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Date Submitted: 6 June 2009
Date Published: 12 June 2009

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**Subject Classification**  Vehicular Technology

**Keywords**  Cooperative diversity; Medium access control; Cross-layer design and optimization;

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Cooperation or Not in Mobile Ad Hoc Networks: A MAC Perspective

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Abstract—In this paper, we investigate benefits of cooperative communication in mobile ad hoc networks (MANETs). Cooperative communication as an effective way to mitigate channel impairments has attracted much attention, especially on the physical layer. However, without properly designed higher-layer protocols, the cooperation gain can decrease and even disappear, due to factors such as limited payload and nonnegligible overhead. A two-hop interference model from a medium access control (MAC) point of view is proposed to study the performance of a cooperative network. Analysis based on the model demonstrates that cooperation may not be beneficial when the number of blocked nodes increases. Further, a busy-tone based cooperative MAC scheme is presented to investigate the gain from cooperative communication and the relationship among influential factors. Simulation results demonstrate that the node density and traffic load greatly impact the effectiveness of cooperative communication.

I. INTRODUCTION

Cooperative communication is a promising diversity technique that has attracted significant research interests [1, 2], where mobile nodes share their information and transmit cooperatively, forming a virtual antenna array and thus providing diversity without the requirement of additional antennas at each node. Most existing works on cooperative communications focus on various issues at the physical layer to improve the point-to-point link quality in a single-user scenario, and the advantages of cooperation are often demonstrated by analyzing signalling strategies based on information theory [3]. However, how to efficiently and fairly allocate resources in a distributed wireless network is still a challenging task, such as in mobile ad hoc networks (MANETs) where there are multiple users. On one hand, many information theoretical results on cooperation are based on an asymptotically large data block length and usually without considering the overhead needed to set up and maintain coordinated transmissions. In practice, however, the payload length is always limited due to error control and may change with various applications, and overhead from each protocol layer is not negligible especially when the payload length is short. Thus, the cooperation gain may disappear if higher-layer protocols are not appropriately designed. On the other hand, for networks such as MANETs, there is no central controller and, due to user mobility, the network topology and the wireless channels change dynamically with time. How to design higher-layer protocols to exploit cooperation gain is a challenging issue in such a networking environment.

In this article, we focus on modeling and analyzing impacts of cooperative communication on MANETs, from a medium access control (MAC) point of view. MAC design for cooperative networks is a relatively new research area. In [4, 5], two similar protocols (called CoopMAC and rDCF) based on the IEEE 802.11 DCF are proposed respectively to mitigate the throughput bottleneck caused by low date rate nodes. A high-rate node is allowed to help a low-rate node through two-hop transmission. Coded cooperation is integrated with CoopMAC to boost its performance in [6]. Based on a cooperative MAC protocol named COMAC, the relationship between throughput/energy gains and transmission distance is investigated for wireless sensor networks in [7]. It is observed that throughput and energy gains can be achieved when the transmission distance is long enough. With joint routing and cooperation, a cross-layer approach is introduced in [8]. Clusters of nodes near each transmitter form virtual multiple-input single-output (VMISO) links to a receiver on the routing table and as far as possible to the transmitter. Space-time codes are utilized to support transmission over a long distance, thus reducing the number of transmission hops and improving communication reliability. However, helper selection and overhead control still need to be refined in these works. Relay selection and thus the associated overhead are not considered in [7]. Before cooperation, enquiries are sent out to one or a group of helpers to check whether it or they can help transmission [4, 5, 6, 8]. The strategies of helper selection are either based on observation of the historical transmissions or random selection. Factors including time-varying channel, traffic load, and node density can influence the efficiency of such strategies. Further research is needed to study the dependency of cooperation gain on the layers above the physical layer.

The remainder of this paper is organized as follows. In Section II, we propose an analytical model to capture factors which impact the network performance when cooperation is adopted. A busy-tone based cooperative MAC is proposed in Section III. Its performance analysis is presented in Section IV. Simulation results are presented in Section V, followed by concluding remarks in Section VI.

