PCQoS: Power Controlled QoS in Wireless Ad Hoc Networks

Javier Gomez, Luis A. Mendez, Victor Rangel
Department of Electrical Engineering
National University of Mexico, D.F., 04510
Email: {javierg,alonso,victor}@fi-b.unam.mx

Andrew T. Campbell
Department of Computer Science
Dartmouth College, Hanover, NH 03755
Email: campbell@cs.dartmouth.edu

***Abstract*—Mobile Ad hoc networks typically use a common transmission power approach for the discovery of routes and the transmission of data packets. In this paper we present PCQoS, a power-controlled QoS scheme for wireless ad hoc networks which builds QoS mechanisms for specific applications that wish to tradeoff better QoS performance for sub-optimal paths. PCQoS allows selected flows to modify their transmit power as a way to add and remove relay nodes from their paths in order to coarsely modify their observed application QoS performance. We present simulation results and show that PCQoS can be used to provide coarse control over traditional QoS metrics (e.g., delay, throughput). To the best of our knowledge the PCQoS protocol represents the first attempt to use variable-range transmission control as a means to provide QoS differentiation to applications in wireless ad hoc networks.**

I. Introduction

The impact of transmission power control on network throughput has been widely studied in the literature in the context of cellular networks [8], and more recently in the case of WLAN, wireless sensor networks [3] and wireless ad hoc networks [9]. The later analysis focuses on the maximum capacity of the network as a function of the transmission range, node density, and average distance between source-destination pairs.

One of the main quality of service (QoS) trade-off involved in a wireless ad hoc network is related to the average number of times a packet is forwarded versus the average number of interfering nodes per attempted transmission. In [9] it is shown that reducing the transmission range is a better solution in terms of increasing the traffic carrying capacity of wireless ad hoc networks. Unfortunately, MAC protocols used in wireless ad hoc networks provide only limited performance in particular those protocols developed for shared medium access control like CSMA.

Power control has had a limited use in existing IEEE 802.11 radios which has become a de-facto standard in wireless ad hoc networks. In fact most IEEE 802.11 radios are usually configured to use the maximum transmit power (e.g., maximum transmission range) available to them. Recently, there has been a push by the research community to explore power-controlled IEEE 802.11 based networks. In this research, however, performance metrics, such as throughput, decrease when reducing the transmission power. These results are in contrast to theoretical results found in [9] and [7]. While the basic IEEE 802.11 standard does not exhibit good performance in wireless ad hoc networks, there are several proposals around the basic IEEE 802.11 standard that are customized for higher spectral reuse, and therefore, increased performance in single and multihop networks. In the next section, we introduce these proposals and show how they can provide the foundations for power controlled differentiated services in wireless multihop networks.

The specific contributions of this paper are as follows. We present several proposals around the IEEE 802.11 standard targeted to achieve higher spectral reuse for single and multihop wireless ad hoc operations [12] [11] [5], and show how these protocols can be used as the foundation for power controlled differentiated services in wireless ad hoc networks. Next, we propose, design, implement, and evaluate *PCQoS*, which is capable of trading off application QoS and energy conservation in wireless ad hoc networks. PCQoS can also be used to establish a set of differentiated service classes in wireless ad hoc networks. For example, wireless ad hoc networks could offer two types of service classes to devices/applications: (i) a gold class, which attempts to improve the throughput and delay observed by applications/devices; and (ii) a best effort class with potentially poorer throughput and delay. We argue that future wireless ad hoc networks would need to provide service differentiation to possibly different classes of applications.

The structure of this paper is as follows. Section II presents an overview of MAC protocols targeted to achieve higher spectral reuse in IEEE 802.11 based networks. A detailed discussion of the motivation behind PCQoS is presented in Section III. In addition, the detailed design of PCQoS is also presented. Section IV explains how PCQoS can dynamically add and remove relay nodes in selected flows. Following this, we study the performance of PCQoS using the ns-2 simulator in Section V. Related work is discussed in Section VI. Finally, we present our conclusion in Section VII.

II. Higher Spectral reuse in IEEE 802.11

One of the main drawbacks of the IEEE 802.11 MAC is that it requires that all nodes in the network use a common transmission power for transmission of control and data packets. In what follows, we discuss a number of proposals based on the IEEE 802.11 standard that remove this limitation providing increased spatial reuse [12] [11] [5]. We refer to these MAC

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proposals as Space Reuse CSMA (SR-CSMA) in the rest of the paper.

