Altruistic Cooperation for Energy-Efficient Multi-Channel MAC Protocols

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ABSTRACT

Recently, a new notion of cooperation was proposed to solve *multi-channel coordination problems*. When a transmit-receive pair wishes to initiate communication, neighboring nodes share their knowledge of channel usage. This helps to substantially reduce collisions and increases throughput significantly. However, it comes at the cost of increased energy consumption since idle nodes have to stay awake to overhear and acquire channel usage information. In fact this can be as high as 264% of a power-saving protocol without cooperation. In this paper, we propose a strategy called *altruistic cooperation* for cooperative multi-channel MAC protocols to conserve energy. The core idea is to introduce specialized nodes called altruists in the network whose only role is to acquire and share channel usage information. All other nodes, termed peers, go in to the sleep mode when idle. This strategy seems naive because it needs additional nodes to be deployed. In fact, it is unclear whether a desirable throughput-energy trade-off can be achieved and whether the cost of additional nodes can offset the performance gain. We perform a close study on this strategy in terms of three aspects: network deployment, cost efficiency, and system performance. Our study indicates that only a few additional nodes need to be deployed and cost efficiency is more than doubled in terms of a new metric called *bit-price ratio* that we propose. By using the strategy, a cooperative protocol is found to save up to 70% energy while not compromising throughput.

Categories and Subject Descriptors

C.2.1 [**Network Architecture and Design**]: Wireless communication

General Terms

Design, Performance

Keywords

Cooperation, Energy Efficiency, MAC Protocol, Multi-Channel

1. INTRODUCTION

The main challenge to multi-channel MAC protocol design for ad hoc networks is a *multi-channel coordination problem*. It consists of a *channel conflict problem*, caused by a node (unintentionally) selecting a busy channel for data transmission,[1] and a *deaf terminal problem*, caused by a node initiating communication with another node which is however on a different channel. The first subproblem results in packet collision and the second leads to unnecessary retransmissions. The mainstream of proposed solutions uses either multiple transceivers or time synchronization to address the problem, but it clearly increases cost, overhead and complexity[7].

Recently, Luo et al. [4] introduce a new notion of *cooperation* and thereby propose a cooperative multi-channel MAC protocol called CAM-MAC. Unlike in traditional MAC protocols nodes making decisions independently, in CAM-MAC idle neighbors actively aid transmit-receive pairs in selecting correct channels and avoiding deaf terminals. The protocol uses a single transceiver and is fully asynchronous, and demonstrates significant throughput advantages. In particular, it substantially outperforms three recent and representative multi-channel MAC protocols, MMAC [8], SSCH [1], and AMCP [6] (see [5]).

However, we point out that the performance gain comes at the cost of significant energy consumption. In order to cooperate, nodes have to stay awake during idle periods in order to gather and share channel usage information, which prevents them from sleeping to save energy. We evaluated this via simulations in a single-hop network, comparing it with a power-saving protocol without cooperation. We found that, when there are 40 nodes forming 20 disjoint source-destination pairs and each source generates traffic at 160kbps, the cooperative protocol consumes energy as high as 264% of the power-saving uncooperative protocol.

This motivates the need of designing energy efficient strategies for cooperative protocols, however it is even more difficult than for traditional protocols, because (i) the *prerequisite* of cooperation is information gathering which can be done only when nodes are awake, and (ii) *extra* energy has to be spent on transmitting/receiving *cooperative messages*. In this paper, we propose a strategy called *altruistic cooperation* which is a simple solution to this challenging problem. The key idea is to introduce additional nodes called *altruists*, whose only role is to cooperate but not carry traffic. These altruists always stay awake so that existing nodes can sleep when idle.

This strategy seems naive since it uses additional resources to improve performance. In fact it is unclear whether (i) the

[1] One of such scenarios is that control packets sent on a certain channel fail to inform neighboring nodes communicating on a different channel, which is termed by [8] as a multi-channel hidden terminal problem.

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total energy can be conserved, (ii) throughput will be compromised, and (iii) the increased network cost will pay off. In particular, we identify three open issues that are fundamental to altruistic cooperation:

1. How to optimally deploy altruists in the network?

2. Can the increased network cost offset performance gain?

3. How it impacts the throughput-energy trade-off?

The above questions will be addressed in the sequel.

2. APPROACH AND BACKGROUND

We take a role-based approach for our study. We identify three possible roles in a protocol, which are self-explanatory: (a) *carry traffic*, (b) *gather information*, and (c) *share information*. Here information means channel usage information. Based on this, we classify nodes into two categories: (i) *peers* are existing nodes whose role is to carry traffic, and can optionally take the other two roles, and (ii) *altruists* are additional nodes whose only role is information gathering and sharing. Table 1 shows that different role assignments combined with the choice of using the power saving mode lead to different schemes. Note that altruists use the same hardware and software (i.e., protocol) as peers, and they only differ in configuration: peers sleep when idle (thus not taking the role of information gathering and sharing) while altruists do not relay traffic (thus taking only the role of cooperation).

