A Framework for Integrated Power Control, Routing and Link Scheduling in Multihop CDMA Networks

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Abstract— **In this paper, we propose a general framework for integration of power control, routing and scheduling relying on time-scales in multihop ad hoc CDMA networks. We exploit the longer time-scale available for link (not packet) scheduling to perform that complex operation only periodically and suggest a feasible incremental strategy for admission control and re-routing between scheduling "refreshes". We also propose a feasible, distributed power control algorithm that maximizes a global (network-wide) utility. Routing identifies minimum SINR nodes per flow and these bottleneck SINRs are monitored by their (interfering) neighbors, i.e., transmission powers are adjusted specifically with the affected flows' bottleneck SINRs in mind.**

I. INTRODUCTION

Currently in ad hoc networks, most of the systems implement CSMA or its variants as their multi-access scheme. In a large ad hoc network, CSMA systems may suffer from large packet queuing delays due at least in part to considerable amounts of collision and associated capture phenomena, despite measures in IEEE 802.11 to minimize these effects [1] (and others), to which large networks are prone, i.e., CSMA/CA networks do not scale well.

CDMA-based systems, however, do not have a collision problem and, therefore, they may be good alternatives for larger and denser networks. To overcome the undesired effects of frequency selective fading, especially at higher data rates, Multi-Carrier CDMA (MC-CDMA, also called CDMA/OFDM) can be used in ad hoc networks to improve performance. This technique has already been standardized in UMTS for cellular systems and seems promising for 4G cellular networks [2,30,38]. The system under consideration in this paper is a time-slotted multihop ad hoc CDMA network.

A. Previous work

There are many studies performed in the area of cross-layer optimization in multihop networks. Of those, some assume elastic (e.g., [11, 33, 44]) and some assume inelastic (e.g., [12, 13, 26]) QoS constraints. What distinguishes these two categories from each other is the convexity or non-convexity of the feasible region of transmit powers. An extensive discussion about this issue can be found in [12]. Below we summarize some of the studies performed in cross-layer optimization of ad hoc networks, mostly the ones that are more relevant to our work, and emphasize the difference between their assumptions, constraints and goals and those of our study. As just mentioned, elastic and inelastic flows are restricted to different constraints and therefore have different solutions. In this paper, we study both cases. However when assuming elastic flows [12, 25, 29], with a slight diversion from the common definition, we allow users to announce their desired QoS. Although the network does not guarantee to satisfy them, it attempts to make the best of these QoS's given fixed routes and schedules. Later in section II, the assumed network model will be explained with more details.

Distributed power control for ad hoc networks has been studied in [11, 13, 21, 33]. The network objective therein differs than that of this paper, in that its network does not attempt to minimize total power and it does not particularly address multihop networks. As we will describe further in the rest of this paper, the overall QoS of a multihop flow is defined by the lowest QoS it receives at each hop. Consequently, maximizing the utility (and QoS) of all subflows in a network does not in general yield in maximum effective QoS for all users. Aside from these differences, in [12] the problem is formulated to jointly optimize data rates and transmit powers while routing and congestion control are also being performed while we assume given links and schedules in this study and focus our attention to power control. Finally, with specific regard to [13], both the network objective and the problem formulation is different from those of our study.

Ad hoc CDMA/TDMA single-hop settings have been studied in [14]. With performing link scheduling and power control jointly, one-hop conflicts and high levels of interference were avoided. The system model used in [14] is similar to ours, however, for one thing, the transmission schedule length is assumed to be fixed in [14] while in our paper, the length of the schedules is a figure of merit, i.e., the frame-length is attempted to be minimized. The other difference between [14] and our study is that in [14], routing is not considered (single-hop), while we consider both routing and scheduling, i.e., the network we assume is multihop. Another major difference between our study and the one in [14] is in admission control. While for inelastic flows, we suggest an admission control mechanism based on the convergence of the power control algorithm (and therefore some flows may get rejected), in [14] all flows are admitted

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to the network while due to high traffic and congestion, some flows' data-transmission may be frequently deferred resulting in unfairness and low data-rates. Although in small networks with a light load this may not happen very frequently, as also mentioned by the authors of [14], it can cause problems in large networks or under high traffic load. Finally, in [14] time-slots are of the order of the duration of one packet whereas herein the subframes are taken to be of much larger duration.

In [41], a framework similar to that of [14] is used to solve the problem of joint power control and scheduling in a centralized fashion for multicasting in ad hoc networks. Each node therein is assumed to be limited with the same constraints that apply to a TDMA system, i.e., a node can only be associated with one other node. As in [14], in [41] routing is not considered. With an approach similar to that of [14, 41], the authors of [31] suggest a centralized algorithm for power control and scheduling and use minimum power routes in a TDMA ad hoc network. Joint power control and routing has also been studied in [26]. However, link scheduling is not specifically addressed to resolve transmit/receive conflict. Also in [5] joint scheduling, routing and power control for TDMA ad hoc networks has also been addressed using a simple interference model in which each node receives interference only from one-hop-distant neighbors.

The problem of assigning channels for transmission/reception in wireless ad hoc networks is relatively challenging. In a wireless network with a base station (a non-ad hoc network), we can use either Frequency Division Duplexing (FDD) or Time Division Duplexing (TDD) for uplink and downlink channels. However, in an ad hoc network, in the absence of a central unit to manage the uplink and downlink transmissions, the problem seems to be more difficult. Using Frequency Duplex Division (FDD) requires two different frequency bands for uplink and downlink. However, there is no global definition of uplink and downlink in a multihop ad hoc network. When one group of nodes is transmitting (upload channel), another group is receiving (download channel). In TDD, the same frequency band is used both for transmit and receive while uplink and downlink transmissions take place in turn. In an ad hoc network however, it's not possible for all nodes to transmit in the same time-slot and receive in the next one, since in each time-slot, there is a group of transmitters and a disjoint group of receivers.

In a wideband CDMA network, by assigning different codes to different users, it is possible for a node to transmit (or receive) two flows at the same time. This is not feasible in a wideband TDMA system.

However, regardless of the implemented multiple-access media, we assume herein that it is not possible for a node's antenna to transmit and receive at the same time. That is, for each time-slot, a node needs to be scheduled to either transmit or receive to avoid self-interference.

