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Distributed Cooperative Rate Adaptation for Energy Efficiency in IEEE 802.11-Based Multihop Networks

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Outline

- Introduction
- Problem Formulation
- Distributed CRA Algorithm
- Performance Evaluation
- Conclusion

Introduction

- Energy efficiency is one of the key issues in wireless multihop networks since most mobile devices are battery operated.
- An effective way to achieve energy efficiency is to reduce the transmission power whenever possible.

Introduction

- However, in a multirate-enabled network, reducing transmission power may result in reduced transmission rate. [assuming that the bit error rate (BER) has to be below than a certain threshold].
- Hence, power control and rate adaptation need to be jointly considered.

Introduction

- In an IEEE 802.11-based multihop network, the hidden terminal phenomenon can result in severe overall energy inefficiency.
- This paper studies the problem of using the rate adaptation technique to achieve energy efficiency in an IEEE 802.11-based ***multihop*** network.

Problem Formulation

- *Problem Statement*
  - Given a wireless multihop network, and the traffic requirements on each link, determine the PHY rate and the corresponding transmission power for each link to minimize the total energy consumption while satisfying the traffic requirements of all links.
- *Analytical Models*

Problem Formulation

- *Problem Statement*
- *Analytical Models*
  - network model
  - signal attenuation model (path loss model)
  - the relationship between the transmission power and the PHY rate
  - the relationship between the energy consumption and the PHY rate
  - the relationship between the channel (access) time and the PHY rate
  - the link conflict model

Network Model

- A wireless multihop network is modeled as a graph $G = (V,E)$, in which V is the node set, and E is the directed-link set.
- dist(s, d) denotes the geographical distance between s and d.
- The minimum traffic requirement on link (s, d) is represented by λ(s, d), and current PHY rate on link (s, d) is represented by R(s, d)

Signal Attenuation Model

- In this paper adopts the path-loss model [25] as the signal attenuation model

$$P_{\mathrm{r}} = c \cdot \frac{P_{\mathrm{t}}}{d^k} \tag{1}$$

- both *c* and *k* are constants, which are determined by environments.

Relationship Between Transmission Power and PHY Rate

- Using the aforementioned signal attenuation model, we can relate the transmission power of a source to the PHY rate as follows:

$$P_{\mathrm{t}}\left(R(s,d)\right) = \frac{P_{\mathrm{r}}\left(R(s,d)\right) \cdot \mathrm{dist}(s,d)^{k}}{c}. \qquad (2)$$

Relationship Between Energy Consumption and PHY Rate

- RTS frames, CTS frames, and ACK frames are all transmitted at the basic rate, while DATA frames are transmitted at the PHY rate selected by the source.

$$\mathrm{En}_{(s,d)}\left(R(s,d)\right) = \frac{\lambda(s,d)}{\text{packet\_size}}\left[P_{\mathrm{t}}(\text{basic\_rate}) \cdot \left(t_{\mathrm{RTS}} + t_{\mathrm{CTS}} + t_{\mathrm{ACK}}\right) + P_{\mathrm{t}}\left(R(s,d)\right) \cdot t_{\mathrm{DATA}}\left(R(s,d)\right)\right] \quad (3)$$

$$t_{\mathrm{DATA}}\left(R(s,d)\right) = t_{\mathrm{PLCP}} + \frac{\text{packet\_size} + \text{overhead\_size}}{R(s,d)} \quad (4)$$

Relationship Between Energy Consumption and PHY Rate

- This paper only considers the power consumption in transmission, since the power consumption in reception and in the idle mode are much smaller than that in transmission

Relationship Between Channel Time and PHY Rate

- According to IEEE 802.11 standard, the channel time used by link (*s, d*) can be derived as follows:

$$\text{Channel Time}_{(s,d)}\left(R(s,d)\right) = \frac{\lambda(s,d)}{\text{packet\_size}} \cdot \left(t_{\text{DIFS}} + t_{\text{RTS}} + 2 \cdot t_{\text{SIFS}} + t_{\text{CTS}} + t_{\text{DATA}}\left(R(s,d)\right) + t_{\text{ACK}}\right). \quad (5)$$

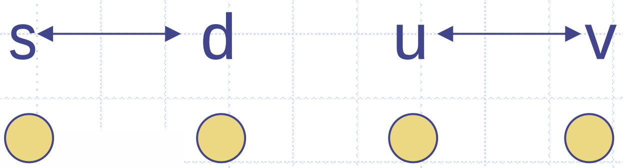
Link Conflict Model

- The sensing range of a node is determined by the clear-channel-assessment (CCA) sensitivity, which is the minimal detectable signal strength.
- This paper assumes that the CCA sensitivity is also the minimal interfering signal strength that can corrupt an intended transmission.
- the interference range $R_I(s)$ of node s with transmission power P_s is

$$R_I(s) = \sqrt[k]{c \cdot \frac{P_s}{\mathrm{CCA}}} \quad (6)$$

Link Conflict Model

- Since bidirectional handshakes are required in IEEE 802.11, then two links, say (*s, d*) and (*u, v*), conflict with each other when any of the following conditions holds:



$$\langle 1 \rangle \ \text{dist}(s,u) \leq \max\left(R_I(s), R_I(u)\right)$$

$$\langle 2 \rangle \ \text{dist}(s,v) \leq \max\left(R_I(s), R_I(v)\right)$$

$$\langle 3 \rangle \ \text{dist}(d,u) \leq \max\left(R_I(d), R_I(u)\right)$$

$$\langle 4 \rangle \ \text{dist}(d,v) \leq \max\left(R_I(d), R_I(v)\right). \qquad (7)$$

