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Cross-Layer Multiservice Opportunistic Scheduling for Wireless Networks

Amoakoh Gyasi-Agyei and Seong-Lyun Kim

Abstract—We consider opportunistic communication in multiservice wireless data networks using centralized controllers. Opportunistic scheduling (OS) is an emerging cross-layer media access control design approach to multiuser communication over fading wireless channels. OS exploits channel variations to maximize wireless throughput. We present a general background of OS schemes and then propose an OS scheme making an optimum trade-off between throughput and fairness, while maintaining stability in different channel environments and guaranteeing minimum service to multiple queues active concurrently at a given user.

I. INTRODUCTION

CURRENTLY, the communications industry is moving through several paradigm shifts, including: network convergence, media convergence, the penetration of the Internet Protocol in both core and radio access networks, and cross-layer protocol design. With network convergence, the fixed Internet is merging with wireless networks, while media convergence is merging video communications, voice communications and data communications. We are indeed in the era of “the transmission medium is no more the message,” which is enabled by recent advancements in digital technology. The traditional way of packaging communications functionalities into independent layers is now viewed more of a bust than a boom, as it comes in the way of protocol optimization and reduction of functionality duplication, among other things.

The transmission media used by wireless data networks is inherently varying due to multipath propagation, the positions of wireless users relative to the radio server, user mobility, and non-stationary clutter [1]. The result is that different users sharing a radio server are liable to different channel conditions at the same time. This is referred to as *multiuser diversity*, the basis of opportunistic scheduling (OS). For this reason, OS is also referred to as multiuser diversity scheduling, channel state dependent scheduling [3], or channel-aware scheduling in the literature. The wireless resource is scarce and expensive, requiring optimized usage to maximize throughput. Achieving overall throughput maximization requires an OS to momentarily postpone scheduling packets to a user with poor link quality until its link hits near its peak [2].

Unlike link/rate adaptation based schemes, OS exploits multiuser diversity to maximize system throughput, rather than combating it. Traditionally, channel variation is considered bad and intricate measures, such as interleaving, power control,

antenna diversity and equalization, are taken to combat it. There is a recent *reverse-engineering trend* which exploits channel randomness to boost network throughput at a cheaper cost. Hence, instead of mitigating fast fading, recent trends would rather enhance or even induce it in order to boost the gains achievable in multiuser diversity based scheduling [2], [1]. A proper functioning of an OS scheme requires feedback of predicted link qualities of all active users sharing a controller before each scheduling decision is made. Such channel feedback is usually integrated into wireless systems for purposes such as power control, load balancing and handoff decisions. Usually, each user measures the received signal-to-noise ratio on the common downlink pilot channel and then feeds it back to the central controller, on the uplink.

Although OS schemes work at the medium access control layer in end-user terminals and radio servers, they are inherently cross-layer in nature. Greedy OS schemes focus only on throughput maximization at the cost of all else. However, opportunistic scheduling schemes making an optimum trade-off between the competing design objectives of throughput maximization, fairness and minimum service guarantees to multiple competing data traffic are more valuable for emerging multi-service wireless data networks. Consider Fig. 1 in which M users share a radio server. Each of these users wants to open multiple (say, c) non-real-time data applications, such as Email, file transfer and Web browsing, at the same time. Only a multiservice OS scheme can guarantee a minimum service level to each of these traffic active concurrently at the same user over a given length of time. Many OS proposals focus on the special case $c = 1$, resulting in a one-to-one mapping between users and queues. Such a special case can easily starve some of the applications active at the same user concurrently. Hence, such schemes would be interesting for multiservice wireless networking only if both wireless link's capacity and device processing power were infinite.