The term *scheduling* is used in different contexts by different authors. In [16] scheduling addresses optimal data rate assignment for all links of the network. In [32, 33], scheduling refers to joint control of layers, i.e., link scheduling, power control, routing, etc (other than rate control). The authors of the paper [32] consider a TDMA ad hoc network and solve a problem of joint power control and scheduling. They obtain a highly centralized method to jointly solve the link scheduling, power control and routing. In their follow-up paper in [33], an imperfect but simpler scheduling is suggested. The objective of both papers [32, 33] is to maximize the total data-rate, and the user QoS is not guaranteed, i.e., the QoS constraints are considered elastic. In these papers, to avoid one-hop interference, each node is restricted to send or receive respectively to or from only one other node and consequently their power control policies cannot be efficiently extended to networks with more relaxed link-scheduling constraints. Among similar studies that assume elastic QoS constraints in multihop networks, the paper [44] can also be named that seeks throughput maximization as its main goal although it does not consider link scheduling. A more comprehensive literature survey in scheduling can be found in our [36].

B. Outline of the paper

In section II, the network model, its architecture and related assumptions are explained and an overview of the different time-scales, code assignment and the required parameter estimation capabilities of nodes are described. In section III power control issues are addressed and while two cases of elastic and inelastic QoS requirements are studied, a power control algorithm is proposed for networks with elastic (continuous) flows.

In section IV, we first address some of the difficulties involved with link scheduling in ad hoc CDMA networks and then discuss the relevant routing strategies. In section V, a framework for integration of scheduling, routing, power control and admission control is proposed. In section III, we discuss elastic and inelastic QoS requirements and propose a power control algorithm for the networks with elastic flows. The results of a simulation study are presented in section VI. Finally, we summarize the paper in section VII.

II. *Assumptions and Network Architecture*

The network is assumed to use CDMA for multiple access. Each node has an omni-directional antenna and communicates with other nodes by modulating its data using a unique signature code per each flow it transmits or relays. Considering a distinct virtual link for each flow that is transmitted over a single edge, this code scheduling task can be translated to a classical form of code assignment problem. The readers are referred to [18, 20, 35] and their relevant references for discussions regarding code scheduling. We assume all nodes share the same frequency channel for communicating data and a separate frequency channel for signaling and control messages. The shared signaling channel will be used to communicate messages related to path-gain announcements, flows' bottleneck SINRs broadcast, the necessary local information to calculate SINR at each node, and the required routing information. Nodes are assumed to have only an approximate estimation of time and consequently the signature codes are not assumed perfectly orthogonal. Note however that, two subflows which belong to two different flows and pass through the same pair of nodes are assumed to have zero cross-correlation as they can be perfectly synchronized.

The achieved utility of each flow is assumed to be a concave function of its bottleneck node's received SINR, i.e. the minimum SINR it receives over all hops. The routing algorithm is responsible to identify the "$\min \mathsf{SINR}$" nodes and ensure that the identity of any one of these nodes is known by all the nodes that reside on the flow this node is being bottleneck for. This task is done in the following manner: assume that route updates for flow φ contain $(X, \mathsf{SINR}_X^\varphi)$. When say node Y receives this information, it performs a simple min operation in the following manner: if $\mathsf{SINR}_Y^\varphi < \mathsf{SINR}_X^\varphi$, node Y sends out routing update messages with the bottleneck information replaced with $(Y, \mathsf{SINR}_Y^\varphi)$. Otherwise, it just relays the messages leaving the bottleneck information intact. Concurrently, the routing algorithm can keep track of the total transmit power of a flow and use this information in routing for breaking possible ties. Using the above methods along with robust routing algorithms and distributed incremental scheduling as described e.g. in [36, 37], the network can suitably accommodate to mobile scenarios. As it is explained in [36,37], incremental scheduling can react with a rather short delay (at most the duration of one time-slot) to service disconnections due to mobility, as these events can be addressed in the same manner as it is done for connection set-up/tear-down. In other words, the mobility effects result in higher join/leave rate which can be handled rapidly for up to some degrees of mobility.

To calculate the received SINR, each node needs information about the path-gains of all nodes in its vicinity. To obtain this information, there are several possible methods, of which one is that each node have a GPS and advertise its location periodically. Alternatively, each node broadcasts a ping message with a standard transmit power level so that the recipient nodes can calculate their path-gains associated with this node.

The integration of power control, routing and scheduling in this work relies on time-scales. A frame (or time-slot) consists of "a number" of subframes (the goal of scheduling algorithm is to minimize this number, i.e. the frame-size). In each subframe, a large number of data packets can be communicated. Also, a portion of each subframe is dedicated to power control iterations as will be explained later in section III. For further illustration in Figure 1 an example of a typical frame with 4 subframes is shown. Note that in this figure, for the purpose of clarity, the size of power control portion is exaggerated. In [37], we have suggested a network architecture based on these time-scales and have described how the power control, routing and scheduling algorithms are integrated. More specifically, we use the following scales:

- very fast: packet transmit time/power control iterations (time between two consecutive iterations)
- fast: power control initiations
- medium: routing/schedule dithering (periodical CBO refreshments)
- slow: connection set-up/tear-down requiring incremental link scheduling

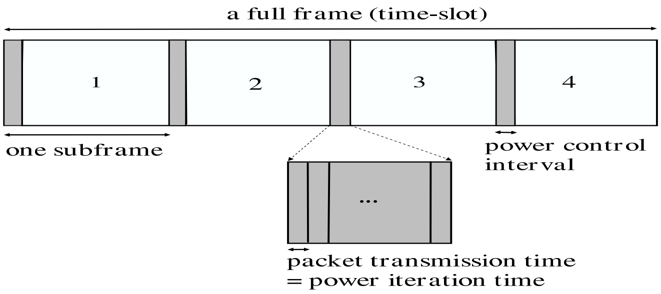

Fig. 1. a typical frame

III. Power Control

Let us assume a fixed set of routes and link schedules. We consider two cases of elastic and inelastic user QoS. We propose a distributed power control algorithm in which although the users still announce a desired QoS, the network does not guarantee to satisfy them. Instead, it attempts to maximize a global utility while making the best of the desired SINRs (herein taken to be equivalent to QoS).

