# A Carrier Sense Multiple Access Protocol with Power Backoff (CSMA/PB)


Charles J. Colbourn, Minghao Cui, and Violet R. Syrotiuk
Computer Science & Engineering
Arizona State University
Tempe, AZ 85287-8809
e-mail: {colbourn,minghao.cui,syrotiuk}@asu.edu

Errol L. Lloyd
Computer and Information Sciences
University of Delaware
Newark, DE 19716
e-mail: elloyd@udel.edu



*Abstract*— **In this paper we propose an alternate approach to collision resolution in a CSMA protocol. Most contention protocols resolve collisions by backing off in time. We introduce *spatial backoff*, the use of power control to resolve collisions by backing off in space. We call this approach *power backoff* (PB) and incorporate it into a CSMA protocol as CSMA/PB. Through simulation, we show that collision resolution using power backoff can be remarkably successful, outperforming IEEE 802.11 in both static and mobile ad hoc network scenarios. CSMA/PB improves end-to-end throughput and uses less energy; overall gains in throughput per unit energy are substantial.**


## I. Introduction

Recently, Gomez and Campbell [1] investigated the impact of variable-range power control on the physical and network connectivity, network capacity, and power savings of wireless multi-hop networks. Inspired by the challenge to develop protocols that exploit power control we propose a medium access control (MAC) protocol for mobile ad hoc networks using *spatial backoff* for collision resolution.

Traditional contention-based MAC protocols resolve collisions by backing off in time. A transmitter increases its contention window size when the channel is already in use or the previous transmission attempt fails; the transmitter then waits for a period related to the window size in the hope that contention is reduced. In CSMA/PB the transmitter backs off in space rather than in time, i.e., the transmitter reduces its transmission power. In a smaller transmission area, the interference and contention are also anticipated to be reduced.

Why might backing off in space be as (or more) effective than backing off in time? Consider a network in which the nodes are uniformly distributed throughout some geographic area. If a node has a transmission range of $r$, then the physical area of the interference is proportional to $r^2$. If the network traffic is also uniformly distributed among nodes, then the magnitude of the contention at each node is also proportional to $r^2$. Since the contention increases proportional to the square of the transmission range, the reduction of the transmission range by, for example, half, results in a four fold decrease in the contention. Consider a path from source to destination, the length (number of hops) of this path is *inversely* proportional to $r$. So overall, the contention along this path is now proportional to $r^2 r^{-1} = r$. Thus a low transmission range yields low overall contention along the path, and therefore higher spatial reuse and higher network throughput.

However in a wireless network, a low transmission range is not always desirable because it may not be possible to reach a next-hop destination. It may increase the number of hops between a source and destination pair, thus increasing the number of transmissions made by intermediate nodes. Furthermore, a problem for all protocols that use power control is how to cope with asymmetric links. Consider Figure 1 with two nodes $A$ and $B$ where dotted and solid circles represent their high and low transmission powers. If $A$ transmits at low power while $B$ transmits at high power, $A$ is within the transmission range of $B$, but not vice versa. If a four-way handshake is initiated by $A$ to $C$ at low transmission power, $B$ may be a hidden terminal to $A$.

The rest of this paper is organized as follows. We summarize related work in Section II. Keenly aware of the potential benefits and also the potential detriments of transmission power control, we develop a spatial backoff algorithm called *power backoff* (PB) for collision resolution in a CSMA based ad hoc network; the resulting protocol is CSMA/PB and it is described in Section III. While spatial backoff alone is effective, it performs even

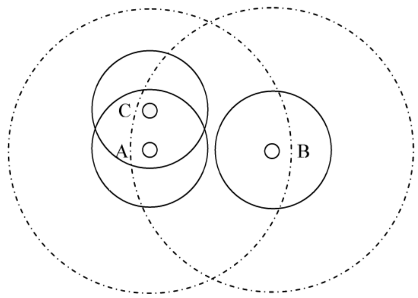


Fig. 1. $B$ may be hidden to $A$ when asymmetric power used.

better when combined with temporal backoff. In Section IV we propose three ways of combining backoff in space with backoff in time. Section V assesses the effectiveness of these variants of CSMA/PB in simulation for a variety of scenarios. We compare their performance with IEEE 802.11 under the same conditions for static and mobile ad hoc network scenarios. In all scenarios, the throughput per unit energy of CSMA/PB exceeds that of IEEE 802.11, often quite substantially. Finally, we present conclusions in Section VI.