II. TWO-HOP INTERFERENCE MODEL

Interference control for spatial frequency reuse is always a key issue in distributed wireless networks, and cooperation by virtue of providing diversity is associated with the issue. We investigate the interference control and spatial frequency
Non-cooperative range helper is illustrated in Fig. 1. In a cooperation mode, helpers H_{i,j} (i ≠ j) send their packets to the next hop neighbor node D_{j} but not in node j’s interference (transmission) range. Obviously, helpers should be conscribed only when cooperation is involved. For simplicity, only one node H_{i} is considered for their communication. For cooperation, we adopt a two-timeslot cooperative strategy: The first slot, the source node broadcasts data to helper nodes, and then in the second slot they transmit cooperatively to the destination node. Thus, a valuable cooperation for point-to-point communication corresponds to

\[ T_{C1} + T_{D1} + T_{D2} < T_{C0} + T_{D0}. \]

However, because of the channel occupancy at the helper H_{i} side, nodes in its neighborhood may detect transmit power from H_{i} and defer their transmission in CSMA/CA based MAC, leading to a harmful impact on spatial frequency reuse, a reduction of the total throughput within the two-hop interference range. We investigate this negative impact by determining the number of transmission blocked nodes during the data transmission time T_{Dj} as follow.

Nodes that may interfere the reception of a data packet at destination D without cooperation (in T_{D0}) belong to set S_{D0},

\[ S_{D0} = N_{D\setminus S}^T - N_{D}^T. \]

Nodes that may interfere the reception of a data packet at a receiver (D or H_{i}) with cooperation need to be separated to two parts, in times T_{D1} and T_{D2}, respectively. Node D is a receiver in both T_{D1} and T_{D2}, and its interference sets in these two time slots are given by

\[
\begin{align*}
S_{D1} &= N_{D\setminus S}^T - N_{D}^T \setminus (\cup_{H_{i}})^{h_{i}}_{i=1} \cup D, & \text{in } T_{D1} \\
S_{D2} &= N_{D\setminus((\cup_{H_{i}})^{h_{i}}_{i=1}, S)}^T - N_{D}^T + \Delta, & \text{in } T_{D2}.
\end{align*}
\]

where R_{nc}(\cdot) and R_{nc}(\cdot) are the information data rate with and without cooperation respectively, h_{i} is the channel gain between nodes i and j. I_{j} is the interference at node j receiver, O_{i} and O_{nc} are the overhead of cooperation and non-cooperation modes respectively. Note that due to the reception at node H_{i}, interference at H_{i} also needs to be considered. Fig. 2 illustrates the time frame structures to transmit a packet with and without cooperation, where T_{C1} and T_{Dj} are the transmission times for control messages and data packet respectively. For cooperation, we adopt a two-timeslot cooperative strategy: In the first slot, the source node broadcasts data to helper nodes, and then in the second slot they transmit cooperatively to the destination node. Requiring more control message exchanges, cooperation usually needs more time on transmission setup, i.e., T_{C1} > T_{C0}, however, time can be saved when the data packet is in transmission depending on the transmission rates, i.e., T_{D1} + T_{D2} < T_{D0}. Also, the data transmission periods in the two cooperative slots may not be equal, depending on the cooperative transmission technique and the channel state. Thus, a valuable cooperation for point-to-point communication corresponds to