II. OVERVIEW

The proper functioning of every multiuser system allowing the sharing of a common limited resource by multiple competing users require a media access control (MAC) scheme, otherwise *the tragedy of the commons* results. The traditional purpose of MAC in wireless networks is the efficient management of protocol access to the *shared* physical medium. Recent MAC schemes, however, perform other functions, such as carrier sensing/scanning, authentication, encryption, and fragmentation of higher layer packet, in order to coordinate the efficient use of a shared finite resource. In general, MAC

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Fig. 1. A queuing model of multiservice wireless scheduling.

schemes can be categorized into channelization schemes, contention-based schemes and scheduling schemes. This article focuses on scheduling schemes exploiting wireless channel variations to maximize wireless resource utility. Furthermore, we limit our discussions to heuristic schemes serving non-real-time data traffic in wireless networks using centralized resource coordinator. Scheduling is an optimization process by which limited resources are shared efficiently over time among parallel and sequential activities.

A. General

There are in general two main philosophies by which MAC schemes for wireless networks can be designed: *link/rate adaptation* (LRA) and *opportunistic scheduling* (OS). Both MAC design philosophies require cross-layer protocol design and/or optimization. However, the two MAC design philosophies use channel state feedback for different purposes.

LRA based MAC is the traditional way of communicating over spatio-temporally varying wireless channels, whereby the inherent randomization in channel characteristics is seen as evil and hence combated via sophisticated mechanisms, such as interleaving, equalization, modulation/coding, power control and antenna diversity. Such schemes therefore transmit data to a user irrespective of its current link condition. This is done by selecting a coding and modulation combination which matches the current achievable bit error rate of a user's link. Hence, they do not use the expensive wireless bandwidth efficiently. Besides spectral inefficiency, LRA based MAC schemes suffer from increased transceiver complexity, implementation costs, processing delay and energy consumption. MAC for all 2G wireless systems, such as GSM, IS-136 and IS-95, are based on LRA. We focus on OS in this article.

OS is the modern approach of communicating over spatio-temporally varying wireless channels whereby multiuser diversity is exploited rather than combated to maximize network capacity. OS algorithms seek to improve wireless network throughput by exploiting the spatial and temporal dependence of wireless channel conditions. Such a scheduler seeks to pick a user to schedule who is currently experiencing good channel conditions. For greedy OS, this is usually achieved to the disadvantage of fairness and traffic timing needs. Application

of OS in multiservice networks requires service feedback in the scheduling policy to guarantee minimum service and fairness to all backlogged non-real-time queues and traffic timing parameters to meet real-time timing constraints [4], [5]. An OS can suspend transmitting data to a user at a poor link state until its link hits near its peak or improves. Hence, in its traditional form, an OS seeks to pick among competing users the one who is currently experiencing the relatively best channel conditions in each scheduling instant. The chance that the OS finds a user whose link is close to its peak increases with the random variability in users' link states and hence the number of users sharing the medium.

OS research so far has focused on conventional cellular network architecture in which the network coverage area is divided into cells, each of which is served by a centralized radio controller. The controller can use a single or multiple carriers. Usually, the system uses a single-slot TDM/TDMA transmission per radio frequency carrier. That is, transmission time is slotted, and in each time slot only one out of the users competing for service in a cell is selected for scheduling on a single radio frequency carrier. Such a single-slot TDM/TDMA transmission can be used for both slotted-CDMA and pure TDMA networks. Mobiles measure the qualities on their forward links and feed back to controller on a periodic basis. Hence, the time slot duration should be much less than the channel coherence time (which is inversely proportional to the Doppler frequency shift) for the feedback channel gains to be useful. Thus, on a fast fading channel where OS achieves its maximum multiuser diversity gains, the channel quality feedback should be very frequent. This can penalize system's signaling load. The OS decides which user to schedule in each time slot using an algorithm which depends on the current link quality of the selected user.

