Packet Scheduling in Multihop Networks with Individual Packet Delay Constraints

Dony J. Muttath and K. Premkumar
Department of Electronics and Communication Engineering
Indian Institute of Information Technology
Design and Manufacturing, Kancheepuram
Chennai 600 127, INDIA.
E–mail: kpk@iiitdm.ac.in

***Abstract*—We consider a problem of *timely scheduling of packets in a multihop wireless network where each packet of each flow is required to reach the destination before a delay deadline.* We ask the following question: given an initial energy in each node, what is an optimal timely scheduling strategy that maximizes end–to–end packet transmissions of flows. We consider a time-slotted system. During each time-slot, a packet of a flow arrives according to a certain arrival process. The route of each flow is fixed. The problem is to choose a set of non-interfering links in each time-slot so that the packets of various flows reach their destinations before deadline. The links experience fading, and thus, the problem is also one of choosing links that correspond to minimum total energy for transmission. We provide a scheduling algorithm based on energy expenditure in each time-slot, which we call Minimum Per-packet Energy (MPE) scheduler, and compare the throughput performance of our proposed solution (MPE) with that of a Modified MaxWeight (MMW) and a Modified BackPressure (MBP) solution. The modification made to MaxWeight and BackPressure is to ensure that all three algorithms (MMW, MBP and MPE) are compared on a common set of constraints.**

***Index Terms*—BackPressure scheduling, delay deadline, MaxWeight scheduling, packet scheduling, throughput optimal scheduling, scheduling with finite energy, stability region.**

I. Introduction

Wireless systems are often constrained by resources such as energy, bandwidth etc. Scheduling of packets in wireless networks enables efficient utilization of resources in a timely manner such that the system achieves energy efficiency or optimal throughput. In a typical wireless ad hoc network, each packet may have to traverse multiple hops before it reaches it's destination. For these multihop wireless networks, it is important to efficiently schedule packets to provide maximum throughput for each competing flows. For a large class of applications like video, or voice over IP, each packet is associated with a delay deadline. For these applications, it is important to schedule transmission of packets such that the packets are delivered before a delay deadline; otherwise, the packets are lost. We consider this problem of scheduling of packets with an individual delay deadline for each packet in this paper.

In this paper, we study multihop wireless networks with multiple source-destination node pairs, with fixed traffic flows. A packet is required to reach the destination before a delay deadline. Each link is scheduled for transmission based on the queue-lengths at all nodes and channel gains at all links. Concurrent transmissions of packets over adjacent links in a network can interfere with each other. An activation vector that consists of a set of links that do not cause interference with each other is desirable. The problem of scheduling is one that chooses an activation vector in each time-slot that maximizes a performance metric (e.g., throughput).

We focus on the following problem in this paper: how to schedule packets that maximizes the throughput of each traffic flow with a constraint on meeting packet delay deadlines and initial energy at nodes over fading wireless links.

Previous work: A lot of work has been done so far for scheduling of packets in wireless network. We focus mainly on the seminal works and their variants that are either energy optimal, or throughput optimal.

[1], [2], [3] are some of the pioneering works for packet scheduling in networks. In [1], Tassiulas and Ephremides propose BackPressure (BP) scheduling policy that achieves a maximal stability region (the set of all vectors of arrival rates for which the system is stable). In [2], a Feasible Earlier Due Date (FEDD) algorithm is proposed that meets the deadline of packets in wireless networks. In [3], it is shown that MaxWeight scheduling is throughput optimal (i.e., an arrival rate vector within the capacity region lies in the stability region). In [4], distributed Queue-length based Back-pressure Random Access (QBRA) algorithms (that use MaxWeight algorithm) for multihop multiflow wireless networks have been proposed. Also, in [5], a Delay based BackPressure (DBP) scheduler with sojourn time as a metric has been proposed for multihop traffic with fixed routes.

The following works [6], [7], [8], and [9] consider energy efficient scheduling of packets in wired/wireless networks. [6] investigates energy-efficient scheduling of packets with deadline constraints over multi access and broadcast channels with fading links. In this work, the authors propose an online scheduling algorithm that adapts to backlog and channel conditions. In [7], energy-efficient scheduling is analyzed for real-time traffic over fading wireless channels. A timely-throughput guarantee for real-time traffic with hard deadlines is considered. In [8], the authors study an optimal low complex online algorithm for centralized scheduling of

978-1-7281-1895-6/19/$31.00 ©2019 IEEE

packets with hard deadline constraints in a multihop, full–duplex wired network. In [9], a decentralized scheduling problem for multihop, multiflow wireless network with unreliable links is posed as an MDP, the objective of which is to maximize the throughput subject to a hard packet deadline and an average power constraint on nodes.

