Cooperative and Opportunistic Transmission for Wireless Ad Hoc Networks

Qian Zhang, Hong Kong University of Science and Technology
Qing Chen, Tsinghua University
Fan Yang, Microsoft Research Asia
Xuemin (Sherman) Shen, University of Waterloo
Zhisheng Niu, Tsinghua University

Abstract

Moving toward 4G, wireless ad hoc networks receive growing interest due to users' provisioning of mobility, usability of services, and seamless communications. In ad hoc networks fading environments provide the opportunity to exploit variations in channel conditions, and transmit to the user with the currently "best" channel. In this article two types of opportunistic transmission, which leverage time diversity and multi-user diversity, respectively, are studied. Considering the co-channel interference and lack of a central controller in ad hoc networks, the "cooperative and opportunistic transmission" concept is promoted. For opportunistic transmission that exploits time diversity, it is observed that the inequality in channel contention due to the hidden terminal phenomenon tends to result in energy inefficiency. Under this design philosophy, we propose a distributed cooperative rate adaptation (CRA) scheme to reduce overall system power consumption. Taking advantage of the time-varying channel among different users/receivers and being aware of the potential contention among neighboring transmissions, we propose a QoS-aware cooperative and opportunistic scheduling (COS) scheme to improve system performance while satisfying QoS requirements of individual flows. Simulation results show that by leveraging node cooperation, our proposed schemes, CRA and COS, achieve higher network throughput and provide better QoS support than existing work.

Wireless ad hoc networking has recently attracted growing interest, and has emerged as a key technology for next-generation wireless networking. Devices enabling the wireless ad hoc networking paradigm are becoming smaller and cheaper, with lots of embedded capabilities delivering services seamlessly to end users and paving the path toward 4G. In an wireless ad hoc network a node sends or forwards packets to its neighboring nodes by accessing the shared wireless channel. A significant characteristic of a wireless channel is time-varying fading due to the existence of multiple transmission paths between a source and a destination. In practice, the channel quality among surrounding hosts[1] can vary significantly for both mobile and stationary nodes. Any change in the line-of-sight path or any reflected path will affect the channel quality and hence change the data rate that is feasible with multirate networks (e.g., IEEE 802.11a supports eight channel rates ranging from 6 to 54 Mb/s). Although traditionally viewed as a source of unreliability that needs to be mitigated, recent research suggests exploiting the channel fluctuations *opportunistically* when and where the channel is strong.

In wireless ad hoc networks there are two main classes of opportunistic transmission. The first is to exploit time diversity of an individual link by adapting its transmit rate to the time-varying channel condition [1–3]. The basic idea is to transmit more packets at higher rates when the channel condition is better. Exploiting multi-user diversity is another class of opportunistic transmission, which jointly leverages the time and spatial heterogeneity of channels to adjust rates. In wireless networks a node may have packets destined to multiple neighboring nodes. Selecting instantaneously an "on-peak" receiver with the best channel condition improves system performance [6–8].

However, most existing opportunistic transmission schemes do not consider the interaction among neighboring transmitters (i.e., a sender individually makes its local decision to maximize its own performance). It is hard to obtain the optimal overall system performance without leveraging node cooperation due to the following challenges. First, with a hidden terminal there is inequality in channel contention among nodes in wireless ad hoc networks, which can result in severe overall performance inefficiency. Second, with the shared wireless medium, co-channel interference has a deep impact on rate selection and flow scheduling in wireless ad hoc networks. Hence, neighboring transmitters should jointly determine the

[1] *Without explicit mention, host and node are exchangeable in this article.*

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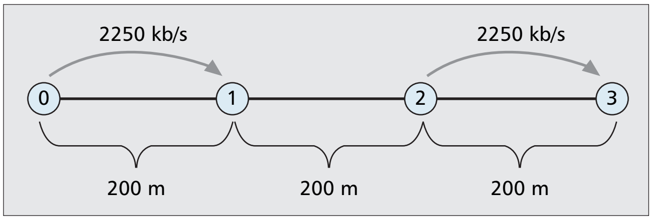


■ Figure 1. *Chain topology and traffic patterns.*

"on-peak" flows and their corresponding rate in a distributed way. Third, different QoS requirements of the system correspond to different optimization targets, e.g., energy efficiency and throughput maximization, which call for different strategies. All these challenges require an efficient node cooperation mechanism to coordinate the transmissions among neighboring nodes.

