A Network Lifetime Aware Cooperative MAC Scheme for 802.11b Wireless Networks

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***Abstract*— Cooperative communication techniques have earlier been applied to design of the IEEE 802.11 medium access control (MAC) and shown to perform better. High rate stations can help relay packets from low-rate stations resulting in better throughput for the entire network. However, this also involves additional energy costs on the part of the relay which can result in reducing the network lifetime. We propose a cooperative MAC protocol NetCoop with the objective of maximizing the network lifetime and achieving high throughput. Based on this design, we also propose a flexible strategy which allows cooperation to be achieved using more than one relay. We show that this can achieve at least as good throughput as that of single relay cooperation while maintaining a high network lifetime.**

***Index Terms*— IEEE 802.11, cooperative MAC, multi-rate**

I. Introduction

Cooperative communication techniques have been shown to improve network performance by combining the transmission powers of multiple users for each transmission. While most of the attention has been on improving the signal-to-noise ratio in the physical layer, research focus has also been devoted to exploiting cooperative diversity at the MAC layer. Existing work on cooperation in the MAC layer can be broadly divided into proactive and reactive strategies. Proactive strategies involve making use of relays to improve the transmission quality between stations where the channel condition is low. In case of reactive strategies, intermediate nodes wait for an indication of incorrect reception of data from the receiver, following which they retransmit cached copies of the original data with the objective of reducing the number of retransmissions.

Some existing proactive strategies focus on multi-rate networks where low rate stations can obtain help from high rate ones. Two such mechanisms were outlined in rDCF [1] and CoopMAC [2] in which the source chooses from a list of potential relays for cooperation. More recently, Shan et al [3] proposed a cross-layer design by combining information from the physical layer to achieve cooperation at the MAC layer.

As shown in the above mentioned papers, cooperation in multi-rate networks can help overcome the negative effect of low-rate stations on the network throughput [5]. However, relaying would imply additional energy consumption for the relay node. In an infrastructure network, the nodes closer to the access point (AP) would typically enjoy better channel conditions and therefore, better data rates with the AP. Hence, they would act as relays for low-rate nodes farther away from the AP. This issue has been looked into by Narayanan and Panwar in [4]. Taking CoopMAC as the reference, they show that a node actually conserves energy by relaying. This is in accordance with earlier studies [6] [7] which have shown that the energy consumption in idle mode results in a majority of the energy consumption in wireless networks. As the transmission duration is shortened for the low rate transmission, the power consumed by the relay node is lower than the power it would have consumed by staying idle for the entire duration of a low rate transmission.

The IEEE 802.11 standard lists five modes for a network interface to operate : transmit, receive, idle, sleep and switch off. While the power consumption values for the first three states do not differ by much, a node can go into a low power sleep state to save energy, though it cannot transmit and receive data in this state. Some existing schemes ([8] - [11]) try to optimize the duration a node spends in the sleep state between its own transmissions so as the save maximum energy. In [10], Cano et al. propose a mechanism in which stations overhear RTS/CTS messages from other nodes and switch off their NICs for the duration mentioned.

Though taking part in cooperation can help save energy for nodes by reducing idle power consumption, it may not be beneficial for nodes which choose to spend idle time in the sleep state. A high data-rate node which acts as a relay thus spends additional power reducing its overall lifetime, which in turn affects the network lifetime. Thus, a potential relay may decline to cooperate and switch to the sleep state instead.

In this paper, we detail a cooperation framework for the MAC layer which seeks to optimize the tradeoff between network lifetime and throughput. Our algorithm NetCoop seeks to enhance cooperation by identifying the best possible relay while being sensitive to the network lifetime. We show that this can help obtain a balance between achieving high network throughput and maintaining a high network lifetime. Using the same framework, we propose a flexible cooperation strategy NetCoopMR which can support multiple relays and can perform at least as well as using a single relay.

In the next section, we discuss the motivation for a network lifetime aware strategy in detail and summarize the objectives.