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\[ T_{C1} + T_{D1} + T_{D2} < T_{C0} + T_{D0}. \]
node D. Since $H_i$ only receives data in $T_{D1}$, its interference set in cooperation mode is

$$S_{H_i} = N^T_{H_i \setminus S} - N^T_{(\cup_{j=1}^N H_j) \cup D}. \tag{5}$$

From (3) to (5), it can be found that there are less interference sources to a receiver with cooperation than without cooperation. However, as a cost, extra spatial and frequency resources are consumed by cooperation. We quantify the amount of resources in terms of the set of blocked nodes that have to defer their transmissions in $T_{D1}$ and $T_{D2}$, respectively, which are given by

$$E_{D1} = N^T_{(\cup_{j=1}^N H_j) \cup D} - N^T_{S}, \tag{6}$$

$$E_{D2} = N^T_{(\cup_{j=1}^N H_j) \cup S} - N^T_{S} - \Delta. \tag{7}$$

Note that spatial and frequency resources in $\Delta$ should not be treated as awaist if they are initiated before $T_{D2}$.

From the above simple analysis, cooperation may not be beneficial under some conditions that (1) traffic load is too high, resulting in a large cost in terms of traffic blocked nodes, and (2) cooperation gain is too small (due to factors including channel state, node density, cooperative technique and protocol overhead) to compensate for its cost. A tradeoff between cooperation and non-cooperation is needed to balance these factors.

Table II lists the blocking and interference states of other three data flows of Fig. 1 based on the above analysis.

### TABLE II

<table>
<thead>
<tr>
<th>Flow 2</th>
<th>Non-cooperation</th>
<th>Cooperation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blocked</td>
<td>Blocked</td>
<td></td>
</tr>
<tr>
<td>Flow 3</td>
<td>Unblocked</td>
<td>Blocked if traffic is initiated in $T_{D2}$, otherwise interfere $H_i$ and $D$.</td>
</tr>
<tr>
<td></td>
<td>and interfere $D$</td>
<td></td>
</tr>
<tr>
<td>Flow 4</td>
<td>Unblocked but do not interfere $D$</td>
<td>Blocked if traffic is initiated in $T_{D2}$, otherwise interfere $H_i$ and $D$.</td>
</tr>
</tbody>
</table>

III. CROSS-LAYER MAC DESIGN

Consider a MANET with a number of mobiles nodes. Each node in the network can be a source, a destination, or a relay node for others. Due to user mobility, a wireless channel is time varying. A transmitter can generate larger interference to its neighbor nodes if their channels are in a better condition due to channel fading. To analyze the gain from cooperative communication and the relationship among the influential factors, a cross-layer designed dual busy-tone based cooperative MAC scheme is proposed here based on 802.11 DCF. The total channel bandwidth in the system is divided into three parts with sufficient spectral separation: an information channel, a transmitter busy-tone (BTt) channel, and a receiver busy-tone (BTr) channel.

Since spatial frequency reuse maximization is difficult to achieve in MANETs due to dynamic network topology, time-varying channel, and lack of central control to acquire network traffic information, we design our protocol for contention based link utility maximization. We first assume that cooperation is always needed and design the MAC protocol; then, we investigate impact of the protocol on the value of cooperation, so as to enable the protocol to intelligently determine if cooperation is worthwhile. By formulating a utility based optimization problem on protocol parameters and cooperation gain, we want to optimize performance of the protocol and provide a way to balance cooperation and non-cooperation in the network with a high traffic load.

Under the assumption of cooperative communication, we first devise a helper selection method. We adopt the helper selection method proposed in [9], where the helper nodes monitor instantaneous channel conditions toward the source and destination via the request-to-send (RTS) and clear-to-send (CTS) packets, and then decide in a distributed fashion which node has the strongest path for information relaying by letting the stronger path holder send a flag packet earlier. Though only one helper (the optimal one) is utilized, information theoretical analysis of outage probability shows [9] that the backoff scheme achieves the same diversity-multiplexing tradeoff as a multi-helper cooperative protocol. Another advantage of this strategy is that higher spatial frequency reuse can be achieved as less traffic nodes are blocked in a high traffic load.

Cooperation is able to increase receiver signal-to-noise-ratio (SNR) to support a higher transmission rate. Thus, different from [9], where only one constant transmission rate is considered, we modify the helper selection strategy by integrating with multi-rate transmission and letting the highest transmission rate provider send a flag earlier.