We now describe the previous work on cross-layer scheduling of packets. Cross-layer problem considers both the channel state (PHY layer) and delay (MAC layer) for scheduling of packets. In [10], the authors discuss the scheduling problem with link demands considering signal-to-interference-and-noise ratio (SINR) requirements. In [11], a problem of determining the minimum-length schedule based on the SINR constraints on wireless links has been studied. [12] considers downlink scheduling of data in wireless networks, and [13] focuses on centralized scheduling for transmission attempts over singlehop and multihop wireless networks.

Our work is different from the existing works in the following manner. In each time–slot for transmission, we select an activation vector that satisfies a certain signal to noise (SNR) requirement, and the transmit power is chosen such that it is just enough to achieve a target packet error rate (PER). The SNR requirement and the transmit power are chosen considering the delay deadline requirement.

Thus, our main objectives are *maximizing the number of packet transmissions in each traffic flow satisfying a delay deadline, and minimizing the average energy of transmission for all traffic flows in the network*. In this work, we address the scheduling problem described above, and present three different procedures that schedule the packet transmissions in multihop multiflow wireless networks. Our proposed schedulers are centralized, and are based on length of queues at all nodes, and the channel states of all links, both of which are assumed to be known to the centralized scheduler.

Contributions of the paper: Almost all works consider an energy efficient scheduling problem for a multiuser network, and propose a centralized solution. Relatively, few work discuss the problem of multihop multiflow networks because of the complexity involved with network state. Some of the energy-efficient problems are formulated in the framework of convex optimization and MDP, which are in-general intractable when the state space increases. Also, we note that very few work focus on the cross-layer scheduling problem, considering both PHY and MAC layer.

In this paper, we propose a centralized energy efficient cross layer scheduler with a constraint on individual packet delay deadlines, and PER over multiuser, multihop, multiflow wireless networks. We propose three sub-optimal schedulers based on threshold policy on channel gain: the first procedure, called Modified MaxWeight (MMW) scheduler is based on the traditional MaxWeight algorithm, the second procedure, called Modified BackPressure (MBP) scheduler is based on the traditional BackPressure algorithm, and the third procedure (which is proposed by us), called Minimum Per-packet Energy (MPE) scheduler is based on selecting the non-interfering links with minimum energy requirements for transmission. Our proposed scheme is energy efficient when compared with MMW and MBP both of which are based only on queue-lengths.

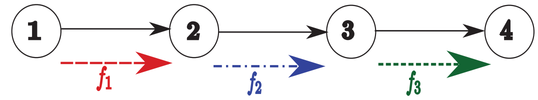

Fig. 1. A linear multihop network is considered for illustration. $\mathcal{V} = \{1,2,3,4\}$, $\mathcal{E} = \{(1,2),(2,3),(3,4)\}$ and $F = 3$ flows. Flow f_1 starts at node 1 and ends at node 2, flow f_2 starts at node 2 and ends at node 3, and flow f_4 starts at node 3 and ends at node 4.

Organization of the paper: The rest of the paper is organized as follows. In Section II, we describe the following components of the system: network, channel, traffic, and queueing models. In Section III, we pose the scheduling problem, and describe the solution to the scheduling problem (MMW, MBP, MPE algorithms) in Section IV. We evaluate the throughput performance and the energy expenditure of the algorithms in Section V. Finally, in Section VI, we provide conclusions.

II. System Model

In this Section, we describe the model of the network, the statistical characteristics of channels/links, and the packet arrival process (or the traffic) and the evolution of the queueing network.

A. Network Model

We consider a wireless network that consists of N nodes and L links, which is represented by a directed graph $G = (\mathcal{V}, \mathcal{E})$, where $\mathcal{V}$ is the set of nodes (with $|\mathcal{V}| = N$) and $\mathcal{E}$ is the set of links (with $|\mathcal{E}| = L$).

The network operates in slotted time, and time-slots are indexed by $k \in \{1, 2, \cdots\}$. For each link $l \in \mathcal{E}$, let us denote the head of link l by $h(l)$ and the tail of the link by $t(l)$. For example, if $l = (a, b)$, then $h(l) = b$ and $t(l) = a$.

B. Channel Model

Each link $l \in \mathcal{E}$ undergoes i.i.d. Rayleigh fading. Let $H_l[k]$ be the channel fading experienced by link $l \in \mathcal{E}$ during time-slot k. The channel fading process $\{H_l[k] : k \in \{1, 2, \cdots\}\}$ is independent and identically distributed (i.i.d.) across links, and for each link, the fading gain is i.i.d. across time-slots.

