Power Controlled Multiple Access Control for Wireless Access Nets

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***Abstract*-In this paper, we develop and investigate a new joint power controlled medium access control (MAC) algorithm for wireless access nets (ANets). In an ANet, the user nodes are associated with a single central node (backbone node) that serves to allocate and manage their resources. Under our new protocol, the net backbone node (BN) instructs the ANet nodes to make power control adjustments while simultaneously allocating to them slots for the requested transmissions of their packets. Our algorithm leads to significant increase in the net throughput level by attaining high spatial reuse while striving to reduce power consumption in that nodes only employ the power levels required to reach their designated destinations. By introducing fair queuing and scheduling elements, we demonstrate the ability of our algorithm to support fairness in our scheduling. Two different methodologies for incorporation of fairness are proposed. We demonstrate the throughout and delay vs. fairness trade-off behavior of our new protocol.**

Keywords-power control; medium access control (MAC); wireless access nets; scheduling; spatial time division multiple access (STDMA); fairness.

I. INTRODUCTION

One major common feature of packet radio networks is the scarcity of spectrum. An important issue is therefore to design multiple access mechanisms to control channel utilization efficiently. This has motivated the need for channel spatial reuse, i.e. having users sufficiently apart use the same time slot, frequency band, or code.

A prevalent medium access scheme for channel spatial reuse is *spatial time division multiple access* (STDMA), in which time is divided into fixed length slots that are organized cyclically. In each cycle, or timeframe, every slot is allocated to different users such that all transmissions are received successfully at their intended receivers. A number of STDMA algorithms with no power control have been proposed in the literature that can be categorized into *link scheduling* [4,7,8,9,10,11,14] and *broadcast scheduling* [4,14,15,16,17,18]. In link scheduling the transmission right is assigned to links and both transmitters and receivers should be determined apriori. In broadcast scheduling, the transmission right is allocated to nodes, in which allows them to transmit to any of their neighbors.

In this paper, we study a single wireless access network (ANet). Such networks are commonly employed by many wireless network architectures that identify an access point/base station (Backbone Node) that serves as a hub connection of nodes into a backbone network, and at times can also serve to manage the networking process within the access net. Examples include the lower hierarchy of hierarchically architectured ad hoc wireless networks, IEEE 802.11 network systems, as well as a wide range of mobile wireless military networks [1],[2],[3]. The backbone nodes (BNs) are chosen from currently active mobile backbone-capable nodes, established or mobile access points, or are represented by (ground and/or airborne) unmanned vehicles that are guided into selected positions (Fig. 1). In an ANet, the user nodes are associated with a BN that serves to allocate and manage their resources (including time/space/power) based on the received transmission requests. Our new integrated protocol allows the net BN to instruct the ANet nodes to make power control adjustments while simultaneously allocating to them slots for transmission/relaying to their neighbors. The inclusion of a power-controlled demand assigned STDMA protocol for sharing the communications medium of an ANet is of critical importance as recent results have shown that by applying optimal power control in an ideal medium access protocol, the aggregate channel utilization can be improved by a factor of $O(\sqrt{\rho})$, where ρ is the node density in the network [6]. Clearly, this joint power control-scheduling is a challenging optimization problem. In fact, the scheduling problem with even a single power level is by itself known to be an NP-hard problem [12].

Though in our integrated power control-medium access control the MAC operation is based on the demand assigned *STDMA link scheduling*, the same analysis can be readily adapted to *STDMA broadcast scheduling*, *spatial frequency division multiple access (SFDMA) broadcast scheduling*, and *SFDMA link scheduling*.

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Our cross-layer power control-MAC algorithm operates in two phases: In the first phase of the algorithm, we transform the problem into a generalization of the graph coloring problem. We present a heuristic method for its solution that belongs to the class of *slot-oriented sequential algorithms* (SOSA) and relies on *minimum edge covering* [7]. Based on this approach, we introduce an algorithm for power-control and slot allocation, under which destructive interference between every pair of simultaneous transmissions is prevented. In the second phase, we take the aggregated effect of interference into consideration (based on the actual SINR at each receiver) and modify it if necessary.

Our purpose in devising this algorithm is to attain higher net throughput level by attaining a high ratio of the average spatial-reuse factor. We strive then to achieve this throughput level by efficient scheduling and reducing the employed transmission power levels. Further, this algorithm results in reduction in power consumption in that nodes only employ the power levels required to reach their designated destination. By introducing fair queuing and scheduling elements, we demonstrate the ability of our extended algorithm to support fairness in our scheduling. Two different methodologies for incorporation of fairness have been proposed. We demonstrate the throughout vs. fairness trade-off behavior of the new protocol. We also analyze the trade-off between fairness and delay through simulation.