We use Fig. 3 to explain the proposed cooperative MAC. A node can start data transmission only when neither second busy-tone signals, BTt and BTr, are sensed, and the data channel is free. Then the source node S initiates its transmission by turning on its BTt and sending an RTS packet to its destination node D after finishing its backoff. The destination node (that is idle and detects no BTr signal) turns on its BTt and sends a CTS packet to receive the data from S and responds to S with a CTS packet including the estimated SNR. Each of the common neighbors of the S and D hears both the RTS and CTS packets and determines the maximal cooperative S-D transmission rate if it does not sense BTr. Denote the maximal non-cooperative S-D rate and the maximal cooperative S-D rate (supported by a potential helper (PH), $h$, which can increase the transmission rate) as $R_1$ and $R_2$, respectively. The rate $R_1$ depends on not only the modulation and coding scheme but also the cooperation technique. Let $M$ denote the number of possible useful cooperative S-D rates, which is a function of the payload length $W$ and non-cooperative S-D rate $R_1$. For efficient helper selection, we evenly partition the useful cooperative rates into $G$ groups. To
minimize helper selection overhead, the values of $M$ and $G$ are to be optimized. Then, a PH contends to be the optimal helper through following three destination-assisted contention procedures, inter-group contention, intra-group contention, and minislot re-contention.

1) **Inter-group Contention:** Before inter-group contention, every PH needs to turn on its BTr to inform S and D of its existence and willingness to help. If S (D) can not detect BTr during the SIFS after the reception (transmission) of a CTS packet, it turns to non-cooperative transmission immediately; correspondingly, D switches its BTt to BTr for the data protection. In addition, non-cooperative transmission should be chosen if the non-cooperative rate $R_1$ is higher than any possible cooperative rates, which can happen with a good S-D channel state and/or a large protocol overhead. In this case, D directly turns on BTr instead of BTt when it sends CTS to S.

After a short interframe space (SIFS), all PHs step to inter-group contention by sending a group indication (GI) signal in the assigned group time slot after a group backoff off time, whose duration $T_{fb1}$ is inversely proportional to the group helping capability defined by cooperative rate, given by

$$ T_{fb1} = g \cdot t_{fb}, \quad 1 \leq g \leq G $$

where $t_{fb}$ is the backoff time slot, and $g$ is the group index. A higher rate helper group, a lower group index. Thus, the members of a higher rate helper group send GI of the members of a lower rate group. Once a PH hears GI from other helpers, it turns off BTr immediately, by which medium resources on its side can be released immediately. A destination-assisted piggyback mechanism shown in Fig. 4 is used to facilitate this information forwarding in case that helpers are hidden from each other, where the destination node sends a stopping indication (SI) signal once it detects a GI signal.

2) **Intra-group Contention:** After inter-group contention, intra-group contention begins, in which the optimal helper finishes its self-appointment by sending a member indication (MI) signal after a backoff time $T_{fb2}$. The duration is inversely proportional to the PH's cooperative rate, given by

$$ T_{fb2} = m \cdot t_{fb}, \quad 1 \leq m \leq M/G $$

where $m$ is the member index in a group. The higher rate member, the smaller member index. Other PHs with a longer backoff time duration in the same rate group are released through the same piggyback mechanism. Then, a ready-to-help (RTH) packet with the information of cooperation strategy is sent by the optimal helper to the source node to invite it to start transmission.

3) **Minislot Re-contention:** In the case of multiple optimal helpers, the source node cannot send out a data packet for the failed reception of the collided RTHs, which will be detected by the good helpers using a timer set as $(SIFS-slot)$. Then collided helpers do re-contention in $K$ minislots ($K \geq 2$). Its contention mechanism is similar to the intra-group contention. The only difference is that they send out indication signals in a randomly selected minislot rather than a fixed one. The duration of a minislot is equal to a backoff slot. Again the source node piggybacks the signal to avoid further collision. The probability of a re-collision depends on the number of minislots, $K$, to be determined in the performance analysis.

