Power Aware Routing using Power Control in Ad Hoc Networks

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***Abstract*— A conventional routing protocol selects a path using the shortest number of hops as a routing metric. It has been proposed that a different routing metric may be useful to achieve energy savings. One such power-aware routing metric is minimizing the aggregate transmit power on a path from a source to a destination. This metric has been used along with a simple power control protocol, which uses the maximum transmit power for the transmission of RTS and CTS and the minimum necessary transmit power for the transmission of DATA and ACK. Although this type of power control protocol does not provide spatial reuse it can conserve energy. We will refer to this kind of power control as the BASIC-like power control protocol. In this paper we show that a power aware routing, minimizing the total transmit power, with BASIC-like power control does not save energy, which contradicts to previous studies in literatures. The reason is simple and intuitive but it has been entirely overlooked. Using the power aware routing metric, the selected paths can be much longer than the shortest path. In other words, there can be more number of hops between a source and a destination. Since BASIC-like power control does not provide spatial reuse nodes on a path have to share and compete for the channel bandwidth. Therefore, the throughput achieved between a source and a destination can be lower than that of IEEE 802.11 without power control. Also, we found that the metric leads to lower data bits delivered per unit of transmit energy. We show that using the shortest number of hops in conjunction with BASIC-like power control conserves more energy than the power aware routing with BASIC-like power control.**

***Index Terms*— IEEE 802.11, power control MAC protocol, energy saving, power aware routing, wireless network.**

I. Introduction

Recently a large volume of research has been conducted on the issue of energy efficiency for wireless networks. Since energy conservation is not an issue of one particular layer of the network protocol stack many researchers have focused on cross layer designs to conserve energy more effectively. One such effort is to employ power control at the MAC layer and to design a power aware routing at the network layer.

Power control is a mechanism that varies a transmit power level when sending packets. The primary benefit of power control is to increase channel capacity by reducing interferences among network nodes. The secondary benefit is to conserve energy by utilizing only necessary transmit power for packet transmissions.

One simple power control protocol as a modification of IEEE 802.11, called BASIC in [5], has been considered to be energy efficient. It considers the 4-way handshake of IEEE 802.11. That is, a source node that wishes to send a packet first transmits an RTS (Request To Send) control packet to its destination. When the destination node receives the RTS it replies with a CTS (Clear To Send). This RTS-CTS handshake reserves the channel for the duration of DATA and ACK transmission. Thus, upon receiving the CTS the source can transmit DATA packets. When the destination receives DATA packets successfully it replies with an ACK.

Fig. 1 illustrates how the BASIC protocol works, assuming node A wishes to send a packet to node B. Like IEEE 802.11, the BASIC protocol uses the maximum transmit power for the transmission of RTS and CTS. Upon receiving an RTS, the receiver B decides the minimum transmit power level it can communicate with the sender A based on the signal strength of the received RTS. Then B includes the minimum transmit power level into a CTS and sends it back to A. After the RTS-CTS handshake, A and B send a DATA and an ACK, respectively, using the minimum transmit power level.

Earlier study [5] shows that the BASIC protocol has a shortcoming that leads nodes in carrier sensing (CS) zone to cause collisions with an ACK at the sender. Carrier sensing zone is an area outside transmission range where nodes can only detect the signal but cannot decode it. Collisions introduced by the BASIC protocol cause more energy consumption and PCM (Power Control MAC) proposed in [5] fixes this problem. Therefore, in this paper we use the PCM protocol as a BASIC-like power control protocol.

The BASIC power control protocol has been used with power aware routing protocols to improve the energy efficiency. For example, power aware routing protocols in [2], [3] select a path that minimizes the aggregate transmit power consumed by all nodes on the path. It has been believed that

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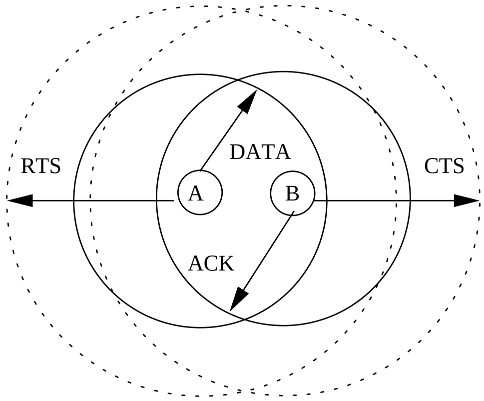


Fig. 1. BASIC: RTS and CTS are transmitted at the highest transmit power, and DATA and ACK are transmitted at the minimum transmit power.

those power aware routing protocols with BASIC-like power control can save energy as compared to the conventional routing, which uses the shortest number of hop as a routing metric. In this paper, however, we show contradicting results. That is, the power aware routing with BASIC-like power control degrades the network throughput as compared to IEEE 802.11 without power control. In addition, we also show the power aware routing protocol cannot achieve energy savings.