Link Conflict Model

- This paper derives the channel time constraints according to the conflict graph proposed in [27].[K. Jain, J. Padhye, V. Padmanabhan, and L. Qiu, “Impact of interference on multi-hop wireless network performance,” in *Proc. ACM MobiCom*, San Diego, CA, Sep. 2003, pp. 66–80.]
- The total channel time utilized by all the links that form a clique in the conflict graph must be less than or equal to 1, i.e.,

$$\sum_{(i,j)\in S} \text{Channel Time}_{(i,j)}\left(R(i,j)\right) \leq 1$$

$$S \in \{\text{all max cliques in the conflict graph}\}. \quad (8)$$

Problem Formulation

- Finally, the problem can be formulated as the following optimization problem:

$$\min_{R(i,j)} \left(\sum_{(i,j)\in E} \mathrm{En}_{(i,j)} \left(R(i,j) \right) \right)$$

s.t.

$$\langle 1 \rangle \; R(i,j) \in \{\text{all possible PHY rates}\}$$

$$\langle 2 \rangle \; \sum_{(i,j)\in S} \text{Channel Time}_{(i,j)} \left(R(i,j) \right) \leq 1.$$

$$S \in \{\text{all max cliques in the conflict graph}\}. \qquad (9)$$

WHY DO WE NEED NODE COOPERATION?

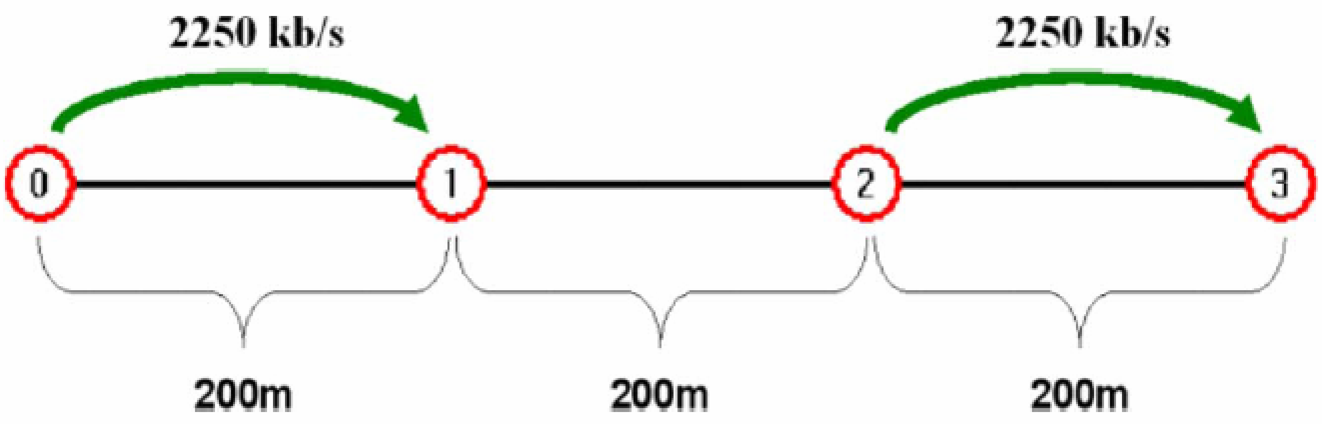


Fig. 1. Chain topology and traffic patterns.

TABLE II
PHY RATES AND ENERGY CONSUMPTION COMPARISONS

	PHY Rate on (0,1)	PHY Rate on(2,3)	Total Power Consumption(mW)
Non-Cooperative Solution	48Mb/s	9Mb/s	6.704
Optimal Solution	18Mb/s	18Mb/s	2.352

Distributed CRA Algorithm

- CRA consists of three modules:
  - information exchange algorithm
    - The "information exchange algorithm" is to help each node obtain relevant information of all the links in its maximum interference range, which includes **the needed channel time for satisfying the traffic requirements** and **corresponding power consumption under all possible PHY rates** on the link.
  - rate selection algorithm
  - node cooperation algorithm