At last, we let a non-cooperative transmission start immediately after a SIFS of the failed reception of the RTH in minislot re-contention. Since the parameters $M$, $G$ and $K$ are constant for given payload length $W$ and non-cooperative S-D rate $R_1$, any receiver nodes (the optimal helper and the destination node) can determine the maximal waiting time for date reception accordingly, and then decide at what time to turn off their busy-tone signals if the source node quits transmission for any reason.

### IV. PROTOCOL ANALYSIS

A. **Collision-free Piggyback Mechanism**

In this section, we analyze the protocol to ensure that the piggyback mechanism is free of collision in a cooperative scenario. The backoff time slot $t_{fb}$ consists of transmission time $t_{tx}$ and idle time $t_{idle}$, $t_{fb} = t_{tx} + t_{idle}$. The transmission duration $t_{tx}$ should be long enough to guarantee a valid detection at the receiver, and the idle duration $t_{idle}$ is to control the collision probability. We can avoid collision by appropriately setting the parameter $t_{idle}$. As illustrated in Fig. 4, denote the propagation delay of the channels, D-good PH, D-poor PH, S-D and S-good PH by $\tau_1$, $\tau_2$, $\tau_3$ and $\tau_4$, respectively. Taking inter-group contention for example, consider the worst case where the two PHs are in neighboring groups and $\tau_1 > \tau_2$. The poor PH stops contention only if

$$ \tau_1 - \tau_2 + t_{tx} + \tau_1 + t_{S1} + \tau_2 \leq t_{fb}. $$

Here we let the SI signal have the same duration with $t_{tx}$. Similarly, effective helper selection can be guaranteed in intra-group contention and minislot re-contention under (10).

In addition, to avoid a collision between the SI signal and the RTH packet at S in the intra-group contention and minislot re-contention, the SI signal should be terminated before the RTH's reception, i.e.,

$$ t_{tx} + \tau_1 + t_{S1} + \tau_3 \leq t_{fb} + \tau_4. $$

Combining (10) with (11), we get

$$ t_{idle} \geq t_{tx} + \tau_1 + \max\{\tau_1, \tau_3 - \tau_4\}. $$
Thus, the most efficient \( t_{idle} \) is
\[
t_{idle} = t_{tx} + \frac{d_1 + \max(d_1, d_2 - d_1)}{c} = \alpha \cdot t_{tx}
\tag{13}
\]
where \( d_i \) is the distance of transmission link with propagation delay defined as \( \tau_i \), \( c \) is the light speed, and \( \alpha > 1 \).

B. Performance Analysis

Since we use the BTr signal to make S and D aware of the existence and willingness of the helpers, cooperation happens only when it is valuable. To get the performance of the proposed protocol, we analyze it case by case.

1) Case One (Direct Transmission): When detecting no BTr signal from PHs, S transmits a data packet directly to D with rate \( R_1 \). The payload (with length \( W \)) and overhead transmission times, \( T_{1,p} \) and \( T_{1,o} \), are given by
\[
T_{1,p} = W/R_1, \quad T_{1,o} = T_{C1} + T_{C2}
\tag{14}
\]
where \( T_{C3} = T_{RTS} + T_{CTS} + T_{SIFS}, T_{C2} = L_O/r_b + T_{SIFS} + T_{ACK} \), with \( T_i \) being the packet \( i \)'s transmission time, \( L_O \) and \( r_b \) being the overhead length and the basic rate for packet overhead, respectively.

