Energy Efficient High Throughput MAC Protocol Analysis for Wireless AD Hoc Networks

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Abstract:
Wireless ad hoc networks are battery powered and in wireless networks that use centralized transmission scheduling, reducing transmission power normally leads to higher network transport throughput. Using short links (i.e., if a long link is broken into several short links then the sum of the transmission floors reserved by the short links is comparable to the floor reserved by the long link.) does not necessarily lead to higher transport throughput. Also, the RTS/CTS based MAC rate control can provide improvement in transport throughput only by a factor of two. In this paper we present some distributed MAC protocols that use physical carrier sensing i.e., busy tone as the control signal and a high throughput MAC protocol which allows concurrent transmission while allowing the network to have a simple design with single channel, single transceiver and single transmission power architecture.

Index terms
Wireless ad hoc networks, IEEE 802.11, throughput, MAC protocol

1. Introduction

Ad hoc wireless networks promise infrastructure-free communication. The total capacity of such networks grow with the area they cover, due to the spatial channel utilization [2],[3] of the spectrum. Also nodes that are sufficiently far apart can transmit concurrently. But in ad hoc networks routing requires nodes to forward each others packet through the network and thus the throughput available to each single node is limited not only by the channel capacity but also by forwarding load imposed by distant nodes. This effect decreases the usefulness of ad hoc routing.

Another fundamental characteristic of mobile wireless networks is the time variation of the channel strength of the underlying communication links. Such time variation occurs at multiple time scales and can be due to multipath fading, path loss due to attenuation, shadowing by obstacles and interference from the users. The impact of such time variation on the design of wireless networks permeates throughout the layers, ranging from coding and power control at the physical layer to cellular hand off and coverage planning at the network layer.

An important means to cope with the time variation of the channel [2],[3] is the use of diversity. The basic idea is to improve performance by creating several independent signal paths between the transmitter and the receiver. Overall system throughput is maximized by allocating at any time the common channel resource to the user that can best exploit it. Strategies of this type incur additional delay, because packets have to be buffered until the channel becomes strong relative to other users. Therefore the time scale of channel fluctuations that can be exploited through multiuser diversity is limited by the delay tolerance of the user or application.

Gupta and Kumar [1] proposed a model for studying the capacity of fixed ad hoc networks, where nodes are randomly located but are immobile. Radios that are sufficiently distant can transmit concurrently. The total amount of data that can be simultaneously transmitted for one hop increases linearly with the total area of the ad hoc network. If node density is constant then the total one hop capacity is $O(n)$, where n is the total number of nodes. As network grows larger, the number of hops between each source and destination may also grow larger, depending on communication patterns. The average path length to grow with the spatial diameter of the network or the square root of the area is $O(\sqrt{n})$. With this assumption, the total end-to-end capacity is roughly $O(n \sqrt{n})$, and end-to-end throughput available to each node is $O(1 \sqrt{n})$.

Gupta and Kumar [1] also demonstrated the existence of a global scheduling scheme achieving $\Omega(1/(\sqrt{n \log n})$ for a uniform random network with random traffic pattern. But the throughput available to each node approaches zero as the number of nodes increases. Also this simple analysis omits the constant factors which determine whether any particular network will have a useful per node throughput.

According to the analysis of ad hoc routing protocols, capacity is the limiting factor i.e., the symptom of failure

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under stress is congestion losses. Evaluation of ad hoc protocols tend to use very low data rates in order to avoid running out of capacity.
Rest of the paper is organized as follows: Section II explains the problems associated with IEEE 802.11 networks. Section III gives the challenges involved in power control, section IV describes the solution in mathematical form, section V discusses the results & contributions and section VI concludes the paper.

2. Problems Accociated with 802.11 Networks

In IEEE 802.11 MAC protocol, all data is transmitted with a constant power using RTS-CTS exchange. Even when two nearby nodes wish to communicate more power is used, while much less power can be sufficient. Thus the standard supports only constant power transmission resulting in a more transmission floor reserved for the communication irrespective of the distance between the transmitter and receiver.
This results in poor spatial utilization [2],[3] or wastage of time and bandwidth. RTS-CTS is used by 802.11 to eliminate hidden & exposed terminal problems. When RTS-CTS messages are exchanged [7] between 2 nodes for data transfer the neighbouring nodes that intend to transmit data defer their transmission till the time the current transmission is complete leading to wastage of power of the neighbouring nodes.

