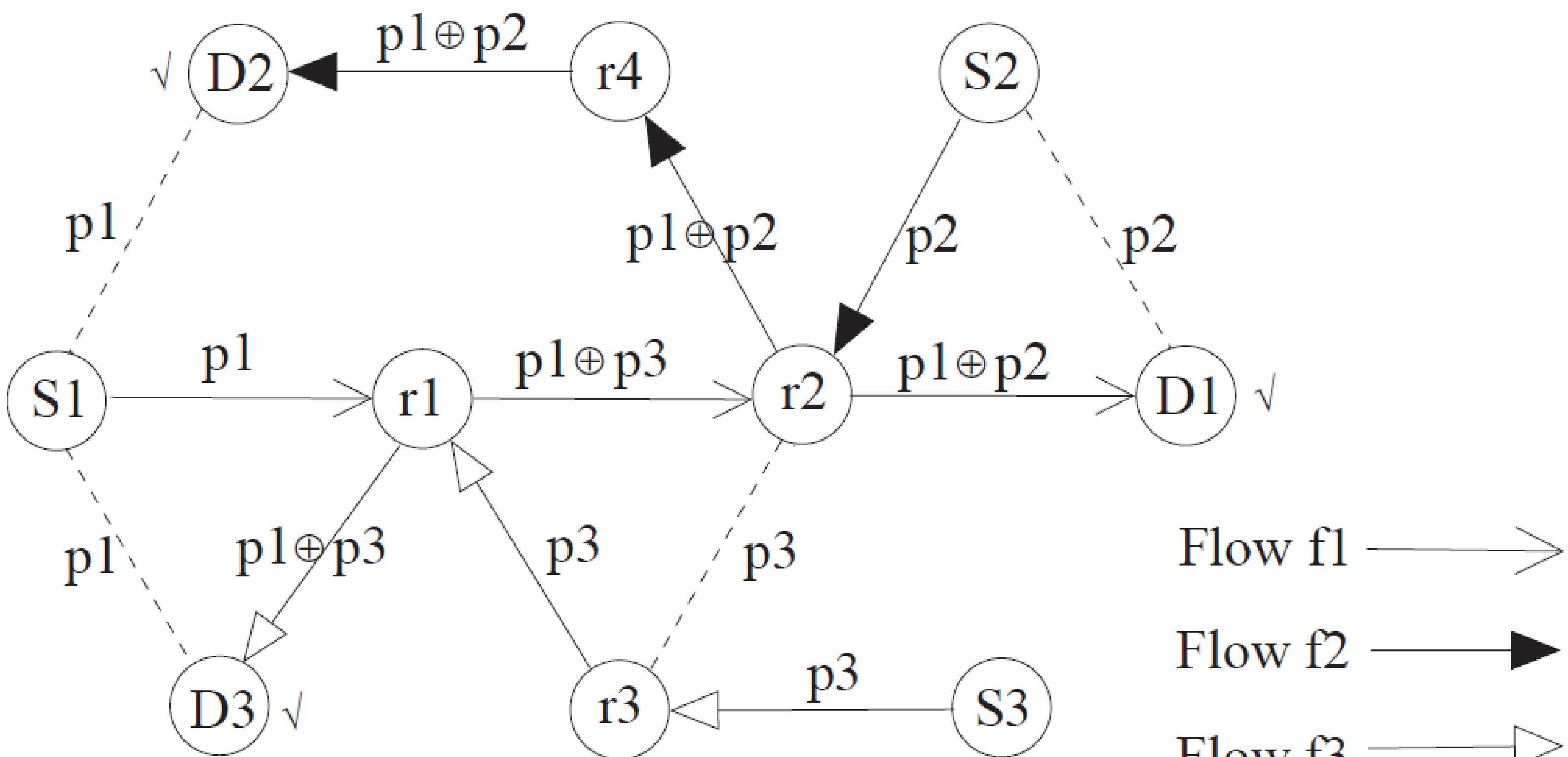
Definition 3. *(Multi-flow interference). For n flows f_1, f_2, ..., f_n intersecting at node c, a new flow f_{n+1} initiates. If the coding behavior of flow f_{n+1} eliminates the transmission of the native packet p_i at nodes in $B(c, f_i)(1 \leq i \leq n)$, some packets may not get decoded successfully.*



(a) Coding with multi-flow interference

Multi-flow Interference

- Multi-flow interference does not exist all the time
- Need to identify in advance to confirm coding nodes.