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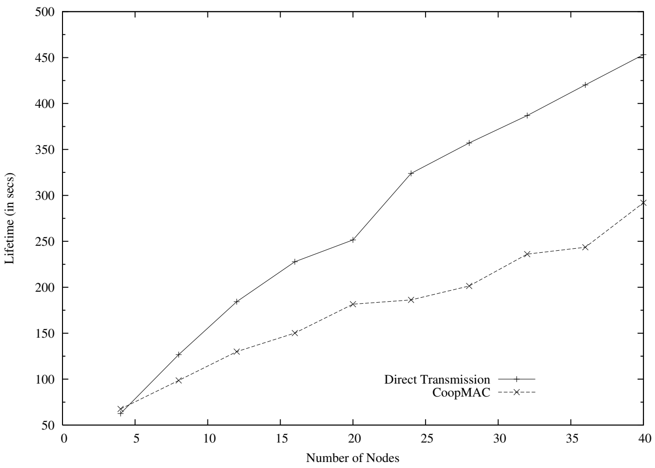

Fig. 1. Network lifetime of CoopMAC when compared to that of direct transmission.

In section III, we elaborate on the design of NetCoop followed by its analysis. In section V, we discuss the motivation for using multiple relays and subsequently elaborate on NetCoopMR. Simulation results are shown in section VI. Section VII concludes the paper.

II. Motivation and Objectives

As mentioned earlier, the energy consumption for a wireless network interface in the active state for the receive and idle modes is not much lower than that consumed in the transmit mode, though the energy consumption in the sleep mode is much lower. We use the power consumption values of the Lucent IEEE 802.11 WaveLAN card [13] which consumes 1.65 W, 1.4 W, 1.15 W and 0.045 W in the transmit, receive, idle and sleep modes respectively.

Similar to [10], we adopt a design where a node enters the sleep mode upon overhearing an RTS/CTS exchange for a transmission not involving itself, waking up after the specified duration. Earlier papers have raised concerns about the transition time of $250\mu s$ between the doze and awake states. However, considering an 802.11b network, the transmission time for a 2KB packet at the maximum transmission rate of 11.0 Mbps would take around 1.5 ms within which this transition could comfortably be achieved twice, i.e. for the node to enter the doze state and wake up again. Also, given the performance benefits of the sleep mode, we expect future wireless interfaces to have better support for this state with shorter transition times.

Considering an infrastructure network, we notice that if cooperation is allowed, the energy consumption for certain nodes closer to the AP could be much more than others. As we see in Fig. 1 for a cooperative strategy such as CoopMAC, this affects the network lifetime drastically.

Since in a cooperative scenario, a node participates in transmissions from other nodes in addition to its own transmissions, its lifetime would depend on the energy consumed due to both. Hence, we define the lifetime of a node in terms of the energy consumption per unit time. Thus, the lifetime of a node i with initial energy E_0 could be expressed as

$$T_i = \frac{E_0}{e_i} \tag{1}$$

where e_i denotes the energy consumption per unit time for node i. We assume all nodes have the same initial battery life. We can, therefore, define the network lifetime as the minimum of the lifetime of all nodes

$$T_{net} = \min_{i \in N_i} T_i \tag{2}$$

As noted earlier, given that cooperation can increase the energy consumption per unit time for the relay nodes, and thereby limit the lifetime of the entire network, we look to maximize the same while focusing on maintaining a high network throughput. We summarize our objectives as follows

$$\max f(T_{net}, \sum S_i) \tag{3}$$

where S_i denotes the throughput of a node i and the function f could be a weighted average of the two parameters. Thus, we aim to design a cooperative MAC protocol which gives better network lifetime than direct transmission. This can, in turn, be interpreted as, given a source s, destination d and a potential relay i, the minimum residual energy for direct transmission is less than that of cooperative transmission. We can formulate this as

$$\min g^{(dir)} \leq \min g^{(coop)} \tag{4}$$

where $g = (E(s), E(i), E(d))$ for any transmission strategy and $E(\cdot)$ denotes the residual energy of a node.