OS based MAC reduces transceiver complexity, resulting in reduced power dissipation in wireless devices. As traffic is scheduled to/from a user only when its link hits near its peak, time to transmit the same amount of data can be reduced. This allows a mobile device to remain longer in energy-conserving mode and prolong its energy lifetime. This is critical for devices whose energy supply cannot be easily replenished. The only major weakness identified so far in OS is the potential traffic delay violations resulting from delaying transmission until a user's link hits near its peak. As shown in Fig. 3, OS is a cross-layer protocol where the estimated instantaneous channel quality indicators of mobiles from the physical layer and traffic service-related information from higher layers are fed to the MAC sublayer where the scheduler operates. The data link sublayer also performs its link level error management operations through the MAC. Here, the channel quality indicators are translated into instantaneously feasible data transmission rates. The traffic information can be service level feedback to monitor fairness, traffic timing parameters, file size, or throughput. Due to its cross-layer nature, OS requires a wider spectrum of expertise on its designers. As cross-layer philosophy confronts traditional protocol design, OS can revolutionize the design of wireless data networks from physical to networking layers.

B. Generalization of Opportunistic Schedulers

We formulate a generalized model for OS schemes that provide fair service to data traffic. Such a generalization of the wireless scheduling problem enables a more accessible comparison of different OS algorithms. From the preceding discussions we can ascertain the need for a scheduler that meets the competing objectives:

- 1) maximizes wireless throughput.
- 2) provides equitable service to queues and/or users.
- 3) guarantees minimum service level to concurrent multiple data services active at a given user.

We use model parameters to represent each of these competing design objectives in an utility function for wireless schedulers. We obtain an optimized trade-off between the design objectives by optimizing the formulated utility function. Let such an utility function be

$$\text{Maximize} \quad f(x, t) = f_1(x, t) \cdot f_2(x, t). \quad (1)$$

The variable x models the instantaneous wireless channel quality and/or traffic parameters. The function $f(x, t)$ should trade off the objectives $f_1(x, t)$ and $f_2(x, t)$ optimally. In this article $f_1(x, t)$ is a measure of the instantaneous feasible data transfer rate, and we define it simply as $f_1(x, t) = R_m(t)$. The function $f_2(x, t)$ is a measure of *equity* that is used to guarantee minimum service level to multiple data services active concurrently at a given user. This measures the level of service that a queue has received, relative to others within a given length of time. The application of OS in networks transporting time-critical traffic would trade off throughput and fairness for timing-related traffic constraints. This article focuses on OS schemes that can be used for wireless networks, such as data networks and wireless sensor networks, which can tolerate the potential delays associated with OS schemes.

C. Taxonomy of OS Algorithms

We classify existing OS schemes into eight classes under four main subgroups and cite some examples of each class in this section. The classification is generally valid for either single-hop or multi-hop, ad hoc or infrastructure wireless networks. However, this article focuses on single-hop infrastructure networks. The details of the sampled schemes can be found in the corresponding references. We emphasize that the list is just a sample of the myriad of OS schemes proposed.

Figure 2 shows a taxonomy of OS schemes. In general, there are eight types of OS schemes, as shown in the figure. All proposed OS schemes can be mapped onto one or more of these eight types. Types I, III, V and VII schemes are designed to serve non-real-time traffic, while Types II, IV, VI and VIII schemes serve real-time traffic. Type A schemes are used in single input, single output wireless networks using single antennas, while Type B schemes work in multiple input, multiple output (MIMO) systems employing spatial diversity. Types C and E schemes work in single-carrier systems, while Types D and F schemes are design for multicarrier (i.e. orthogonal frequency-division multiplexing or OFDM) networks. As shown in Fig. 2, the amount of outstanding R&D issues and

Fig. 2. Taxonomy of cross-layer wireless scheduling schemes.

the difficulty in algorithmic design increase as one moves from left to right. In fact, research on Type D schemes has just started while Type F schemes are unexplored. Examples of OS schemes for each class are: proportional fair [2], [6] and maximum signal-to-noise ratio [7] for Type I, modified largest weighted delay first [14] for Type II, multicarrier proportional fair [8] for Type III and the max-delay-utility rule [9] for Type IV. Type V schemes differ from Type I schemes only that they use multiple antennas for transmission or/and receiving. Type VI schemes are the MIMO versions of Type II schemes. We leave discussions on Type F schemes for future work.