(b) Coding without multi-flow interference

Routing Metric

- Path Evaluation
  - Coding benefit
  - link quality
  - path length
- Coding Benefit $\beta(P_i)$ of path P_i

$$\beta(\theta_j) = \frac{\gamma_{min}(\theta_j)}{\sum_{1 \le k \le n(\theta_j)} \gamma(f_k)} (n(\theta_j) - 1) \tag{4}$$

Accordingly, the benefit of route P_i is,

$$\beta(P_i) = \sum_{1 \le j \le m} \beta(\theta_j) \tag{5}$$

Routing Metric

- Influence of link quality

$$Ex(P_i) = \sum_{1 \leq x \leq h(P_i)} \left(\frac{1}{q(l_x)} - 1\right) = \sum_{1 \leq x \leq h(P_i)} \frac{1}{q(l_x)} - h(P_i) \tag{8}$$

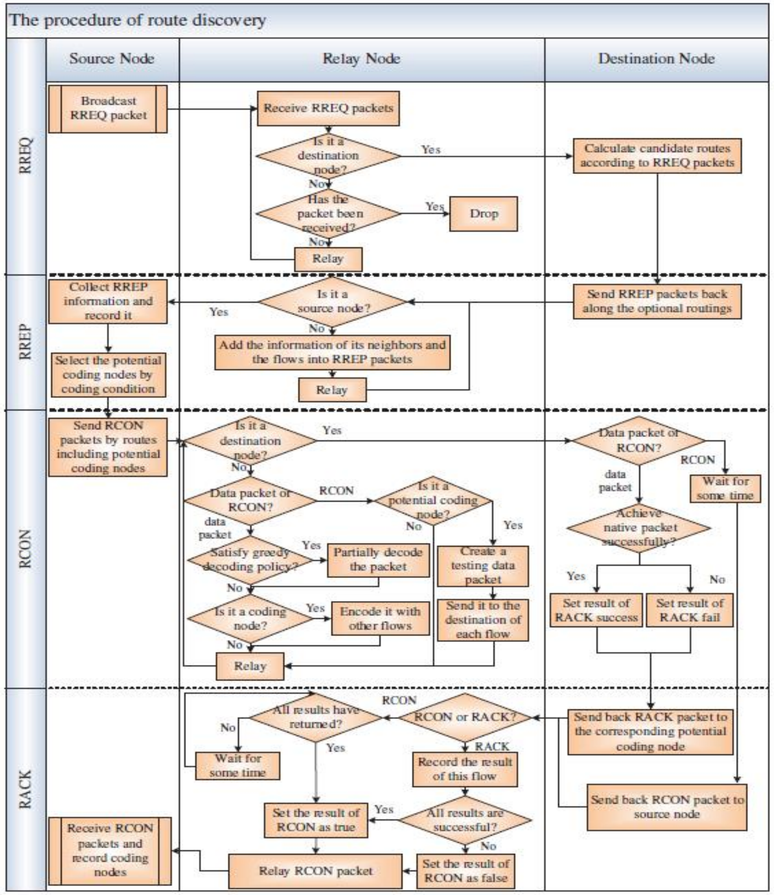
  - $h(P_i)$ is the number of hops of path P_i