C. Traffic Model

We consider a set of F flows through the network which is denoted by $\mathcal{F} = \{1, 2, \cdots, F\}$. For each flow $f \in \mathcal{F}$, let the node $s(f) \in \mathcal{V}$ be the source, and the node $d(f) \in \mathcal{V}$ be the destination. Also, the route of each flow f is given by a sequence of links that carries the flow f, i.e., $\mathcal{R}(f) = [l_1(f), l_2(f), \cdots, l_{n_f}(f)]$, where n_f is the number of links between source and destination of flow f. Note that $t(l_1(f)) = s(f)$ and $h(l_{n_f}(f)) = d(f)$.

At the beginning of each time-slot k, a packet arrives at the source node $s(f)$ of each flow f according to an arrival process. In this work, we consider an i.i.d. Bernoulli(λ_f) process for each flow f, where $0 < \lambda_f < 1$ is the probability of a packet arrival in any time-slot. Let $A_n^{(f)}[k]$ be the number of exogenous arrivals (that arrives from outside of the network) of flow f at node n at the beginning of time-slot k. Note that

$$A_n^{(f)}[k] = \begin{cases} 0, & \text{if } n \neq s(f), \\ 1 \text{ w.p. } \lambda_f, & \text{if } n = s(f), \\ 0 \text{ w.p. } 1-\lambda_f, & \text{if } n = s(f). \end{cases} \quad (1)$$

Each packet is of one time-slot length. The deadline constraint that we consider in this paper is that each packet of flow f should be delivered to it's destination within a delay of $n_f D$ time-slots, where n_f is the number of hops of flow f; otherwise, it is dropped from the network.

D. Queuing Model

In this work, we follow the same notation as in [1]. Let $Q_n^{(f)}[k]$ be the number of packets of flow f waiting in node n just after the beginning of time-slot k. Note that each packet that waits in a queue has a waiting time of less than D time-slots in that queue; otherwise, the packet is dropped from the queue (and from the network). Note that if node n is not in the route of flow f, the queue-length $Q_n^{(f)}[k] = 0$ for all time-slots k. Also, note that the queue-length at destination nodes $Q_{d(f)}^{(f)}[k] = 0$. Define the vector of queue-lengths of flow f, $\mathbf{Q}^{(f)}[k] = \left[Q_1^{(f)}[k], Q_2^{(f)}[k], \cdots, Q_N^{(f)}[k]\right]^T$, where, as usual, $\mathbf{q}^T$ denotes the transpose of $\mathbf{q}$. Also, define the vector of new packet arrivals at each node for flow f as $\mathbf{A}^{(f)}[k] = \left[A_1^{(f)}[k], A_2^{(f)}[k], \cdots, A_N^{(f)}[k]\right]^T$.

Define the $N \times L$ routing matrix of flow f, $\mathbf{R}^{(f)} = [R_{vl}^{(f)}]$ as follows.

$$R_{vl}^{(f)} = \begin{cases} -1, & \text{if } v = t(l), \\ 1, & \text{if } v = h(l) \text{ and } h(l) \neq d(f) \\ 0, & \text{otherwise.} \end{cases} \quad (2)$$

Note that the routing matrix $\mathbf{R}^{(f)}$ takes care of incrementing queues at the head of the links, and decrementing queues at the tail of the links. During time-slot k, let us denote the vector of links chosen for transmission of flow f by $\mathbf{U}^{(f)}[k] = \left[U_1^{(f)}[k], U_2^{(f)}[k], \cdots, U_L^{(f)}[k]\right]^T$, where $U_l^{(f)}[k] = 1$ if link l is scheduled for transmission of flow f during time-slot k, and is zero, otherwise. Note that the links that are chosen for transmission are such that they do not interfere with each other. Thus, the queueing evolution is given by,

$$\mathbf{Q}^{(f)}[k+1] = \mathbf{Q}^{(f)}[k] + \mathbf{R}^{(f)}\mathbf{U}^{(f)}[k] + \mathbf{A}^{(f)}[k+1]. \quad (3)$$

In Eqn. (3), it is to be noted that a packet is served in one time-slot (which is taken care of by the routing matrix $\mathbf{R}^{(f)}$), and hence, the service rate of each link/server is 1 packet per slot. Note that we have a queueing system that comprises a network of queues for each $f \in \mathcal{F}$ that evolves according to Eqn. (3). Note that the waiting-time of each packet in the queue is incremented until it receives service. If the waiting-time is more than D, then the packet is dropped from the queue, and the queue-length is decremented by one. For the sake of brevity, we don't provide the evolution of queue-lengths with delays (and dropping of packets based on delays; see [14] for a detailed analysis).