The rest of the paper is organized as follows. Section II reviews the related work. Section III presents an overview of power aware routing with BASIC-like power control, and investigate its energy efficiency. Section IV describes our simulation model and discusses the simulation results. Section V concludes the paper.

II. Related Work

BASIC-like power control has been widely used for the purpose of energy conservation [3], [6], [9]. The deficiency of the BASIC protocol has been addressed in [5], where the authors proposed a solution, called PCM (Power Control MAC). Since PCM fixes the problem we use PCM as BASIC-like power control.

Combined with the BASIC-like power control MAC protocol, power aware routing protocols have been studied to enhance energy savings. One such effort is PARO (Power Aware Routing Optimization) [3], which uses the BASIC protocol for its MAC protocol. For a routing metric, PARO chooses a path that minimizes the total transmit power consumed by all nodes on the path. Thus, when using PARO it is likely to have more number of hops than when using a conventional routing protocol with the shortest number of hops.

Doshi *et al.* [2] implement an on-demand minimum energy routing protocol based on DSR [4]. Like PARO, the protocol uses the same metric that minimizes the total transmit power with BASIC-like power control.

Several power aware routing metrics are presented in [13]. Among the metrics, the authors emphasize metrics that are represented as a function of remaining battery power in order to extend the network lifetime. They show a routing protocol using these metrics can reduce the cost per packet over the shortest hop routing.

CMMBER (Conditional Max-Min Battery Capacity Routing) [15] is a maximum battery life routing, which tries to not only minimize the overall transmission power but also avoid to use nodes that have low battery capacity. In CMMBER, if a route from a source to a destination contains nodes with low battery capacity (below a threshold) it is avoided to extend the network lifetime. On the other hand, if every node in some possible routes has sufficient remaining battery capacity then a path that minimizes the total transmit power is chosen.

Another protocol to extend the network lifetime is proposed in [11]. Using the location information the protocol chooses a path that minimizes the energy consumed to deliver a packet. A zone-based online power-aware routing protocol is proposed in [8], which also seeks to optimize the network lifetime.

Other optimizations also include topology control [10], [11], [12], [16], energy efficient spanning trees for multicasting and broadcasting [17], [18], and using power saving mode at the MAC layer [1], [19], [20].

III. A Power Aware Routing Using Power Control

A. An Overview of Power Aware Routing Optimization

In this section we briefly overview how PARO [3] works. We study PARO as an example of the power aware routing with BASIC-like power control, which selects the minimum total transmit power path. PARO has 3 core algorithms – which are overhearing, redirection, and route-maintenance for mobility.

The overhearing algorithm handles packets that are received by the MAC successfully. When a node overhears a packet from its neighbor it creates an entry in the overhear table or refreshes the entry if the entry for the neighbor already exists. The entry includes the minimum transmit power necessary to communicate with the neighbor based on the signal strength of the received packet and the power level at which the packet was sent. The information of the latter is included inside the packet by the sender.

Using the overhearing algorithm, the redirection algorithm can perform the route optimization, which leads to find paths that require less transmit power to forward a packet. Once a node finds a path that consumes less transmit energy the node becomes a redirector and transmits a redirect message to the sender. The redirect message includes a new energy efficient path.

Since only one intermediate node (redirector) can be added in a path at a time PARO optimizes routes one step at a time. Therefore, the number of iterations required to reach an optimum route is the same as the number of redirectors included in the route.

Unlike a static network, the route maintenance algorithm is required for a network where nodes are mobile. In PARO, source nodes transmit *route-maintenance* packets to destination nodes whenever there is no data packet to send for a fixed time interval, *route-timeout*. From the *route-maintenance* packets and data packets nodes can maintain fresh routes.

B. Energy Efficiency of PARO

We first show the performance of PARO with a simple scenario depicted in Fig. 2. It is a simple chain topology, which consists of 3 nodes. Nodes are shown as a circle, and the arrow between two nodes indicates a traffic flow. For this specific topology, node A is a source that transmits packets to node C. The distance between adjacent node pairs is 50 m.

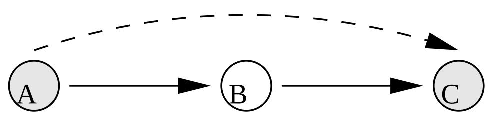


Fig. 2. Chain topology: node A can transmit packets to node C directly, or forward them through an intermediate node B.

In Fig. 2, node A can either send a packet directly to node C using the shortest path routing, or forward them through an intermediate node B using PARO. The dashed line from A to C in Fig. 2 indicates the former case and two other flows, A-B and C-D, indicate the latter case.