- Routing metric definition

$$\begin{aligned} MuCAR(P_i) &= h(P_i) - \beta(P_i) + Ex(P_i) \\ &= \sum_{1 \leq x \leq h(P_i)} \frac{1}{q(l_x)} - \frac{\gamma_{min}(\theta_j)}{\sum_{1 \leq k \leq n(\theta_j)} \gamma(f_k)}(n(\theta_j) - 1) \end{aligned} \tag{9}$$

Implementation: route discovery

- Implementation includes
  - Route discovery: find all possible routes/paths
  - Route selection: select the best one for routing
- Route Discovery
  - *RREQ (Routing REQuest)*
  - *RREP (Routing REPly)*
  - *RCON (Routing CONfirm)*
  - *RACK (Routing ACKnowledge)*



Implementation: route selection

- Route Selection
  1. route with the smallest MuCAR metric value for data delivery
  2. link quality is used for route selection, if two routes have the same MuCAR metric value
  3. route with the smaller path length is used, if two routes have the same MuCAR metric value and link quality

Implementation: greedy aggregation

- There may only exist m ($m < n$) flows satisfying our coding condition for coding
- Instead of evaluating the coding opportunity of n intersection flows just once, we repeat the evaluation by decreasing n progressively when the evaluation test result is false, until n is equal to 2.
- It can maximally code multiple flows together.

Implementation: data transmission

- Encoding
  - XOR packets from different flows based on the smallest rate of flows.

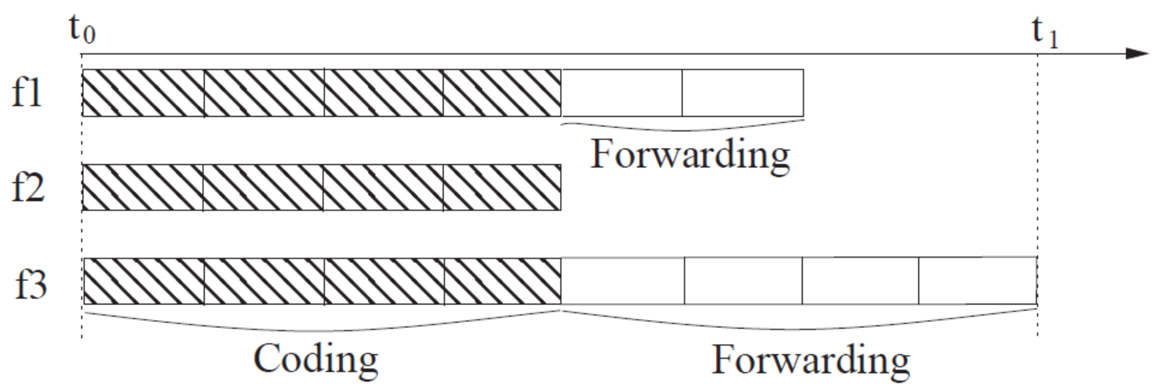


Fig. 4. Coding on flows with different rates at coding node c

  - Packets of the slowest flow will be fully encoded, and part of the packets from the other faster flows are relayed directly.

Simulation

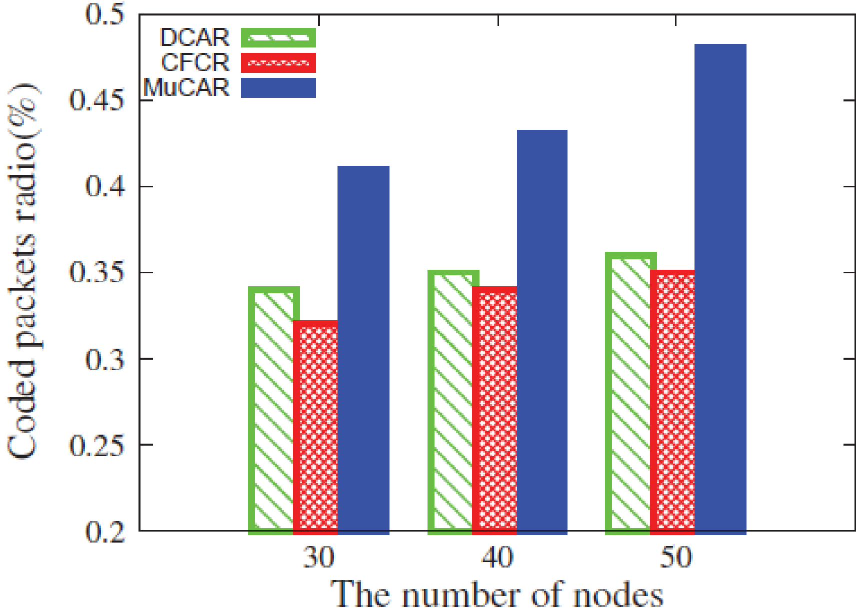
- Algorithm in comparison
  - DCAR [TMC2010]
  - CFCR [TPDS2014]
  - On ns2 simulator
- Metrics
  - Effective Coding Benefit
  - Throughput
  - Delay