We interchangeably use the terms flow, session and user in the following sections. A session is defined as a communication flow between a transmitter end-system and a receiver end-system with a certain QoS requirement. Therefore, one can distinguish between two flows, being communicated between the same transmitter-receiver pair, belonging to two different network flows. Since the network under study is a multihop network, each flow may consist of several subflows.

More specifically, we use the following notations in the rest of this paper. Each flow (user/session) is indicated by $\varphi \in F$ when F is the set of all flows. We use $H \supseteq F$ to refer to the set of all flows that request access to the network whether or not they get accepted. $\tau(\varphi)$ and $\rho(\varphi)$ represent respectively the set of transmitter nodes of flow φ and its receiver nodes when F is the set of all flows. The next hop of flow φ at node i is indicated by $\nu(\varphi, i)$ (obviously $\nu(\varphi, i) \in \rho(\varphi)$). P_i^φ is the transmit power of the i^{th} node that is allocated to flow φ, SINR_i^φ is the signal to interference and noise of flow φ at node i, β^φ is the desired SINR of φ (over all of its hops), $T(t)$ is the frame-size at time-slot t and B is the spreading gain of the employed CDMA scheme. Finally, we indicate the subset of subflows scheduled in subframe m by $W^{(m)}$. We indicate each subflow $v \in W$ as a triple (i, j, φ) where i and j are respectively the consecutive source and destination of subflow φ , i.e., $i \in \tau(\varphi)$, $j \in \rho(\varphi)$ and $j = \nu(\varphi, i)$. Finally, we indicate the subset of subflows scheduled in subframe m by $W^{(m)}$.

A. Power Control-Objectives and Constraints

Assume the below network objective:

$$v_{net}(t) = \sum_{\varphi \in H} u(\frac{x^{\varphi}(t)}{T(t)}) - \alpha \sum_{\varphi \in F} \sum_{i \in \tau(\varphi)} P_i^{\varphi}(t) \quad (1)$$

subject to the following constraints:

$$0 \leq \sum_{\varphi \in F} P_i^{\varphi}(m;t) \leq P^{\max}, \forall i \in \tau(\varphi), \forall m = 1 \cdots T(t) \quad (2)$$

where $x^{\varphi}(t)$ is the received QoS of flow φ, $P_i(t)$ is the total transmit power of node i over all subframes at time-slot t, $T(t)$ is the current frame-length, $u(.)$ is a concave utility function, $\alpha > 0$ is a scaling factor and $P_i^{\varphi}(m;t)$ is the balanced transmit power of node i allocated to flow φ at subframe m and frame t. Note that according to the problem formulation in (2), the maximum power restriction is applied to instantaneous power at each node. Also note that, $P_i^{\varphi}(t)$ is used to refer to the power that node i dedicates to transmit flow φ's traffic, regardless of the subframe at which it is done. Clearly, according to this definition, the following equality always holds:

$$P_{total}(t) = \sum_{\varphi \in F} \sum_{i \in \tau(\varphi)} P_i^{\varphi}(t) = \sum_{m=1}^{T(t)} \sum_{v \in W^{(m)}} P_i^{\varphi}(m;t) \quad (3)$$

where $P_{total}(t)$ is the total power spent in time-slot t and as defined earlier, subflows $v \in W^{(m)}$ are of the form (i, j, φ) and are scheduled in the m^{th} subframe. Two interpretations of $x^{\varphi}(t)$ in (4) and (9) result in two different optimization problems as they reflect inelastic and elastic flows respectively. For the first interpretation, let us assume $x^{\varphi}(t)$ to be defined as followed:

$$x^{\varphi}(t) = X \prod_{j \in \rho(\varphi)} \mathbf{1}\left\{\mathsf{SINR}_j^{\varphi} \geq \beta^{\varphi}\right\} \quad (4)$$

where $x_{\varphi}(t)$ represents a boolean parameter that is either zero or X (a fixed number) and $\mathsf{SINR}_j^{\varphi}$ is defined as followed:

$$(5)$$

$$\mathsf{SINR}_j^{\varphi} =$$

$$\frac{h_{ij} P_i^{\varphi}}{N_0 + 1/B\left(\sum_{k \neq j,i} \sum_{\psi \in F} P_k^{\psi} h_{kj} + \sum_{\psi \neq \varphi} P_i^{\psi} h_{ij}\right)}$$

for all $j \in \rho(\varphi), \varphi \in F$. Note that, under (4),

$$v_{net}(t) = \sum_{\varphi \in H} \left(\frac{u^{\varphi}(X/T(t))}{X}\right) x^{\varphi}(t) - \alpha \sum_{\varphi \in F} \sum_{i \in \tau(\varphi)} P_i(t)$$

$$(6)$$

Now, simply note that after fixing $T(t)$ and the routes, maximizing v_{net} for all $\alpha > 0$ is equivalent to solving the following minimization problem, where the former is only subject to the constraints on the powers P alone (not SINRs).

$$\min \sum_{\varphi \in F} \sum_{i \in \tau(\varphi)} P_i^{\varphi}(t) \quad (7)$$

subject to (2) and QoS constraints:

$$\mathsf{SINR}_j^{\varphi} \geq \beta^{\varphi}, \forall j \in \rho(\varphi), \forall \varphi \in F \quad (8)$$

It can be easily seen that since x^{φ} is a boolean parameter and can only take the values of 0 and X, the first term is maximized when all QoS constraints in (8) are satisfied.

Alternative to the definition of equation (8) for QoS constraints, we could have defined

$$x^{\varphi}(t) \equiv X \min\left\{\frac{\min_{j \in \rho(\varphi)} \mathsf{SINR}_j^{\varphi}(t)}{\beta^{\varphi}}, \quad 1\right\} \quad (9)$$

for all φ (interpretation 2). In this case, maximizing the utility function (1) is associated (not equivalent) to solving (7) subject to only (2). Note that with (9), $v_{net}(t)$ is continuous in the $x^{\varphi}(t)$ and therefore represents an elastic flow.