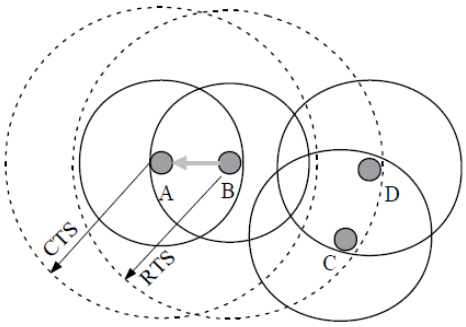

Fig.1. RTS-CTS Exchange with constant Power

In fig.1 nodes A & B use a constant power for RTS-CTS exchange thereby node C is deferred for its transmission to node D as the transmission floor is reserved for A & B. This results in 2 problems: wastage of energy and less channel reuse. If a lower power transmission had been used simultaneous transmissions could occur.
Although RTS/CTS exchange[7] (also known as Virtual channel sensing) is needed to reduce the likelihood of collisions due to hidden terminal problem, it has two drawbacks:

1. It negatively impacts the channel utilization by not allowing concurrent transmissions to take place over the reserved floor.
2. The second problem of the fixed power approach is that the received power may be far more than necessary to achieve the required Signal-to-noise ratio [SINR] thus wasting the nodes energy and shortening its lifetime.

Thus there is a need for a solution, possibly a multilayer one that allows concurrent transmissions to take place in the same vicinity and simultaneously conserves energy. Transmission power[4] determines the range over which the signal can be coherently received and in determining the performance of the network (throughput, delay and energy consumption).Thus it is clear from the above discussion that 802.11 allows one single transmission to occur in a given area at a time and thus is inefficient for transmission in ad hoc networks.

3.Challenges Involved in Power Control

The following are the various challenges involved in power control:

- To detect the ongoing transmission.
- RTS-CTS at constant power and data at lower power.
- Multiple access interference and near-far problem.
- No central authority

4. Solution Framework

In this section we study the space time utilization[2] in a simple model of RTS-CTS based systems with fixed transmission rates. We consider RTS-CTS based MAC protocols[4],[5] where each transmission pair reserves a transmission floor by exchanging RTS-CTS messages[7]. The control messages are sent in the same channel as data packets. We explain how the receiver computes its maximum tolerable interference PMTI. We assume that the transmission signal power decays with distance d as d–α where α is a constant with a range of 2 to 4 in a mobile environment.
Suppose node p is sending data to node q with transmission power Ptx(p) .
If the distance between nodes p and q is dpq then received power Prx(p) (q) at q is

$$P^{(p)}{}_{rx}(q) = \frac{P^{(p)}{}_{tx}\, G_{pq}}{d^{\alpha}{}_{pq}} \qquad (1)$$

where Gpq is the antenna gain also Gpq=Gqp=G i.e., gain associated with transmitting from p→ q or q → p is same. Hence there is no asymmetry in gain.

For a successful transmission and correct decoding at the receiver, The SINR at the receiver should be larger than a predefined capture threshold β.

ie., $$\frac{P^{(p)}{}_{rx}(q)}{\sum_{k\neq i} P^{(k)}{}_{rx}(q) + P_n(q)} \geq \beta \qquad (2)$$

$[\beta = P^{(p)}{}_{rxthreshold}(q) = P_{background} * SINR]$

Let $P^{(q)}{}_{current}$ denote accumulated interference power due to current scheduled transmissions in the vicinity of node q. Then

$$P^{(q)}{}_{current} = \sum_K G_{qk} * P^{(k)}{}_{tx} \qquad (3)$$

where k is a transmitter recorded in node q's ANL.If node q is a master receiver ,its $P^{(q)}{}_{current}$ will be zero because its ANL is empty at the moment of computing $P^{(q)}{}_{current}$.

The total future interference that node q can tolerate without violating its SINR is given by:

$$P^{(q)}{}_{margin} = \frac{P^{(p)}{}_{rx}(q)}{SINR} - P^{(p)}{}_{rxthreshold}(q) - P^{(q)}{}_{current} \qquad (4)$$

where $P^{(p)}{}_{rx}(q)$ is the received power of control packet from transmitter $p \rightarrow q$.