III. Network Lifetime Aware Cooperative MAC Protocol (NetCoop)

Here, we discuss the design of the NetCoop algorithm. We base our design on that of the CoopMAC protocol proposed earlier in [2]. Similar to [2], every station maintains a table recording the data rate between other pairs of stations by overhearing the exchange of control messages and packet headers. Unlike CoopMAC, however, stations switch to the sleep mode for transmissions not meant for itself. Additionally, stations periodically update their neighbouring stations with their residual battery life. This is included as a seperate field in the RTS message. A station which acts as a relay also includes it when it replies with a helper ready to send (HTS) message used in [2] to accept relaying. Subsequently, all neighbours overhearing the exchange of these control messages update their tables listing potential relays with their respective values of the residual battery life.

When a station wants to send data, it obtains a transmission likelihood Φ for each possible mode of transmission based on the potential throughput improvement as well as the effect on the energy consumption of the node. Subsequently, it chooses the mode of transmission with the minimum value of Φ. The the NetCoop algorithm is listed in Fig. 2.

If a relay is chosen, it similarly computes its own value of Φ as well as that of the source. It accepts the relay request if $\Phi_i < \Phi_{source}$. However, since the source chooses the mode of transmission with the minimum value of Φ, a relay would only

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NETCOOP (source):
    T_dir ← Time taken for direct transmission
    L ← Packet Size in Bytes
    for each node i in neighbourhood including itself:
        a ← first hop data rate
        b ← second hop data rate
        Φ_i = tx_likelihood(i, a, b, T_dir, L)
    Choose mode of transmission k= min_i {Φ_i}
    If k == source:
        transmit directly
    else:
        transmit using first hop data rate to relay k
TX_LIKELIHOOD(i, a, b, T_dir, L):
    q_res,i ← Residual Energy of i
    P_tx ← Transmit Power
    P_rx ← Receive Power
    Transmission time, T_i = 8L/a + 8L/b
    Energy consumption, q_i = P_rx 8L/a + P_tx 8L/b
    Q_i = q_i / q_res,i
    S_i = T_i / T_dir
    Φ_i = Q_i × S_i
    return Φ_i
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Fig. 2. Pseudocode for The NetCoop Algorithm

be chosen if this condition is satisfied. Hence, an equilibrium is reached and a node chosen as the relay would always accept.

Fig 3 shows an example of the NetCoop algorithm. Here, S is the source with a 1 Mbps data rate to the AP. S can obtain help from either of the two possible relays A and B, both of which are reachable at 11 Mbps from the source. The data rates at which A and B can transmit to the AP are 11 Mbps and 5.5 Mbps respectively. The residual energies in Joules for S, A and B are 4, 1.5 and 5 respectively. As cooperation through node A can result in better first and second hop data rates, it would be the preferred choice for relay. However, the value of transmission likelihood (Φ) for B is lower owing to higher residual energy. Hence, B is chosen as a relay instead of A.

The NetCoop algorithm can be thought of as applying a dual filter to the choice of relay by choosing a node on the basis of both the throughput improvement as well as energy constraints. It can easily be followed that the objective in (4) is also satisfied. In case of direct transmission, the source always transmits at the direct transmission rate which results in the same energy consumption irrespective of the residual energy. In case of NetCoop, the source actively chooses the mode of transmission which is affected least due to relaying. Thus, if a particular node is low on residual energy, the source would look for a different option which results in lower effective loss of energy.

IV. Analysis

As discussed in the last section, the design of NetCoop ensures that the choice of a relay is sensitive to both the

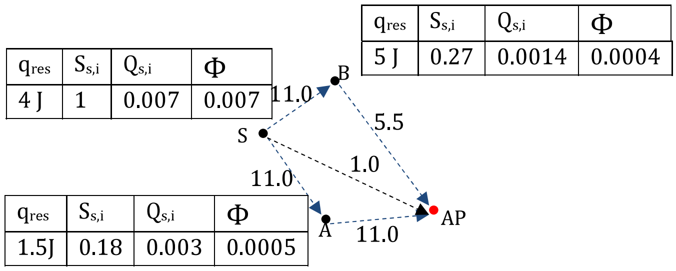

Fig. 3. Illustration of the NetCoop cooperation strategy. Here, relay B is chosen instead of A as the latter has low residual energy.

throughput improvement as well as the energy consumption. Here, we show that the resulting network lifetime is also better than that of direct transmission as well as that of purely throughput driven cooperation.