Fig. 3 shows simulation results of the chain topology. PARO indicates power aware routing with BASIC-like power control. For simulation purpose, PCM (Power Control MAC) [5] is used for BASIC-like power control. In graphs, PCM indicates PCM with shortest path routing and IEEE 802.11 means the IEEE 802.11 MAC without power control using the shortest path routing. All schemes considered in this paper use the shortest path routing protocol except PARO, which uses the power aware routing. Thus, when we say PCM or IEEE 802.11 it will mean the scheme with the shortest path routing.

Fig. 3 (a) shows the aggregate throughput on the chain topology. The graphs for IEEE 802.11 and PCM are overlapped. When the network load is low the aggregate throughput of all schemes perform the same. However, the aggregate throughput of PARO starts suffering at 700 Kbps per flow, and does not increase beyond 600 Kbps. Since BASIC-like power control uses the maximum transmit power for RTS and CTS, all nodes A, B, and C in Fig. 2 are within their transmission ranges. When PARO is used, A will transmit packets to B and then B will forward them to C. In this situation, two flows (A-B and B-C) share bandwidth and they contend each other for channel bandwidth, which results in low throughput. This is not a surprising result as studied in [7]. As the expected path length increases, the bandwidth available for each node to originate packets decreases. However, this is entirely overlooked in [2], [3], focusing only on the aspect of energy consumption.

Fig. 3 (b) shows the total data delivered per unit of transmit energy. Since PCM uses the minimum necessary transmit power for data transmissions between A and C (of which distance is 100 m apart) it achives more energy savings than IEEE 802.11. PARO also performs better than IEEE 802.11. However, it is important to note that PCM performs better than PARO. In PARO packets travel more number of hops, where RTS and CTS are sent at the maximum transmit power in each hop. Also, there is extra energy consumption associated with transmitting more RTS and CTS. Furthermore, since there is no spatial reuse in PARO more number of flows from a source to a destination will contend each other. This can cause packet retransmissions, which leads more energy consumption.

From the simple topology we show that the power aware routing with BASIC-like power control may not be energy efficient as compared to PCM. This is mainly because there is no spatial reuse in BASIC-like power control – if a packet travels more number of hops it results in lower throughput.

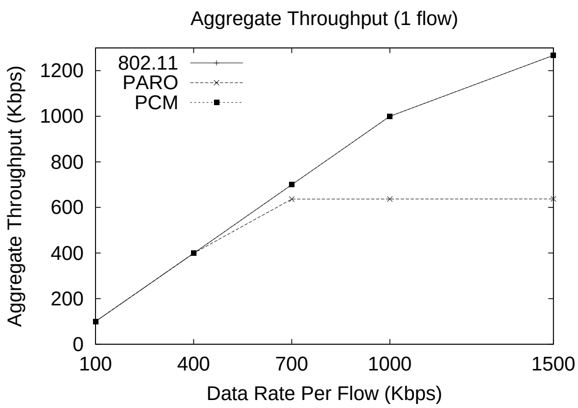
C. Overhearing Process with Power Control

In PARO, the overhearing algorithm is used to find paths that require less transmit power consumption to forward a packet. By overhearing neighbors' transmissions a route can be optimized.

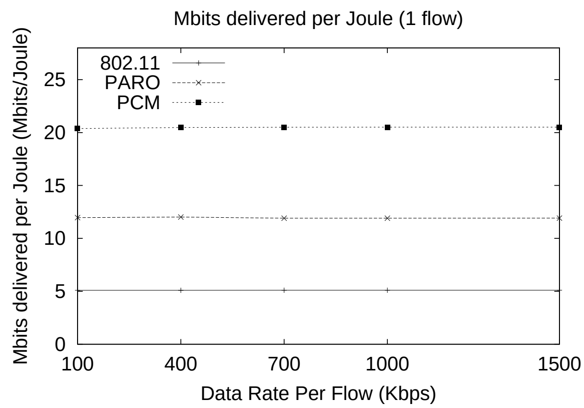
In general, the overhearing algorithm can also be used in a conventional routing protocol to find the shortest path. For instance, in DSR [4] the overhearing algorithm is performed by promiscuous mode to shorten a path if it can provide shorter path. When a node overhears packets it checks if it can forward packets with shorter hops. If so, it sends a RREP (Route Reply) packet to the sender to notify a new route.

However, the overhearing algorithm may not be performed as expected if it is used with power control. That is, when power control is used a packet is sent at the minimum necessary transmit power. Thus, the number of neighbors that can overhear the packet is reduced. When compared with IEEE 802.11, PCM (and also PARO) can use longer paths since the overhearing algorithm does not perform all the time. As discussed with PARO, using longer paths can degrade the aggregate throughput, which results in poor energy efficiency. This side effect has appeared during our simulations. We fix this problem by having all nodes in the network do not use power control periodically – that is, all nodes periodically use the maximum transmit power. With this simple modification, the overhearing process can be performed by all nodes in the network periodically. We include this modification in our simulations as an option for PCM, which is indicated as PCMO (PCM with Option). Specifically, in our simulation nodes give up power control every one second for the duration of 50 $msec$. Note that since this option forces all nodes to uses the maximum transmit power periodically, the power consumption using this option will be slightly higher than that of PCM.