The max. tolerable interference (MTI) that each future neighbouring node can add to node q is calculated as:

$$P^{(q)}{}_{MTI} = \frac{P^{(q)}{}_{margin}}{N^{(q)}{}_{ACG}(1+\alpha)} \qquad (5)$$

where $N^{(q)}{}_{ACG}$ is the number of access slots (AS) in the ACG(automatic control gain) of node q. α $(\alpha > 1)$ is the ratio between the interferences caused by nodes outside and inside the transmission range. It depends mainly on the propagation path loss factor. In practice, $\alpha \equiv 0.5$ for 2-ray models and uniformly distributed nodes. If node k is transmitting at the max. power P_{max} and has a distance of d_{kq} to the receiver

$$P^{(k)}{}_{rx}(q) = \frac{P_{max} G}{d^{\alpha}{}_{kq}} \geq \frac{P^{(p)}{}_{tx} G}{d^{\alpha}{}_{pq} \beta} \geq P^{(q)}{}_{margin} \qquad (6)$$

then node k will interfere with reception of node q. From equation (5) we have

$$d_{kq} \leq \left(\frac{P_{max} d^{\alpha}{}_{pq} \beta}{P^{(p)}{}_{tx}} \right)^{1/\alpha} \qquad (7)$$

Let $\left(\frac{P_{max} d^{\alpha}{}_{pq} \beta}{P^{(p)}{}_{tx}} \right)^{1/\alpha} = d_{int}(q)$, the distance threshold within which a node transmitting at P_{max} can interfere with node q's reception from node p.

In wireless ad hoc networks, it is difficult for a node to predict the future transmissions and the transmission power that its neighbors will use, especially when nodes are mobile. In heavily loaded systems, node q needs to inform all potential interferers to stay silent. Then, the transmission range of CTS should be at least $d_{int}(q)$. Note that we only consider the interference of one neighbor to get the lower bound on the CTS range of $d_{int}(q)$. When more than one neighbor can interfere the transmission, the CTS range should be even larger than $d_{int}(q)$. Thus, $d_{int}(q)$ gives a lower bound for the reserved transmission floor. To ensure that all nodes within $d_{int}(q)$ can decode the CTS message, the received power of the CTS at a distance $d_{int}(q)$ must satisfy

$$\frac{P^{(p)}{}_{tx} G}{d_{int}(q)} \geq P_{recv} \qquad (8)$$

to make the neighbors hear the CTS message, where P_{recv} is the receiver sensitivity. Consequently, the CTS transmission power should be

$$P^{(q)}{}_{tx} \geq \frac{P_{recv} P_{max} d^{\alpha}{}_{pq} \beta}{P^{(p)}{}_{tx} G} \qquad (9)$$

Note that the required CTS power can be larger than P_{max} when $\beta > 1$ and d_{pq} is close to d_{max}. To comply with the maximal transmission power, the possible link length of d_{pq} should be smaller than d_{max} in this case. Otherwise, the CTS message will not be able to inform all possible interfering neighbors.

From (9), we see that the transmission power $p^{(q)}{}_{tx}$ of the CTS is inversely proportional to the transmission power $P^{(p)}{}_{tx}$ of data and RTS. So, there is a trade-off between the transmission power of RTS and CTS. When we reduce the power of the data packet, we need to increase the power of CTS accordingly, since the receiver is more vulnerable to interference.

Using the above method a power level is mutually agreed upon between a sender & receiver such that no ongoing communication is affected. The RTS-CTS unlike 802.11 do not cause other possible transmission to stop, but introduce bounds on the maximum power that can be

used for communication allowing limited interference communication.
The maximum transmission range is given by

$$d_{max}= \left(\frac{GP_{max}}{P_{recv}}\right)^{1/\alpha}$$

(10)
Combining (9) and (10) we get

$$P^{(q)}_{tx}\, P^{(p)}_{tx} \geq \left(\frac{d_{pq}}{d_{max}}\right)^{\alpha} P^{2}_{max}\beta$$

(11)
The transmission range of CTS and RTS is defined as $d_c=(P^{(q)}_{tx}\, G/ P_{recv})^{1/\alpha}$ & $d_r= (P^{(q)}_{tx}G/ P_{recv})^{1/\alpha}$ and will satisfy

$$d_c d_r= (P^{(q)}_{tx}\, P^{(p)}_{tx})^{1/\alpha}\left(\frac{G^2}{P^2_{recv}}\right)^{1/\alpha}$$

$$\geq \frac{d_{pq}}{d_{max}}\left(\frac{G^2 P^2_{max}\beta}{P^2_{recv}}\right)^{1/\alpha}$$

$$= \beta^{1/\alpha}\, d_{max}\, d_{pq.}$$

(12)