Information Exchange Algorithm

TABLE III
LINK INFORMATION OF FIG. 1

Information of link (0, 1)			
Rate Index	PHY Rate(Mb/s)	Channel Time(s)	Power Consumption(mW)
0	54	0.374	6.643
1	48	0.380	5.776
2	36	0.397	2.961
3	24	0.432	1.727
4	18	0.467	1.176
5	12	0.537	1.087
6	9	0.607	0.928
7	6	0.747	1.053
Information of link (2, 3)			
0	54	0.374	6.643
1	48	0.380	5.776
2	36	0.397	2.961
3	24	0.432	1.727
4	18	0.467	1.176
5	12	0.537	1.087
6	9	0.607	0.928
7	6	0.747	1.053

Distributed CRA Algorithm

- CRA consists of three modules:
  - information exchange algorithm
  - rate selection algorithm
    - With this link information, each node uses the “rate selection algorithm” to calculate and obtain the most energy efficient setting of PHY rates for all the links in its maximum interference range.
  - node cooperation algorithm

Rate Selection Algorithm

$$
\text{benefit\_ratio}(l,i,j) = \begin{cases} \dfrac{\text{power\_consumption}(l,i) - \text{power\_consumption}(l,j)}{\text{channel\_time}(l,j) - \text{channel\_time}(l,i)}, & i \neq j \\ 0, & i = j \end{cases} \tag{10}
$$

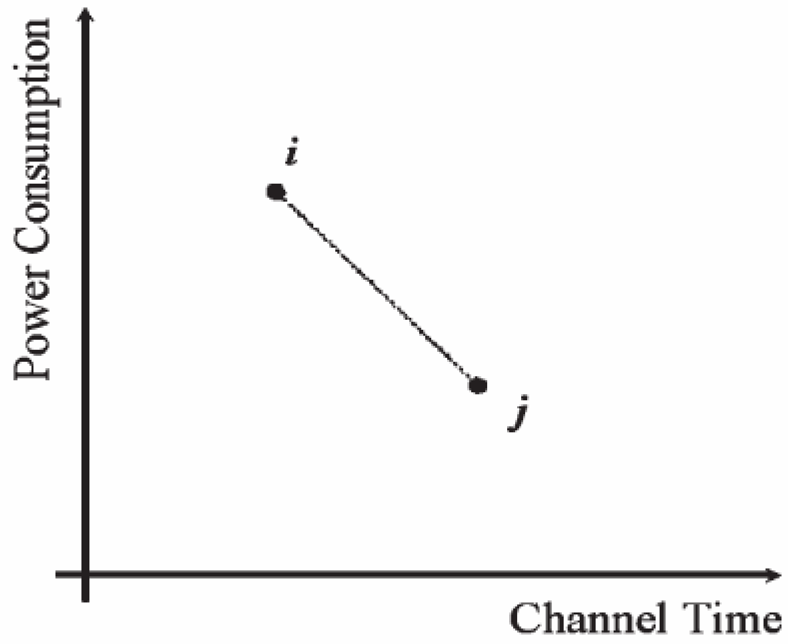


Fig. 4. Physical meaning of benefit ratio.

Rate Selection Algorithm

Step 1: Set the PHY rate for each link in A's maximum interference range to the highest value as the initial setting.

Step 2: For each link within A's maximum interference range, select a PHY rate that has the largest $\Delta E/\Delta T$, where ΔE denotes energy reduction and ΔT denotes the channel time increase, as compared to the current setting. Then, choose the link that has the largest $\Delta E/\Delta T$ among all the links within A's maximum interference range (The power/rate of all other links is not changed). Note that ΔE should be greater than 0. If we can not find a setting that could result in $\Delta E>0$, the algorithm ends.

Step 3: Check whether the new PHY rate of the link is feasible by (8). If it is feasible, select the new rate setting; otherwise, reset to the previous setting.

Step 4: Go to Step 2.

Distributed CRA Algorithm

- CRA consists of three modules:
  - information exchange algorithm
  - rate selection algorithm
  - node cooperation algorithm
    - Then, each node requests its neighboring nodes to check the feasibility of this new rate setting through the “node cooperation algorithm.” The node cooperation algorithm accepts rate change when the new rate is feasible and can reduce the energy consumption.