III. SCHEDULING PROBLEM

In Eqn. (3), we can stack the state of queues of all flows, and obtain an overall system evolution. Define

$\mathbf{Q}[k] = \left[\mathbf{Q}^{(1)}[k], \mathbf{Q}^{(2)}[k], \cdots, \mathbf{Q}^{(F)}[k]\right]$,

$\mathbf{R} = \left[\mathbf{R}^{(1)}, \mathbf{R}^{(2)}, \cdots, \mathbf{R}^{(F)}\right]$,

$\mathbf{U}[k] = \left[\mathbf{U}^{(1)}[k], \mathbf{U}^{(2)}[k], \cdots, \mathbf{U}^{(F)}[k]\right]$, and

$\mathbf{A}[k] = \left[\mathbf{A}^{(1)}[k], \mathbf{A}^{(2)}[k], \cdots, \mathbf{A}^{(F)}[k]\right]$. Thus, we have,

$$\mathbf{Q}[k+1] = \mathbf{Q}[k] + \mathbf{R}\mathbf{U}[k] + \mathbf{A}[k+1]. \quad (4)$$

Note that $\mathbf{Q}[k]$ and $\mathbf{A}[k]$ are $N \times F$ matrices, $\mathbf{R}$ is an $N \times F$ matrix, where the fth column of $\mathbf{R}$ is itself an $N \times L$ matrix of integers from $\{1, -1, 0\}$, and $\mathbf{U}[k]$ is an $L \times F$ matrix.

The above is an evolution of a discrete-time dynamical system, in which the state of the system is $\mathbf{Q}[k]$, and the action chosen during time-slot k is $\mathbf{U}[k]$, and the disturbance is $\mathbf{A}[k+1]$. Note that the evolution of $\mathbf{Q}[k]$ is a controlled Markov chain, where $\mathbf{U}[k]$ is the control applied during time-slot k. One can define a reward function (or a cost function) that maximizes average throughput (or minimizes average energy). Thus, using the theory of Markov Decision Processes (MDP), one can obtain an optimal scheduling policy which yields optimal control $\mathbf{U}[k]$ during each time-slot k.

The MDP approach to solve a scheduling problem yields an optimum solution (see [14]); but, in general, this approach is computationally prohibitive

The scheduling problem we pose in this paper is the following. Each node $v \in \mathcal{V}$ is provided with an energy of E_v at the beginning of slot 1. As nodes transmit packets, it looses some energy. In this setting, we are interested in finding an answer to the following question: using initial energy of $[E_1, E_2, \cdots, E_N]$, what is the maximal throughput that can be obtained across each of flow $f \in \mathcal{F}$, while maintaining a delay constraint on the packet sojourn time.

IV. SCHEDULING ALGORITHMS

In this Section, we describe variants of classical scheduling algorithms like MaxWeight and BackPressure. Also, we propose an opportunistic scheduler which during any time-slot attempts to schedule links with minimum possible energy.

If there are L links in a network, the number of possible binary L-vectors is 2^L; a binary vector represents whether a link is scheduled for transmission, which is indicated by 1, or not, which is indicated by 0. If links l_1 and l_2 share a common node, then they can not be scheduled

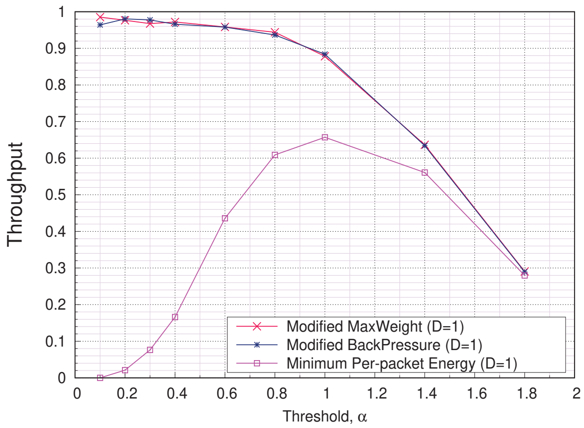

Fig. 2. Throughput versus Threshold on fading gain for a linear network with $N = 4$, $L = 3$, $F = 3$, where each flow is of one hop length. Delay deadline for each packet is 1 time-slot. Throughput of flow 1 is plotted (and the throughput obtained by other flows also show a similar trend).