THE PARAMETERS OF SIMULATION

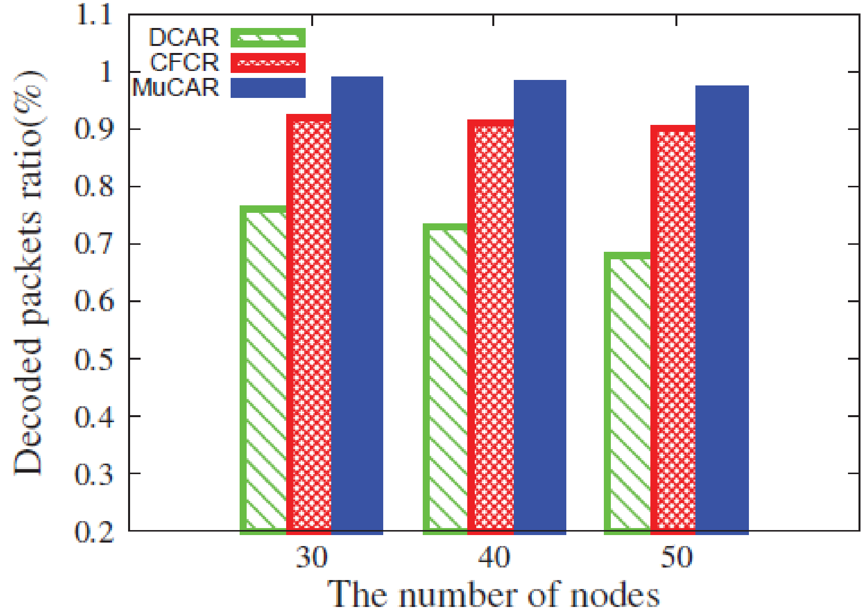
Simulation Parameter	Value
MAC protocol	IEEE802.11
Data flow type	UDP/CBR
Packets size	1000B
Flow rate	100kbps
Packet loss ratio	2%
Number of nodes	30
Number of flows	8
Transmission range	250m
Area	1500m * 1500m