Components of CRA

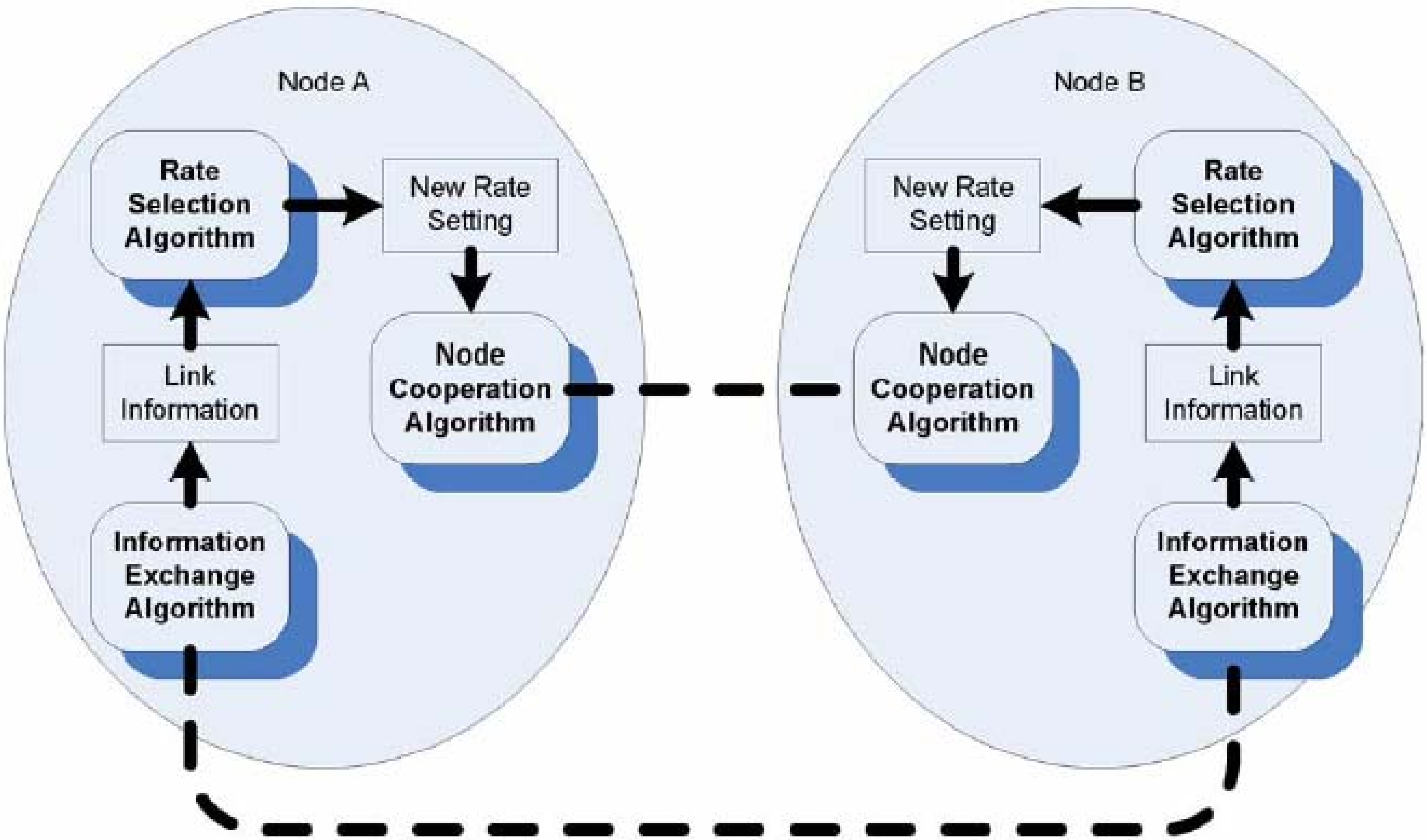


Fig. 2. Architecture of CRA.

PERFORMANCE EVALUATION

TABLE IV
SIMULATION PARAMETERS

$t_{DIFS} = 50\mu s$ $t_{SIFS} = 10\mu s$ $t_{PLCP} = 32\mu s$ $packet\_size = 512bytes$	$t_{RTS} = 58.67\mu s$ $t_{CTS} = 50.67\mu s$ $t_{ACK} = 50.67\mu s$ $overhead\_size = 48bytes$

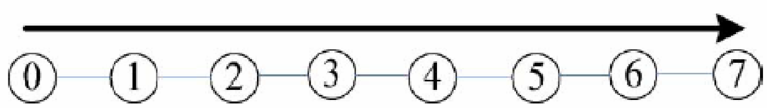


Fig. 5. Traffic pattern in chain topology.