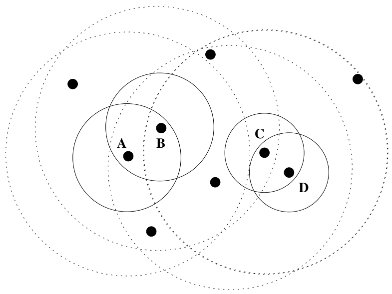

Fig. 1. We show the operation of SR-CSMA by a way of an example. In this case nodes A and C are going to transmit to nodes B and D, respectively. When a fixed common transmission power is used (dotted circles), only one transmission can take place at a time since the other transmission will sense the medium busy and wait for another opportunity to transmit. When nodes reduce their power to just the minimum necessary to reach the intended destination (solid circles), both transmissions can take place simultaneously.

The two main principles governing the design of SR-CSMA MAC protocols are [12]:

(i) *power conservation principle*, which dictates that each source must transmit using the minimum transmission power necessary to reach the intended receiver; and

(ii) *cooperation principle*, which dictates that no source that initiates a new transmission can disrupt on-going transmissions by transmitting too "loud".

Performance results shown in [12] [11] [5] indicate that these protocols allow for a greater number of simultaneous transmissions than IEEE 802.11. The benefits of using these protocols over IEEE 802.11 increase as the traffic becomes more localized. A negative property of SR-CSMA protocols is that they favor short-range transmissions over long-range ones under high traffic loads [12]. We highlight this observation because it is this unfairness what we use to our advantage in the PCQoS discussed in Section III in support of QoS differentiation. As an example, we implemented PCMAP [12] which is an example of a SR-CSMA in a network simulator in order to first understand this unfair behavior, and then experiment with PCQoS.

Table I shows the performance of PCMAP. There are 400 nodes in a 500x500 meter network with a 100 flows, each one of them sending 16 512-Byte packets for 10000 seconds of simulation time. Only 1 hop exists between source and destination nodes, for a connectivity range of 250 meters (complete details of the simulation settings can be found in Section V). Each source selects a destination at random within its 250 meters maximum range. Table I shows the number of flows and the unfairness factor (normalized to 1 for flows in the 200-250 meter range) over five distance ranges (viz. 0-50, 50-100, 100-150, 150-200, and 200-250 meters, respectively) from their associated sources. The unfairness factor in this case expresses the transmission opportunities to the destinations located within the different transmission ranges. An extreme example of this unfairness phenomena exhibited by PCMAP is reflected in that any of the 3 destinations located within the 0-50 meter range have 23 times more transmission opportunity than any of the 36 destinations located in the 200-250 meter range.

Range [meters]	Number of Flows	Unfairness Factor
0-50	3	x23
50-100	14	x10
100-150	19	x7
150-200	28	x3
200-250	36	**x1**

TABLE I
THROUGHPUT UNFAIRNESS OF PCMAP

The inherent unfairness toward long-range transmission is not specific to PCMAP, but is a common behavior of SR-CSMA protocols. Counter-intuitively, we use this unfairness as the basis for providing service differentiation in wireless ad hoc networks. The intuition is as follows. If we *break a long-range transmission into shorter-range transmissions, then we can increase the transmission opportunity of the resulting shorter-range transmissions, improving the end-to-end QoS observed of a particular flow*. This goal can be achieved by adding relay nodes between source-destination pairs. Such approach, however, could be detrimental to other flows and to the overall capacity of the network to carry traffic. In what follows, we study this tradeoff that we call PCQoS and discuss its benefits and drawbacks in detail in the next section. We will use the term *redirector* instead of relay node to differentiate while adding intermediate hops in links that otherwise can communicate directly.

III. PCQoS: Realizing the QoS-Power Trade-off

We consider building QoS mechanisms for specific applications that wish to trade-off better QoS performance. This tradeoff could be achieved by simply adding redirectors introduced between source-destination pairs, thereby enabling certain coarse control of the throughput and delay performance seen by applications.

When enabling the addition or removal of redirectors to achieve some coarse QoS control, we need to pay particular attention to which flows add or remove redirectors in order to assure "stable" and meaningful operations for the wireless network as a whole. This it is because adding one redirector to one flow impacts the QoS performance of possibly (in the worst case) all other flows in the network. We call this phenomenon the *domino effect*. The domino effect can be seen as the global impact of a local greedy strategy by a node/application/user. In order for one flow to have certain control over its QoS, it is necessary to control the overall number of redirectors in the network in a certain manner.