## II. Related Work

The analysis of collision resolution schemes has been the subject of intense research. For example, despite its wide usage in IEEE 802.11, binary exponential backoff (BEB) results in an unstable protocol under certain modelling assumptions [2]. The existence of stable protocols in this setting also depends on the type of feedback available from the channel and on how the user population is modelled. For acknowledgment based protocols, Kelly [3] showed that a large class of backoff schemes, including polynomial backoff, is unstable in the infinite user population model. In contrast, for a finite user population, any super-linear polynomial backoff protocol has been proved stable, while binary exponential backoff remains unstable above a certain arrival rate [4].

The dimension of space in the backoff strategy appears in many guises. One idea is to use multiple channels with the same aggregate channel capacity thereby spacing out transmissions over channels and not just over time. Nasipuri et al. [5] propose a multichannel MAC protocol using “soft reservation” of the channels. The nodes use their own channel usage history for channel selection. In [6] this scheme is extended to select the best channel according to the signal-power on multiple channels so as to distribute the interference on multiple channels evenly. So et al. [7] proposed a multi-channel MAC enabling nodes to dynamically negotiate channels such that multiple communication can take place in the same region. Multi-channel protocols have improved the overall throughput of CSMA.

Another idea is to use a form of frequency hopping over multiple channels. Tang et al. [8] present Hop Reservation Multiple Access, where they use RTS/CTS transmission to perform channel reservation. In [9] a similar approach is proposed except that the receiver initiates the collision avoidance instead of the transmitter.

Transmit power control has been applied at the MAC layer to decrease power consumption. Karn [10] allowed a transmitter to specify its transmission power level in the RTS, and the receiver to set the desired transmission power level in the CTS. The receiver determines the transmission power level based on the required signal-to-noise ratio. The data and ACK packets are then transmitted at the power level indicated in the CTS packet. This scheme and the improvement by Jung et al. [11] reduce the power consumption at the price of throughput. Indeed, the best transmission concurrency they can achieve is the same as IEEE 802.11.

Power control has also been applied is to increase spectrum reuse. Increasing concurrent transmissions around the receiver is the goal in [12], [13], [14], [15], with most using an additional control channel. In [14], Muqattash et al. provide a solution in a single channel. Although these protocols increase the channel throughput, the main difficulty is that most of them require additional hardware, signalling overhead, and have restrictive assumptions (e.g., fixed packet size).

Strongly related to the use of power control to increase spectrum reuse is the use of power control to prevent collisions. Fuemmeler et al. [16] argue that for CSMA protocols, the product of the transmit power and carrier sense threshold should remain constant. By incorporating this collision prevention condition into a protocol, spatial reuse is improved. Chu [17] suggests that the contention window of IEEE 802.11 is a function of the distance from the transmitter to its next hop destination. A smaller window is used for nodes closer together since the contention in the transmission range required to reach the destination is likely to be reduced. Recently, Yang et al. [18] examined in detail the possibility of increasing system performance by reducing the carrier-sense range, while taking into account the MAC overhead. The performance improvement results from the higher level of spatial reuse that is possible with a reduced carrier-sense range. In their conclusion Yang et al. suggest as future work adjusting contention based on node access behaviour.

## III. Carrier Sense Multiple Access with Power Backoff (CSMA/PB)

### A. Fundamental Assumptions

Throughout the remainder of this paper, we assume that each node of the network is equipped with an omni-directional antenna and a half-duplex transceiver. We further assume that the radio transceiver in each node can be tuned to a number of discrete power levels, with each power level naturally corresponding to a unique transmission range. The minimum and maximum power levels are denoted by $p_{min}$ and $p_{max}$ respectively. In addition, we assume that the tuning of a transceiver to a particular transmit power level can be accomplished on a per-packet basis and that tuning to a particular power level does not involve any significant cost.

Most CSMA protocols assume that the links are bidirectional (i.e., symmetric). If nodes are all transmitting at the same power level, then this is a natural assumption although *unidirectional* links may exist due to noise, interference, etc. When using power control (and in contrast to typical existing CSMA protocols) nodes naturally transmit at differing power levels, and unidirectional links may occur more frequently. This asymmetry has to be considered in the CSMA/PB protocol design.

### B. The CSMA/PB Protocol

Using CSMA/PB, the transmission of each data packet follows a four-way handshake with some added elements related to power control. The basic operations follow IEEE 802.11 so that minimal modifications are needed. To describe the protocol, we consider a node $s$ that transmits a series of data packets and let $p_i$ be the power level utilized by $s$ in transmitting the $i^{th}$ data packet.