In this article we prompt the "cooperative and opportunistic transmission" concept, and present two schemes to address time diversity and multi-user diversity in wireless ad hoc networks, respectively. Specifically, we propose a distributed cooperative rate adaptation (CRA) scheme to achieve energy efficiency in wireless ad hoc networks. Given the neighboring link information, each node adopts a rate selection algorithm to calculate the most energy-efficient setting of rates for all links in its maximum interference range. Then the node consults the neighboring nodes about the feasibility of this new physical layer (PHY) rate. The procedure is repeated until it converges. Moreover, we propose a cooperative and opportunistic scheduling (COS) scheme to exploit multi-user diversity for wireless ad hoc networks while fulfilling given quality of service (QoS) requirements. By exchanging interference information, average channel conditions, and QoS factors among neighboring nodes in a two-hop transmission range, cooperative scheduling aims to find out the globally optimal set of simultaneously transmitting flows. In addition, through cooperation, some transmissions are deferred to favor some other links that have not achieved their QoS requirements. Simulation results demonstrate the effectiveness of the proposed two opportunistic transmission schemes in wireless ad hoc networks.

Related Work

Opportunistic Multirate Media Access

It is well known that the time-varying nature of a wireless channel can be captured by coherence time, Tc, which is a statistical measure of the time duration over which the channel impulse response is essentially invariant. Therefore, the channel signal-to-noise ratio (SNR) values separated by more than Tc can be approximately independent. The fact that coherence intervals are on the order of multiple packet transmission times provides a key motivating factor for designing opportunistic scheduling policies for multirate wireless ad hoc networks.

The first commercial implementation to exploit this multirate capability is Auto Rate Fallback (ARF) [1]. With ARF, after a number of consecutive successful transmissions, the sender tries to transmit at a higher rate, and vice versa after consecutive losses. An enhanced protocol, Receiver Based Auto Rate (RBAR), is proposed in [2]. Motivated by the fact that a receiver has better understanding of the channel condition, the key idea of RBAR is for receivers to measure the channel quality and control the sender's transmission rate. An advanced medium access control (MAC) protocol called Opportunistic Auto Rate (OAR) is presented in [3] with the key observation that the channel coherence time typically exceeds multiple packet transmission times for both mobile and stationary users. Consequently, when encountering a high-quality channel, OAR grants the user a channel access time that allows multiple packet transmissions back to back. As the subsequent packet transmissions are also highly likely to be successful at the higher data rate, OAR obtains a throughput gain over RBAR and ARF.

ARF, RBAR, and OAR can be characterized as opportunistic across users, exploit periods of high channel quality to achieve throughput gain. However, none of them exploit the presence of *diversity* in frequency domain (in the form of multiple channels). Recent studies indicate that significant throughput gain can be obtained by selection of a better quality channel. With such an observation, Multichannel Opportunistic Auto Rate (MOAR) and opportunistic multichannel MAC (OMC-MAC) are proposed to exploit the channel variation across multiple channels and achieve multichannel diversity gain [4].

Opportunistic Scheduling with Multi-User Diversity

The fundamental rationality for leveraging multi-user diversity lies in that, in practice, the channel between any sender-receiver pair is independent of other sender-receiver pairs. Exploiting multi-user diversity is firstly studied by Knopp et al. for cellular networks [6], which demonstrated that the total uplink capacity can be maximized by picking the user with the best channel to transmit. Motivated by this study, practical opportunistic scheduling schemes have been implemented in Qualcomm's High-Data Rate system and the 1xEV-DO system in 3G standards.

In contention-based networks, the key challenges for exploiting multi-user diversity are the absence of a central scheduler and a dedicated channel for closed-loop feedback. Almost during the same timeframe, two schemes that exploit time and space-varying channels for wireless ad hoc networks are proposed: opportunistic media access and rate adaptation protocol (OSAR) [7] and Medium Access Diversity (MAD) [8], respectively. In these schemes two similar channel probing mechanisms are introduced: Multicast Request-To-Send (RTS) in OSAR and Group RTS in MAD. After probing, the sender schedules the rate-adapted transmission to the receiver that experiences the best channel condition. A new rate adaptation scheme, Packet Concatenation (PAC), is proposed in MAD. Adopting PAC, a sequence of physical data frames to the same receiver are transmitted back-to-back, while eliminates the acknowledgments (ACKs) and short interval frame space (SIFS) between consecutive data packets. In both OSAR and MAD, a sender individually makes its local decision without considering the interaction among neighboring transmitters. However, without explicit coordination among the neighboring transmitters, it is hard to fulfill the QoS requirement for individual flows (we elaborate on this further later).

Cooperative and Opportunistic Rate Adaptation for Energy Efficiency

Energy efficiency is one of the key issues in wireless ad hoc networks since most mobile devices are battery-operated. An effective way to achieve energy efficiency is to reduce the transmission power whenever possible. However, in a multirate enabled network, reducing transmission power may result in reduced transmission rate. Moreover, in an wireless ad hoc network, the hidden terminal phenomenon will cause one node to have smaller contention probability than another node (say, a node in the "hidden" position); hence, different nodes will have different probabilities of winning the channel access (we call this phenomenon inequality of channel access).