In order to control the impact of the domino effect in the network it is necessary to limit the number and rate of adding or removing redirector operations in the network. The simplest way to accomplish this objective is to limit the number of flows that are allowed to add or remove redirectors. For example, *gold service* flows can have such control to optimize their application performance while *normal* users cannot. In PCQoS, we propose that only a subset of flows/applications are given the capability of adding or removing redirectors. Flows with the flexibility of adding or removing redirectors in this manner would be more sensitive than other flows in terms of their QoS requirements. More specifically, lets define "gold" for flows (high priority) that require QoS and are power sensitive and "normal" (low-priority) for flows that tolerate best effort QoS. Separating flows using different priorities is not a limitation of PCQoS, but a common property of protocols that attempts to improve the average performance or a certain set of flows in detriment to others, as is the case of the DiffServ model discussed in the IETF.

A. Protocol Description

The PCQoS protocol is defined by the *monitoring* and *control* phases. During monitoring periods, gold flows monitor the continuous flow of packets from their respective sources and may decide to take QoS Power-control actions or not based on a user/application specific policy. During the control phase, redirectors can be dynamically added or removed from routes of gold flows.

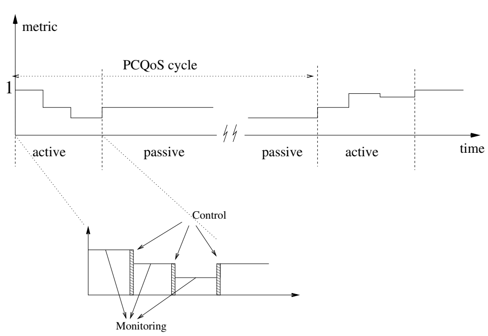

Fig. 2. PCQoS Operational Cycle

Figure 2 illustrates the operational cycle of PCQoS. In this figure, we show an example trace of the performance behavior for a QoS metric (e.g., throughput, delay, etc.) for a "hypothetical flow" over time. The PCQoS cycle has *active* and *passive* operational periods. During active periods, gold flows can add or remove redirectors from their paths in order to coarsely modify their QoS/power performance trade-off. Different gold flows may have different QoS/power policy objectives. However, there are several base policies that gold flows must obey while adding or removing redirectors in order to assure the stable operation of the wireless network (we will explain these baseline policies below). By a stable network we mean a situation where a user/flow/application may trigger the addition of one more redirector to its original link only if by doing so the performance of a certain metric improves by a certain predefined margin. After a gold flow finishes adding or removing redirectors from its path, it moves into a "passive" operational mode for a longer interval when no redirectors can be either added or removed even if during that interval the observed QoS performance changes. The motivation of having active and passive periods in PCQoS is to reduce the likelihood that two gold flows in the same neighborhood add or remove redirectors from their paths at the same time.

Active intervals are composed of several monitoring and control periods. Figure 2 focuses on one active interval for further elaboration. A destination node monitors the performance of a metric (e.g., end-to-end packet delay, throughput, etc.) for sometime before a specific policy triggers the addition or removal of redirectors. The duration of monitoring periods should allow for the reception of multiple packets to compute the average value of the metric being measured or controlled. The duration of active periods depends on the specific policy being used and may extend over several monitoring/control intervals.

B. Monitoring-Control Phase

In the design of PCQoS we consider the following metrics: packet delay (*PD*), packet throughput (*PT*) and transmission power (*TP*). However, other metrics could also be monitored depending on a particular application/policy. Based on the monitoring of one or more metrics, the receiver decides whether the observed QoS/power performance is satisfactory based on the user-specific policy being used, and may take further action (e.g., add or remove a redirector) to modify the number of redirectors in its path during this active period.

C. User Policy

Optimizing a metric to achieve a certain performance level (e.g., minimize PD or maximize PT) by adding or removing redirectors is difficult and it is not always feasible due to the "domino effect" discussed earlier. In addition, multihop wireless networks have a maximum traffic carrying capability and the upper bound capacity that is shared by all flows in the network. Optimizing throughput and delay, as well as transmission power, simultaneously is extremely challenging.