Suppose there are $n$ power levels, $p_{max} = n$ and $p_{min} = 1$. Initially, the power level of $s$ is set to the maximum power level (i.e., $p_1 \leftarrow p_{max}$). To transmit the $i^{th}$ data packet, $s$ first senses the channel; if the channel is busy, the node updates the *network allocation vector* (NAV) as in IEEE 802.11. If the channel is free, $s$ transmits an RTS at power level $p_i$. That RTS includes the power level $p_i$ being used to transmit the packet. Following that transmission there are two cases:

1) If $s$ subsequently receives the corresponding CTS, then the $i^{th}$ data packet is transmitted at power level $p_i$. If the transmission is successful, then $s$ receives an ACK.
2) If $s$ does not receive a CTS, then the RTS may have been involved in a collision. In this case, the current transmission power level ($p_i$) of $s$ is reduced and $s$ sends a new RTS at a reduced power level if the channel is free.

The difference between our power backoff and temporal backoff is that when a backoff is needed, temporal backoff increases the contention window size and waits for a period related to the window size. Power backoff reduces the transmission power level.

The complete CSMA/PB transmitter and receiver protocols appear in Figures 2 and 3, respectively.

```
if there is a data packet to transmit from s to r then
   if packet i has same destination as i − 1 then
      p_i ← p_{i−1}
   else
      p_i ← p_max
   end if
   retry ← 0; CW ← CW_min
   success ← false
   while not success and retry < MAXRETRY do
      set timer for random period in (0, CW) and wait
      if a transmission is sensed then
         set NAV, wait for expiry
      else
         send RTS using power level p_i
         if a CTS is received then
            send DATA using power level p_i
            if an ACK is received then
               success ← true
            end if
         end if
      end if
      retry ← retry + 1
      p_i = max(p_i − 1, p_min)
   end while
   if not success then
      discard packet, report failure
   end if
end if
```

Fig. 2. Basic CSMA/PB transmitter protocol.

Similar to Karn [10], the power level $p_i$ is included in the RTS. The purpose is to avoid problems arising from unidirectional links that may result when the transmitter and receiver use different transmission powers.

An important issue in CSMA/PB is determining the appropriate transmission power level for the *next* packet (packet $i + 1$) in the series after a successful packet exchange. In IEEE 802.11, the contention window is reset to its minimum size after each successful four-way handshake. In CSMA/PB, the value of $p_{i+1}$ depends on the next hop destination of packet $i+1$. If that destination is the same as that of packet $i$, then the power level $p_i$ is retained as the value of $p_{i+1}$. If the destination is different, then the value of $p_{i+1}$ is initialized to $p_{max}$.

As in IEEE 802.11, when a neighbour $z$ of $s$ or $r$ *overhears* an RTS or a CTS packet associated with the transmissions of $s$ and $r$, then node $z$ sets its NAV for the duration of the data-ACK transmission.

**if** RTS received is intended for this destination **then**
  send CTS at transmission power $p_i$
**else if** DATA received is for this destination **then**
  send ACK at the power level $p_i$
**else**
  set a NAV for this packet; keep silent
**end if**

Fig. 3. Basic CSMA/PB receiver protocol.

If a node reaches the minimum transmission power level, a retry strategy is followed with the node able to make MAXRETRY number of attempted transmissions at that minimum power level before the packet is dropped. In CSMA/PB, the contention window (CW) is fixed at 32 and is never changed in the protocol. The only purpose for this contention window is to introduce a small amount of jitter in the retry in case nodes become synchronized.

## IV. Combining CSMA/PB with Time Backoff

While spatial backoff alone is promising, better adaptation in some scenarios is required. For example, in a dense network with a large number of active transmitters, most of the transmitters back off to the minimum transmission power level. There is no action CSMA/PB can take to alleviate continued contention. This motivates us to combine spatial backoff with temporal backoff.

One way to combine spatial backoff with temporal backoff is to follow one approach by the other. Figure 4 shows a transmitter with $n = 3$ transmission power levels, first backing off in space. Once the minimum power level is reached, the transmitter then backs off in time using BEB. Retransmissions always occur at the minimum power level. This is accomplished by replacing line 23 in Figure 2 by the statements in Figure 5.

Another way to combine backing off in space and time is to alternate approaches. Figure 6 illustrates backing off in space and followed by backing off in time. This is accomplished by replacing line 23 in Figure 2 by the statements in Figure 7.

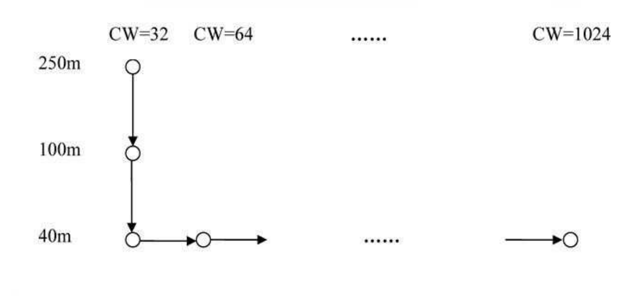


Fig. 4. Spatial followed by temporal backoff.