	PHY rate on (0, 1)	PHY rate on (2, 3)	Total power consumption (mW)
Non-cooperative solution	48 Mb/s	9 Mb/s	6.704
Optimal solution with node cooperation	18 Mb/s	18 Mb/s	2.352

Table 1. *PHY rates and energy consumption comparisons.*

It can be shown later that this inequality of channel access can result in severe overall energy inefficiency. Thus, it calls for node cooperation in rate adaptation to achieve high overall energy efficiency.

Why Node Cooperation?

In this section, through an example, we will illustrate how the inequality in channel competition can result in unfair channel access and energy inefficiency. Consider a network with chain topology as shown in Fig. 1. There exist two flows with the same traffic rate requirement of 2250 kb/s from node 0 to 1 and from node 2 to 3, respectively. Each node uses IEEE 802.11a. Since node 2 is a "hidden terminal" of node 0, the transmission from node 2 to node 3 can corrupt the concurrent signals received by node 1 from node 0. However, since node 3 is out of the interference range of both node 0 and node 1, the transmission on (2, 3) will not be corrupted by the transmission on (0, 1).

In IEEE 802.11 data transmission is initiated by the sender when it senses the channel is idle. In Fig. 1 the channel sensed idle by node 2 is also free for node 3 to receive data. However, the channel sensed idle by node 0 may actually be busy in node 1 due to the hidden terminal effect. Therefore, node 2 gains an advantage over node 0 in channel contention. With a non-cooperative strategy, each node only takes its own energy efficiency into consideration for rate adaptation; then node 2 will choose the most energy efficient rate (9 Mb/s in this case), as long as its own traffic requirement can be satisfied. To fulfill its own QoS requirement, node 0 then has to adopt a higher rate with higher transmission power. In this case, although node 2 can save some energy with a low PHY rate, the total transmission power consumption for both nodes 0 and 2 is still high. This could result in global energy inefficiency. Table 1 shows the adopted PHY rates and total transmission power consumption for the non-cooperative solution and the optimal solution with node cooperation, respectively. It can be seen that there is significant gap between these two solutions. In summary:

- In wireless ad hoc networks, the inequality in channel contention could result in unfair channel time allocation among links/
- If each node only takes its own energy efficiency into consideration, this unfair channel time allocation could result in global energy inefficiency.

Therefore, to achieve global optimality in energy consumption, node cooperation among nodes is needed. In the following, we propose such a mechanism. a cooperative rate adaptation (CRA) algorithm.

Distributed Cooperative Rate Adaptation

The distributed CRA scheme consists of information exchange, rate selection, and node cooperation. Information exchange is to help each node obtain relevant information on 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 rates on the link. With this link information, each node uses the rate selection algorithm to calculate the most energy-efficient setting of rates for all the links in its maximum interference range. Then each node requests its neighboring nodes to check the feasibility (the probability that QoS requirements can be fulfilled) of this new rate setting through node cooperation. The rate change is accepted when it is feasible and can reduce energy consumption.

In [5] we have proven that the rate-adaptive power minimization problem is NP-complete and it can be mapped to the typical multiple-choice knapsack problem. Although we decompose the problem into subproblems for each node, a subproblem at each node is still a multiple-choice knapsack problem. Thus, we seek a heuristic solution, where each node adopts the following rate selection algorithm to calculate the most energy-efficient setting of PHY rates for all the links in its maximum interference range.

Step 1 Set the rate for each link in node 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 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 ΔE ΔT among all the links within A's maximum interference range. If we can not find a setting that results in $\Delta E > 0$, the algorithm ends.

Step 3 Check whether the new rate of the link is feasible. If it is feasible, select the new rate setting; otherwise, reset to the previous setting.

Step 4 Go to step 2.

Suppose there are K available rates, which are indexed from 0 to $K - 1$ in the descending order. If link l switches its rate from i to j, we define the *benefit ratio* of replacing rate i with j on link l (power consumption reduced over channel time increased) by

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

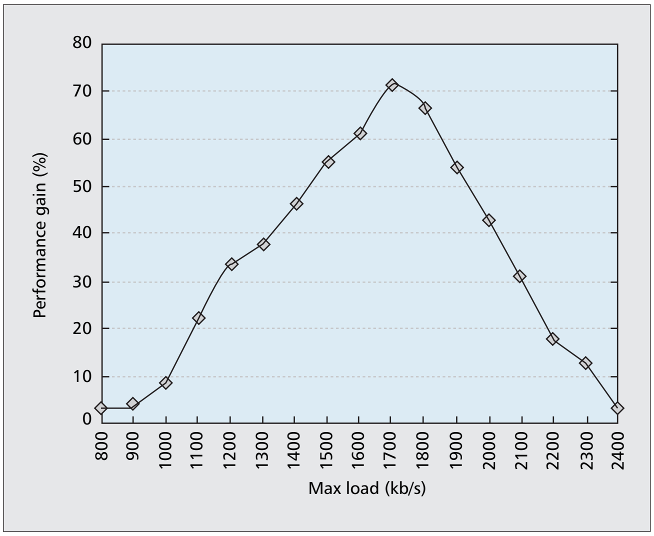
where *channel_time*(l, i) is the needed channel time for satisfying the traffic requirements on l under rate i, and *power_consumption*(l, i) is the power consumption on l under rate i. It can be seen that step 2 in this rate selection algorithm is to find the link with the maximum achievable benefit ratio among all the links.