2) Case Two (No Collision in Intra-group Contention): When detecting a BTr signal from PHs, S and D wait for the optimal helper’s contention signals, i.e., GI, MI, and RTH. In the case of only one best helper, there is no RTH collision in intra-group contention. In this case, the payload and overhead transmission times, \( T_{2,p} \) and \( T_{2,o} \), are given by
\[
T_{2,p} = W/R_{C1} + W/R_{C2}
\tag{15}
\]
\[
T_{2,o} = T_{C1} + T_{fb1} + T_{fb2} + T_{C2} + T_{C3}
\tag{16}
\]
where \( R_{C1} \) and \( R_{C2} \) are the transmission rates of the first and the second hops in cooperation, respectively, and \( T_{C3} = T_{RTS} + 2T_{SIFS} + L_O/r_b \).

3) Case Three (No Collision in Minislot Re-contention): Due to the position and/or a similar channel condition of the source-helper-destination, collision cannot be avoided completely in intra-group contention. Making use of the re-contention in \( K \) minislots, it is possible to mitigate the problem. The probability of no collision in minislot re-contention depends on the parameter \( K \) and the number of collided helpers, \( n \), and is given by
\[
P_{\text{succ}}(K,n) = \binom{n}{i} \frac{K}{i^K} \cdot (K/K)^{n-i} \tag{17}
\]
where \( K \geq 2 \) and \( n \geq 2 \). Obviously, a large \( K \) value reduces the collision probability, but also increases the overhead time.

Compared with case two, successful re-contention activates the helper-based transmission, and the payload transmission time \( T_{3,p} \) is the same as that given in (15). However, the overhead transmission time, \( T_{3,o} \), by selecting the \( k \)th minislot, is increased to
\[
T_{3,o}(k) = T_{2,o} + T_{RTH} + T_{SIFS} + T_{slot} + k \cdot t_{fb}
\tag{18}
\]
and the probability that one of the \( n \) contending helpers wins the contention by selecting the \( k \)th minislot is
\[
P_{\text{win}}(k) = \left\{ \begin{array}{ll}
\frac{n(K-k)^{n-1}}{K^n}, & k = 1, 2, \cdots, K - 1 \\
0, & k = K.
\end{array} \right.
\tag{19}
\]

4) Case Four (Collision in Minislot Re-contention): Finally, we consider the last case that re-contention fails when more than one competing helper chooses the same minislot. According to the protocol, S will send out a data packet anyway but without cooperation, and the helper-based transmission degrades to a direct transmission from S to D. Thus, the payload transmission time \( T_{4,p} \) equals to \( T_{1,p} \), while the overhead transmission time \( T_{4,o} \), by selecting the \( k \)th minislot, is increased to
\[
T_{4,o}(k) = T_{1,o} + T_{fb1} + T_{fb2} + 2T_{RTH} + 2T_{SIFS} + T_{slot} + k \cdot t_{fb}
\tag{20}
\]
Given \( n \) competing helpers which recontent in the \( K \) minislots, the probability of re-contention fails due to more than one helper selecting the \( k \)th minislot is
\[
P_{\text{fail}}(k) = \left\{ \begin{array}{ll}
\sum_{i=2}^{n} \binom{n}{i} \frac{1}{i^K} (K/K)^{n-i}, & k = 1, ..., K - 1 \\
1/K^n, & k = K.
\end{array} \right.
\tag{21}
\]

C. Parameters Optimization

Based on the preceding analysis, the protocol parameters can be determined for link throughput maximization by solving such a problem: If helpers exist, how to set parameters \( K \), \( M \) and \( G \), according to the channel condition, payload length \( W \), and the average number\(^2\) \( n \) of collided helpers to achieve the maximal link throughput?

To answer the question, an integer optimization problem for the maximal mean throughput is formulated as
\[
\max J \\
\text{s.t. } J \geq \rho W/(T_{1,p} + T_{1,o})
\tag{22}
\]
where
\[
J = \left\{ \begin{array}{ll}
\frac{W}{T_{2,p} + T_{2,o}}, & n = 1 \\
\sum_{k=1}^{n} \left[ \frac{W \cdot P_{\text{win}}(k)}{T_{3,p}(k) + T_{3,o}(k)} + \frac{W \cdot P_{\text{fail}}(k)}{T_{4,p}(k) + T_{4,o}(k)} \right], & n \geq 2
\end{array} \right.
\]
and \( \rho \geq 1 \) is used to balance cooperation and non-cooperation for spatial and frequency reuse control. For a traffic load, only when the throughput gain is larger than \( \rho \) times, cooperation is active.