B. Power control for flows with continuous QoS

Assume that the routes and schedules are fixed and the latter are specified by the set of flows transmitted by node i over all subframes m, $\tau^{-1}(i) = \{\varphi \in F \mid i \in \tau(\varphi)\}$. Also, node i's vector of transmission power is $\underline{P}_i \equiv \{P_i^{\varphi} \mid \varphi \in \tau^{-1}(i)\}$.

We now describe an alternative to power control method [42] for elastic flows with QoS given by

$$u^{\varphi}\left(\min_{i \in \tau(\varphi)} \mathsf{SINR}_{\nu(\varphi,i)}^{\varphi}\right) \quad (10)$$

Note that since u^{φ} is nondecreasing, e.g.,

$$u^{\varphi}(\xi) = \kappa^{\varphi} \log(1 + \gamma^{\varphi} \frac{\xi}{\beta^{\varphi}}) \quad (11)$$

or the bounded form

$$u^{\varphi}(\xi) = \kappa^{\varphi} \arctan(\gamma^{\varphi} \frac{\xi}{\beta^{\varphi}}) \quad (12)$$

for scalars $\kappa^{\varphi}, \gamma^{\varphi} > 0$, we can "distribute" u^{φ} through the min operations (10). Also note that the effective utility of each flow also depends on the fraction of time a subflow can transmit data, i.e. the schedule length [36, 37]. Since this effect can be reflected in the values of γ^{φ}, we do not explicitly show this dependency to simplify the notations.

A decentralized power control game can be formulated wherein each node i seeks

$$\underline{P}_i^* \equiv \arg \max_{<\underline{P}_i, \mathbf{1}> \leq P_i^{\max}} g_i(\underline{P}_i) \quad (13)$$

where

$$g_i(\underline{P}_i) \equiv \sum_{\varphi \in \tau^{-1}(i)} u^{\varphi}\left(\mathsf{SINR}_{\nu(\varphi,i)}^{\varphi}\right) - \alpha_i \sum_{\varphi \in \tau^{-1}(i)} P_i^{\varphi} \quad (14)$$

and

$$<\underline{P}_i, \mathbf{1}> \equiv \sum_{\varphi \in \tau^{-1}(i)} P_i^\varphi$$

Here, we assume:

- Node $\nu(\varphi, i)$ estimates and feeds back to node i the quantities $\mathsf{SINR}^\varphi_{\nu(\varphi,i)}$ and the path attenuations $h_{i\,\nu(\varphi,i)}$.
- The $u^\varphi(\cdot)$ and β^φ attributes of the flow φ are communicated to node i by the routing algorithm.

Ignoring for the moment the $P_i^{\max}$ constraints, in the argument of the u^φ functions, at each iteration of power control, node i would seek to solve

$$\nabla_{\underline{P}_i} g_i(\underline{P}_i) = \underline{0}, \tag{15}$$

possibly via simple numerical gradient ascent, i.e.,

$$\underline{P}_i \ += \ s \nabla_{\underline{P}_i} g_i(\underline{P}_i)$$

with step-size parameter $s > 0$ [8, 34]. Note that through the SINR terms, g_i also depends on P_j^ψ for $\psi \notin \tau^{-1}(i)$ and $j \neq i$. Also, for $\psi \in \tau^{-1}(i)$, the term $\partial g_i / \partial P_i^\psi$ involves terms

$$\frac{\partial \mathsf{SINR}^\psi_{\nu(\psi,i)}}{\partial P_i^\psi} \ = \ \frac{\mathsf{SINR}^\psi_{\nu(\psi,i)}}{P_i^\psi} \tag{16}$$

and, for $\varphi \neq \psi$,

$$\frac{\partial \mathsf{SINR}^\varphi_{\nu(\varphi,i)}}{\partial P_i^\psi} \ = \ \frac{-\left(\mathsf{SINR}^\varphi_{\nu(\varphi,i)}\right)^2}{P_i^\varphi} \tag{17}$$

Also, the third type of gradient terms, $\partial g_i / \partial P_j^\psi$, appears for $j \neq i$ and is of the form:

$$\frac{\partial \mathsf{SINR}^\varphi_\nu(\varphi, i)}{\partial P_j^\psi} = \left(\frac{-h_{ji}}{P_k^\varphi h_{ki}}\right) (\mathsf{SINR}_i^\varphi)^2 \tag{18}$$

where $i = \nu(\varphi, k)$.

Note that the right-hand sides of the first two displays involve only terms that are assumed readily known by node i in this decentralized setting.

If $\underline{P}_i^*$ solving (15) does not satisfy the $P_i^{\max}$ constraints or results in terms $\mathsf{SINR}^\varphi_{\nu(\varphi,i)} < \beta^\varphi$, the optimization (14) could instead involve a Lagrangian made up of g_i and these constraints. For example, the Lagrangian accounting for $P_i^{\max}$ constraint is

$$l_i(\underline{P}_i, \lambda_i) \ \equiv \ g_i(\underline{P}_i) + \lambda_i (P_i^{\max} - \sum_{\varphi \in \tau^{-1}(i)} P_i^\varphi)$$

Note that the optimal (maximizing) value of the nonnegative Lagrange multiplier, if there is slackness in the constraint, is $\lambda_i = 0$. So, one needs to simply replace α_i with $\alpha_i - \lambda_i$ in the unconstrained solution $\underline{P}_i^*$ satisfying (15) and select $\lambda_i \geq 0$ so that the constraint

$$<\underline{P}_i, \mathbf{1}> \leq \ P_i^{\max} \tag{19}$$

is met.

This decentralized power control game will *not* generally converge to powers $\underline{P}_i^*$ (collectively denoted by just $\underline{P}^*$) that maximize the global objective

$$v(\underline{P}) \ = \ \sum_{\varphi \in F} u^\varphi \left(\min_{i \in \tau(\varphi)} \mathsf{SINR}^\varphi_{\nu(\varphi,i)} \right) - \sum_i \alpha_i \sum_{\varphi \in \tau^{-1}(i)} P_i^\varphi \tag{20}$$

even if $\alpha = \alpha_i$ for all i. That is, roughly

$$\nabla_{\underline{P}} \ v(\underline{P}^*) \ \neq \ \underline{0}$$

as in general the above algorithm does not account for terms like (18). This is explicitly verifiable for simple examples, e.g., when all nodes have identical utilities. Indeed, very special cases of the game may not have unique Nash equilibria. Continuity of the game iteration and the convexity and boundedness of the domain of transmission powers implies existence of Nash equilibria simultaneously satisfying (15) at all nodes i by Brouwer's fixed point theorem [7].