Table 1: Roles Assignment

Schemes	Traffic	Gather	Share	PSM
Auto-PSM	peer	×	×	✓
Autonomous	peer	peer	×	×
In-situ Coop	peer	peer	peer	×
Altruistic Coop	peer	altruist	altruist	peer

The details of the above schemes are as follows. The altruistic cooperation scheme and in-situ cooperation scheme are identical cooperative protocols—in the former only the additional altruists cooperate, while in the latter the existing nodes both relay traffic and also cooperate. This cooperative protocol is an improved version of CAM-MAC [4]. It uses a PRA/PRB/CFA/CFB control channel handshake, where PRA/PRB is like 802.11 RTS/CTS for negotiating a data channel, and CFA/CFB is to confirm the channel selection. Cooperation is introduced via INV messages: if any neighbor judges that the handshake will lead to a multi-channel coordination problem (based on the overheard PRA/PRB), it prepares to send an INV to invalidate the handshake. The INV contains the channel usage information of the *ongoing* data channel communication (not the one to be established). More details can be found in [5].

The autonomous protocol is identical to the cooperative protocol except that the cooperation element is removed, i.e., neighbors do not send INV messages. The autonomous-PSM protocol is identical to the autonomous protocol except that a power saving mode is used, i.e., nodes enter sleep when idle.

Our assumptions are as follows. Each node in the network has a single half-duplex transceiver that can dynamically switch among multiple orthogonal frequency channels but can only use one at a time. One channel is designated as the control channel and the others are designated as data channels. All nodes have identical transmission and interference ranges. Propagation delay is negligible. Other assumptions include:

- *Control channel handshake*: A transmitter and a receiver perform a handshake on the control channel to negotiate a data channel. The data channel is randomly chosen from the set of channels deemed free by both of them. The handshake carries channel usage information (e.g., "who will use which channel for how long").

- *Data channel handshake*: Upon a successful control channel handshake, both nodes switch to the chosen data channel and the transmitter sends a data packet without sensing the data channel. Then the receiver sends an acknowledgment packet on the same data channel upon successful reception. Following that nodes switch back to the control channel.

- *Reactive cooperation*: A node cooperates only if it identifies a multi-channel coordination problem.

2.1 Cooperation Coverage

DEFINITION 1. *An* unsafe pair *(UP) consists of two peers that can cause multi-channel coordination problems to each other. A* covered unsafe pair *(CUP) is an UP in which* both *peers are within the radio range of an altruist. In other words, they are* covered *by at least one common altruist.*

The necessary and sufficient condition of causing multi-channel coordination problems (i.e., forming an UP) is given below.

PROPOSITION 1. *In an undirected graph where vertices represent peers in a network and edges represent peers' neighbor relationships, let d_i be the degree of an arbitrary peer i. If power saving mode is not used, then two adjacent peers (i, j) form an UP if and only if:*

1) $d_i \geq 2$, $d_j \geq 2$, and $d_i = d_j = 2$ does not hold, or

2) $d_i = d_j = 2$, and i and j are not on the same three-cycle (triangle).

If the power saving mode is used (i.e., peers sleep when idle), then the condition remains unchanged for the channel conflict problem, while for the deaf terminal problem it changes to: $d_i \geq 1$, $d_j \geq 1$, and $d_i = d_j = 1$ does not hold.

DEFINITION 2. Cooperation coverage *is the ratio between the number of CUPs and the number of UPs in a network. A network achieves* full cooperation coverage *if all UPs are CUP, i.e., the ratio is 100%.*

2.2 Simulation Setup

To compute power consumption, we did a survey on commercial wireless cards. By simple calculations based on [3], IEEE 802.11 WaveLAN PC cards consume a power of 1327/967/843/66 mW in TX/RX/IDLE/SLEEP state for the 2Mbps category, and of 1346/901/741/48 mW for the 11Mbps category. According to [2], Cisco Aironet 350 series Wi-Fi cards consume a power of 2250/1350/75 mW in TX/RX/SLEEP state. Other products such as Intel Pro 2011, 3Com xJack, Compaq WL1000, and Siemens SS1021 also have the similar data. Therefore we use the average of all above as 25/18/15/1

×50mW for the TX/RX/IDLE/SLEEP state. In simulations, we calculate the fraction of time each node stays in the four states respectively, and do a weighted sum using these rates.