The rest of the paper is organized as follows. In section II, we introduce the system assumptions. The PCSA algorithm is elaborated in section III. We describe two extensions of the PCSA algorithm for incorporating fairness in section IV. Simulation results are discussed in section V, and finally conclusions are presented in section VI.

II. SYSTEM DESCRIPTION

We assume all nodes are equipped with omni-directional antennas and identical half-duplex radios that allow them to adjust their transmission power continuously in a packet by packet fashion. Each node can reach the backbone node at a properly selected power level less than or equal to P_{MAX}. We assume that each transmitter that is allocated a time slot operates at a fixed data rate, of say R [bits/sec]. Further, routing is not considered in this paper and assumed to be given. Noting the net throughput to be determined by the factor $R*SRF/L$, where SRF denotes the net's spatial reuse factor and L represents the average path length (measured in hops), it is of interest to achieve a high SRF ratio. The link gain for every ordered pair of nodes in the ANet is known by the BN. The BN spatially reuses its assets (time and space) among its active clients, so that in a single time, multiple non-interfering transmissions can be scheduled. To reduce interference among simultaneous transmissions, the BN calculates and assigns the power level at which the sending transmitters should operate at each time slot.

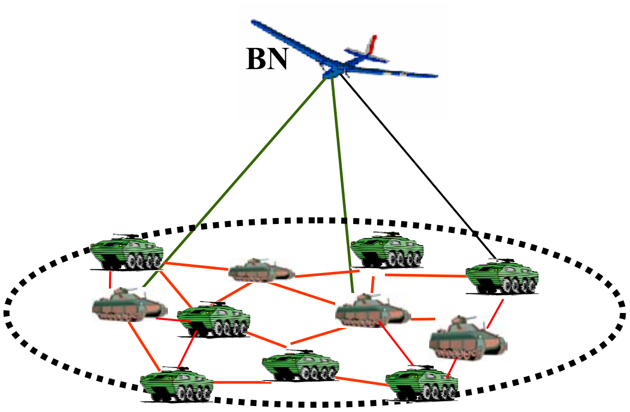

Fig. 1. Illustration of an access net (ANet), consisting of a backbone node (BN) and 11 user nodes.

Under our traffic model, we assume a point-to-point traffic, i.e. every packet has exactly one destination. Traffic is assumed to fluctuate unpredictably, so that no traffic process model is assumed to be known apriori. Time slot duration is assumed to be equal to transmission time of a packet plus the maximum propagation delay. Length of every timeframe is set to be fixed and equal to K time slots. We denote the *transmission request matrix* composed at the BN as R_{ψ}, where $R_{\psi} = \{R_{\psi}(i,j)\}$ and $R_{\psi}(i,j)$ represents the number of packet transmission requests corresponding to packets that will be available for transmission from source i to destination j at the start of the $\psi - th$ timeframe. These requests include the newly generated packet transmission requests and the transmission request backlogs that have not been assigned by allocations in previous timeframes. Through the establishment of a control multiple access channel (based on an embedded random access channel used by nodes to initially send request control packets to the BN, and subsequently the use of piggybacking of request packets in assigned slots), the packet generation matrix R_{ψ} is composed in the BN at the start time of the $\psi - th$ timeframe.

The request matrix can be processed at the BN to achieve fairness, provide for flow and congestion control or attain QoS based performance (e.g., by using weighted fair queuing or PGPS based queue-ordering and scheduling of nodal requests, based on recording the resources allocated to nodes over a sliding window of length of W slots, and using packet's Class/Type of Service differentiating indicators, or reservation based admission control setups). Requests are considered for store-and-forward service by allocating slots for the transmission of individual packets, as well as for real-time service whereby slots are allocated periodically to assign a real-time channel to a node at a requested rate for the duration of its activity.