Performance evaluation for CRA

We developed a simulator using C++ to evaluate and compare the performance of CRA with that of the non-cooperative heuristic under various topologies and traffic patterns. We conduct simulations under three types of topologies: chain, grid, and random topologies. In all the simulations, performance gain is defined by

$$1 - \frac{Energy\ consumption\ by\ CRA}{Energy\ consumption\ by\ non-cooperation\ heuristic}.$$

Due to page limits, we only show the results with random topology. The geographical area is a square of 1000 m $\times$ 1000 m, where 50 nodes are randomly placed and 15 traffic requests are randomly created. The traffic rate of each request is uniformly distributed from 0 to a predetermined maximal load. We perform a series of simulations by varying the maximal load. For each setting, the performance gain of CRA is



■ Figure 2. *Performance gain of CRA over a non-cooperative heuristic under random topologies.*

obtained by averaging the simulation results performed under 50 randomly generated network topologies. Figure 2 shows the performance gain of CRA under different maximal loads. It can be seen that in most cases, CRA achieves high average performance gain (up to 72 percent) over the non-cooperative heuristic. Note that when the data rate is around 800 kb/s, each link on the chain can satisfy its traffic requirement by using the most energy efficient rate; so there is no need for optimization (i.e., the non-cooperative heuristic achieves the same performance as that of CRA). Moreover, when the data rate is above 2400 kb/s, each link on the chain has to use the highest rate to meet its traffic requirement; hence, there is no room for optimization. Thus, the performance gain of proposed CRA mainly comes when the data rate is between 800–2400 kb/s.

QoS-Aware Cooperative and Opportunistic Scheduling

In wireless ad hoc networks a node may have packets destined to multiple neighboring nodes, where the channel conditions to different neighbors can be totally different. Due to the co-channel interference in wireless ad hoc networks, two links that contend with each other cannot be scheduled concurrently. Hence, neighboring transmitters should jointly determine the on-peak flows. While selecting on-peak receivers, it is also important to consider QoS requirements of each flow. To favor a flow that does not achieve its requirement, the transmitter should offer more transmission opportunities to that flow. Moreover, the neighboring transmitters should be coordinated to reserve the shared wireless bandwidth to reduce the potential collision to that flow.

Why Cooperative Scheduling?

In this section we illustrate that the existing opportunistic schemes, taking OSAR as an example, cannot pick up the globally optimal transmitting link set that maximizes overall network performance due to the local decision. Moreover, we show that the QoS requirements are not easily satisfied without cooperation among neighboring transmitters.

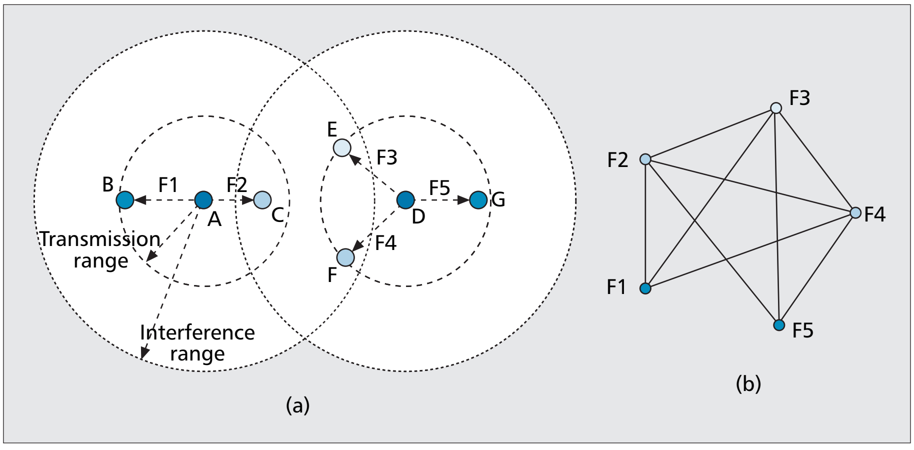
As shown in Fig. 3, transmitter A has two candidate receivers, B and C. Meanwhile, transmitter D is going to communicate with E, F, and G. In this example C is out of node D's transmission range but in its interference range. Thus, node D is a hidden terminal to node C. Suppose that there is no ongoing communications at the beginning, and node A sends its group RTS (GRTS). As OSAR suggests, node A will pick up its nearest neighbor, C, as its receiver. Node D cannot decode node C's CTS, so it sends its own GRTS. Node D chooses node G for data transmission, as E and F suffer interference from ongoing transmission A→C. By OSAR, two flows A→C and D→G are arranged to transmit simultaneously. However, due to the hidden terminal effect, the transmission of flow A→C fails once node D transmits. Actually, for this specific example, flows A→B and D→G are optimal from the global point of view to avoid potential contention.