Along with the above modification, we also make nodes to



(a) Aggregate throughput



(b) Total data delivered per joule

Fig. 3. Chain topology: the curves for PCM+SPR and 802.11 overlap in (a). The aggregate throughput of PARO does not increase beyond 600Kpbs due to the contention between two flows.

use the maximum transmit power for all the routing control packets, such as RREQ (Route Request), RREP (Route Reply), and RRER (Route Error). Therefore, routing information will be overheard by all the neighbors and route discovery or maintenance will not be affected by power control. In the following section, we show more simulation results for various scenarios, which also include the same topology used in [3].

IV. Performance Evaluation

We simulated PARO [3], which selects the minimum energy path using BASIC-like power control, PCM (Power Control MAC) using the shortest path routing, PCM with the Option using the shortest path routing, and IEEE 802.11 with the shortest path routing without power control. In graphs we indicate these protocols as PARO, PCM, PCMO, and IEEE 802.11, respectively. We use the following metrics to evaluate these schemes.

- *Aggregate throughput over all flows in the network*: This metric will show if any energy saving is achieved by the sacrifice of throughput.
- *Total data delivered per unit of transmit energy consumption (Mbits delivered per joule)*: This metric measures the amount of data delivered per joule of *transmit* energy. The total data delivered over all flows is divided by the total *transmit* energy consumption over all nodes in the network. The energy consumed in packet reception is not considered in this metric. We use this metric as a measurement of energy efficiency – the greater the value of this metric, the more energy savings.

A. Simulation Model

We use ns-2 with the CMU wireless extensions [14] for our simulations. The duration of each simulation is 20 seconds. Each flow transmits CBR (Constant Bit Rate) traffic, and the rate of traffic is varied in different simulations. The channel bit rate is 2 Mbps and the packet size is fixed at 512 bytes. Each node starts with enough energy so that it will not run out of its energy during the simulations. All simulation results are the average of 30 runs.

For the radio propagation model, a two-ray path loss model is used [14]. The transmitted signal is attenuated by $1/d^2$ at near distances and by $1/d^4$ at far distances, where d is the distance between the source and the destination nodes. We do not consider fading in our simulations.

As in [5], we consider four transmit power levels, 2 mW, 15 mW, 75.8 mW, and 281.8 mW, roughly corresponding to the transmission ranges of 60 m, 120 m, 180 m, and 250 m, respectively. The capture threshold is set to 10 dB.

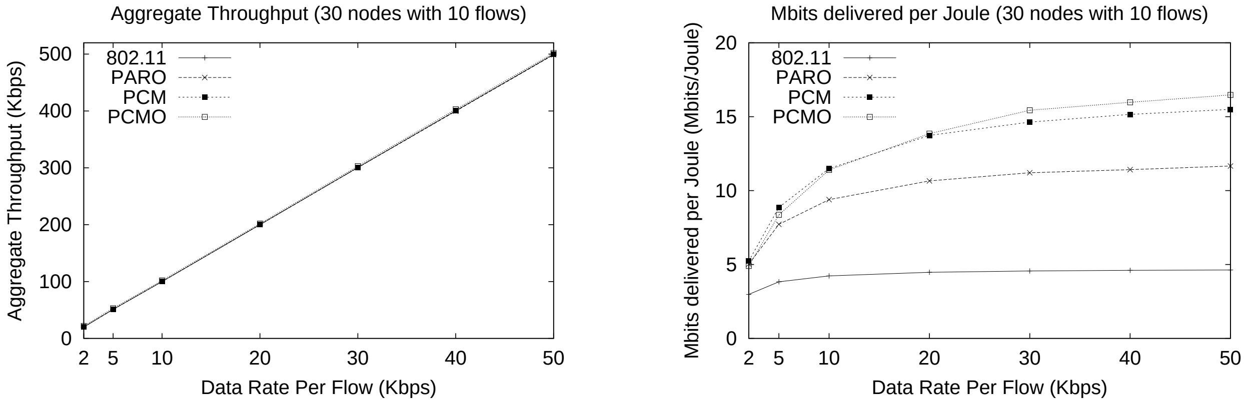
For the random topologies, we first simulate with 30 nodes in a 100 x 100 m^2 area, which is the same topology used in PARO. For each scenario, 10 source and 10 destination nodes are randomly chosen. In addition, we simulated another random topologies with a larger network, where 50 nodes are randomly placed in a 1000 x 1000 m^2 area. Like the scenario with 30 nodes, 10 source and 10 destination nodes are randomly chosen among 50 nodes. Besides, we simulated a congested network with more number of flows, where 20 source and 20 destination nodes are randomly chosen among 50 nodes. Note that in all scenarios, any source or destination node can also be an intermediate node that forwards traffic for other nodes.