**if** $p_i \neq p_{min}$ **then**
  $p_i \leftarrow p_i - 1$
**else**
  $CW \leftarrow min(CW \times 2, CW_{max})$
**end if**

Fig. 5. Implementation of spatial followed by temporal backoff.

Of course, the backoff could instead occur in the temporal domain and be followed by backoff in the spatial domain. This is illustrated in Figure 8. In order for such an approach to be practical, the maximum contention window size $CW_{max}$ is reduced to 256 from 1024 used in IEEE 802.11. As before, replacing line 23 in Figure 2 by the statements in Figure 9 implements this combined approach.

Of these three approaches to combining backoff in space with backoff in time, in an active and dense network, the first approach aggressively reduces the transmission power to the minimum level. If sources

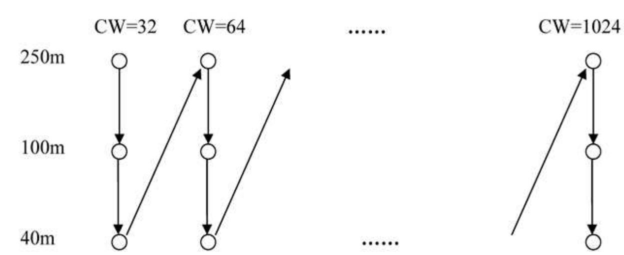


Fig. 6. Alternating spatial and temporal backoff.

**if** $p_i \neq p_{min}$ **then**
  $p_i \leftarrow p_i - 1$
**else**
  $CW \leftarrow min(CW \times 2, CW_{max})$
  $p_i \leftarrow p_{max}$
**end if**

Fig. 7. Implementation of alternating spatial and temporal backoff.

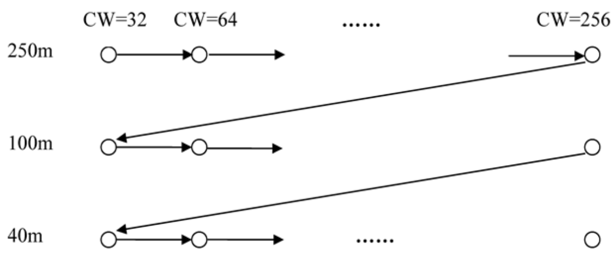


Fig. 8. Alternating temporal and spatial backoff.

**if** $CW \neq CW_{max}$ **then**
    $CW \leftarrow CW \times 2$
**else**
    $CW \leftarrow CW_{min}$
    $p_i \leftarrow max(p_i - 1, p_{min})$
**end if**

Fig. 9. Implementation of alternating temporal and spatial backoff.

and destinations of flows are far apart, this encourages longer paths with short hops to be utilized, increasing the overhead from multihop forwarding.

When alternating approaches to backoff, the asymmetric links are more likely to arise when backing off in the spatial domain first. Nodes with high transmission power levels have an advantage in gaining access to channel than nodes with low transmission power because high power nodes are potentially hidden to low power nodes. Starting the alternation by backing off in time is the most conservative combination, essentially running IEEE 802.11 at each of the $n$ transmission power levels.

## V. Evaluation of CSMA/PB

We evaluate the performance of IEEE 802.11 and variants of CSMA/PB using $n = 3$ transmission power levels in the `ns-2` network simulator version 2.26 [19]. The variants of CSMA/PB use: spatial followed by temporal backoff ("direct"); alternating spatial and temporal backoff ("power first"); alternating temporal and spatial backoff ("time first"); and, "power first" with a copy mechanism to avoid asymmetric links. In this variant, when a node overhears a transmission, it sets its transmission power level to the minimum of the overheard packet and its current transmission power level.

If the routing protocol does not take into account variation in power levels it will use unnecessary paths when the power is high and have no path when the power is low. Therefore, routing must take power levels into account. We use an optimistic centralized strategy designed to explore the potential of spatial backoff.

Let $w(v_i, v_j)$ denote the transmission power needed for node $v_i$ to transmit in one hop to $v_j$; this is $\infty$ if no such power level exists. Then for each $s$-$t$ flow and each transmission power level $\rho$, $1 \leq \rho \leq n$, a path $s = v_0 v_1 \ldots v_k = t$ is found such that $w(v_0, v_1) \leq \rho$ and $w(v_0, v_1) + \sum_{j=1}^{k-1} w(v_j, v_{j+1})$ is minimized.