4.1 Comparison with Linear Power Assignment

Linear power assignment chooses a transmission power to guarantee a fixed receiving power level of ρP_{recv}, where ρ is a constant [2]. In such a scheme, we have

$$P^{(p)}_{tx} = \frac{\rho P_{recv} d^{\alpha}_{pq}}{G}$$

$$d_{int}(q) = \left(\frac{GP_{max}\beta}{\rho P_{recv}}\right)^{1/\alpha}$$

(13)
Using the expression of dmax in (10), the transmission range of CTS is $d_{int}(q)= (\beta/\rho)^{1/\alpha}\, d_{max}$, which is a constant comparable to d_{max} . Therefore, even when nodes p and q are very close to each other, node q still needs to send the CTS to clear a transmission floor with an area proportional to πd^2_{max}. We observe that when the CTS is sent in the same channel as data packets, linear power assignment suffers from the same problem as 802.11, i.e., the area taken by the CTS is proportional to d^2_{max} , irrespective of the link distance. When the CTS is sent in the same channel as the data, it will also interfere with the data transmission. Therefore, most linear power assignment schemes use a separate control channel for the CTS/busy tone[2],[3] so that the interference generated by the CTS/busy tone can be minimized.

4.2 Power Control in Routing Layer

The RTS/CTS mechanism is the most widely used collision resolving method. However, the network throughput of such protocols is mainly decided by a global parameter, i.e., the maximal transmission range d_{max}. In most ad hoc networks, the maximal transmission distance is a predefined network parameter to guarantee network connection. So, the routing-layer choices cannot greatly affect the network throughput[10].

4.3 Energy Consumption

Aside from increasing the network throughput, the other main objective of power control is to reduce the energy used in transmission. Since the transmission power decreases as d^{α} with the distance d in linear power assignment, when a long link is broken into several short links, the total energy used in transmission can be saved [10]. From (11), the optimal transmission power for link with length d_{pq} is

$$P^{(q)}_{tx} = \left(\frac{dpq}{d_{max}}\right)^{\alpha/2} P_{max}\beta^{1/2} = C_m d^{\alpha/2}_{pq} \qquad (14)$$

where $C_m= d^{-\alpha/2}_{max}P_{max}\beta^{1/2}$ is a constant. In our scheme, the transmission power decreases with the link length in a much slower fashion. When $\alpha= 2$, the power used in transmission will be $C_m\, d_{pq}$. Thus, when we break long links into short links, the sum of energy used in transmission over the short links is the same as that used over the long link. In other words, one does not obtain much savings in energy by transmitting over shorter hops when $\alpha=2$. Shorter links will result in smaller total power consumption only for $\alpha>2$. This shows that our optimal transmission range for spatial utilization is not optimal for energy saving. If the main objective is energy saving, we need to sacrifice some throughput for energy. We can send data by linear power assignment while increasing the power of CTS. The total energy consumption can be reduced, since the CTS packet is normally much shorter than data packets.

4.4 Busy-Tone Approach

The busy-tone approach described in [2] uses a separate channel for the receiver to send a “busy” signal while it is receiving a packet. The busy tone will notify nodes around the receiver so that they will not interfere with it. Consider a transmitter/receiver pair *(p,q)*. Similar to the analysis, the receiver q needs to notify nodes within $d_{int}(q)$ when the transmitter p uses a transmission power of $P^{(p)}_{tx}$. The receiver uses a busy tone that is sent with a power of [2]:

$$P^{(q)}_{tx} = \frac{d^{\alpha}_{int}(j) P_{phy}}{G} \quad (15)$$

where P_{phy} is the physical carrier sensing threshold[8],[9]. So, the busy tone sent by the receiver q can be sensed at a distance of $d^{\alpha}_{int}(j)$. Define the transmission range of the busy tone as

$$d_b = \left(\frac{P^{(q)}_{tx} G}{P_{phy}} \right)^{1/\alpha} = d_{int}(j).$$

(16)

A potentially interfering node k within d_b will sense the busy tone and refrain from using the maximal transmission power to send a packet during the reception of node q. The busy-tone approach still allows the node k to use a smaller power, which will not interfere with node q, for it to transmit, even it is within a distance of d_b to node q. Suppose that the transmitter k receives the busy tone from node q with a power of $P^{(q)}_{rx}(k)$. Then, the transmission power budget that node k can use is defined as [3]

$$P_{budget}(k) = min \left\{ \frac{P_{max} P_{phy}}{P^{(q)}_{rx}(k)}, P_{max} \right\}$$

(17)

Thus, the power budget for a node k closer to the receiver q will be smaller. By (1), it is easy to see that the interference of node k at node q will be smaller than $P_{margin}(q)$ if node k keeps its power to be smaller than $P_{budget}(k)$. The busy-tone approach can achieve very high spatial utilizations, since it only blocks transmissions where the transmission power is high enough to interfere with ongoing transmissions. Also, the control message (busy tone) is transmitted in a separate channel that can use high power without interfering with data packets.