B. Simulation Results

B.1 Random Topology: 30 nodes in 100 x 100 m^2

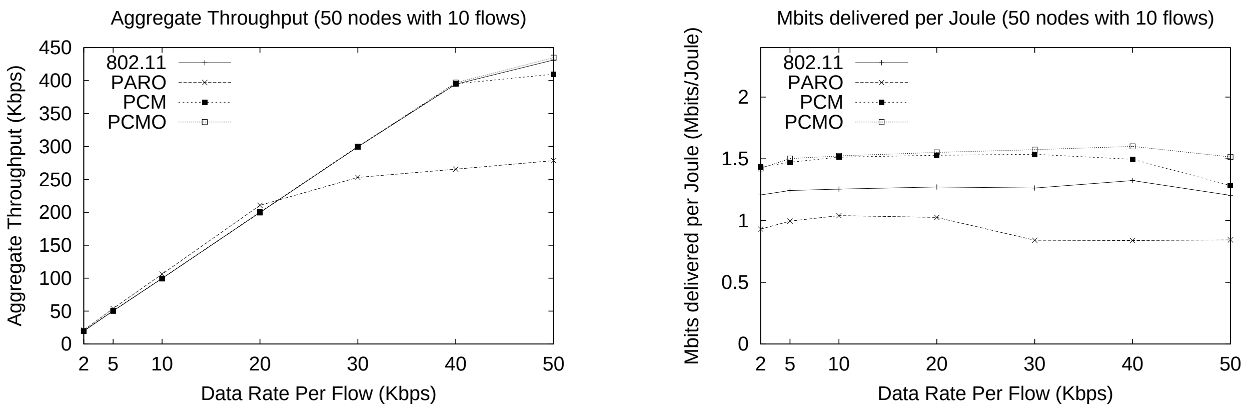
Fig. 4 shows the simulation results of a random topology with 30 nodes in a 100 x 100 m^2 area. Ten source and ten destination nodes are randomly chosen. Each flow transmits CBR traffic and the rate of each traffic flow is varied from 2 Kbps to 50 Kbps.

In Fig. 4 (a), the aggregate throughput of all schemes are the



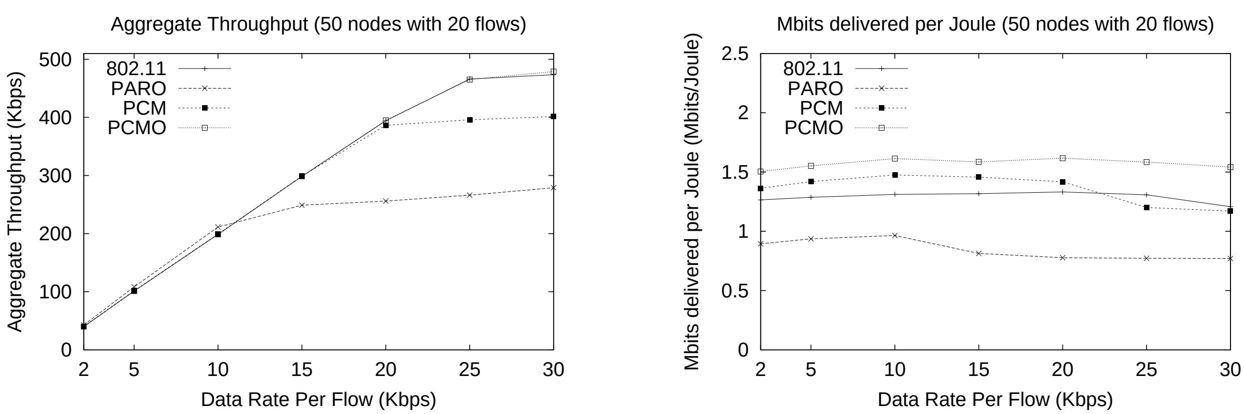
(a) Aggregate throughput (b) Total data delivered per joule

Fig. 4. Random topology with different network loads (30 nodes in 100 x 100m^2): the curves for PCM+SPR, PARO, and 802.11 overlap in (a).



(a) Aggregate throughput (b) Total data delivered per joule

Fig. 5. Random topology with different network loads (50 nodes with 10 flows in 1000 x 1000m^2).