The routing table $T[1 \ldots N, 1 \ldots n]$ at each node contains entries for each of the $N$ destinations at each of the $n$ power levels. $T[t, \rho]$ specifies the next-hop node on the path to $t$ at transmission power level $\rho$; if the path weight is $\infty$ then there is no path whose first hop is at power $\rho$. If $n = 1$ (as in IEEE 802.11), a minimum hop-count path is computed.

In our *power-aware routing* protocol, if node $v_i$ receives a packet to forward towards $t$, the next hop node $v_{i+1}$ depends on the transmission power level $\rho$ used by $v_i$. Node $v_i$ selects $v_{i+1} = T[t, \rho]$ as the next hop node.

Table I shows other important simulation parameters.

TABLE I
Simulation parameters

| | |
|---|---|
| Data packet size | 1000 $Kbytes$ |
| Traffic type | UDP |
| Traffic arrival rate | 0.5 $Mbps$ |
| Channel data rate | 1 $Mbps$ |
| Simulation time | 200 $s$ |
| Antenna | Omni-directional |
| Carrier sense range | 2 × transmission range |
| Transmission power level 3 | 0.2818W (250 $m$) |
| Transmission power level 2 | 7.214E-3 W (100 $m$) |
| Transmission power level 1 | 8.5872E-4 W (40 $m$) |

We compare the protocols using two metrics: the *total throughput* (the total amount of data delivered by all the flows in the network) and the *throughput per unit energy* (the total throughput divided by the total amount of energy spent by all the nodes in the network).

### A. Static Chain Topology

We first consider a static chain topology. Ten nodes are arranged in a line 30 $m$ apart (see Figure 10). The first scenario has 3 single-hop flows from nodes 1, 5, and 9 to nodes 2, 6, and 10. The second scenario has 2 multi-hop flows from nodes 1 and 2 to nodes 9 and 10.

Figure 11 plots throughput in the single-hop flow scenario. All variants of CSMA/PB outperform IEEE 802.11 except "time first" which decreases transmission power too slowly to exploit the potential for spatial reuse. In this scenario, all three flows can transmit simultaneously if the lowest transmission power is used. The "power first with copy" performs the best, as the

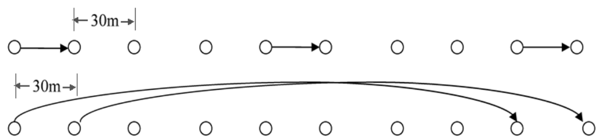


Fig. 10. Chain topology with single-hop and multi-hop flows.

nodes reach the lowest transmission power quickly. The copy mechanism accelerates this decrease since once a node successfully transmits at minimum power, the overhearing neighbours copy this power level. The "direct" protocol does not use the copy mechanism and therefore takes slightly longer for all the nodes to reach the minimum transmission power.

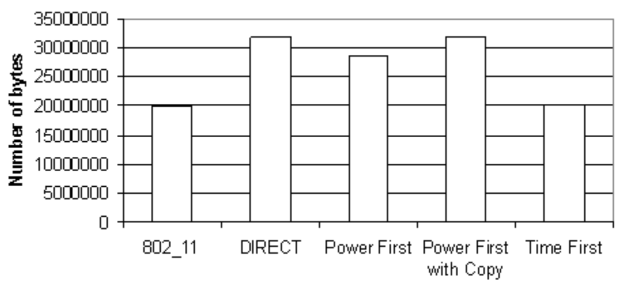


Fig. 11. Throughput in chain topology with single-hop flows.

Figure 12 shows larger absolute differences in throughput per unit energy. While IEEE 802.11 and "time first" are close in throughput, the throughput per unit of energy for "time first" is 30% higher than that of IEEE 802.11. Table II shows the number of packets transmitted at each power level in each of the 5 protocols. This confirms the results in Figures 11 and 12.

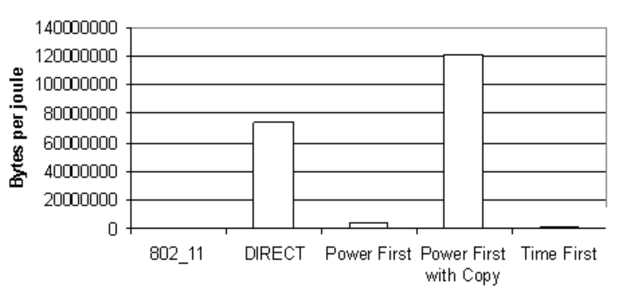


Fig. 12. Throughput/energy in chain topology with single-hop flows.

Figure 13 shows the throughput achieved in the chain topology with multi-hop flows. All variants of CSMA/PB suffer because of competing multi-hop flows. Nodes using higher transmission power gain access to the channel over nodes using lower power. In "power first" and "time first," nodes can use high transmission power more frequently than the other two CSMA/PB protocols, thus their throughput is higher. However, as expected, they also consume more energy.