Consider adding a certain QoS requirement (e.g., bandwidth) to flow A→C in the above network. By OSAR, node A should offer this flow more transmission opportunities, since it suffers a high collision probability induced by hidden terminal D. However, the more opportunities are given, the more packets are lost due to collision. It means that without coordination among transmitters, higher bandwidth requirements may lead to severe effective throughput degradation. However, if node D cooperatively defers its transmission or, in other words, keeps silent when A is transmitting, the QoS requirement of flow A→C may easily be achieved and the overall throughput increase.

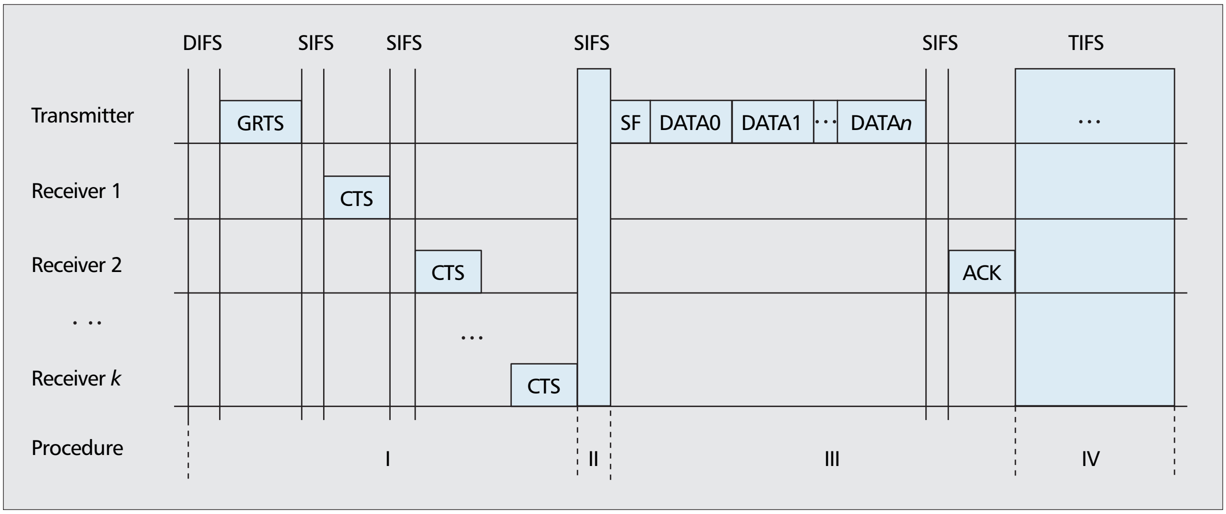
Cooperative and Opportunistic Scheduling

The problem of cooperatively exploiting multi-user diversity for wireless ad hoc networks has been formulated in our previous work [9]. We found a scheduling policy that maximizes the average system performance while satisfying generalized QoS requirements of individual flows. With the help of information sharing, we propose a distributed COS algorithm to find the globally best set of flows that can transmit simultaneously and maximize overall system performance. In addition, we introduce the cooperation strategy among neighboring transmitters to favor flows with QoS requirements by deferring the transmission of other flows.

The basic procedure of COS includes four components: channel probing, credit calculation, data transmission, and flow scheduling. Group RTS and prioritized CTS are used in



■ Figure 3. *An examples with two transmitters which both have several candidate receivers: a) topology for the two-trasmitter scenario; b) corresponding contention graph.*



■ Figure 4. *Illustration of cooperative and opportunistic scheduling on the frame format.*

the channel probing module to estimate channel conditions and facilitate information exchange within two-hop transmission range. Detailed information, including the average supported data rates and QoS factors of the flows that are in the node's local contention graph (LCG) (Fig. 3b), is piggybacked on the outgoing GRTS and CTS packets. In the credit calculation module, each transmitter should calculate the credit of each maximal independent subset (MIS), where the flows in the same independent subsets can transmit simultaneously, before the data transmission. After that, the credit of all the flows and all the transmitters can also be calculated, while the flow with the highest credit is picked up as the transmitter's outgoing flow. In the data transmission step, the transmitter sends back-to-back packets on this selected flow with the PAC mechanism as designed in [8]. To fulfill the QoS requirement, after one sequence of transmission (i.e., RTS, CTS, DATA, and ACK), the flow scheduling is performed in the transmitter to decide the time interval inserted before starting the next transmission. The typical timeline on the frame format is shown by Fig. 4. Next we describe in detail two important parts of the proposed COS: credit calculation and flow scheduling.