Lemma 1: Total energy consumption of the set of nodes involved in cooperation using NetCoop is never greater than that of direct transmission.

Proof: We can show this by comparing the total energy consumption for the source(s), destination(d) and the relay(i). Let the data rate for direct transmission be R_0 and the first and second hop data rates using a relay be R_1 and R_2 respectively. In case of direct transmission, the energy consumption would involve that of the source in the transmit mode while the destination and the relay node would consume power in the reception and sleep modes respectively. We ignore the energy consumption due to the overheads as they would be negligible. For a packet of size L bytes, this would be equal to $Q_{dir} = (8L)(\frac{1.65+0.045+1.4}{R_0})$ using the power consumption values mentioned earlier. In case of NetCoop, the energy consumption during transmission from the source to the relay would be $Q_{si} = (8L)(\frac{1.65+1.4+0.045}{R_1})$ while that during transmission from relay to destination would be $Q_{id} = (8L)(\frac{1.65+1.4+0.045}{R_2})$. The total energy consumption would thus be $Q_{NetCoop} = Q_{si} + Q_{id}$.

The minimum values of R_1 and R_2 which can theoretically be chosen for a particular value of R_0 can be given as

R_0	1.0	2.0	5.5	11.0
R_1, R_2	2.0, 2.0	5.5, 5.5	11.0, 11.0	-

From here, we can conclude $\frac{1}{R_0} \geq (\frac{1}{R_1} + \frac{1}{R_2})$, which implies that $Q_{dir} \geq Q_{NetCoop}$. In terms of the total residual energy, this would imply, $E^{dir}_{total} \leq E^{NetCoop}_{total}$. ■

Proposition 1: The network lifetime for cooperation using NetCoop is never less than that of (a) direct transmission, (b) cooperation without energy constraints.

Proof: (a) As we have discussed in section III, the design of NetCoop satisfies the objective outlined in equation 4 for a particular set of nodes involved in cooperation. Hence, the same would be valid for all such sets of nodes across the network, implying that the residual energy at any time would be higher in case of NetCoop. Consquently, the network lifetime would also be better for NetCoop than direct transmission.

(b) In order to compare the network lifetime of NetCoop to that of cooperation without energy constraints, we compare the behaviour for both in the presence of multiple relays. Let us suppose there are two possible relays i and j for the source s to choose from, with the first and second hop data rates being the same for both. Let's say before a transmission, $h^{(C)} = h^{(NC)} = \min(E(s), E(i), E(j), E(d)) = E(i)$, i.e. node i has the minimum residual energy. We use (C) to denote cooperation without energy constraints and (NC) for NetCoop while $h^{(\cdot)}$ denotes the minimum residual energy before transmission. Subsequent transmission with cooperation using either i or j would reduce the residual energy of the chosen relay by a value Δ_{coop}. For transmission with (C), the source can choose either i or j as the throughput improvement is the same for both. On the other hand, when using NetCoop (NC), the source would always choose node j as it has higher residual energy than i. Now, for all cases $\hat{E}(i) < \hat{E}(j)$ where $\hat{E}(\cdot) = E(\cdot) - \Delta_{coop}$, since $E(i) < E(j)$ and Δ_{coop} is the same for both. Thus, when i is chosen by (C), $\hat{h}^{(C)} < \hat{h}^{(NC)}$ while when j is chosen by (C), $\hat{h}^{(C)} = \hat{h}^{(NC)}$. Here $\hat{h}^{(\cdot)} = \min(\hat{E}^{(\cdot)}(s), \hat{E}^{(\cdot)}(i), \hat{E}^{(\cdot)}(j), \hat{E}^{(\cdot)}(d))$ denoting the minimum residual energy after transmission. Hence, $\hat{h}^{(C)} \leq \hat{h}^{(NC)}$ in all cases. The same result can be followed if we consider the scenario where the potential throughput improvement from i and j are not equal. In this case, the source would choose j when $E(i) < \gamma_{ij} E(j)$ where γ_{ij} would depend on the first and second hop data rates for i and j.