In PCQoS, gold users have no performance goals restrictions. What PCQoS does restrict on the other hand, are the policies (e.g., mechanisms or rules) that gold users can use while attempting to reach their individual QoS and energy savings goals. These policies are necessary to limit the inherent QoS degradation in the network resulting from the addition of redirectors by gold users. In PCQoS we identify two stable operational points or policies that are feasible for gold flows:

• *Normal:* This is the default behavior of IEEE 802.11 or SR-CSMA based networks without redirectors (e.g., packets are transmitted directly between source-destination pairs). This case corresponds to transmitting with the common agreed transmission power in IEEE 802.11, or with the minimum transmission power between source-destination pairs in SR-CSMA based networks. However, applying no power control means that long range flows in the SR-CSMA MAC case will suffer degraded performance due to the unfairness of the protocol.

• *Metric Saturation Point (MSP):* Under this policy gold users are allowed to actively add or remove redirectors. For instance when bigger is better (i.e., throughput), we define the metric saturation point as the point where the action of adding one more redirector to a path would not provide any significant improvement in the performance of a particular metric being controlled.

Definition: Let M_k be the value of the performance metric being controlled after adding k redirectors to the route. Assuming bigger is better (i.e., throughput), redirector $k+1$ will be added to the route only if

$$M_{k+1} > M_k(1+\delta) \qquad (1)$$

where δ is this predefined margin that makes it worth adding one more redirector. The idea behind limiting the number of redirectors is to limit the potential negative effect of adding more redirectors in terms of additional QoS degradation observed by other flows (both gold and best effort flows) in the wireless network.

In PCQoS, each one of the selected flows (e.g., gold flows) is capable of adding and removing redirectors in order to achieve their QoS/power performance tradeoff in a greedy fashion. We define the targeted performance of such a flow as $Metric^{target}$. This target could be application specific, service class specific or a default for all gold flows in the network. We define monitored performance of having N redirectors in a path as $Metric_N^{measured}$. During the monitoring-positioning periods, a gold flow will add or remove redirectors in order to bring the observed performance $Metric_N^{measured}$ closer to the target performance $Metric^{target}$. In all cases gold flows can add redirectors as long as the metric saturation point policy described above has not been reached, which is a necessary requirement to maintain the healthy operation of the network.

The performance of QOS metrics such as throughput or delay could be improved by either adding or removing redirectors, depending on the specific operational conditions experienced in the network. Under certain conditions the throughput and delay performance may improve by adding redirectors due to the unfair behavior of power controlled MAC, as discussed earlier. However, under other network conditions removing redirectors could improve the throughput and delay performance because less costly packet-forwarding (i.e., less packet contention among the redirectors in the path) takes place. As a result gold flows may need to determine experimentally whether adding or removing redirectors leads to better performance or not as the case may be.

It is important to note that even if a flow is able to reach its target performance level during an active period, PCQoS cannot guarantee that the performance level can be maintained during preceding passive operational periods. This is because during these periods other gold flows may attempt to optimize their own performance metrics thereby affecting by some magnitude the QoS performance observed by all other flows in the network, as is the case with the domino effect.

IV. Adding and Removing Redirectors

Until now we have been adding and removing redirectors without actually explaining how these two operations can take place in wireless ad hoc networks. In PCQoS we use the Power Aware Routing Optimization *(PARO)* protocol to perform these operations [6]. PARO is a routing protocol that operates above the link layer but below the network layer capable of adding redirectors to split longer-range links into several shorter-range links.

At first, the operation of PARO may seem counter-intuitive because in the first iteration of PARO the source node communicates with the destination node directly without involving any packet forwarding by redirectors. Any node capable of overhearing both source and destination nodes (node C in Figure 3) can compute whether packet forwarding can reduce the transmission power in comparison to the original direct exchange between source and destination nodes. When this is the case, an intermediate node may want to become a *redirector* and send a *route-redirect* message to the source and destination nodes to inform them about the existence of a better route in terms of power efficiency to communicate with each other.

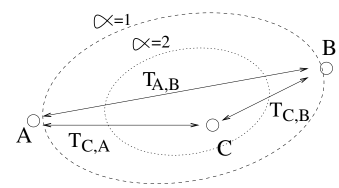

Fig. 3. Redirect Operation

In Figure 3 we show the case where only one intermediate redirector node is added to a route between a source-destination pair. The same procedure can be applied repeatedly to further optimize a route into smaller links with the result of adding more redirectors between source-destination nodes. In the example shown in Figure 3, redirectors can be added between A↔C and B↔C and so on.