Credit Calculation — To pick up the flows that maximize network throughput, each transmitter should calculate the credit of each MIS before data transmission. Through the information exchange during the channel probing and LCG building process, a transmitter can gather all the parameters needed in optimal scheduling criteria (as indicated in the following equation), such as the contention graph, the supported data rate of each flow, and their QoS factors.

$$Q^*(t) = S_{m^*}(t),\ m^* = \arg\max_m \left\{ \sum_{i \in S_m} \mu_i (1+\lambda_i) \right\},$$

where $\mu_i(t)$ is the highest rate that the ith link supports in timeslot t, and λ_i is the QoS factor of the ith flow.

After the calculation of the credits of all the MIS, the credit of all the flows and all the transmitters can also be determined. Here, a flow's credit is set to the largest credit of the MIS that includes this flow, and a transmitter's credit is set to the largest credit of the flows originated by this transmitter. Taking Fig. 3 as an example, there are four MIS, $\Omega = \{Sm(t)\} = \{\{F_1, F_5\}, \{F_2\}, \{F_3\}, \{F_4\}\}$ and we assume that the credits of the four MIS are 7, 6, 5 and 4 respectively. In this case, $S1(t)$ has the largest credit, where the credits of flows $F1$ to $F5$ are {7, 6, 5, 4, 7} and the credits of the transmitter A and D are both 7. Then a set of flows, in one MIS with the largest credit, in this example, flows 1 and 5, are scheduled to transmit simultaneously. After the transmissions, each flow updates its QoS factor according to the following equation:

$$\lambda_i^{k+1} = \begin{cases} \lambda_i^k + a^k (G_i - C_i^k), & \text{if } G_i > C_i^k \\ 0 & \text{otherwise} \end{cases},$$

where G_i denotes the long-term QoS requirement of the ith flow, C_i^k is the throughput achieved until time slot k, and for the stationary case, we can set $a^k = 1/k$; otherwise, we set a^k to a small constant to track the system variation.

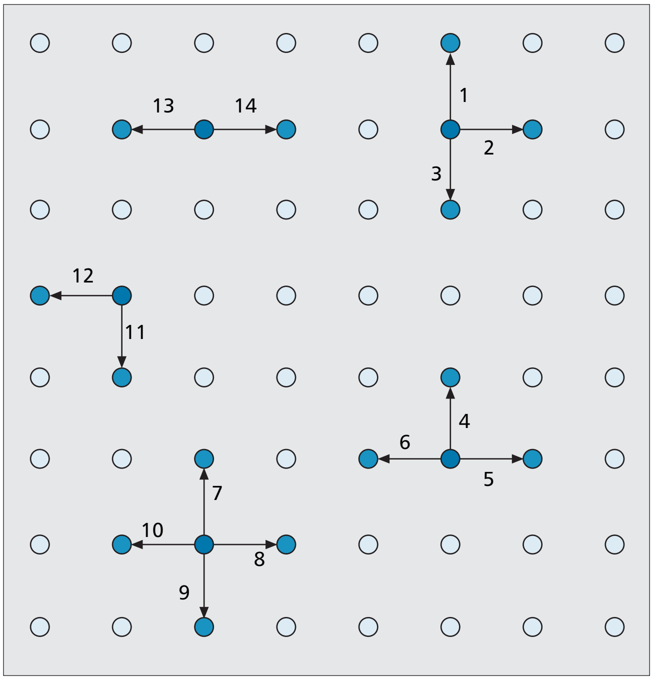
Flow Scheduling — To fulfill the QoS requirement for some specific flows, we may need to defer the transmission of the other neighboring flows. In COS, an interval called a traffic-control interframe space (TIFS), is inserted into two consecutive DATA transmissions if the transmitter is not scheduled. The transmitter adjusts the length of TIFS according to the order of its credit. The optimal length of TIFS is the duration from now until the transmitter's credit becomes the largest. Hence, the optimal value depends on the number of neighboring transmitters, coherent time of the varying channel, and QoS requirements of contending flows. TIFS can be adjusted as

$$TIFS = \begin{cases} 0 & \text{if } seq = 1 \\ TIFS_{\min} & \text{if } TIFS = 0 \text{ and } seq > 0, \\ \min(TIFS \times seq, TIFS_{\max} & \text{otherwise} \end{cases}$$

where seq denotes the credit order of one transmitter among all the transmitters in its LCG. seq = 1 means that this transmitter has the largest credit. The exponential increase leads to quick convergence to the optimal value, whereas TIFS is reset to zero once the credit has become the largest.