TABLE II

POWER LEVEL USAGE IN CHAIN TOPOLOGY, SINGLE-HOP FLOWS

| | 250m | 100m | 40m |
|---|---|---|---|
| IEEE 802.11 | 81102 | 0 | 0 |
| Direct | 8 | 11388 | 113381 |
| Power First | 12274 | 55139 | 56604 |
| Power First with Copy | 12 | 78 | 124876 |
| Time First | 65838 | 18179 | 5051 |

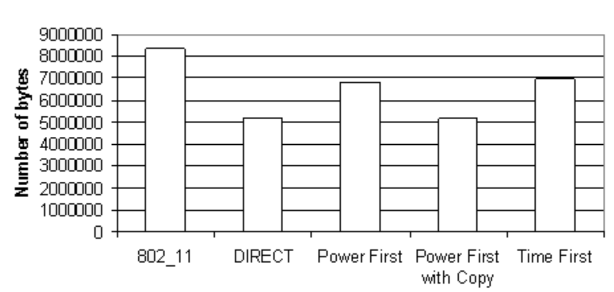


Fig. 13. Throughput in chain topology with multi-hop flows.

Despite this, Figure 14 shows that all variants of CSMA/PB obtain higher throughput per unit energy than IEEE 802.11. Table III shows the number of packets transmitted at each power level. "Direct" and "power first with copy" consume the least energy; their throughput suffers from taking short hops to the destination.

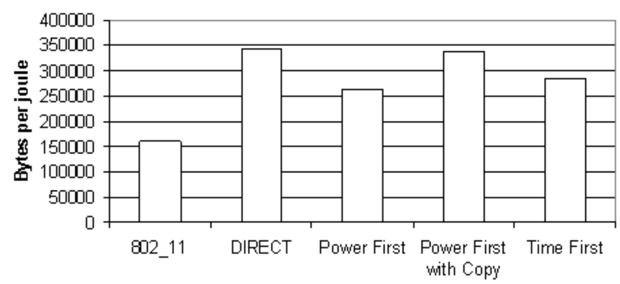


Fig. 14. Throughput/energy in chain topology with multi-hop flows.

## *B. Static Cluster Topology*

We now consider a static cluster topology in which there are two groups of 5 nodes, each with two intra-group flows between nodes $30\,m$ apart, and a single inter-group flow between a pair of nodes $200\,m$ apart (see Figure 15).

TABLE III

POWER LEVEL USAGE IN CHAIN TOPOLOGY, MULTI-HOP FLOWS

| | 250m | 100m | 40m |
|---|---|---|---|
| IEEE 802.11 | 79635 | 0 | 0 |
| DIRECT | 22636 | 8186 | 66445 |
| Power First | 39425 | 21237 | 34363 |
| Power First with Copy | 23535 | 20204 | 60051 |
| Time First | 36908 | 27033 | 22023 |

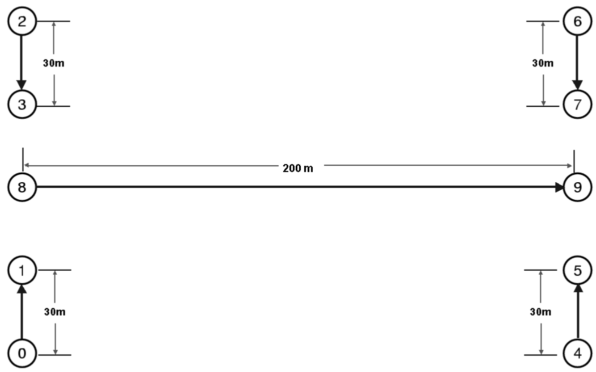


Fig. 15. Static cluster topology.

Figure 16 shows throughput for the cluster topology. All variants of CSMA/PB except "time first" obtain higher throughput than IEEE 802.11. With spatial backoff, concurrency within clusters leads to higher throughput. Figure 17 shows that "direct" and "power first with copy" obtain the highest throughput per unit energy.

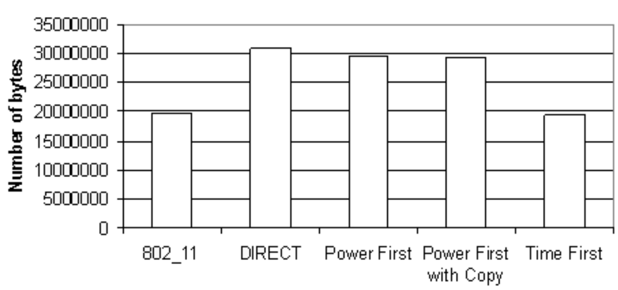


Fig. 16. Throughput in static cluster topology.