There is one control channel and five data channels with channel capacity 1Mbps each. Data packets are generated at each source according to a Poisson point process. Payload size is 2KB. We ignore channel switching delay since it is common to all schemes that we compare.

In single-hop scenarios, peers form disjoint source-destination pairs (i.e., flows). In multi-hop scenarios, nodes are uniformly distributed in a terrain of 1500m×1500m. The radio range is 250m. In each simulation with n peers, n non-disjoint flows are randomly formed by designating each peer as the source of one flow and the destination of another flow. Shortest path routing is used.

We use a discrete event-driven simulator that we developed on Fedora Core 5 with a Linux kernel of version 2.6.9. We terminate each simulation when a total of 100,000 data packets are sent over the network. All results are averaged over 15 randomly generated networks.

3. NETWORK DEPLOYMENT

Consider a random network with peers distributed on a plane according to a 2D Poisson point process, the question is to determine the density of altruists to be deployed, ρ_{alt}, in order to guarantee a certain cooperation coverage, p_{cov} (say 90%).

Denote by p_{ij}^{cov} the probability that an arbitrary UP (i, j) is covered (i.e., is a CUP). By Definition 1, p_{ij}^{cov} is equivalent to the probability that there is at least one altruist in the common radio range of i and j, which is given by

$$p_{ij}^{cov} = 1 - e^{-\rho_{alt} A_{ij}}, \qquad (1)$$

where A_{ij} is the intersected area of i and j's radio ranges.

The problem is equivalent to guaranteeing $p_{ij}^{cov} > p_{cov}$ for all UPs (i, j), hence we have

$$\min_{(i,j)} p_{ij}^{cov} > p_{cov}. \qquad (2)$$

By determining the minimum we can finally obtain

$$\rho_{alt} > -\frac{\ln(1 - p_{cov})}{(\frac{2\pi}{3} - \frac{\sqrt{3}}{2})r^2}. \qquad (3)$$

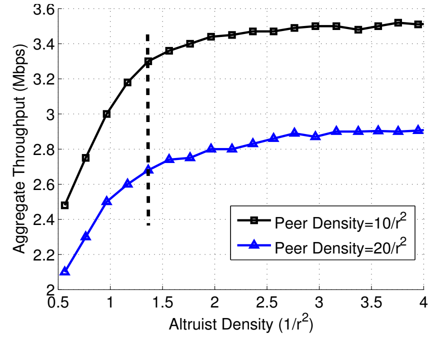
Inequality (3) gives the lower bound to the altruist density that guarantees a cooperation coverage of p_{cov}. We provide typical values in Table 2, where the unit of density is r^{-2}.

Table 2: Altruist Density versus Cooperation Coverage

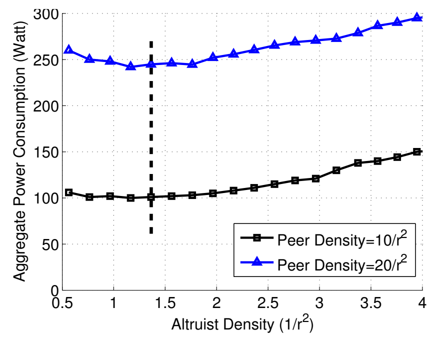
p_{cov}	50%	60%	70%	80%	90%	95%	99%
$\rho_{alt} >$	0.56	0.75	0.98	1.31	1.87	2.44	3.75

A judicious choice of altruist density is a key to the performance of altruistic cooperation. We conduct simulations in multi-hop networks and vary altruist density from $0.56/r^2$ to $3.75/r^2$, which corresponds to a cooperation coverage from 50% to 99% as indicated in Table 2. Two peer densities are considered: $10/r^2$ and $20/r^2$, which amount to 360 and 720 peers in a network, respectively. The traffic generation rate at each peer is 25kbps.

The results are shown in Fig. 1. We observe the following: in Fig. 1(a), both curves level off at the altruist density of around $1.36/r^2$, while in Fig. 1(b), both curves have a minimum also at around $1.36/r^2$. This suggests that an optimal throughput-energy trade-off can be achieved within the range of 1.3–$2/r^2$.



(a) Throughput.



(b) Energy consumption.

Figure 1: Multi-hop performance versus altruist density.

We also highlight the independence between altruist density and peer density, as indicated by both our analysis (no ρ_{peer} appears in (3)) and simulations. This property of independence significantly simplifies altruist deployment in practice.

4. COST EFFICIENCY

Cost efficiency is important from a system design perspective. To evaluate it, we propose a metric called *bit-price ratio* (BPR), which captures the trade-off among three critical factors: network throughput, lifetime, and cost. This metric is defined as

$$BPR \triangleq \frac{S}{(N_p + N_a) \cdot \max(P_p^{max}, P_a^{max})}, \qquad (4)$$

where S is aggregate network throughput, N_p and N_a are the total number of peers and altruists, respectively, and P_p^{max} and P_a^{max} are the maximum power consumption among all peers and all altruists, respectively.