V. PCQoS Evaluation

We use the *ns-2* network simulator to analyze the operation of PCQoS. We use the PCMAP MAC protocol running at 2 Mbps as an example of a SR-CSMA MAC, as defined in [12]. We extended our previous implementation of the baseline PARO protocol [6] to implement PCMAP and the positioning and monitoring components of PCQoS. Each point in the presented graphs are the average of 10 experiments, each of them using a different seed number while locating nodes in the network. We evaluate a network of 400 nodes in a 500x500 meter network with 100 flows each sending sixteen 512-byte packets per second. Each source picks a destination at random within its 250 meter range.

For these experiments we select the following 5 scenarios shown in Table II. The term $N < x >$ in Table II means N gold flows in this range added x redirectors to their paths. We selected these 5 scenarios because we think they better show the advantages and drawbacks of PCQoS: Scenario 1 corresponds to a SR-CSMA network without PCQoS (i.e., no redirectors are added to any route). Scenario 2 corresponds to the case where PCQoS is applied randomly in 10 of the 36 flows in the 200-250 meter range, and there is one redirector between end points only. Scenario 3 is the same as Scenario 2 except that now 3 redirectors are positioned between end points. In Scenario 4 one third of the flows in the 100-150, 150-200, and 200-250 meter range added one redirector only to their paths. Finally, in Scenario 5 all flows in the network added as many redirectors to their paths as necessary so that all resulting links were in the 0-50 meter range.

	0-50 3 flows	**50-100** 14 flows	**100-150** 19 flows	**150-200** 28 flows	**200-250** 36 flows
S1	0	0	0	0	0
S2	0	0	0	0	$10 < 1 >$
S3	0	0	0	0	$10 < 3 >$
S4	0	0	$6 < 1 >$	$9 < 1 >$	$12 < 1 >$
S5	0	$14 < 2 >$	$19 < 3 >$	$28 < 5 >$	$36 < 7 >$

TABLE II
SIMULATION SCENARIOS FOR AGGREGATE PERFORMANCE ANALYSIS

Because of page limitations we only show throughput results for single-hop routes in PCQoS. Figure 4 shows the fraction of the total packets received by destinations for each scenario over five distance ranges (0-50, 50-100, 100-150, 150-200, and 200-250 meters, respectively) from their sources. The fact that we got 3, 14, 19, 28 and 36 flows for 0-50, 50-100, 100-150, 150-200, and 200-250 meter range, respectively in Table II, is a direct result of letting each source pick a destination at random within its 250 meter range (see Section II).

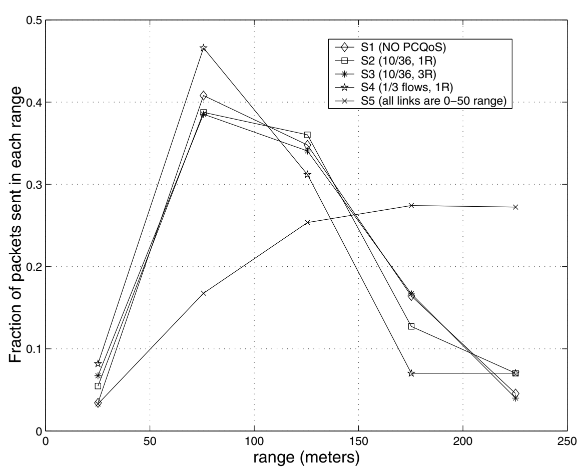

Fig. 4. Throughput Performance of PCQoS

Lets first look at Scenario 2 where 10 out of 36 flows in the 200-250 meter range added 1 redirector to their paths only, and compare its performance with Scenario 1 (no PCQoS). As we can see in Figure 4, the fraction of the total packets received by destinations in the 200-250 meter range improves slightly compared with scenario 1. This is a direct result of the increased throughput obtained by the 10 gold flows in this range that have implemented PCQoS. The negative side is that now we have less packets received for flows in the 150-200 meter range compared with scenario 1. Flows in the 150-200 meter range obtained lower throughput in Scenario 2 because there are now 20 more *links* (due to the 10 flows in the 200-250 meter range split into 2 100-150 links) that increase the unfairness behavior toward the 150-200 meter range flows. This is a clear example of the domino effect where a local greedy decision impact the performance seen by others. A similar effect can be observed for Scenario S3.