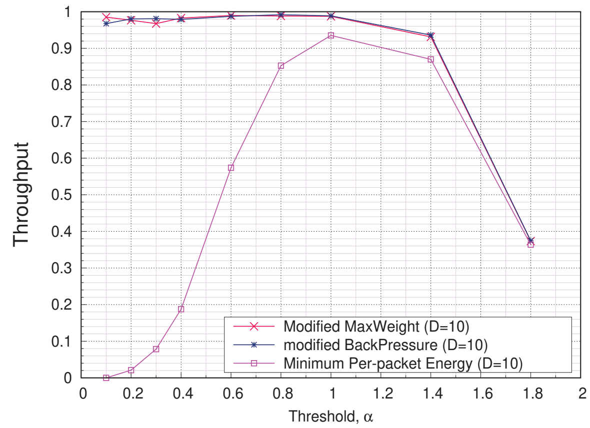

Fig. 3. Throughput versus Threshold on fading gain for a linear network with $N = 4$, $L = 3$, $F = 3$, where each flow is of one hop length. Delay deadline for each packet is 10 time-slots. Throughput of flow 1 is plotted (and the throughput obtained by other flows also show a similar trend).

simultaneously; a common tail, would mean that a node transmits to two different nodes at the same time, and a common head node would mean that a node receives from two different nodes at the same time, and both cases are not possible. Also, a node can not transmit and receive at the same time. Taking these interference conditions into account, we can define the set of all activation vectors[1]. Let $\mathcal{U}$ be the set of all activation vectors for the given network. The complexity in finding $\mathcal{U}$, the set of all possible activation vectors is an NP-hard problem.

Since, we consider a wireless network, during each time-slot, each link l undergoes fading $H_l[k]$. During each time-slot k, the SNR of link l is given by

$$\Gamma_l[k] = \frac{H_l[k]^2 E_s}{\sigma^2}, \tag{5}$$

where E_s is the energy of a packet, and σ^2 is noise variance of the additive white Gaussian noise (AWGN). Let γ be the minimum signal–to–noise ratio (SNR) required for a reliable communication. We consider those links l for which $\Gamma_l[k] > \gamma$. Note that the condition $\Gamma_l[k] > \gamma$ corresponds to $H_l[k] > \gamma\sigma^2/E_s$. Let $\alpha = \gamma\sigma^2/E_s$, and hence, we require $H_l[k] > \alpha$.

In the following subsections, we provide a Modified MaxWeight (MMW) algorithm and a Modified BackPressure (MBP) algorithm that considers the SNR requirement for packet transmission. Note that the classical MaxWeight and BackPressure algorithms do not consider any SNR requirement. Finally, we provide a scheduling algorithm called Minimum Per-packet Energy (MPE) scheduler that is based on per-packet transmission energy of schedules, at the end of this Section.

For all the scheduling algorithms that we describe below, we first compute the set of all possible activation vectors for time-slot k. At the beginning of each time-slot k, the queue-lengths $Q_n^{(f)}[k]$s are known. Let the set of all activation vectors be $\mathcal{U}$. Note that for each vector in $\mathcal{U}$, only the links for which $H_l[k] > \alpha$ is chosen. Thus, at the beginning of each time-slot k, $\mathcal{U}[k] \subseteq \mathcal{U}$ is chosen such that all active links in $\mathcal{U}[k]$ have an SNR of at least γ. Note that $\mathcal{U}[k]$ is the set of all possible activation vectors for time-slot k.

[1]An activation vector is a binary L-vector which indicates the set of all links that can be simultaneously scheduled without any interference.

A. *Modified MaxWeight Algorithm*

Recall that $\mathcal{U}[k]$ is the set of all activation vectors which satisfy the SNR requirement, $H_l[k] > \alpha$. For each activation vector $\mathbf{u} = [u_1, u_2, \cdots, u_L] \in \mathcal{U}[k]$, we define the MMW metric,

$$\text{MMW}(\mathbf{u}) = \sum_{l:u_l=1} \sum_{f:l\in\mathcal{R}_f} Q_{t(l)}^{(f)}[k]. \tag{6}$$

The activation vector $\hat{\mathbf{u}} \in \mathcal{U}[k]$ is then chosen such that

$$\hat{\mathbf{u}} = \arg\max_{\mathbf{u}\in\mathcal{U}[k]} \text{MMW}(\mathbf{u}). \tag{7}$$

If α is large and D is small, there is a possibility that some packets do not see a good channel when they wait for their service, and may eventually get dropped. Thus, the choice of α plays an important role in throughput. However, a small α would mean that the packets may require more energy for transmission, and thus may result in poor throughput. Thus, there is a tradeoff in choosing α for an optimum throughput.