BPR can be understood as $Throughput \times Lifetime/Cost$, which gives the amount of data that can be delivered by a network throughout its operational time, normalized by available system resources. The lifetime is defined as the period from the start of network operation until the first node runs out of battery. For networks without altruists, simply set $N_a = 0$ and $P_a^{max} = 0$.

BPR allows for a fair comparison of cost efficiency across different protocols. We compute BPR for different protocols via simulations in multi-hop networks, where for altruis-

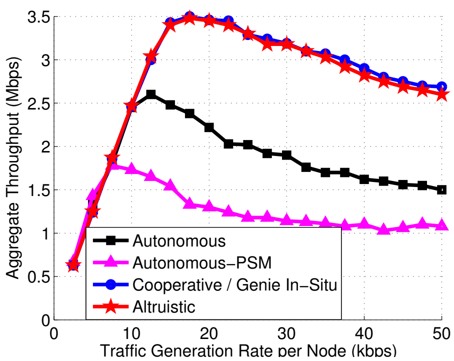
Table 3: BPR Comparison

Peer Density ($1/r^2$)	5	10	20	30
BPR_{Auto}	22.3	9.32	3.8	2.26
$\text{BPR}_{AutoPSM}$	33	10.9	4.1	2.7
$\text{BPR}_{InSituCoop}$	22.5	14.8	6	3.77
$\text{BPR}_{AltCoop}$	42.4	31.2	10.9	5

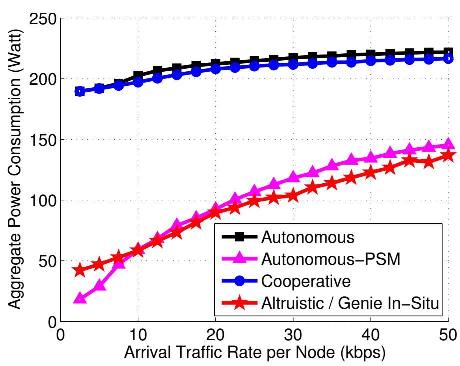
tic cooperation, we deploy altruists with a density of $1.31/r^2$ based on the suggestion from Section 3 (1.3–$2/r^2$), which corresponds to a cooperation coverage of 80%. Traffic generation rate is 25kbps. The results are summarized in Table 3. We can see that altruistic cooperation is the clear winner among all the four schemes (more than twice BPR of the other three in most cases). This shows that, introducing additional nodes contributes to performance gain and more than offsets the increased cost.

5. PERFORMANCE EVALUATION

We evaluate performance of all the four schemes in Table 1 in multi-Hop networks. Peer density is $10/r^2$, and for altruistic cooperation, altruist density is set to be $1.31/r^2$, as used in Section 4.



(a) Throughput.



(b) Energy consumption.

Figure 2: Multi-hop network performance.

From the throughput shown in Fig. 2(a), we observe clear gaps among the schemes. At the traffic generation rate of 20kbps, the autonomous scheme achieves 1.73 times the throughput of autonomous-PSM, and the two cooperative schemes achieve 1.55 times the throughput of the autonomous scheme. The gap between autonomous and autonomous-PSM is because of the role of information gathering, and the gap between the cooperative schemes and the autonomous scheme is because of the role of information sharing which is introduced by cooperation. More importantly, we see that altruistic cooperation does not sacrifice throughput in comparison to in-situ cooperation.

From the energy consumption shown in Fig. 2(b), we see that altruistic cooperation and autonomous-PSM consume a substantially lower amount of energy than in-situ cooperation and the autonomous scheme. At the traffic generation rate of 20kbps, altruistic cooperation uses power of only 39% of both in-situ cooperation and the autonomous scheme. Furthermore, altruistic cooperation even slightly outperforms autonomous-PSM under higher traffic load. This is because, although altruists incur added energy drain, they help avoid a large number of retransmissions caused by multi-channel coordination problems.

6. CONCLUSION

Cooperation which refers to distributed information sharing instead of data forwarding helps multi-channel MAC protocols to improve network throughput. However this can incur significant energy consumption. In this paper, we propose an energy efficient strategy, called altruistic cooperation, to address this problem. We demonstrate that altruistic cooperation achieves high throughput and low energy consumption simultaneously, and is cost efficient in terms of bit-price ratio.

This paper is the first treatment of energy efficiency for cooperative multi-channel MAC protocols, and also presents a further study on the new notion of cooperation. We believe, based on our investigation, that this notion of cooperation has significant implications to future protocol design.

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