Because of page limitations again we only show the detailed performance of scenario 3 where 3 redirectors are positioned between end points of 10 out of the 36 flows located within 200-250 meters using PCQoS. For comparison we also show the throughput when no redirectors are added for the same 10 flows. As we can see in Figure 5 in most cases the addition of 3 redirectors translated into higher throughput for these flows compared with no PCQoS.

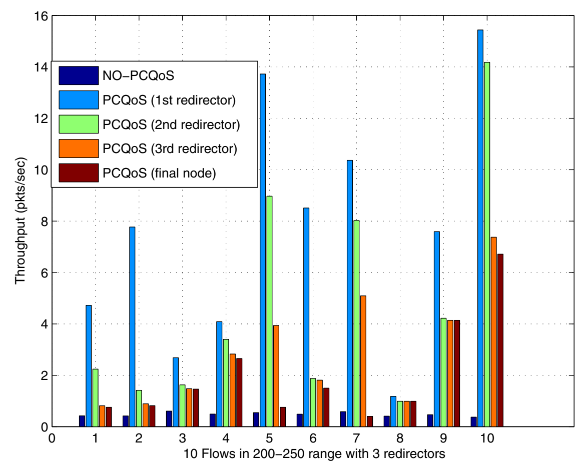

Fig. 5. Throughput Performance of 10 flows in the 200-250 meter range having 3 redirectors.

Figure 5 also shows the average throughput received after each redirector of selected gold flows. The common trend is that the average throughput received after redirector i in the path from source to destination is higher than in redirector $i + 1$. This is a pattern already reported in the literature [4] and created by traffic sources with no rate control (e.g., UDP). It is likely that this anomaly will disappear if a congestion control mechanism is used at the transport layer (e.g., TCP).

Figure 6(top) shows the aggregate average throughput of all 100 flows in the network for Scenarios 1-5. From this figure we can observe that still the highest throughput is achieved by Scenario 1 where no QoS was implemented (SR-MAC without PCQoS). It is important to note, however, that for scenarios S2, S3 and S4, the aggregate throughput is almost equivalent to the throughput obtained by scenario S1, meaning that PCQoS is capable of providing some coarse QoS control to selected flows without reducing the original capacity of the network. Only for Scenario 5 we get significantly less aggregate throughput, but this happens because too many flows

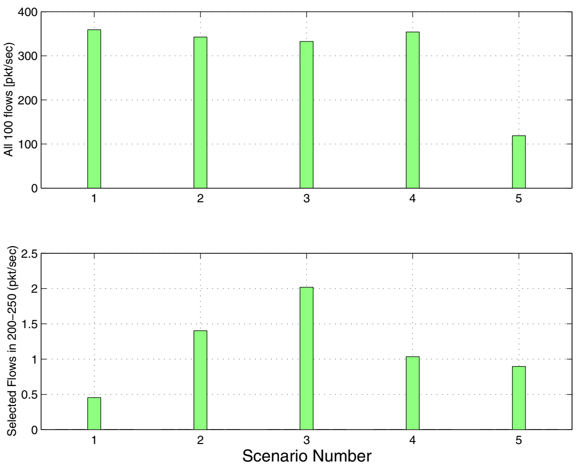

Fig. 6. Aggregate Throughput Performance of PCQoS

introduced redirectors. Scenario 5 was included in Figure 6(top) only for comparison purposes, and it was obtained manually by *disabling* the metric saturation policy of PCQoS. It is unlikely that this behavior will happen once the metric saturation policy is in place, since flows wont add as many redirectors as in Scenario 5 seeing that the QoS performance is getting worse. Scenario 5 shows the importance of the metric saturation policy as a way to control the overall stability of the network.

Figure 6(bottom) shows the average received throughput for selected gold flows in the 200-250 meter range only for Scenarios 1-5. As a reference, the 36 flows in scenario 1 obtained an average throughput of 0.45 pkt/sec per flow. In Scenarios 2 and 3 the use of PCQoS in selected flows increases throughput by 309% and 445%, respectively. In Scenarios 4 and 5 the throughput gains are less impressive compared with scenarios 2 and 3, but still higher than Scenario 1 for these flows.

VI. Related Work

The state of the art in QoS control for wireless ad hoc networks is best represented by the COWPOW system [13]. In [13], the authors present a system where mobile nodes are capable of switching the value of the common-range transmission power they use. Mobile nodes in this system periodically reduce this value and stop right before the first partition of the network occur. As we mention in earlier, this method consumes more power and reduces the capacity compared with a method based on variable-range transmission principles. Another important difference of PCQoS and the COMPOW proposal is that in contrast to common-range transmission based proposals where users get a similar QoS performance, PCQoS supports service differentiation with multiple policies. We believe that such a system is better suited to support different types of emerging applications that may require different QoS/power trade-off being supported by the network.