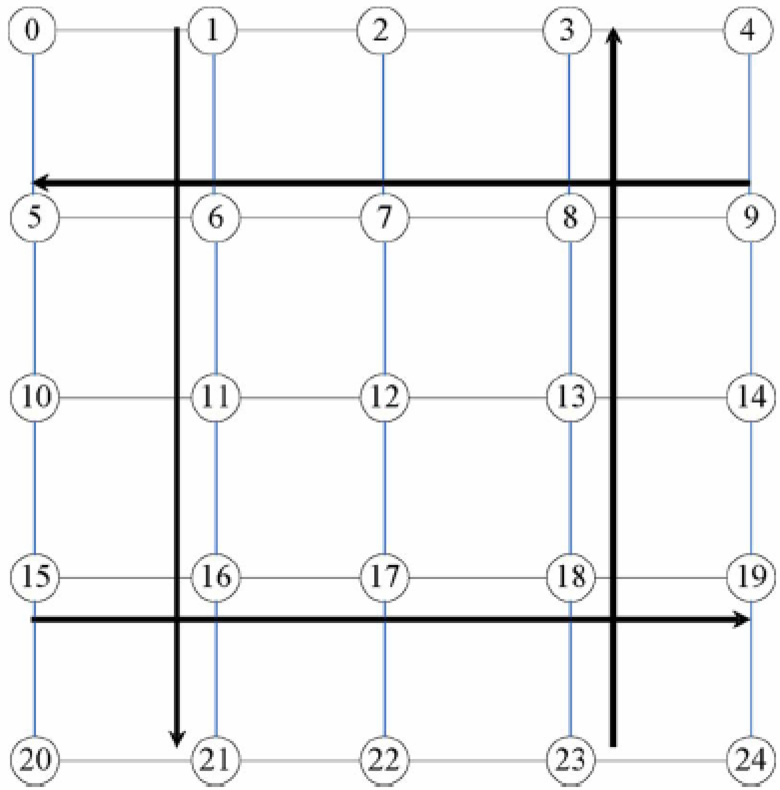


Fig. 8. Traffic pattern in grid topology.

PERFORMANCE EVALUATION

- This paper compares the performance of CRA and the non-cooperative heuristic in terms of total power consumption of the whole network and performance gain defined by

$$\text{performance\_gain} = 1 - \frac{\text{CRA Energy Consumption}}{\text{Noncooperative Heuristic Energy Consumption}}. \quad (11)$$

PERFORMANCE EVALUATION

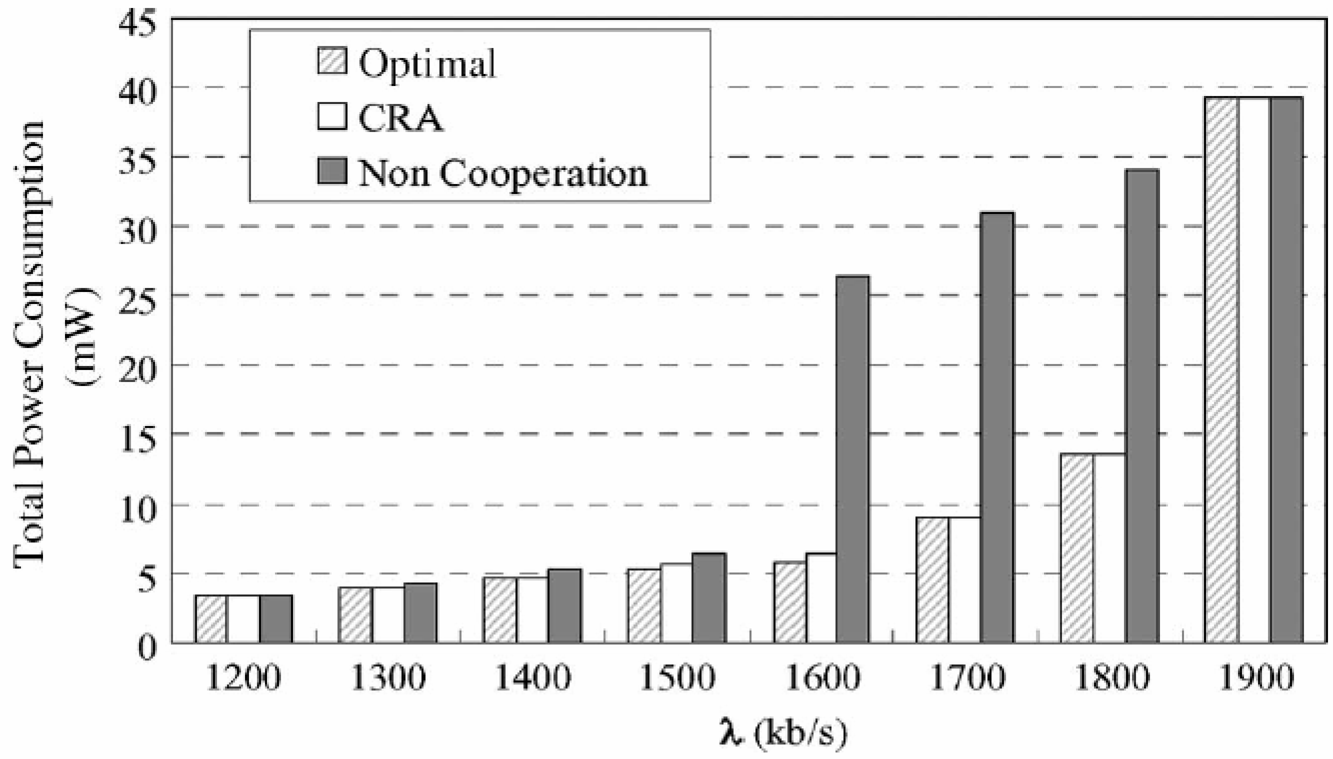


Fig. 6. Power consumption comparison in chain topology.