### C. Mobile Ad Hoc Network

In this scenario we consider a *mobile ad hoc network* (MANET) with 60 nodes in a $500 \times 250\,m$ area. 50 nodes are each moving according to the (steady-state initialized) random way-point mobility model at $2\,m/s$ with a 2 second pause time [20]. Between the remaining 10 nodes, we establish 5 flows, one from each of 5 fixed sources positioned evenly along the left-hand edge of the

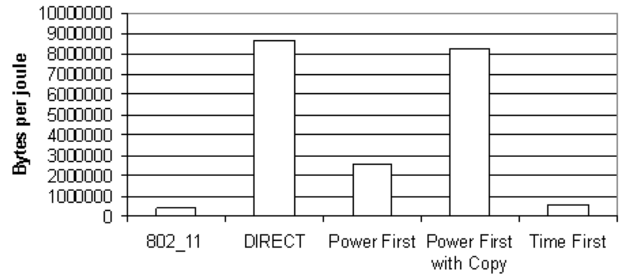


Fig. 17. Throughput/energy in a static cluster topology.

rectangular area to destinations positioned across from them on the right-hand side of the area (see Figure 18).

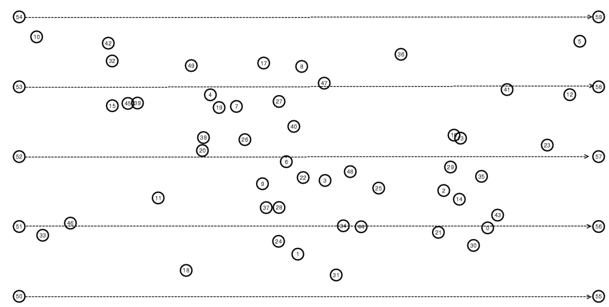

Fig. 18. Multi-hop flows in a mobile ad hoc network.

Figure 19 shows the throughput in this scenario. All variants of CSMA/PB obtain higher throughput than IEEE 802.11. This is no surprise since, in IEEE 802.11, there is no concurrency among the 5 flows. With spatial backoff the flows can run concurrently. Among the CSMA/PB variants, "direct" and "power first with copy" suffer the most. The throughput for "power first" is unexpectedly high. While this variant of CSMA/PB can suffer from a large number of asymmetric links, this seems to be an advantage when the network is busy and all the flows are multi-hop. The throughput per unit energy of all variants of CSMA/PB outperforms IEEE 802.11 in the mobile scenario (see Figure 20).

## VI. CONCLUSIONS

In this paper, we propose an alternate approach to collision resolution in a CSMA protocol, namely the use of power control to resolve collisions by backing off in space rather than backing off in time. To improve adaptation to changing network conditions, we combine our *power backoff* (PB) approach, CSMA/PB, with temporal backoff. Simulation results for a variety of static and mobile mobile ad hoc network scenarios show that CSMA/PB *always* outperforms IEEE 802.11

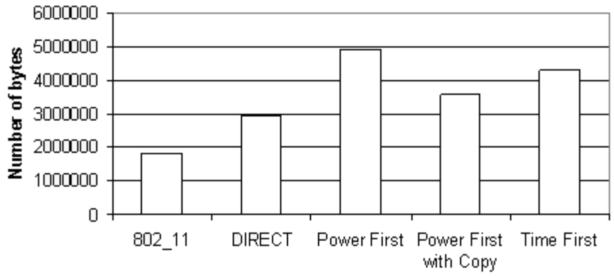


Fig. 19. Throughput in a MANET with multi-hop flows.

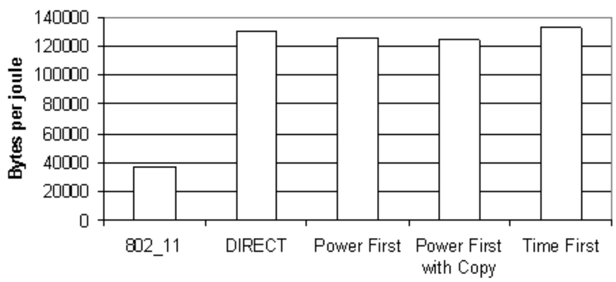


Fig. 20. Throughput/energy in a MANET with multi-hop flows.

in throughput per unit energy, often by a significant margin. However, we caution that these results are based on an optimistic centralized power-aware routing strategy that illustrates the *potential* of power backoff. The strong results suggest an investigation of CSMA/PB with distributed power-aware protocols is warranted.

## ACKNOWLEDGMENTS

The research of V. R. Syrotiuk and M. Cui is supported, in part, by NSF ANI-0240524 and ITR-0220001. Any opinions, findings, conclusions or recommendations expressed are those of the authors and do not necessarily reflect the views of NSF.