B. *Modified BackPressure Algorithm*

For each $\mathbf{u} = [u_1, u_2, \cdots, u_L] \in \mathcal{U}[\mathbf{k}]$, obtain the modified BackPressure (MBP) metric,

$$\text{MBP}(\mathbf{u}) = \sum_{l:u_l=1} \sum_{f:l\in\mathcal{R}_f} \left(Q_{t(l)}^{(f)}[k] - Q_{h(l)}^{(f)}[k]\right). \tag{8}$$

The activation vector $\hat{\mathbf{u}} \in \mathcal{U}[k]$ is then chosen such that

$$\hat{\mathbf{u}} = \arg\max_{\mathbf{u}\in\mathcal{U}[k]} \text{MBP}(\mathbf{u}). \tag{9}$$

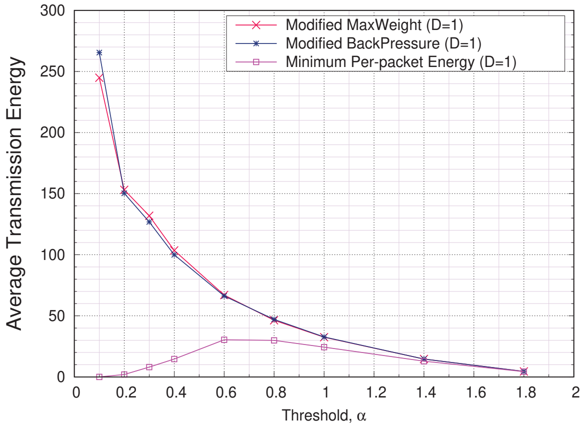

Fig. 4. Average Transmission Energy versus Threshold on fading gain for a linear network with $N = 4$, $L = 3$, $F = 3$, where each flow is of one hop length. Delay deadline for each packet is $D = 1$ time-slot. The plot is for flow 1 (and the other flows also show a similar trend).

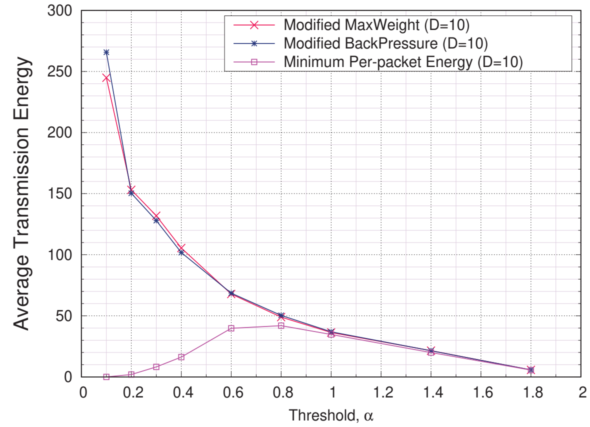

Fig. 5. Average Transmission Energy versus Threshold on fading gain for a linear network with $N = 4$, $L = 3$, $F = 3$, where each flow is of one hop length. Delay deadline for each packet is $D = 10$ time-slots. The plot is for flow 1 (and the other flows also show a similar trend).

C. Proposed Algorithm

Let $E_l[k]$ be the energy required to transmit a packet, to achieve an SNR of γ, on link l during time-slot k. Note that

$$E_l[k] = \frac{\gamma\sigma^2}{H_l[k]^2}. \tag{10}$$

For each $\mathbf{u} = [u_1, u_2, \cdots, u_L] \in \mathcal{U}[k]$, obtain the minimum per-packet energy (MPE) metric

$$\text{MPE}(\mathbf{u}) = \frac{\sum_{l:u_l=1} \sum_{f:l\in\mathcal{R}_f} E_l[k]\mathbf{1}_{\{Q^{(f)}_{t(l)}[k]>0\}}}{\sum_{l:u_l=1}}, \tag{11}$$

where $\mathbf{1}_{A>0} = 1$ if $A > 0$, and is zero, otherwise. The activation vector $\hat{\mathbf{u}} \in \mathcal{U}[k]$ is then chosen such that

$$\hat{\mathbf{u}} = \arg\min_{\mathbf{u}\in\mathcal{U}[k]} \text{MPE}(\mathbf{u}). \tag{12}$$

The discussion on the tradeoff between α and throughput (see Section IV A) holds in the case of MBP and MPE schedulers also.

V. Numerical Results

We analyzed various performance metrics of the following scheduling algorithms that we described in the previous Section: i) modified MaxWeight, ii) modified BackPressure, and iii) minimum per-packet energy algorithms.

We consider a linear network of four nodes, i.e., $N = 4$ with $L = 3$ (see Figure 1). The vertex set of the graph is $\{1, 2, 3, 4\}$, and the set of all links is $\{(1, 2), (2, 3), (3, 4)\}$. We consider three flows, i.e., $F = 3$, with the route of flow 1 being $\mathcal{R}(1) = [(1, 2)]$, that of flow 2 being $\mathcal{R}(2) = [(2, 3)]$, and that of flow 3 being $\mathcal{R}(3) = [(3, 4)]$. We took a very simple network, only for the sake of illustration.