PERFORMANCE EVALUATION

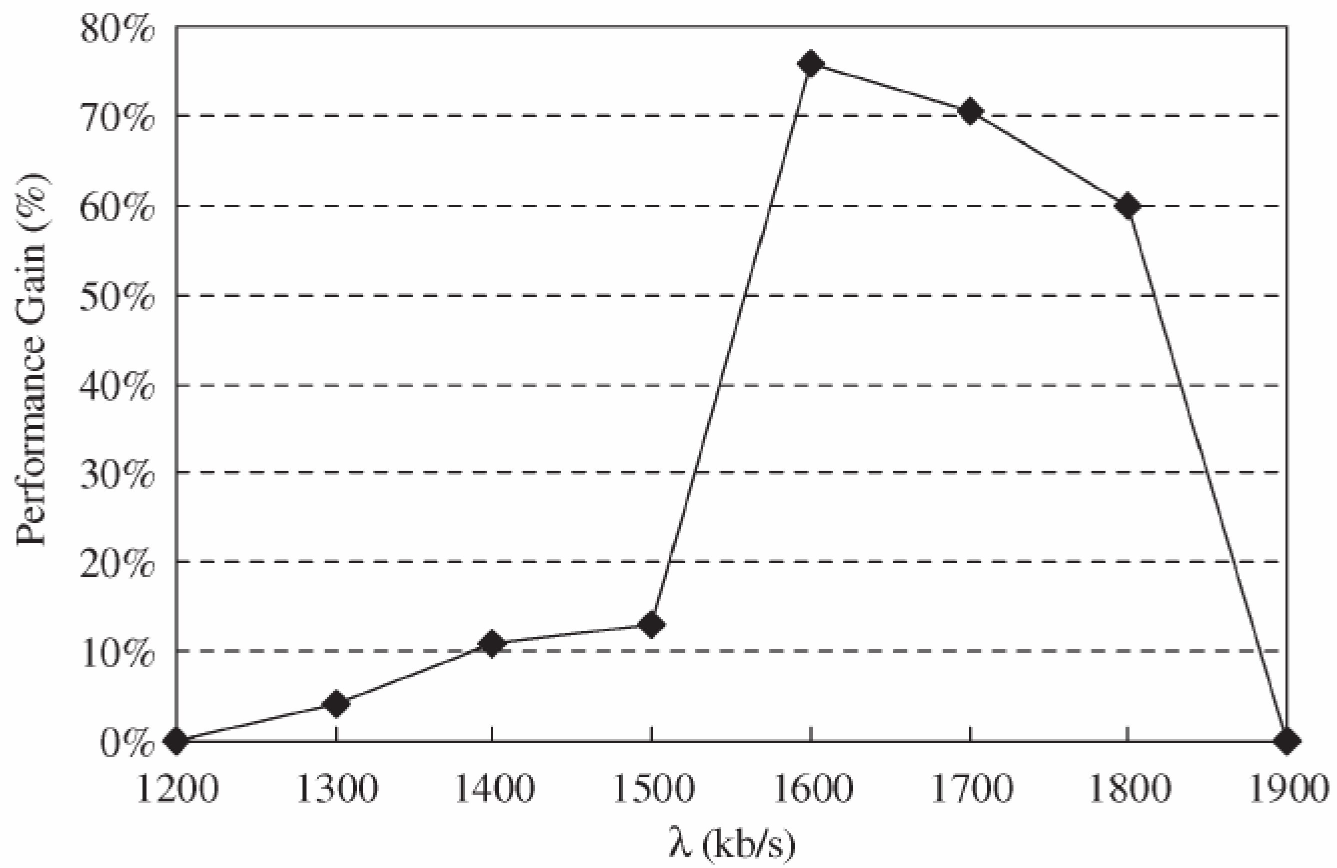


Fig. 7. Performance gain of CRA over noncooperative heuristic in chain topology.