A different orthogonal way to achieve QoS in ad hoc networks is by flow privatization. In this line of thinking we find the INSIGNIA [10] and SWAN [1] systems. In the work described in [2], the authors discuss the impact of TCP throughput on the number of forwarding nodes in static wireless ad hoc networks for unreliable links. Results presented in [2] show that there is an optimum transmission range that maximizes TCP throughput.

VII. Conclusion

In this paper we studied the impact of adding or removing redirectors in a multihop network on traditional QoS metrics. We first study this impact for IEEE 802.11 and SR-CSMA [12] MACs based wireless ad hoc networks and showed the severe limitations of these MAC protocols for single and multihop wireless operations. We discussed the unfair performance of source-destinations pairs based on location under SR-CSMA based wireless networks. We showed how this behavior can be used as a foundation for service differentiation in wireless ad hoc networks. We proposed PCQoS, which builds QoS mechanisms into the baseline PARO system for specific applications that wish to tradeoff better QoS performance for sub-optimal energy savings. In PCQoS, selected flows add or remove redirectors from their paths in order to coarsely modify their observed QoS performance. To the best of our knowledge, PCQoS represents the first QoS/power-aware controlled routing protocol for wireless ad hoc networks that is based on the foundation of variable-range transmission control.

References

[1] Gahng-Seop Ahn, Andrew T. Campbell, Andras Veres, and Li-Hsiang Sun. SWAN: Service Differentiation in Stateless Wireless Ad Hoc Networks. *In Proceeding of IEEE Infocom, New York, NY*, 2000.

[2] I. Ali, R. Gupta, S. Bansal, A. Misra, A. Razdan, and R. Shorey. Energy Efficiency and Throughput for TCP Traffic in Multi-hop Wireless Networks. *In Proceedings of Infocom*, New York, NY, 2002.

[3] Habib M. Ammari and Sajal K. Das. Trade-off between Energy Savings and Source-to-sink Delay in Data Dissemination for Wireless Sensor Networks. *International Workshop on Modeling Analysis and Simulation of Wireless and Mobile Systems*, march 2005.

[4] J. Li et al. Capacity of Ad hoc Wireless Networks. *In Proceedings of ACM Mobicom*, July 2002.

[5] Kuei-Ping et al. A Power Saving MAC Protocol by Increasing Spatial Reuse for IEEE 802.11 Ad Hoc WLANs. *AINA Conference, Taipei, Taiwan*, 2005.

[6] J. Gomez, A. T. Campbell, M. Naghshineh, and C. Bisdikian. PARO: Supporting Transmission Power Control for Routing in Wireless Ad Hoc Networks. *ACM/Kluwer Journal on Wireless Networks (WINET), Vol. 9, No. 5, pp 443-460*, 2003.

[7] Javier Gomez and Andrew T. Campbell. A Case for Variable-Range Transmission Power Control in Wireless Multihop Networks. *Proceedings of IEEE Infocom, Hong Kong*, march 2004.

[8] D. Goodman and N. Mandayam. Power Control for Wireless Data. *MOMUC*, November 1999.

[9] P. Gupta and P. R. Kumar. The Capacity of Wireless Networks. *IEEE Transaction on Information Theory, Vol. IT-46, no. 2*, 2000.

[10] S. Lee and A. Campbell. INSIGNIA: In-Band Signaling Support for QOS in Mobile Ad Hoc Networks. *MOMUC*, Berlin, October 1998.

[11] D. Maniezzo, P. Bergamo, and M. Gerla. How to Outperform IEEE 802.11: Interference Aware (IA) MAC. *Proceedings of MEdHocNet 2003, Mahdia, Tunisia*, June 2003.

[12] J. Monks, V. Bharghavan, and W. Hwu. A Power Controlled Multiple Access Protocol (PCMAP) for Wireless Packet Networks. *In Proceedings of Infocom*, Anchorage, Alaska, April 2001.

[13] S. Narayanaswamy, V. Kawadia, R. S. Sreenivas, and P. R. Kumar. Theory, Architecture, Algorithm and Implementation of the COMPOW Protocol. *Proceedings of the European Wireless Conference, Florence, Italy*, February 2002.