Thus, the minimum residual energy of the nodes involved in cooperation using NetCoop would not be less than that of cooperation without energy constraints. This, in turn, implies that the lifetime for the set of nodes using NetCoop is at least equal to that of purely throughput driven cooperation. As the same would be the case for all such sets of nodes across the network, the network lifetime for NetCoop is never less than that of cooperation without energy constraints.

Hence, from (a) and (b), we can conclude that the network lifetime for NetCoop is never less than that of either direct transmission or cooperation otherwise. ∎

V. Multi-Relay Network Lifetime Aware Cooperative MAC

We have discussed how the optimal node can be chosen for cooperation using a single relay given the throughput and energy requirements for each node. To our knowledge, multi-relay cooperation at the MAC layer has not been investigated earlier. Here, we discuss the motivation for such a design and subsequently propose a strategy NetCoopMR which extends cooperation to use multiple relays.

A. Motivation for Cooperation using Multiple Relays

While the throughput benefits of cooperation using multiple relays may be limited in an 802.11b network due to a small set of possible data rates, it can still be beneficial in certain scenarios. This can be understood if we examine a situation where a source S with a direct transmission rate of 2.0 Mbps to the AP obtains help for a (11.0, 5.5) Mbps transmission. While this could be the optimal mode of transmission for the source considering its own neighbourhood, the relay might still be able to reduce its own energy consumption further. This could be possible if the relay itself could obtain cooperation from another node in its neighbourhood with sufficiently high residual energy to support relaying. For example, a $(11.0, 11.0, 11.0)$ cooperation would result in the same throughput improvements while minimizing the energy consumption at the second and third hops. This could hence further balance the energy consumption across the network.

TABLE I
Transmission Range for different data rates

Data Rate (Mbps)	Transmission Range (m)
11.0	48.2
5.5	67.1
2.0	74.7
1.0	100.0

B. Design of Network Lifetime Aware Cooperative MAC with Multiple Relays (NetCoopMR)

Transmission using multiple relays can potentially involve nodes beyond the transmission range of the source, thus extending the potential for cooperation across the network. Thus, we design our algorithm NetCoopMR which handles cooperation using multiple relays to achieve a local optima at each hop. Based on the algorithm for NetCoop, each node tries to maximize the network lifetime and throughput over its succeeding hop.

Using the NetCoop algorithm in section III, the source identifies a relay for the best possible mode of transmission. It then transmits an RTS and waits for a CTS from both the relay as well as the destination. Once this exchange takes place, the source transmits data to the relay. The relay, simultaneously, runs the NetCoop algorithm on its neighbours to identify the best mode of transmission for the second hop. If it identifies another node which can act as a relay for transmission to the destination, it engages in another RTS/CTS exchange after an SIFS and subsequently transmits data to it. Each relay thereby identified follows the same procedure to identify the best mode of transmission for the succeeding hop. This continues till a node decides to transmit directly to the destination.

The RTS transmitted by each hop contains the duration of the succeeding hop. Any other node listening to the channel sleeps for that duration. As the RTS is transmitted after an SIFS, it excludes any chance of a collision. Any node which wakes up after its sleep duration would sense the channel to be free for a DIFS before it attempts transmission. As the relay would transmit after an SIFS, it would thus go back to the sleep mode.

Proposition 2: A local optimum is achieved at each hop for multi-relay cooperation using NetCoopMR.