Performance Evaluation of COS

The simulations for demonstrating the effectiveness of COS are conducted with ns-2.29. We compare COS with OAR and OSAR. The available rates are set to 1 Mb/s, 2 Mb/s, 5.5 Mb/s, and 11 Mb/s based on IEEE 802.11b. To evaluate the performance of OSAR with QoS constraints, we combine OSAR with the single-cell optimal scheduling criterion, where a transmitter activates the flow whose credit $\mu_i(1+ \lambda_i)$ is the



■ Figure 5. *An example of 14 random flows generated in a grid topology.*

largest among all its originating flows. We set up an 8 × 8 grid topology with 64 nodes in which a 14-flow example is illustrated, as shown in Fig. 5.

From Fig. 6a, it can be seen that without any QoS constraint, the network throughputs adopting OAR, OSAR, and COS are 8.70 Mb/s, 10.16 Mb/s, and 13.72 Mb/s, respectively. In other words, COS achieves 35 percent performance gain over OSAR and 60 percent over OAR. The reason is that the throughput of flows 1, 2, and 5 increases intensely. Given QoS requirements of the first six flows as $G1 = G2 = \ldots = G6 =$ 1.0 Mb/s, Fig. 6b shows that COS successfully achieves the requirements by cooperatively controlling the sending pattern of surrounding transmitters. Without node cooperation, OSAR fails to reach the targets.

Conclusion

In general, the channel quality of wireless hosts varies significantly for both mobile and stationary nodes. Rather than trying to mitigate such channel variation, recent studies are targeted at exploiting the channel fluctuations by transmitting information opportunistically when and where the channel is strong. Two types of opportunistic transmission have been studied in this article, which leverage time diversity and multiuser diversity of the data transmission, respectively. More specifically, a distributed cooperative rate adaptation scheme is proposed to achieve energy efficiency in wireless ad hoc networks by exploiting time diversity in opportunistic transmission. A QoS-aware cooperative and opportunistic scheduling scheme is proposed to improve system performance while satisfying the QoS requirements of specific flows by taking advantage of a time-varying channel among different receivers. In conclusion, opportunistically accessing the varying wireless channel opens a new direction for wireless networking related research. Besides the time diversity and multi-user diversity discussed in this article, channel diversity and path diversity are also potentially able to provide opportunities to improve overall system performance. How to leverage node cooperation to exploit all the different types of diversity in wireless networks is worth further study.

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References

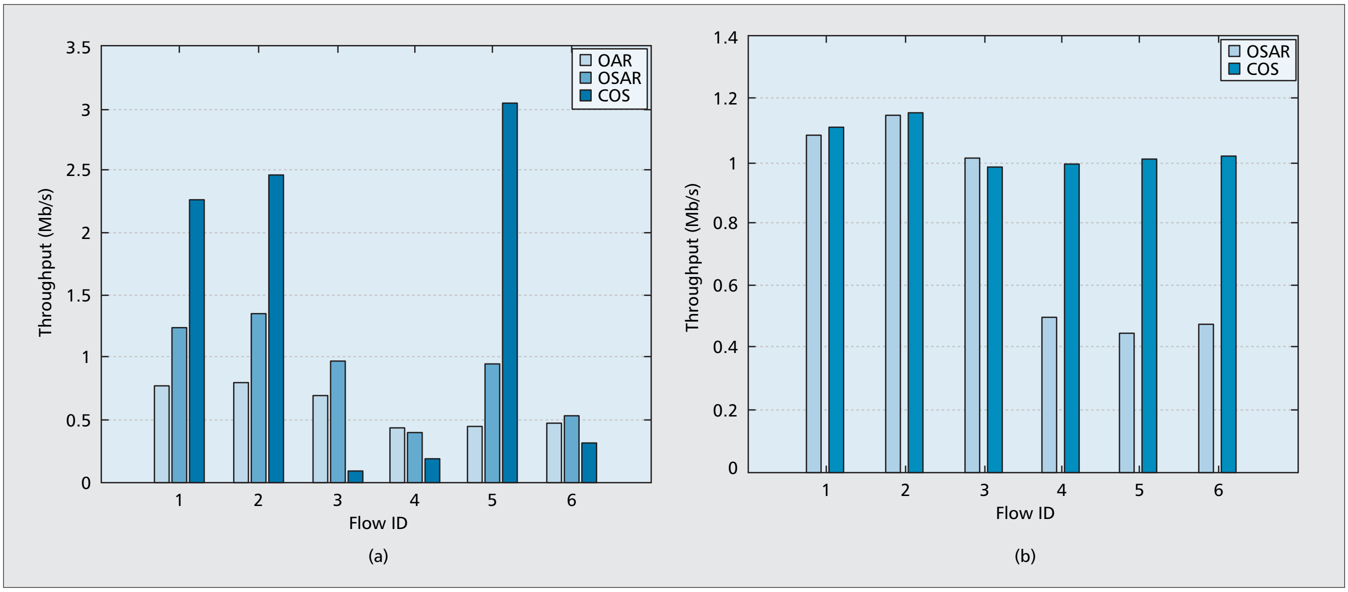
[1] A. Kamerman and L. Monteban, "WaveLAN II: A High-Performance Wireless LAN for the Unlicensed Band," *Bell Labs Tech. J.*, Summer 1997.