Let $\{A_k, A_k \in W\}$ be the subset of nodes simultaneously transmitting at the same time slot. Let P_k be the power level chosen by node A_k, for $A_k \in W$. Then the transmission from a node $A_i, A_i \in W$, is successfully received by a node $A_j, A_j \notin W$, iff

$$\frac{G_{ji}P_i}{\sum_{\substack{k\in W \\ k\neq i}} G_{jk}P_j + \eta_j} \geq \beta, \tag{1}$$

whereby β is the minimum required *SINR*, η_j is the thermal noise power at receiver j, and G_{jk} is the link gain modeling the path loss for transmission from A_k to A_j [5]. In the reminder of the paper, we represent a transmission from node A_i to node A_j by $A_i \rightarrow A_j$.

III. The Power Controlled Scheduling Algorithm (PCSA)

Let assume i→j is the only transmission in the ANet. We define $P_{MIN}(i,j)$ as the minimum transmission power level less than P_{MAX} that satisfies the following inequality

$$\frac{G_{ji}P_i}{\eta_j} \geq \beta', \tag{2}$$

whereby $\beta' > \beta$. We refer to (2) as the *per link minimality constraint.*

Definition: A *feasible transmissions scenario* is defined as a combination of simultaneous transmissions $i_1 \rightarrow j_1$, $i_2 \rightarrow j_2, \ldots,$ $i_M \rightarrow j_M$, which under the per link minimality constraint results in $SINR \geq \beta$ in all intended receivers.

Let's define set *V* as the union of all packet transmission requests *(i,j)* that are available for transmission at the beginning of the underlying timeframe. The *interference graph* is represented by the undirected graph *G(V,E),* in which *V* and E are the set of vertices and the set of edges of graph *G*, respectively. Vertices (i_1,j_1) and (i_2,j_2) are connected to each other by an edge if and only if one of the following conditions is satisfied:

i. Nodes i_1, j_1, i_2, and j_2 are not distinct.

ii. Simultaneous transmissions of $i_1 \rightarrow j_1$ and $i_2 \rightarrow j_2$ under the per link minimality constraint result in SINR less than β' in j_1 and/or j_2.

The Power Controlled Scheduling Algorithm (PCSA) operates based on a special coloring of the interference graph *G*. Recall that the classical graph coloring problem is defined as the minimization of number of colors used for coloring all nodes of the graph [13]. Our joint power control scheduling problem can be defined as maximization of number of the colored nodes of graph *G* given a finite set of colors with dimensionality *K* (i. e. the number of slots in a timeframe), such that every set of transmission requests having the same color constitutes a feasible transmission scenario.

PSCA is a two-phase algorithm that operates on a slot by slot basis. After the end of phase two, PCSA removes all the scheduled transmissions for the underlying slot from graph G and proceeds to the next time slot. We refer to the resulted graph as *the residual interference graph*. Recall that a vertex and an edge is said to *cover* each other if they are incident. A vertex covering set is a set of vertices that covers all edges in the underlying graph [13].

In phase one, PCSA strives to find a minimum vertex covering set in the residual interference graph, by using a greedy approach based on the maximum degree in the residual interference graph. The complement of a minimum vertex covering set is a maximum independent set [13]. Based on the definition of the interference graph *G*, simultaneous transmissions of every two transmission requests (vertices) in a maximum independent set under the per link minimality constraint results in SINR levels greater than or equal to β' in both intended receivers. However, considering the accumulative effect of interference, the simultaneous transmissions of all transmission requests (vertices) in the maximum independent set under the per link minimality constraint may not necessarily constitute a feasible transmission scenario.

In phase two, PSCA checks whether the derived maximum independent set is a feasible transmission scenario. For this purpose, the resulted SINR in every intended receiver is compared to the minimum required SINR, β. If all the SINR levels are greater than or equal to β, PCSA assigns all the transmission requests to the underlying slot and removes them from the residual interference graph. If there exists at least one SINR that is less than β, one transmission is removed out of the independent set and the new SINR levels are compared to β. This procedure repeats until the remaining transmission requests constitute a feasible transmission scenario. Clearly, the process converges after a finite number of iterations, since the cardinality of the maximum independent set is always finite.

Under the condition that we have different priority classes for packet transmission requests, in phase one PCSA first only considers the class with the highest priority and then it sequentially proceeds to lower priority classes if possible. Moreover, in phase two PCSA removes the packet transmission requests from the derived independent set starting from the lowest priority class and it then proceeds sequentially to higher priority classes if required.

IV. FAIRNESS ALGORITHMS

We consider a link scheduling to be fair as the variation in the number of time slots allocated to different links in the network is reasonably low. In this section we introduce two extensions of the PCSA algorithm that take fairness into consideration. The difference between these two algorithms relies on their definition of the high priority and the low priority class.