Simulation

- Results - Effective Coding Benefit



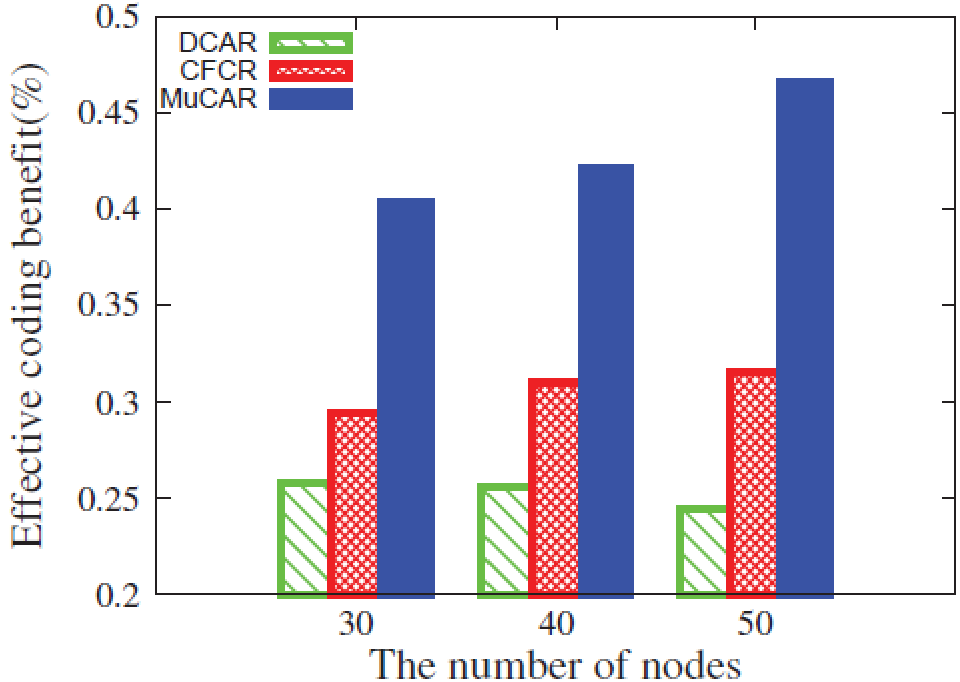
(a) Coded packets ratio



(b) Decoded packets ratio

Simulation

- Results - Effective Coding Benefit



(c) Effective Coding Benefit

Coding benefit = coded packets ratio * decoded packets ratio.