We consider a Bernoulli arrival process with the probability of arrival being 0.1 for all flows. Each packet is required to reach it's destination before a sojourn time of D slots. We have chosen various values of D, and we report in this Section, the results for $D = 1$, and $D = 10$. Note that $D = 1$ corresponds to no waiting, i.e., the packet should be transmitted as and when it arrives.

We study the scheduling algorithms outlined in the previous Section (see Eqns. (6) – (12)) for the following metrics: throughput, average transmission energy, and the throughput per unit transmission energy. These metrics are obtained through simulation, which is carried out for 10^5 slots, and each simulation is repeated for 100 times to get a better average of the performance metrics.

We compute the throughput of all flows, where the throughput is defined as the ratio between the number of packets that are successfully delivered and the number of packets that have arrived. If the fading gain of a link is below a threshold $0 < \alpha < \infty$, we do not use the link, and for the other case of the fading being larger than α, we compute the transmit energy for the link using Eqn. (10). Note that the channel fading is taken to be i.i.d. Rayleigh with a mean squared fading gain being unity. We plot the throughput thus obtained in Figures 2 and 3.

In Figures 2 and 3, we see that MMW and MBP algorithms perform the same in terms of throughput, which is evident. As we consider a single-hop flows, in our example, the metric $\text{MMW}(\mathbf{u})$ (defined in Eqn. (6)) would yield the same value as the metric $\text{MBF}(\mathbf{u})$ (defined in Eqn. (8)). Also, for the MPE algorithm the throughput is poor for low thresholds, which increases with the threshold up to a certain point, and then decreases. Note that the throughput for any threshold is higher for $D = 10$ than for $D = 1$, as packets have a higher probability of reaching the destination for larger D.

In Figures 4 and 5, we plot the average transmission energy versus threshold for $D = 1$ and $D = 10$, respectively. The average transmission energy for MMW and MBP monotonically decreases, whereas for MPE, it increases and then decreases. The increase is due to more packets being

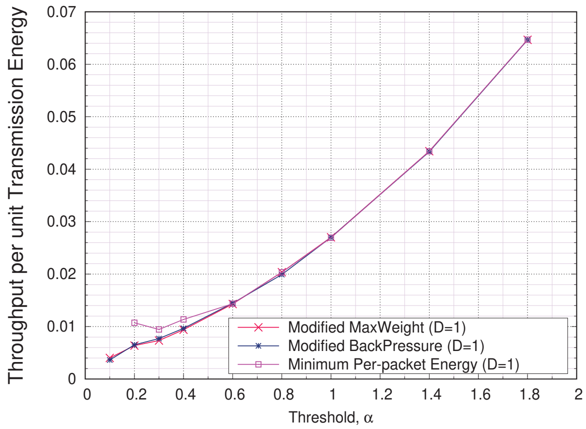

Fig. 6. Throughput per *unit Transmission Energy* versus Threshold on fading gain for a linear network with $N = 4$, $L = 3$, $F = 3$, where each flow is of one hop length. Delay deadline for each packet is $D = 1$ time-slot. The plot is for flow 1 (and other flows also show a similar trend).

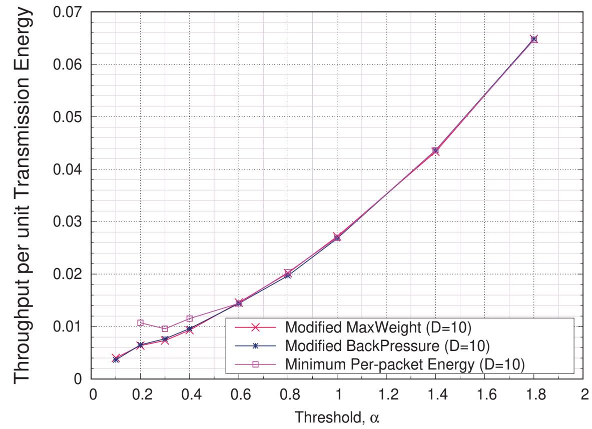

Fig. 7. Throughput per *unit Transmission Energy* versus Threshold on fading gain for a linear network with $N = 4$, $L = 3$, $F = 3$, where each flow is of one hop length. Delay deadline for each packet is $D = 10$ time-slots. The plot is for flow 1 (and the other flows also show a similar trend).

transmitted in the region $\alpha \in (0, 0.8)$. Also, average transmission energy is marginally higher for $D = 10$, as more energy is needed to transmit more packets (as higher throughput requires higher transmission energy).