The problem can be solved off-line for given modulation and coding scheme and cooperative strategy. The one-to-one mapping between channel statistics and the transmission rate makes it an integer optimization problem.

\(^2\)We consider it as a priori condition and check it in the simulation.
V. Simulation Results

In the simulation, traffic at a source node is generated according to a Poisson process with mean rate $\lambda$ packets/s. Cross-layer design between physical and MAC layers are considered here. Thus, to have a fair comparison between cooperation and non-cooperation, we suppose that both schemes adopt the same routing protocol such as the shortest-path routing. We model the channel with joint log-distance path loss and Rayleigh fading, and change the channel gain independently after each coherence time. For simplicity, assume that the channel gain remains unchanged in one conversation. To evaluate the performance gap between cooperation and non-cooperation and the relationship among the influential factors (including node density, traffic rate, channel condition), we simulate the proposed protocol and compare it with IEEE 802.11a under two scenarios. In the first scenario, to study impact of node density, 10 fixed data flows each with $\lambda = 10$ packets/s are simulated in the network with 20, 40, 60, 80, and 100 nodes, respectively. The second scenario is to study impact of traffic load, where a different number of data flows (10, 20, and 30) each with $\lambda = 10$ packets/s are simulated in the network with 60 nodes. The random waypoint mobility model is adopted to model the node mobility. Simulation parameters such as network area $L^2$, path loss exponent $\kappa$, and node moving speed $v_{\text{min}}/v_{\text{max}}$, are listed in Table III. Other parameters are set to be the same as in IEEE 802.11a 20Mhz bandwidth transmission.

Fig. 5(a) shows the throughput results of scenario one. The throughput is defined as the total end-to-end received data packets per second in the network. The network throughput with the non-cooperative transmission is almost fixed when the number of nodes is larger enough to guarantee the network connectivity. However, the network throughput with cooperation increases with the node number due to increased chances of existing more and better helpers in the network. The performance degradation of cooperation when the node number is larger than 80 is due to more likely failures in helper contention. Notice that the protocol parameters for $n = 2$ mostly fit a small/medium scale network. Fig. 5(b) shows the ratio of cooperation based transmission hop number to the total transmission hop number in the scenario. It is observed that the number of valuable cooperative links increases with the node density.

Fig. 6(a) compares the network throughputs between cooperation and non-cooperation in scenario two. At the relatively high traffic load, the performance gain from cooperative transmissions is not significant, raising a question whether cooperation is worthwhile (taking into account of potential increase in system complexity). A smaller throughput gain is achieved by cooperation when the number of data flows increases. This performance degradation is caused by two factors: 1) A higher traffic load leads to a fewer nodes being able to join cooperation; and 2) Cooperation in a higher traffic load blocks more traffic nodes. Fig. 6(b) shows the ratio of the cooperation based transmission hop number to the total transmission hop number in scenario two. It is clear that cooperation is greatly suppressed in a network with a high traffic load.

VI. Conclusion

In this paper, we study cooperative communications based on a two-hop interference range model. Whether or not cooperation is helpful is investigated from a spatial frequency reuse point of view. With cooperation, a cooperative link benefits from less interference due to more suppressed interference sources; however, the increased number of traffic blocked nodes can degrade the network performance due to a lower spatial frequency reuse. A cross-layer designed busy-tone based MAC scheme is proposed to exploit potential performance gain by cooperative communications. Simulation of the proposed MAC scheme demonstrates that node density and traffic load can have a significant influence on the performance gain of a cooperative network.

REFERENCES