Now assume that for each flow, the routing algorithm informs each node on its path whether the node is the minimum SINR ("bottleneck" [23]) node of the flow, i.e., it determines and informs

$$B(\varphi) \ \equiv \ \arg \min_{j \in \rho(\varphi)} \mathsf{SINR}_j^\varphi \tag{21}$$

Also assume that all nodes j broadcast *only* the SINRs of their transmitted sub-flows φ, together with all associated downlink path-gains h_{ij} *such that* $j \in B\,(\varphi)$ along with h_{kj} where $j = \nu(\varphi, k)$ for some node k, see equations (16),(17) and (18). So, node i instead optimizes

$$\sum_{j \in R(i)} \sum_{\varphi \in B^{-1}(j)} u^\varphi(\mathsf{SINR}_j^\varphi) - \alpha_i \sum_{\varphi \in \tau^{-1}(i)} P_i^\varphi \tag{22}$$

over its transmission powers $\underline{P}_i$ where $R(i)$ is the set of nodes in the interference region of i including i itself.

Theorem: If $\alpha = \alpha_i$ for all i, distributed/decentralized joint optimization of (22) will also optimize the global objective v in (20).

Proof: The first-order necessary conditions for optimality of v over the complete set of sub-flow transmission powers $\underline{P}$ are the same as those that jointly optimize (22) for all nodes i. Q.E.D

This result is akin to that of [27] in a wired context. Now note that the above algorithm in its current form, can suffer from significant power oscillations because of the following reason. If a node i does not have any bottleneck nodes in its transmission range, the first term in (22) disappears and therefore, to maximize (22) node i simply zeros out P_i^φ for all $\varphi \in \tau^{-1}(i)$. Consequently, in the next iteration, node i becomes a bottleneck for all of the flows it relays. To prevent the algorithm from creating additional bottlenecks, we modify (22) to:

$$g_i^0(\underline{P}_i) \equiv \sum_{j\in R(i)} \sum_{\varphi\in B^{-1}(j)} u^{\varphi}(\mathsf{SINR}_j^{\varphi}) - \alpha_i \sum_{\varphi\in\tau^{-1}(i)} P_i^{\varphi} \tag{23}$$

$$+\gamma \sum_{\varphi\in\tau^{-1}(i)} (\mathsf{SINR}^{\varphi}_{\nu(\varphi,i)} - \mathsf{SINR}^{\varphi}_{B(\varphi)})$$

where $\gamma > 0$. Note that the third term is the penalty that node i pays if it chooses its transmit powers P_i^{φ} such that it creates new bottlenecks. Since ideally at the optimal balanced point, all nodes will be bottlenecks, i.e., $B(\varphi) = \rho(\varphi)$, the local and global optima still refer to the same point. It is easy to see that neither the global objective nor the local ones, respectively (20) and (23), are concave functions in P_i^{φ} for nodes i and their associated flows $\varphi \in \tau^{-1}(\varphi)$. However, it can be easily proved that any local optimum of this problem is regular and as a result, the KKT conditions (see (15)) are necessary (and not sufficient) for optimality [3]. Consequently, this algorithm may converge to any of the local optima.

IV. ROUTING AND SCHEDULING

In this section we briefly address routing and link scheduling in multihop networks. Some more details in integrated routing and scheduling can be found in our [36].

A. Link Scheduling

Let us assume that the routing tables have already been set up and that the scheduling algorithm schedules the subframes according to the specified routes.We use the symbols $TX(X)$ and $RCV(X)$ to indicate that a node is, respectively, transmitting to or receiving from node X in a subframe.

We break all flows to one-hop flows, e.g, if flow 1 passes through nodes $2 \rightarrow 4 \rightarrow 5$, then after breaking this flow, we will have two one-hop flows ($2 \rightarrow 4$ and $4 \rightarrow 5$). If two one-hop flows have conflict, they cannot route their data in the same subframe and need to be assigned different subframes.

Given a set of F unidirectional end-to-end routes for the current flows, we obtain the set W consisting of all one-hop flows ν where $W = \{\nu_n\}_{n=1}^{|W|}$, $|W| = \sum_{\varphi\in F} h_{\varphi}$ and h_{φ} is the number of hops of route φ. Let $s(\nu)$ be the source node of the unidirectional one-hop flow v and $d(\nu)$ be the destination node of such a flow. The flows ν_1, ν_2 in W conflict if and only if $s(\nu_1) = d(\nu_2)$ or $s(\nu_2) = d(\nu_1)$. Conflicting one-hop flows cannot be transmitted in the same subframe.

By a slight modification in the definition of a "conflict graph" defined in [18,24] and their relevant references, each subflow can be represented as a vertex and link two vertices if their corresponding subflows conflict. Therefore, finding a minimum-length conflict free schedule is equivalent to a vertex coloring problem which is known to be NP-complete [17]. Several algorithms in the literature are proposed to find suboptimal solutions to this problem, e.g., [15,19,28,43]. In [36], we proposed using an infrequently used "contention-based ordering" (CBO) algorithm originally developed for connection-level switch fabric arbitration [43]. We emphasize that what makes CBO algorithm suitable for scheduling in CDMA networks, is that it allows simultaneous transmissions to (reception from) more than one node, whereas the algorithms proposed for TDMA-based systems, e.g. the ones in [15,19,28,43], only allow a node to associate with at most one other node at each time.