A larger throughput comes at the cost of more average transmission energy. This makes us ask the following question: are we gaining more throughput per unit transmission energy. We answer this in Figures 6 and 7, where we plot the throughput per unit transmission energy versus threshold on channel gain. We note that for low thresholds, the throughput per unit transmission energy is marginally higher in the case of MPE scheduler for both $D = 1$ and $D = 10$.

VI. Conclusions

In this work, we consider the problem of scheduling in a multihop multiflow wireless network in which the packets are required to reach the destination within a delay of D time-slots. Packets arrive according to an arrival process at the source nodes, and the fading links pose an energy-efficient packet scheduling problem. A Modified MaxWeight (MMW) and a Modified BackPressure (MBP) algorithms are described. In the classical MaxWeight and BackPressure algorithms, all activation vectors are chosen for the constraint set, whereas in the MMW and MBP algorithms only those vectors for which only the links with fading gain above threshold are chosen. Also, we describe another scheduler based on Minimum Per-packet Energy (MPE) used for transmission in every time-slot. We study by simulation, the throughput, average transmission energy, and the throughput per unit transmission energy for all the scheduling algorithms we described. In future, we explore an analytical performance evaluation for the algorithms.

References

[1] L. Tassiulas and A. Ephremides, "Stability properties of constrained queueing systems and scheduling policies for maximum throughput in multihop radio networks," *IEEE Transactions on Automatic Control*, vol. 37, no. 12, pp. 1936–1948, Dec 1992.

[2] S. Shakkottai and R. Srikant, "Scheduling real-time traffic with deadlines over a wireless channel," *Wireless Networks*, vol. 8, no. 1, pp. 13–26, Jan 2002. [Online]. Available: https://doi.org/10.1023/A:1012763307361

[3] A. L. Stolyar, "Maxweight scheduling in a generalized switch: State space collapse and workload minimization in heavy traffic," *The Annals of Applied Probability*, vol. 14, no. 1, pp. 1–53, 2004.

[4] J. Liu, A. L. Stolyar, M. Chiang, and H. V. Poor, "Queue back-pressure random access in multihop wireless networks: Optimality and stability," *IEEE Transactions on Information Theory*, vol. 55, no. 9, pp. 4087–4098, Sep. 2009.

[5] B. Ji, C. Joo, and N. B. Shroff, "Delay-based back-pressure scheduling in multihop wireless networks," *IEEE/ACM Transactions on Networking*, vol. 21, no. 5, pp. 1539–1552, Oct 2013.

[6] E. Uysal-Biyikoglu and A. El Gamal, "On adaptive transmission for energy efficiency in wireless data networks," *IEEE Transactions on Information Theory*, vol. 50, no. 12, pp. 3081–3094, Dec 2004.

[7] S. Zuo, H. Deng, and I. Hou, "Energy efficient algorithms for real-time traffic over fading wireless channels," *IEEE Transactions on Wireless Communications*, vol. 16, no. 3, pp. 1881–1892, March 2017.

[8] Z. Mao, C. E. Koksal, and N. B. Shroff, "Optimal online scheduling with arbitrary hard deadlines in multihop communication networks," *IEEE/ACM Transactions on Networking*, vol. 24, no. 1, pp. 177–189, Feb 2016.

[9] R. Singh and P. R. Kumar, "Throughput optimal decentralized scheduling of multihop networks with end-to-end deadline constraints: Unreliable links," *IEEE Transactions on Automatic Control*, vol. 64, no. 1, pp. 127–142, Jan 2019.

[10] S. A. Borbash and A. Ephremides, "Wireless link scheduling with power control and sinr constraints," *IEEE Transactions on Information Theory*, vol. 52, no. 11, pp. 5106–5111, Nov 2006.

[11] S. Kompella, J. E. Wieselthier, and A. Ephremides, "A cross-layer approach to optimal wireless link scheduling with sinr constraints," in *MILCOM 2007 - IEEE Military Communications Conference*, Oct 2007, pp. 1–7.

[12] P. Liu, R. Berry, and M. L. Honig, "Delay-sensitive packet scheduling in wireless networks," in *2003 IEEE Wireless Communications and Networking, 2003. WCNC 2003.*, vol. 3, March 2003, pp. 1627–1632 vol.3.

[13] A. Pantelidou and A. Ephremides, "The scheduling problem in wireless networks," *Journal of Communications and Networks*, vol. 11, no. 5, pp. 489–499, Oct 2009.

[14] Dony J. Muttath, M. Santhoshkumar, and K. Premkumar, "Energy optimal packet scheduling with individual packet delay constraints," in *IEEE International Conference on Advanced Networks and Telecommunications Systems (IEEE ANTS)*, Dec. 2018.