PERFORMANCE EVALUATION

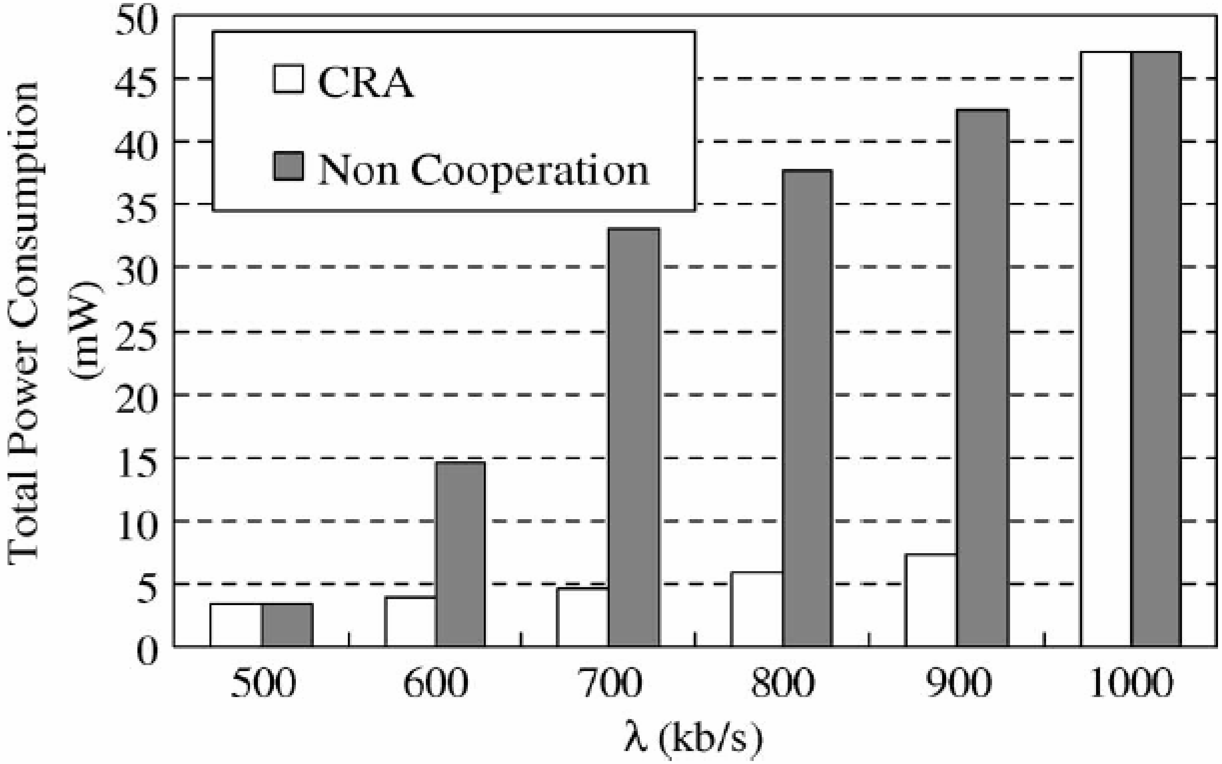


Fig. 9. Power consumption comparison in grid topology.

PERFORMANCE EVALUATION

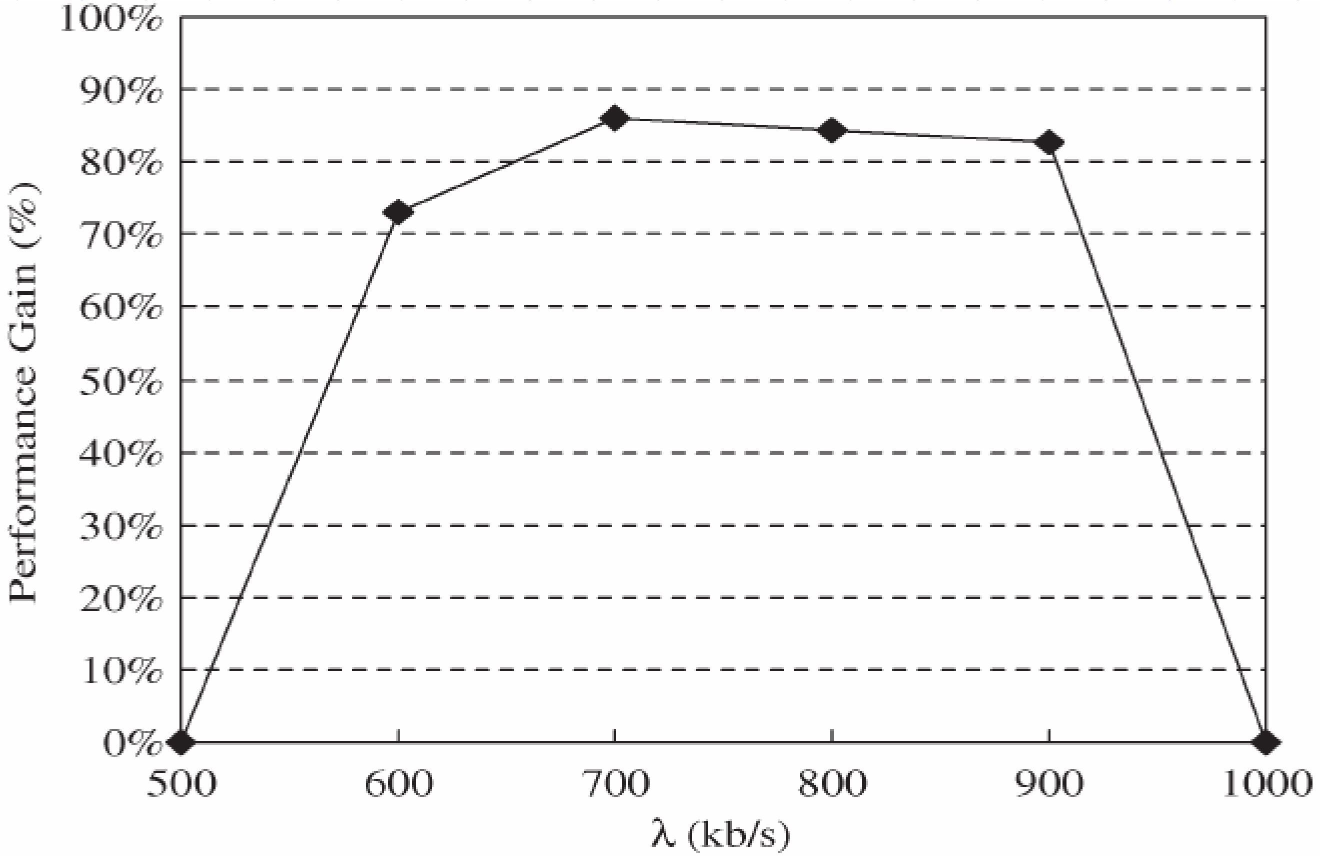


Fig. 10. Performance gain of CRA over noncooperation heuristic in grid topology.