In [36], we also proposed a simple distributed "incremental" CBO (ICBO) algorithm that adjusts the scheduling tables upon flow leave/joins while the tables are periodically refreshed by performing (centralized) CBO. ICBO is a typically suboptimal but practical approach wherein the link-layer schedules are only periodically refreshed, i.e., as fast as existing computational resources will allow for such a complex problem. A period between refreshes could have two phases. In the first phase, a quick and feasible "incremental" modification of the schedule would occur to accommodate recently arrived and account for recently departed connections. In the second phase, no new connections are admitted and a "refreshed" schedule would be computed based on the existing connections at the end of the first phase of the period. Clearly, connections arriving to the network during the second phase of a period would suffer set-up delay. Note that if in the second phase the network admits more flows, it would have to reject them at the upcoming refresh time. Let us call the maximum required processing time to calculate CBO tables T_C and the refresh period $T_R > T_C$. For a clear design choice, let us consider the following two cases:

- If $T_C = T_R$, i.e., no ICBO, maximum (worst case) set-up delay is equal to $2\,T_C$ and minimum delay is T_C.
- If $T_R > T_C$, i.e., ICBO used, maximum set-up delay is T_C and minimum set-up delay is negligible (ICBO delay).

Now simply note that the average delay in the first case is $1.5\,T_C$ compared to $0.5\,T_C$ in the second case. Also, we may replace CBO with another scheduling algorithm and similarly make a hybrid centralized/decentralized algorithm. Figure 2 illustrates ICBO hybrid scheme and the admission and computation intervals more clearly. In this Figure, X denotes the connection arrivals handled by ICBO and O denotes those queued until the next T_R period. Note that the delayed connections (shown by O) are processed using CBO (respectively, using ICBO all as a batch) at the start of next T_R period for the case where $T_R = T_C$ (respectively, $T_R > T_C$).

As mentioned earlier in section II, a Common Control Channel (CCCH) is assumed available for broadcasting the modified scheduling information using an out-of-band frequency to avoid any transmit/receive conflict with data flows and ensure that all nodes have consistent scheduling tables between CBO refreshment epochs.

B. Routing and Scheduling in Ad Hoc CDMA Networks

A simple approach to power-aware routing is to determine the route with maximum residual energy defined as the minimum residual energy of component nodes, or the min-

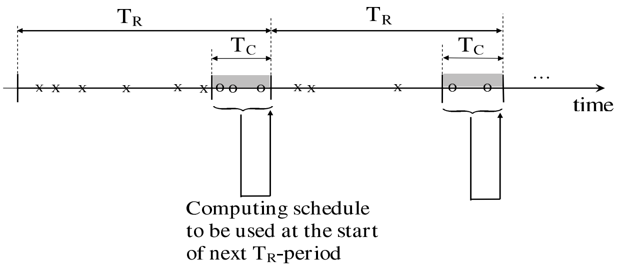

Fig. 2. ICBO connection admission phases

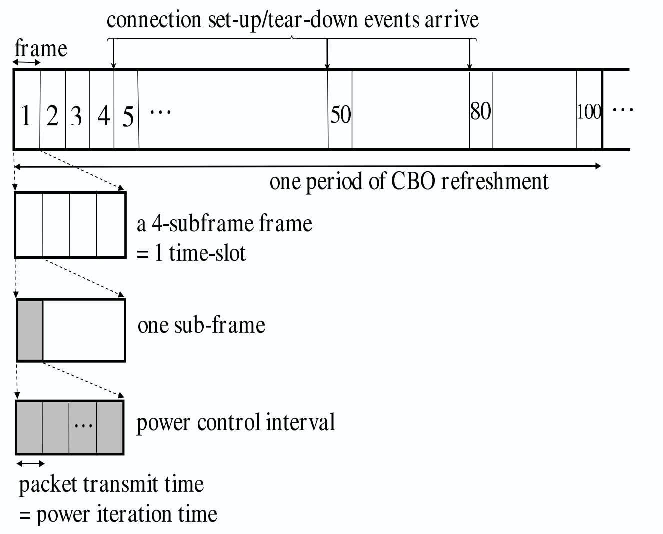

Fig. 3. illustration of 100 time-slots with 4-subframe per frame and a CBO refreshment period of 100 time-slots-routing and incremental scheduling performed upon a connection set-up/tear-down indicated by ↓ in the figure.

imum node energy each normalized by the link transmission power or path-gain [10, 40] along the route. In addition to energy considerations, we can also consider an additive delay cost, usually measured in terms of hops, see, e.g., [9, 22, 39]. Clearly, to maximize network resource utilization, routing should also consider link scheduling. In [36], we proposed an integrated routing-scheduling algorithm wherein a route is penalized if it requires frame-size augmentation. Using this idea together with the link metric proposed by [10]:

$$k_{ij} = \frac{h_{ij}}{P_i^{\max} - \sum_{\varphi \in \tau^{-1}(i)} P_i^{\varphi}} \tag{24}$$

when k_{ij} is the cost of link $i \rightarrow j$ and the above expression identifies the residual received power at node j from node i, one can both perform some form of congestion control and prevent long frame-sizes.

V. THE INTEGRATION FRAMEWORK AND THE OPERATING TIME-SCALES

Let us assume that the current network is stable and all users are satisfied with their provided QoS. Also assume the new requests to access the network are only processed at the boundaries of the time-slots. Upon receiving a new access request, routing and scheduling algorithms cooperate (as described in section IV-B and [36]) to decide on the new flow's path. The new access request initially encounters a set-up delay as explained in subsection IV-A. Based on the network's specifications on elastic or inelastic flows, different admission control policies may be taken at this point. For elastic flows, once set-up in the schedules, flows are considered fully accepted. However, for inelastic flows, this can not be the case for the following reason: After including the new flow in the network and performing power control, it is not yet known whether the new set of flows can feasibly achieve their required QoS requirements or not, until the power control is actually performed and converges to an interior point in the feasible power region [42]. Therefore, full admission control in inelastic networks requires an additional time-slot for convergence check in addition to set-up delay due to scheduling.

We emphasize herein that this integration scheme relies on time scales. Since link scheduling is the most complex operation, it is performed incrementally between consecutive "refreshes" along with routing updates. The centralized refresh epochs only happen periodically in the longer time-scale. Power control is performed in the faster time-scale which is the duration of a subframe. A simple example scenario is shown in Figure 3 that together with Figure 1 illustrates these time scales.