4.5 Comparison to Other Power Control Schemes

The various power control schemes are compared as follows:

- NTPC (no power control). This protocol sends RTS, CTS, and data in the maximal power, which is just the 802.11 MAC protocol with the physical carrier sensing turned off[7],[8],[9].
- TPC-O (optimal power control). In this scheme, RTS, CTS, and data are sent at the optimal power.
- TPC-L1 (linear power assignment 1). This scheme uses linear power assignment for RTS and data, i.e., RTS and data are sent at a power, which ensures that the received power is just 3 dB above Precv. In this scheme, the CTS is sent using maximal power to prevent collisions[2],[3].
- TPC-L2 (linear power assignment 2)[2],[3]. The only difference between TPC-L1 and TPC-L2 is that the CTS power in TPC-L2 is the same as the data/RTS power. Thus, this scheme uses minimal transmission floor for short links. However, it takes the risk of a high collision rate.
- TPC-E (power control for energy saving). This scheme sends RTS/CTS at maximal power but uses linear power assignment for data transmission. Such schemes are usually used for saving transmission energy, which is the BASIC protocol in [10]. Note that for TPC-O, TPC-L1, and TPC-L2, the required power for RTS/CTS may exceed Pmax when the transmission range is close to dmax. In this case, we only use Pmax to send the control message.

5. Results & Contributions

The main results and contributions in this paper are listed as follows:

- Reducing the transmission power does not necessarily lead to less “interference” to other links.
- The area of the transmission floor is proportional to dij dmax β1/α where dij is the link length and dmax is the maximum transmission range resp.
- Routing mechanisms that favor short hops over long hops can give at most a constant factor improvement in network performance[6]. This indicates that power control should reside at the MAC layer and not at the routing layer.
- With the optimal RTS/CTS-based MAC scheme[7], we show that changing the transmission rate with respect to the link distance can at most increase the throughput by a factor of 2.

6. Conclusion

This paper focuses on Power Controlled MAC layer in ad hoc networks. A detailed study of the various challenges involved for deploying power control in wireless ad hoc networks is carried out. The various solutions to the problems are also discussed and analyzed. Some approaches to implement a power controlled MAC layer for ad hoc networks are also studied in detail and a combined common framework is identified.

References

[1] P. Gupta and P.R. Kumar, " The Capacity of Wireless Networks", IEEE Trans. Information Theory, vol. 46, no 2, pp. 388-4-4, 2000.
[2] J.P. Monks and V. Bhargavan, "A Power Controlled Multiple Access Protocol for Wireless Packet Networks", Proc. IEEE INFOCOM '01, pp. 219-228, 2001.
[3] A. Muqattash and M.Krunz, "CDMA based MAC protocol for Wireless Ad hoc Networks", MobiHoc 2003,pp.153-164, 2003.
[4] A. Muqattash and M.Krunz, "A distributes Transmission Power Control Protocol for Mobile Ad hoc Networks", IEEE Transactions on Mobile Computing, vol. 3, no. 2, pp. 113-128, 2004.
[5] Eun-Sun Jung and Nitin H. Vaidya, "A Power Control MAC Protocol for Ad hoc Networks", Proceedings of the 8th annual international conference on Mobile Computing and Networking, Mobicom 2002,pp.36-47, 2002.
[6] T. Moscibroda and R.Wattenhofer, "The Complexity of Connectiviey in Wireless Netowrks", Proc. IEEE INFOCOM, 2006.
[7] P.Karn,"MACA: A new channel access method for Packet Radio",proc.ninth ARRL computer networking conference., pp.134-140,1990.
[8] X.Yang and N.Vaidya, "On Physical Carrier Sensing in Wireless Ad Hoc Networks", Proc. IEEE INFOCOM '05, pp. 2525-2535 2005.
[9] H.Zhai and Y.Fang, "Physical Carrier Sensing and Spatial Reuse in Multirate and Multihop Wireless Ad Hoc Networks", Proc. IEEE INFOCOM '2006
[10] Wei Wang & Vikram Srinivasan "Power Control for Distributed MAC Protcols in Wireless Ad Hoc Netoworks", Proc. IEEE TRANSACTIONS ON MOBILE COMPUTING VOL 7, 2008.

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