## REFERENCES

[1] J. Gomez and A. T. Campbell, "A case for variable-range transmission power control in wireless multihop networks," in *Proceedings of the 23rd Annual Joint Conference of the IEEE Computer and Communications Societies*, vol. 2, March 2004, pp. 1425–1436.

[2] D. Aldous, "Ultimate stability of exponential backoff protocol for acknowledgement based transmission control of random access communication channels," *IEEE Transactions on Information Theory*, vol. 33, no. 2, pp. 219–223, 1987.

[3] F. P. Kelly, "Stochastic models of computer communication systems," *J. Royal Statistical Society (B)*, vol. 47, pp. 379–395, 1985.

[4] J. Hastad, F. T. Leighton, and B. Rogoff, "Analysis of backoff protocols for multiple access channels," in *Proceedings of the ACM Symposium on the Theory of Computing*, May 1987, pp. 241–253.

[5] A. Nasipuri, J. Zhuang, and S. R. Das, "A multichannel CSMA MAC protocol for multihop wireless networks," in *Proceedings of IEEE Wireless Communications and Networking Conference*, September 1999, pp. 1402–1406.

[6] A. Nasipuri and S. R. Das, "Multichannel CSMA with single power-based channel selection for multihop wireless networks," in *Proceedings of IEEE Vehicular Technology Conference*, September 2000, pp. 211–218.

[7] J. So and N. H. Vaidya, "Multi-channel MAC for ad hoc networks: Handling multi-channel hidden terminals using a single transceiver," in *Proceedings of ACM International Symposium on Mobile Ad Hoc Networking and Computing*, May 2004, pp. 222–233.

[8] Z. Tang and J. J. Garcia-Luna-Aceves, "Hop-reservation multiple access (HRMA) for ad-hoc networks," in *Proceedings of the 18th Annual Joint Conference of the IEEE Computer and Communications Societies*, March 1999, pp. 194–201.

[9] A. Tzamaloukas and J. J. Garcia-Luna-Aceves, "A receiver-initiated collision-avoidance protocol for multi-channel networks," in *Proceedings of the 20th Annual Joint Conference of the IEEE Computer and Communications Societies*, April 2001, pp. 189–198.

[10] P. Karn, "MACA – a new channel access method for packet radio," in *Proceedings of the 9th ARRL/CRRL Amateur Radio Computer Networking Conference*, September 1990, pp. 134–140.

[11] E.-S. Jung and N. H. Vaidya, "A power control MAC protocol for ad hoc networks," in *Proceedings of the 8th ACM International Conference on Mobile Computing and Networking*, September 2002, pp. 36–47.

[12] J. P. Monks, V. Bharghavan, and W.-M. Hwu, "A power controlled multiple access protocol for wireless packet networks," in *Proceedings of the 20th Annual Joint Conference of the IEEE Computer and Communications Societies*, April 2001, pp. 219–228.

[13] A. Muqattash and M. Krunz, "Power controlled dual channel (PCDC) medium access protocol for wireless ad hoc networks," in *Proceedings of the 22nd Annual Joint Conference of the IEEE Computer and Communications Societies*, 2003, pp. 470–480.

[14] ——, "A single-channel solution for transmission power control in wireless ad hoc networks," in *Proceedings of the Fifth ACM International Symposium on Mobile Ad Hoc Networking and Computing*, May 2004, pp. 210–221.

[15] S. Wu, Y. Tseng, and J. Sheu, "Intelligent medium access for mobile ad hoc networks with busy tones and power control," *IEEE Journal on Selected Area in Communications*, vol. 18, no. 9, pp. 1647–1657, 2000.

[16] J. Fuemmeler, N. H. Vaidya, and V. V. Veeravalli, "Selecting transmit powers and carrier sense thresholds for CSMA protocols," University of Illinois, Urbana-Champaign, Tech. Rep., October 2004.

[17] B. Chu, "Improving IEEE 802.11 performance with power control and distance based contention window selection," Master's thesis, University of Illinois, Urbana-Champaign, 2005.

[18] X. Yang and N. H. Vaidya, "On physical carrier sensing in wireless ad hoc networks," in *Proceedings of IEEE Infocom Conference*, vol. 4, March 2005, pp. 2525 – 2535.

[19] "The network simulator — ns-2," University of California, Berkeley, http://www.isi.edu/nsname/ns/.

[20] W. Navidi and T. K. Camp, "Stationary distributions for the random waypoint mobility model," *IEEE Transactions on Mobile Computing*, vol. 3, no. 1, pp. 99–108, January-March 2004.