Investigating the network's reaction to a link-breakage is also of interest, as it may occur frequently in a wireless ad hoc setting. When a link-breakage takes place, alternative routes are found for all flows that the link used to serve. Due to the time-slotted structure of the system, we again assume that changes only occur at the time-slot edges or their effects will be deferred till the next time-slot edge. Therefore, a link-breakage causes similar sequence of events to those a new access request does. The difficulty arises in inelastic networks when the new set of flows are not feasible given their required QoS's. As most of the times it is not desirable to discontinue the service of the affected existing users, the connection admission strategies are not suitable in these circumstances. One simple solution in these situations may be to increase the frame-size to distribute the traffic over a larger number of subframes at the cost of reducing overall throughput [36].

VI. SIMULATION RESULTS

A. Integration of Power control, Routing and Scheduling for Inelastic Flows

To visualize a network that uses the above integration scheme, we simulated a simple network scenario and illustrated the achieved network utility (1). We emphasize that this is only for visualizing the general framework and the different time-scales.

The simulated network consists of 20 nodes. Access requests (flows) arrived at every time-slot boundary. Flows were assumed long-lived, i.e., they did not leave the network during the simulation time. We used the simple Bellman-Ford routing algorithm which cooperates with scheduling algorithm as explained in section IV-B and [36]. We did not implement routing based on the link costs defined in (24), however, we expect that using this metric followed by a minimum-cost routing algorithm to result in a higher network life-time as it prevents from fast energy-drainage, while causing a slightly lower network utility (1) as the total spent power is in general higher. We used CBO scheduling algorithm [36] (and not ICBO) for the ease of implementation, as since the flows were assumed long-lived CBO and ICBO do not differ much in terms of their resulting frame-sizes. We defined links based on path-gains. To include all possible signal attenuation factors, i.e. power attenuation which is inversely related to distance, fading and shadowing, we generated random path-gains between every pair of nodes in the interval of [0.005 0.8] and assumed that path-gains are uncorrelated (indeed the reason for the upper bound to be 0.8 was attempting to not violate uncorrelatedness). Based on the second-order attenuation model for power propagation, these path-gains correspond to a square-shaped $10m \times 10m$ network. Finally, we used MIMD power control algorithm [42] which gives the users the exact SINR they asked for. We also chose the maximum nodal power high enough so that during the simulation, no new joining flow is rejected due to the limit in this parameter's value, i.e., all rejected requests were caused by the inability of power-control algorithm to converge. This was only to compensate for the effects of long-lived flows. As before, we assumed the utility of a user is a concave function of its QoS and used the bounded utility function [6] given by

$$u(x) = \kappa \log(1 + \gamma x) \tag{25}$$

to quantify the simplified global objective function (6).

Figure 4 illustrates the network's objective defined in equation (1) and shows the saturation effect as well as the undesirable effect of frame-size augmentation. To enable both terms of equation (1) to contribute, the scaling factor α was chosen (based on the results of the simulation data) as 10^{-4}. The complete list of parameters used in the simulation scenario can be found in table I.

We observe that in Figure 4, the total benefit tends to saturate at first, it then decreases abruptly when the frame-size is augmented (at time 20) and it increases gradually after this point until it reaches to a saturation level again.

B. Distributed Power Control for Elastic Flows

In this section, we present the results of a simulation study to evaluate the performance of the proposed power control algorithm. For comparison, we apply the Multiplicative Increase- Multiplicative Decrease power control algorithm see e.g. [14, 42], along with ours for the same network scenario. We refer to our suggested algorithm as EFPC (Elastic Flows Power Control) and will use this notation in the figures and tables that follow.

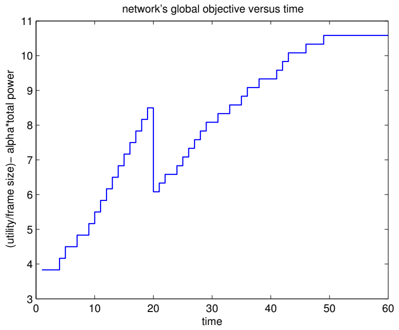

Fig. 4. Global Network Objective over time-inelastic flows

Number of nodes	20
Flows' required SINRs	random integers ∈ [1 10]
Max. node power per flow	10
Min. node power	0.001
Noise variance	3.5
Max. number of iterations	30
α	10^{-4}
γ	0.1
κ	$2/\pi$
X	1

TABLE I

SIMULATION PARAMETERS FOR INTEGRATED SCHEME

In simulation, we defined a simple network of 10 nodes uniformly distributed in a $10m \times 10m$ area that conduct 7 fixed flows routed and scheduled according to shortest-path routing and CBO scheduling algorithms [36]. Also, each pair of one-hop transmitters and receivers were assumed to be no further than $3m$ away from each other. This distance is used both for transmission and interference range that are herein taken to be equal for simplicity. Note that the dimensions of the domain and the interference range do not indeed matter as the order differences can be absorbed in the constant factors of (23). We chose the above network dimensions and interference range relatively similar to those in [21]. The transmission/interference range was chosen such that there are reasonably small number of neighboring/interfering nodes around any given one while network connectivity is maintained. In other words, assuming uniform distribution of the nodes over the network area and ignoring truncation of range by domain boundary, on average we have $(N-1) \times \frac{\pi R^2}{L^2}$ neighboring (interfering) nodes around each node, where N is the number of nodes in the network, R is the transmission range and L is the length of the assumed square-shaped network. By replacing the above given numbers in this simple formula, on average we get 3 neighbors/interferers for each node. Obviously the transmission/interference range should be large enough so