Proof: This can be understood if we extend the analysis in section IV for multiple relays. As the transmission for each hop can be thought of as analogous to cooperation using a single relay, both Lemma 1 as well as Proposition 1 are valid for each hop and the relay thereby chosen. Hence, the choice of transmission for each hop results in the best performance leading to a local optima. ∎

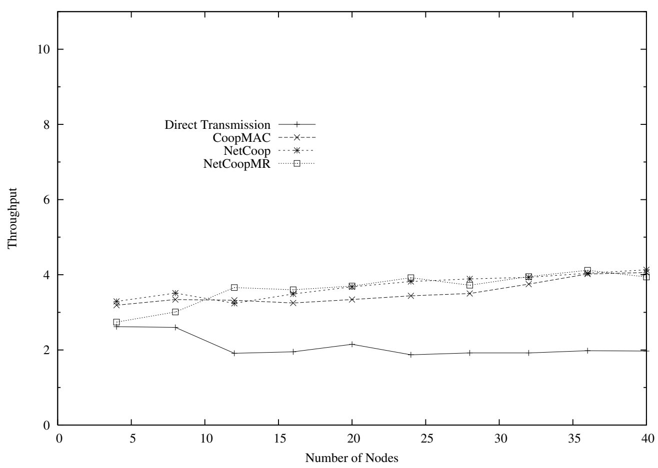

Fig. 4. Network Throughput of Multi-Relay cooperation compared to the three other schemes.

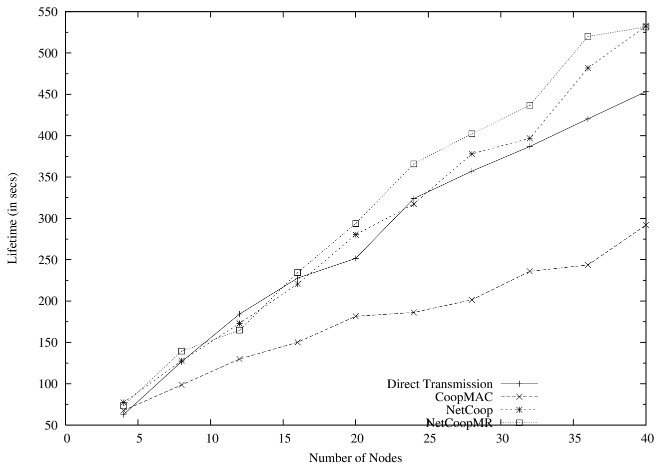

Fig. 5. Network Lifetime of Multi-Relay cooperation compared to the three other schemes.

VI. Simulation Results

We simulate the performance of NetCoop and NetCoopMR using a custom event-driven simulator. The simulator has been used to correctly reproduce our earlier research while its accuracy has been verified by simulating the legacy 802.11 DCF and comparing the results to that of [12]. We use it to compare the performance of NetCoop and NetCoopMR to that of direct transmission and a purely throughput driven cooperation strategy such as CoopMAC.

For the network setup, nodes are placed randomly in a square region of side 200 metres. The AP is placed at the centre. We simulate an 802.11b network which supports four possible data rates: 11.0 Mbps, 5.5 Mbps, 2.0 Mbps and 1.0 Mbps. The transmission ranges for different bit rates are the same as those used in [2], shown in table I. We assume that all nodes start with identical battery capacities. The initial battery life in terms of energy is varied from 5 J to 60 J. Since we observed the behaviour for all cases to be similar, we only show the results for battery capacity equal to 60 J. The power consumption values are the same as those mentioned earlier in section II. A fixed payload size (L) of 2048 bytes is considered. All stations operate under saturation conditions and always have a packet ready to send.

As we see from Figs. 4 and 5, NetCoop and NetCoopMR result in high network lifetime while maintaining a network throughput comparable to that of CoopMAC. At high densities, NetCoop outperforms CoopMAC by about 75% and direct transmission by about 25%. Also, the performance of NetCoopMR is at least as good as that of NetCoop at all densities.

VII. Conclusion

We proposed the design of a cooperative MAC protocol NetCoop based on a cooperation framework which seeks to optimize the tradeoff between network throughput and network lifetime. We also argue that a flexible cooperation strategy which supports more than one relay is more likely to optimize the network performance. Using the same framework, we design NetCoopMR which allows multi-relay cooperation. Our simulation results show that both NetCoop and NetCoopMR maximize network lifetime without sacrificing the throughput.

As part of our future work, we would like to investigate the optimization of cooperation in an ad hoc scenario. Also, we foresee a more suitable scenario for multi-relay cooperation in 802.11a/g networks which support a larger set of data rates than 802.11b.

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