Simulation

- Results - Throughput

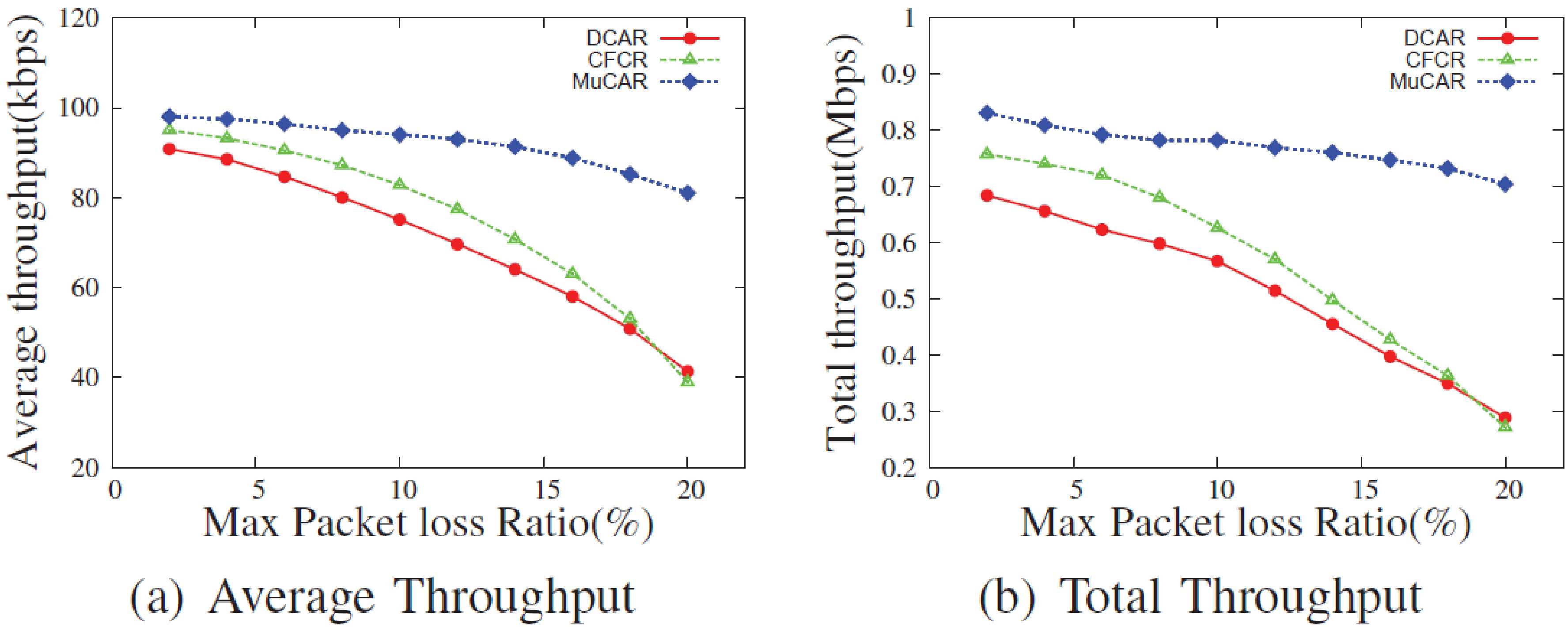


Fig. 6. Throughput Evaluation under Different MPLR

Simulation

- Results - Throughput

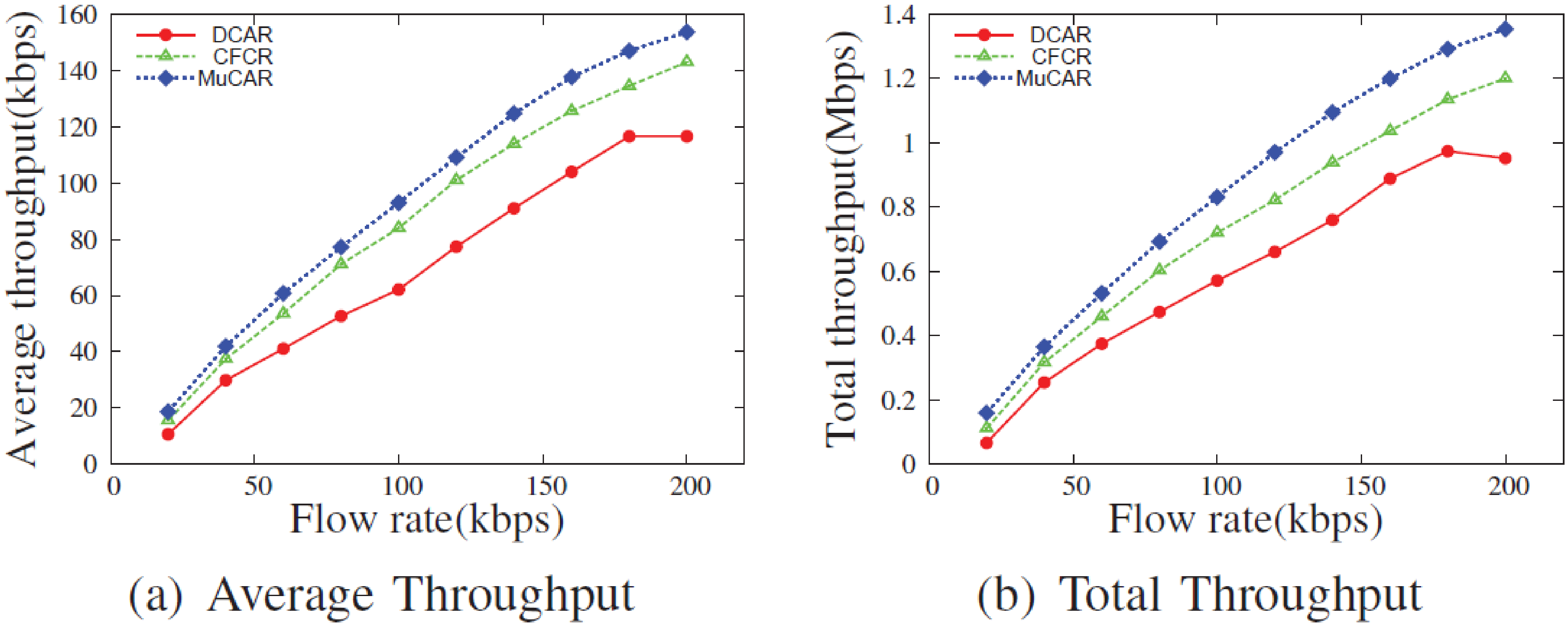


Fig. 7. Throughput Evaluation under Different Flow Rate

Simulation

- Results - Delay

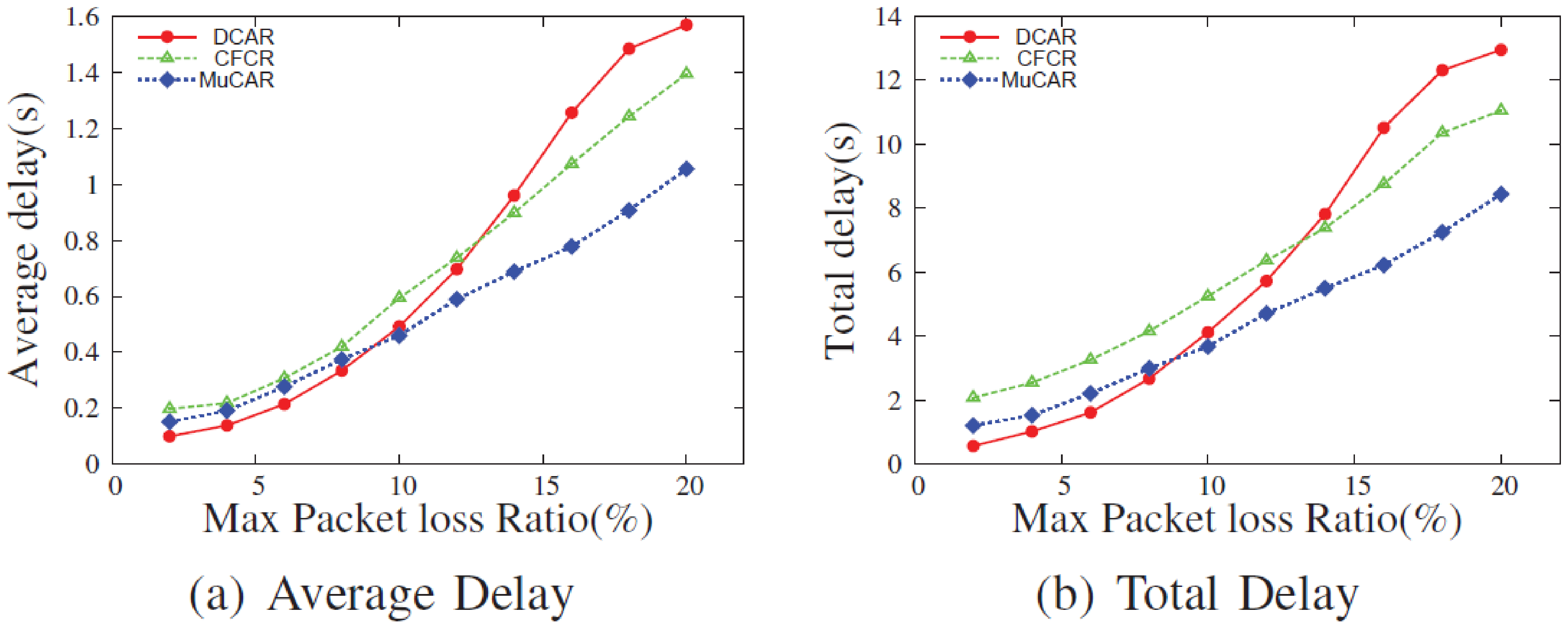


Fig. 8. Delay Evaluation under Different MPLR

Conclusion

- MuCAR can directly encode multiple flows to increase coding opportunities in routing.
- MuCAR can avoid multi-flow interference in multiple flow coding situation.
- MuCAR has better throughput and delay in wireless network with link quality varies.


Thanks
QUESTIONS?