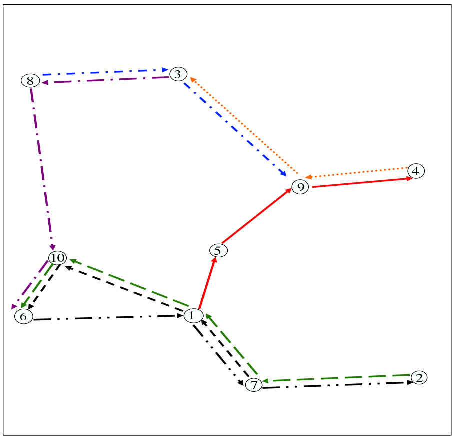

Fig. 5. Assumed Scenario

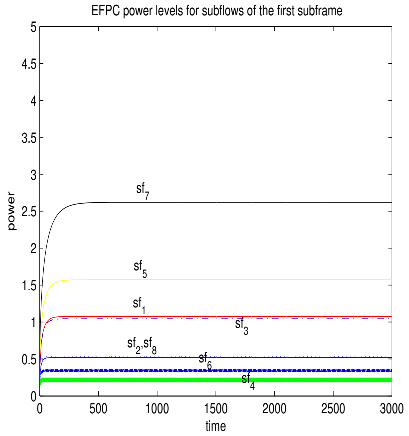

Fig. 6. EFPC's power levels

that $P^{\max} h_{ij}$ can be neglected for any pair of nodes i and j, e.g., it should be at least smaller than $P^{\min}$. Indeed, we chose to follow a fourth-order attenuation model, i.e. $h_{ij} = d_{ij}^{-4}$, where d_{ij} is the distance between nodes i and j and $P^{\max} R^{-4} \leq P^{\min}$.

We used (11) as the utility function with $\kappa^{\varphi} = \beta^{\varphi}$ for all φ. The motivation behind this choice of κ^{φ}'s was that by taking the derivatives in (15) it can be observed that such a choice leads to updating each subflow's power according to its flow's required SINR. The simulation parameters as well as the resulting routes and schedules are shown respectively in the Tables II, IV and III. The network scenario under assumption is also shown in Figure 5 (the distances are not accurate). Figures 6 and 7 respectively show the power levels obtained by EFPC and MIMD algorithms at first subframe for all the subflows communicated at this subframe, see Table III. Transmit power levels in these figures are labeled by the subflows they belong to when the subflows themselves are named in the order they appear in Table III's first column (corresponding to the first subframe). Also, Figure 8 compares the achieved utilities of the two algorithms. Note that the final utility is based on the minimum achieved SINR of flows over all subframes.

It can be seen in Figures 6 and 7 that the obtained power levels at the equilibrium are in general lower for EFPC compared to MIMD. Also, as can be seen in the figures, although MIMD converges faster, EFPC obtains significantly higher global utility. It should be noted that, as previously described, EFPC assumes elastic QoS constraints, i.e., the network does not guarantee the desired QoS of the users. However, considering the overall network benefit, the network does attempt to provide each user with a QoS close to their request. The resulting SINRs obtained for the given specific scenario are shown in Table IV.

VII. SUMMARY AND FUTURE WORK

In this paper, we proposed a framework for integration of power control, routing and scheduling. Using different

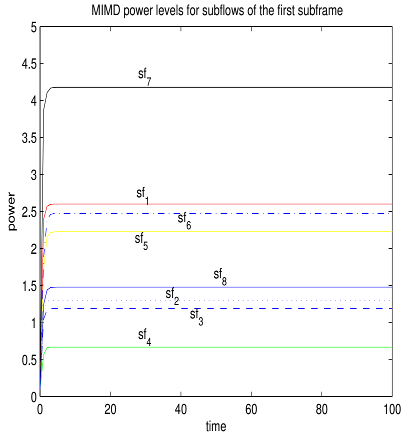

Fig. 7. MIMD's Power levels

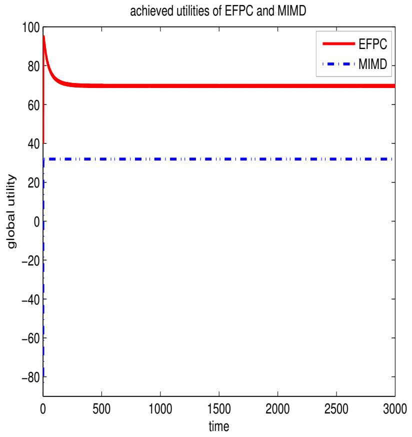

Fig. 8. Comparison between EFPC and MIMD's final utility (20)

κ_φ	β_φ
$\gamma_\varphi, \forall\varphi$	100
Interference Range	3m
λ	0.1
$\alpha_\varphi, \forall\varphi$	6
B	128
$\mathrm{P}^{\min}$	0.1
$\mathrm{P}^{\max}$	5
Noise power	0.005

TABLE II
Simulation Parameters

subframe 1	subframe 2	subframe 3
7→ 1(φ_2)	1→ 7(φ_7)	1→ 5(φ_1)
7→ 1(φ_4)	10→ 6(φ_2)	1→ 10(φ_2)
6→ 1(φ_7)	2→ 7(φ_4)	1→ 10(φ_4)
7→ 2(φ_7)	3→ 8(φ_6)	-
9→ 3(φ_5)	3→ 9(φ_3)	-
8→ 3(φ_3)	4→ 9(φ_5)	-
9→ 4(φ_1)	5→ 9(φ_1)	-
8→ 10(φ_6)	10→ 6(φ_6)	-

TABLE III
conducted subflows over 3 subframes

time-scales, our integration strategy involved a framework for negotiation among all these modules. We also proposed a distributed power control algorithm for networks with elastic flows where based on the characteristics of multi-hop networks, the utility of a user is defined as a function of the lowest SINR it receives over all hops. For this purpose, we defined a partially cooperative game in which each node considers not only its own local utility, but also that of the bottleneck nodes in its neighborhood when choosing transmit powers for the flows it relays. We illustrated that, if an optimal (global or local) point exists, this game will converge to it. Investigation on the asynchronous convergence of the algorithm is left as future work [4]. Also, we are extending this work to scenarios in which the nodes are mobile in the slow time-scale of our framework (see section II and [37]).

flow	QoS-req	EFPC's SINR	path
φ_1	16.67	10.73	1→ 5 → 9 → 4
φ_2	6.67	2.89	7→ 1 → 10 → 6
φ_3	6.67	3.12	8→ 3 → 9
φ_4	3.33	1.44	2→ 7 → 1 → 10 → 6
φ_5	10	4.62	4→ 9 → 3
φ_6	3.33	1.32	3→ 8 → 10 → 6
φ_7	3.33	1.04	6→ 1 → 7 → 2

TABLE IV
flows

VIII. Acknowledgment

The authors wish to acknowledge helpful discussion with Prof. Ness Shroff.

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