[2] G. Holland, N. Vaidya, and P. Bahl, "A Rate-Adaptive MAC Protocol for Multi-Hop Wireless Networks," *Proc. ACM MOBICOM '01*, pp. 236–51, July 2001.

[3] B. Sadeghi *et al.*, "Opportunistic Media Access for Multirate Ad Hoc Networks," *Proc. ACM MOBICOM '02*, Sept. 2002, pp. 24–53.

[4] D. Zheng and J. Zhang, "Protocol Design and Throughput Analysis of Opportunistic Multi-Channel Medium Access Control," *CIIT '03*, Scottsdale, AZ, Nov. 2003.

[5] K. Wang et al., "Distributed Cooperative Rate Adaptation for Energy Efficiency in IEEE 802.11-based Multi-Hop Networks," *IEEE Trans. Vehic. Tech.*, 2006.



■ Figure 6. *Throughput of the first six flow in the example as illustrated by Fig. 5: a) without QoS requirements; b) with QoS requirements:* G*1* = G*2* = … = G*6* = *1.0 Mb/s.*

[6] R. Knopp and P. Humblet, "Information Capacity and Power Control in Single-Cell Multiuser Communications," *Proc. IEEE ICC '95*, vol. 1, June 1995, pp. 331–35.
[7] J. Wang *et al.*, "Opportunistic Media Access Control and Rate Adaptation for Wireless Ad Hoc Networks," *Proc. IEEE ICC '04*, vol. 1, June 2004, pp. 154–58.
[8] Z. Ji *et al.*, "Exploiting Medium Access Diversity in Rate Adaptive Wireless LANs," *Proc. ACM Mobicom '04*, Sept. 2004, pp. 345–59.
[9] Q. Chen, Q. Zhang, and Z. Niu, "QoS-Aware Cooperative and Opportunistic Scheduling Exploiting Multi-User Diversity for Rate Adaptive Ad Hoc Networks," HKUST tech. rep., 2006.

Biographies

QIAN ZHANG [M'00, SM'04] (qianzh@cs.ust.hk) is an associate professor in the Department of Computer Science and Engineering, Hong Kong University of Science and Technology. He has published more than 150 refereed papers in international leading journals and key conferences in the areas of wireless/Internet multimedia networking, wireless communications and networking, and overlay networking. He is an Associate Editor for *IEEE Transactions on Wireless Communications*, *IEEE Transactions on Vehicular Technologies*, *IEEE Transactions on Multimedia*, and *Computer Networks*. He received the TR 100 (*MIT Technology Review*) world's top young innovator award in 2004.

QING CHEN [StM] (qingchen99@mails.tsinghua.edu.cn) received his B.S. degree from the Department of Electronic Engineering, Tsinghua University, Beijing, China, in 2003. Currently, he is a Ph.D. candidate in the Department of Electronic Engineering, Tsinghua University. His research interests include power control, MAC layer scheduling, and quality of service in wireless ad hoc networks.

FAN YANG [M'05] (fanyang@microsoft.com) received B.S., M.S., and Ph.D. degrees in computer sscience from Nanjing University, China, in 1997, 2000, and 2003, respectively. He joined Microsoft Research Asia (MSRA), Beijing, China, in March 2004 as an associate researcher in the Wireless and Networking Group. His research interests include wireless networking, distributed computing, multimedia communications, mobile computing, and Internet architecture and protocols.

XUEMIN (SHERMAN) SHEN [M'97, SM'02] (xshen@bbcr.uwaterloo.ca) is a professor and associate chair for graduate studies, Department of Electrical and Computer Engineering, University of Waterloo, Canada. His research focuses on mobility and resource management in interconnected wireless/wireline networks, UWB wireless communications systems, wireless security, and ad hoc and sensor networks. He serves as the Technical Program Committee Chair for IEEE GLOBECOM '07. He also serves as an Associate Editor for *IEEE Transactions on Wireless Communications*, *IEEE Transactions on Vehicular Technology*, *ACM Wireless Networks*, and *Computer Networks*. He is a registered Professional Engineer of Ontario, Canada.

ZHISHENG NIU graduated from Northern Jiaotong University, Beijing, China, in 1985, and got his M.E. and D.E. degrees from Toyohashi University of Technology, Japan, in 1989 and 1992, respectively. In 1994 he joined Tsinghua University, Beijing, China, where he is now a professor in the Department of Electronic Engineering. From April 1992 to March 1994 he was with Fujitsu Laboratories Ltd., Kawasaki, Japan. His current research interests include teletraffic theory, radio resource management, mobile Internet, and stratospheric communication systems.