(a) Aggregate throughput (b) Total data delivered per joule

Fig. 6. Random topology with different network loads (50 nodes with 20 flows in 1000 x 1000m^2).

same – all curves are overlapped. PARO performs better than IEEE 802.11 in terms of energy efficiency in Fig. 4 (b) as in [3]. However, as we explained in the chain topology in Fig. 3 PARO performs worse than PCM due to the channel contention among flows. As mentioned earlier, if using BASIC-like power control there are less number of nodes that can overhear a packet since data packets are sent at the minimum necessary transmit power. Thus, a selected route in PARO may be longer than the shortest path. PCMO, which uses the maximum transmit power periodically, performs slightly better than PCM in Fig. 4 (b). In PCMO more number of nodes may overhear packet transmissions so a route can be optimized to be the shortest path. As we shall see in next section PARO does not save energy all the time – it can even consume more energy than IEEE 802.11 without power control.

B.2 Random Topology: 50 nodes in 1000 x 1000 m^2

We now present simulation results of a random topology with 50 nodes in a 1000 x 1000 m^2 area, varying network load and the number of traffic flows.

Fig. 5 shows the simulation results, where 10 source and 10 destination nodes are randomly chosen among 50 nodes. Fig. 6 shows simulation results for 20 flows – 20 sources and 20 destinations are randomly selected.

In Fig. 5 (a) and 6 (a), as the network load gets higher the aggregate throughput of PARO gets lower than that of PCM or IEEE 802.11. This is similar to Fig. 3 (a). BASIC-like power control offers no spatial reuse. Besides, in PARO packets tend to travel longer hops, which leads to more contentions among flows from a source to a destination. Therefore, the throughput achieved by PARO is lower than other schemes, especially at high load.

One more thing to mention is that the aggregate throughput of PCM in Fig. 5 (a) is slightly lower than that of IEEE 802.11 at 50 Kbps. Similarly, in Fig. 6 (a) the aggregate throughput of PCM is lower than IEEE 802.11 at 25 or 30 Kbps. As explained earlier, the overhearing algorithm may be performed by less number of nodes in BASIC-like power control since data packets are transmitted at the minimum necessary transmit power. Thus, paths used in BASIC-like power control can be longer than the shortest path, which can result in a low throughput at high load. This issue has not been addressed in [5], where only one hop flows are considered. PCMO achieves the same aggregate throughput in Fig. 5 (a) and 6 (a) by having all nodes use the maximum transmit power periodically.

Fig. 5 (b) and 6 (b) show the total data delivered per unit of transmit energy in the random topology using 10 flows and 20 flows, respectively. The energy efficiency of PARO is even lower than that of IEEE 802.11. PCM conserves more energy as compared to PARO or IEEE 802.11, and at high load PCMO performs slightly better than PCM.

B.3 More Simulation Results in 1000 x 1000 m^2

We now present more simulation results for a random topology with 50 different scenarios in a 1000 x 1000m^2 area. Fig. 7 shows the simulation results for 50 nodes with 10 flows. The data rate of each traffic flow is fixed at 50 Kbps. Fig. 8 is the same graph but each value in all schemes are normalized by the value achieved by PCMO. For example, in Fig. 8 (a), a value for PARO indicates an aggregate throughput achieved by PARO divides by that of PCMO. Therefore, if a value in Fig. 8 is greater than 1 it means that PCMO performs better than the corresponding scheme. If a value is around 1 it means that the scheme performs similar to PCMO.

As we saw in other graphs earlier, in Fig. 7 (a) or 8 (a) PARO achieve poor aggregate throughput as compared to PCM or IEEE 802.11. The performance of PCM, PCMO, and IEEE 802.11 are similar.

In Fig. 7 (b) and 8 (b) the total data delivered per unit of transmit energy for PARO is lower than those of other schemes. PCM and PCMO performs similar to each other, which is better than PARO and IEEE 802.11. Recall that PCMO makes all nodes in the network use the maximum transmit power periodically. Thus, if PCM and PCMO maintain the same route for all the network flows, PCMO will consume additional energy than PCM.