Under the Throughput Based Fairness Algorithm (TBFA) the total number of packets transmitted on every link within the last W timeframes is recorded. If this number is less than a threshold Δ, TBFA assigns high priority to the transmission packet requests associated with the underlying link for the next timeframe. Otherwise, the transmission requests are resided in the low priority class. Under the Delay Based Fairness Algorithm (DBFA), at the beginning of every timeframe we compare the *lifetime* of every transmission request with a threshold. Every transmission request that has a lifetime greater than a threshold is then resided in the high priority class. All the remaining packet transmission requests are moved into the low priority class.

V. SIMULATION RESULTS

In our simulation we assume nodes in the network are distributed independently and uniformly in a disk with radius of 500 meter. Further, we assume that power decays inversely proportional to the fourth order of the distance between the transmitter and the receiver. Every node generates packets based on a Poisson arrival process with intensity λ packets per slot for each of its neighbors. Further, the maximum power is set to be equal to 50 mW. We concentrate here on small network with 10 nodes, since it adequately captures the interactions addressed in this paper.

In Fig. 2, we compare the throughput values of PCSA, TBFA, and DBFA. As expected, the throughput of PCSA is always greater than or equal to the throughput of the fair algorithms. This is due to the fact that PCSA always provide the highest degree of freedom for the scheduling purposes.

Under low packet generation rates, independent of definition of priority classes, eventually all the packets will be transmitted. As a result, for relative low packet generation rates, the throughout values in PCSA, DBFA, and TBFA are identical (Fig. 2).

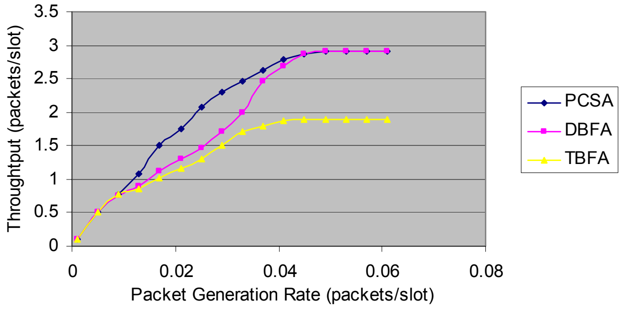

Fig. 2. Simulation of throughput values of PCSA, TBFA, and DBFA.

Under average packet generation rates, TBFA explicitly generates the high priority and the low priority classes. Since in the process of scheduling, TBFA first considers only the high priority class, it achieves lower spatial reuse factor with respect to PCSA. As a result, the throughput level in TBFA under average packet generation rates is lower than the throughput level in PCSA. Due to the similar argument, under average packet generation rates, the throughput level in DBFA is lower than that in PCSA (Fig. 2).

Under high packet generation rates, DBFA again generates the high priority and the low priority classes. However, in contrast to the case of average packet generation rates, the high priority class includes a sufficient number of all possible transmission requests. Consecutively, DBFA asymptotically provides the same spatial reuse factor as PCSA (Fig. 2).

In Fig. 3, we compare the delay of PCSA, TBFA, and DBFA. Clearly, the delay of PCSA is always lower than the delay of the other two algorithms. The analysis of Fig. 3 based on different packet generation rates is similar to the analysis of Fig. 2.

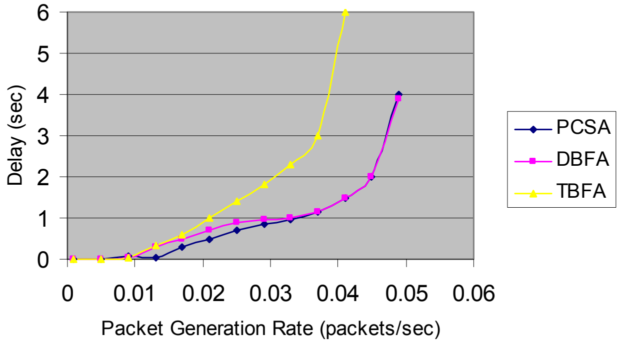

Fig. 3. Simulation of delay of PCSA, TBFA, and DBFA.