PERFORMANCE EVALUATION

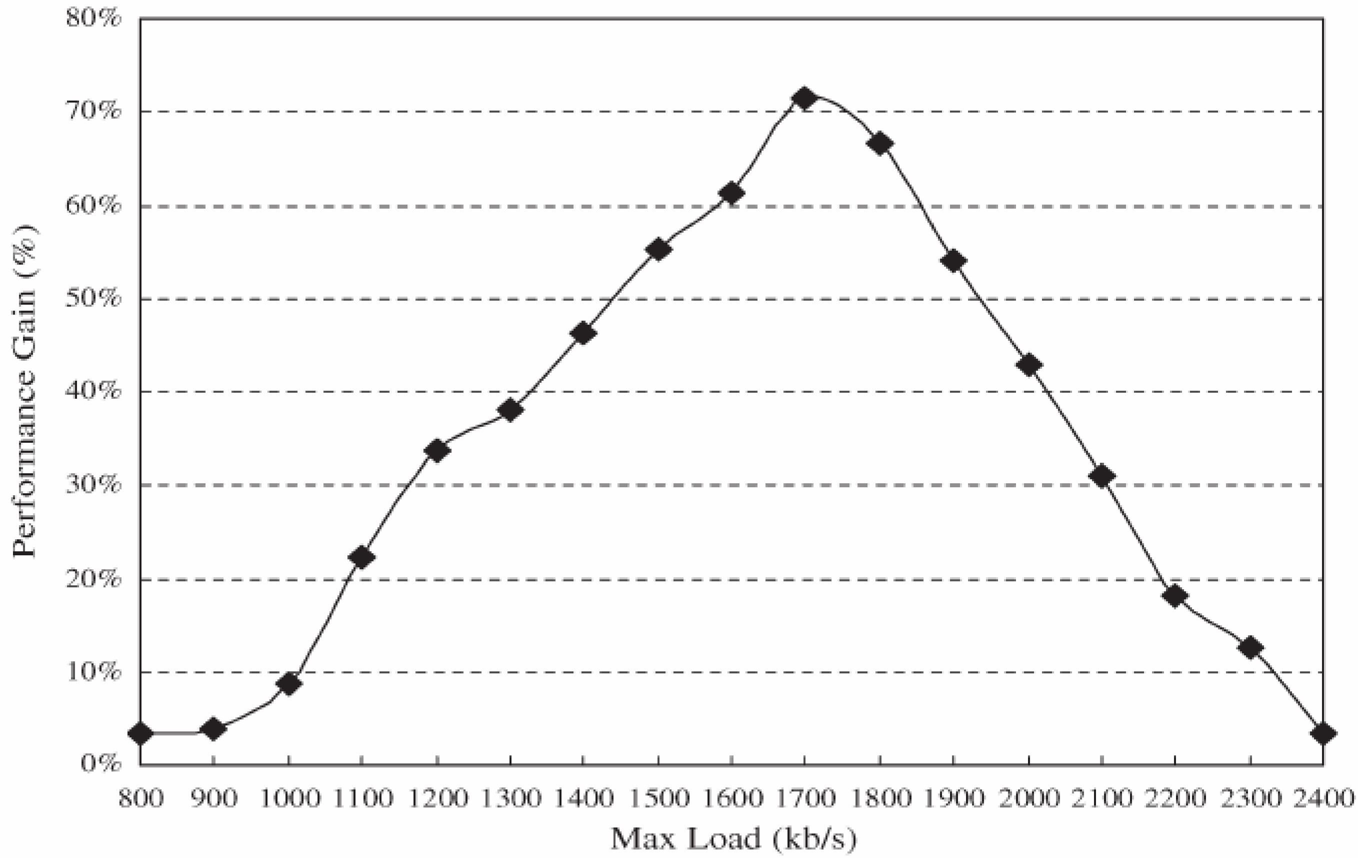


Fig. 11. Performance gain of CRA over noncooperative heuristic in random topologies.

Conclusion

- Energy efficiency is a key issue in wireless multihop networks.
- This paper proposed a distributed CRA scheme to achieve energy efficiency in IEEE 802.11-based multihop networks.
- To evaluate the performance of CRA scheme. The results show that CRA scheme can reduce the power consumption up to 86% as compared to the existing (non-cooperative) algorithm.