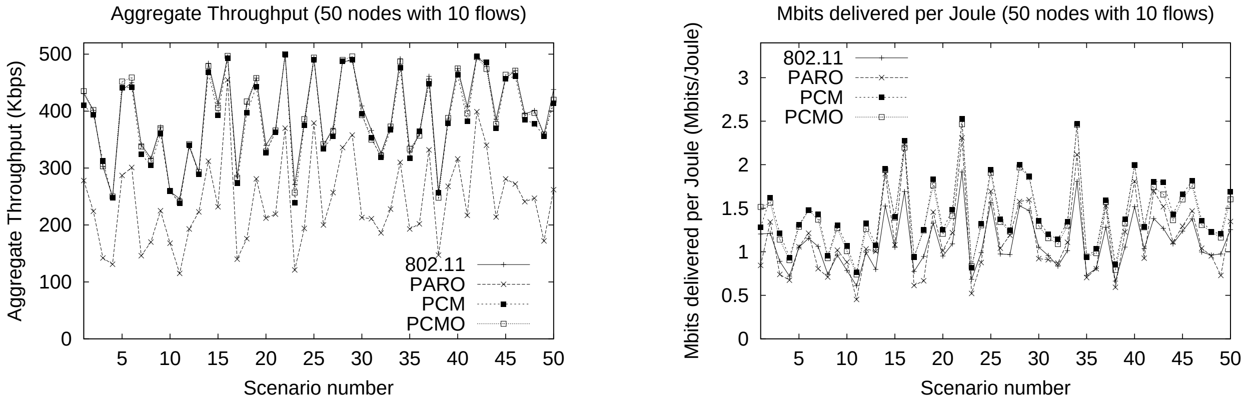
Fig. 9 shows the simulation results when there are 20 flows in the network, and Fig. 10 is its normalized graph – each value is divided by the value achieved by PCMO. Fifty different scenarios are considered at the data rate of 25 Kbps. These graphs show the same trends as Fig. 7 and 8. In Fig. 9 (a) and 10 (a), PARO has poor aggregate throughput as compared to PCM and IEEE 802.11, and all other schemes perform the same. In Fig. 9 (b) and 10 (b), PCM and PCMO perform similar to each other, but their performances are better than PARO and IEEE 802.11. PARO performs even worse than IEEE 802.11.

V. CONCLUSION

A power aware routing, which minimizes the total transmit power, with BASIC-like power control has been considered energy efficient. In this paper we use PARO as an example. Contradicted to previous studies such as PARO, we have shown the power aware routing with BASIC-like power control is not energy efficient – it may even consume more energy as compared to IEEE 802.11 without power control. The power aware routing forces a packet to travel more number of hops, with the minimum necessary transmit power in each hop, from a source to a destination as compared to the shortest path routing. Since BASIC-like power control does not provide spatial reuse, as a packet travels longer hops it creates an overhead. That is, all flows on a single path have to share the channel bandwidth and contend each other to forward a single packet. Therefore, the aggregate throughput achieved by PARO is much lower than that of IEEE 802.11 without power control. This becomes a serious problem especially when the network load is high. Due to the poor throughput, the energy savings achieved by is low. This is a simple and obvious but has been entirely overlooked in the past.

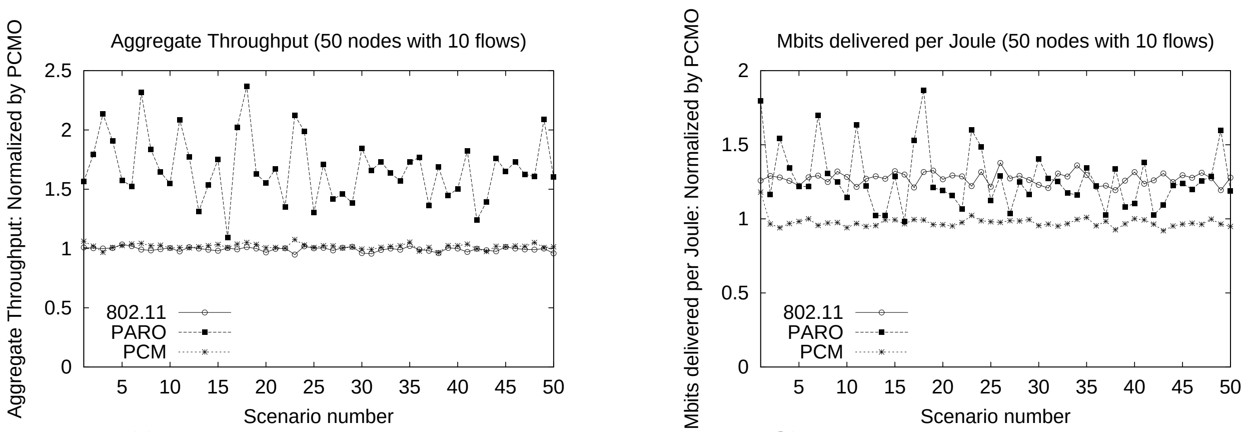
We have shown that the shortest path routing with BASIC-like power control performs better (more energy efficient) than both PARO and IEEE 802.11. We have also found that using BASIC-like power control it is possible the aggregate throughput to be degraded. Since data packets are sent at the minimum necessary transmit power there can be less number of nodes that overhear data packets. This can result in using a longer path than the shortest path. This problem can be fixed by forcing every node in the network to use the maximum transmit power periodically so that all nodes can overhear more number of packet transmissions to find the shortest path.