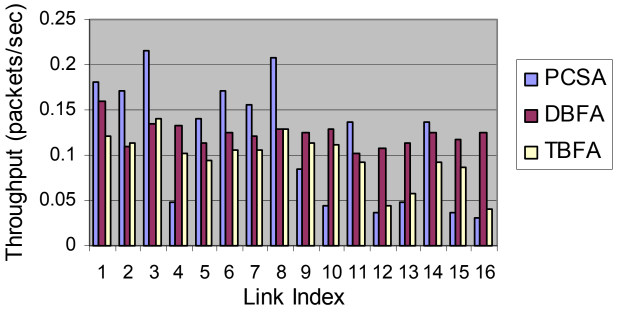

Fig. 4. Illustration of throughput of different links in PCSA, TBFA, and DBFA.

In Fig. 4, we consider the dispersion of throughput over the links of a randomly generated topology with 10 nodes and 16 links. We note that DBFA provides a superior result in terms of fairness with respect to PCSA and TBFA.

VI. CONCLUSIONS

In this paper, we develop and investigate a new joint power controlled medium access control (MAC) algorithm for wireless access nets (ANets). The Power Controlled Scheduling Algorithm (PCSA) is a two-phase algorithm operating based on a special coloring of the underlying interference graph. We show our algorithm to lead to significant increase in the net throughput level by attaining high spatial reuse while striving to reduce power consumption in that nodes only employ the power levels required to reach their designated destination. By introducing fair queuing and scheduling elements, we demonstrate the ability of our extended algorithm to support fairness in our scheduling. We analyze the trade-off between throughput and. fairness, as well as the trade-off between delay and fairness through our simulation results.

REFERENCES

[1] I. Rubin, A. Behzad, R. Zhang, H. Luo, and E. Caballero, "TBONE: A mobile-backbone protocol for ad hoc wireless networks," in *Proc. IEEE AEROSPACE,* 2002.

[2] M. Gerla, R. Kapoor, M. Kazantzidis, and P. Johansson, "ad hoc networking with bluetooth," in *Proc. WMI MOBICOM,* 2001.

[3] T. Salonidis, P. Bhagwat, L. Tassiulas, and R. LaMaire, "Distributed topology constrauction of Bluetooth personal area networks," in *Proc. IEEE INFOCOM,* 2001.

[4] R. Ramanathan and E. L. Lloyd, "Scheduling algorithms for multi-hop radio networks, " *IEEE/ACM Trans. Networking*, April 1993.

[5] J. Zander, "Jamming in slotted ALOHA multihop packet radio networks," *IEEE Trans. Comm.*, October 1991.

[6] P. Gupta and P. R. Kumar, "The capacity of wireless networks," *IEEE Trans. Inform. Theory,* March 2000.

[7] I. Rubin and A. Behzad, "Cross-layer routing and multiple-access protocol for power-controlled wireless access nets," in *Proc. IEEE CAS Workshop on Wireless Communications and Networking,* 2002.

[8] B. Hajek and G. Sasaki, "Link scheduling in polynomial time," *IEEE Trans. Inform. Theory*, September 1988.

[9] C. G. Prohazka, "Decoupling link scheduling constraints in multihop packet radio networks," *IEEE Trans. Comp.*, March 1989.

[10] J. Grönkvist and A. Hansson, "Comparison between graph-based and interference-based STDMA scheduling, in *Proc. ACM MOBIHOC,* 2001.

[11] J. Grönkvist," Assignment methods for spatial reuse TDMA, in *Proc. ACM MOBIHOC,* 2000.

[12] E. Arikan, "Some complexity results about packet radio networks," *IEEE Trans. Inform. Theory*, July 1984.

[13] M. Behzad, G. Chartrand, and L. L. Foster, *Graphs and Digraphs*, Wadsworth International mathematics Series, Boston, 1981.

[14] S. Ramanathan, "A unified framework and algorithm for channel assignment in wireless networks," *Wireless Networks* (5), 1999.

[15] C. Zhu and M. S. Corson, "A five-phase reservation protocol (FPRP) for mobile ad hoc networks," *Wireless Networks*, vol. 7, no. 4, pp. 371-384, July 2001.

[16] I. Chlamtac and A. Farago, " Making transmission schedules immune to topology changes in multi-hop packet radio networks," *IEEE/ACM Trans. Networking*, February 1994.

[17] X. Ma and E. L. Lloyd," An incremental algorithm for broadcast scheduling in packet radio networks," in *Proc. IEEE MILCOM,* 1998.

[18] F. N. Ali, P. K. Appani, J. L. Hammond, and V. V. Mehta, "Distributed and adaptive TDMA algorithms for multi-hop mobile networks," in *Proc. IEEE MILCOM,* 2002.