Future work includes to design a power aware routing that



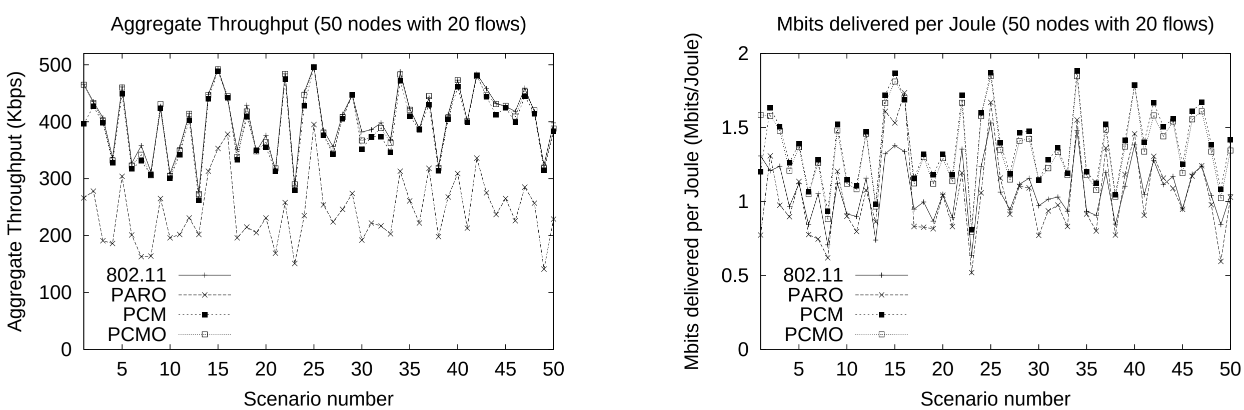
(a) Aggregate throughput (b) Total data delivered per joule

Fig. 7. Random topology for 50 different scenarios with a 50 Kbps data rate per flow (50 nodes in 1000 x 1000m^2): 10 flows.



(a) Aggregate throughput: normalized (b) Total data delivered per joule: normalized

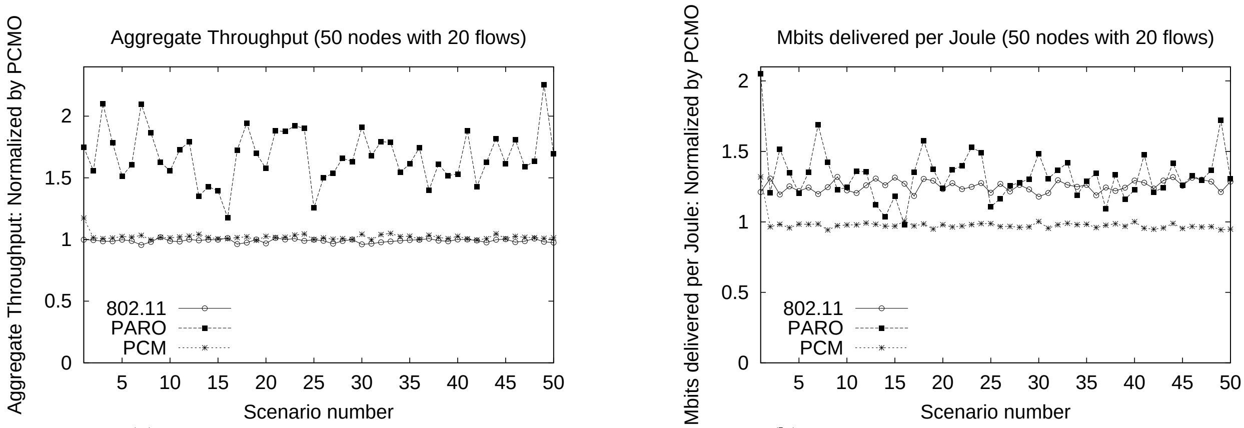
Fig. 8. Random topology for 50 different scenarios with a 50 Kbps data rate per flow (50 nodes in 1000 x 1000m^2): 10 flows.



(a) Aggregate throughput (b) Total data delivered per joule

Fig. 9. Random topology for 50 different scenarios with a 25 Kbps data rate per flow (50 nodes in 1000 x 1000m^2): 20 flows.

provides more energy savings. One simple algorithm using the existing protocols can be finding a path that minimizes the total transmit power on the path (like PARO) among the shortest paths. If there is only one shortest path, this will be the same as PCM. However, if there are more than one shortest paths, the minimum transmit power path will be chosen among them. The performance of this algorithm may depend on the network topology and scenarios. We have performed some simulations with this algorithm, but the improvement of this scheme was not significant. It will be also interesting to see how the power aware routing performs with other types of power control that provides spatial reuse.



(a) Aggregate throughput: normalized (b) Total data delivered per joule: normalized

Fig. 10. Random topology for 50 different scenarios with a 25 Kbps data rate per flow (50 nodes in 1000 x 1000m^2): 20 flows.

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