D. Related Work

Many interesting OS schemes have been proposed for wireless networks recently. However, this section reviews only OS schemes that are closely related to the OS scheme proposed in this article. Except OCASD, all the OS schemes surveyed below map users to queues on a one-to-one basis, i.e. $c = 1$. Hence, they cannot quantify the service level of individual flows backlogged simultaneously at a given user. This leads to a potential starvation of some queues in case any user keeps multiple queues simultaneously.

1) *Round-Robin scheduler*: In round-robin (RR) scheduling arriving packets are queued by users, while the scheduler polls queues for service in a cyclic order irrespective of the wireless link conditions of the users to send/receive the packets. As greedy users flood their own queues, RR is able to provide *user protection*. By scheduling users/queues in a cyclic order, RR is able to provide fairness. Hence, it is used as *fairness benchmark* with respect to other schedulers.

2) *MaxSNR scheduler*: The maximum SNR (MaxSNR) scheduling picks the user among all active users in the system at scheduling instant which has the best signal-to-noise ratio, or equivalently, the best feasible data rate [7]. Here, $f_2(x, t) = 1$.

3) *PF scheduler*: Proportional fair sharing (PF) scheduling [6], [10], [2] is an OS scheme which provides fairness across users but not flows. In each time slot PF picks the user

among all backlogged users in the system which has the best feasible data rate normalized by its average throughput it has received so far. The PF is adopted in the downlink of the High Data Rate (HDR) system, which is defined in the 3GPP2's cdma2000 IS-856 standard [10]. Here, $f_2(x, t)$ is the reciprocal of average user throughputs in bits/sec.

4) *OCASD scheduler*: The Optimum Channel-Aware Scheduling with Service Differentiation (OCASD) [1] is a traffic-aided OS which optimizes the trade-off between short-term fairness, traffic delay and throughput maximization. Compared to a blind scheduling policy, such as classical round-robin which starves low signal-to-noise users (i.e. those usually located far from the serving radio base station) of service, OCASD delivers superior throughput gains while offering short-term fairness and considering traffic delay constraints. Here, $f_2(x, t)$ is the queue service history dependent multiplicative factor to $R_m(t)$.

III. BEST LINK LOWEST THROUGHPUT FIRST (BLOT) SCHEDULING

Most popular OS proposals such as the PF scheduling [6], [10], [2] assume that each user maintains a single active application (or queue) at a given time. Such OS schemes starve some queues in the case where a user keeps multiple concurrent applications (see Fig. 1). Also, PF is known to be unstable in finite-queue wireless systems [11]. In this section we propose an OS scheme which: (a) is as simple as PF, (b) provides a similar throughput as PF, (c) guarantees a minimum service to individual applications active concurrently at a given user, and (d) is stable in different channel environments.

A. System Model and Assumptions

Instead of a connection-oriented base station, a cellular wireless data network uses an Internet Protocol based base station. The base station works as a central controller for both communications directions, where it polls users for uplink channel access. Suppose a packet-based central controller serves M wireless users in a cell of a cellular wireless network at a given time (Fig. 1). In general the size of the user population M at any time is a random variable. Each user can open multiple (say, c) concurrent data applications which are queued independently, as illustrated in Fig. 1.

In the following let t be time slot index or instantaneous time and $i, i = 1, 2, \dots, c$ be the queue index, $R_m(t), m = 1, 2, \dots, M$ be the instantaneous feasible data transmission rate on mobile user m 's channel, $L_i(t)$ be the length of the head-of-line packet in queue i , and $B_i(t)$ be the amount of traffic that has been scheduled from queue i up to time t . In this article we refer to the vector $x = (i, m)$, i.e. user m to exchange the head-of-line packet in its queue i , as a *connection*. Note also that i and m are actually the indices of the optimization variables used by the scheduler in its decision making. Here, queue i maps onto $B_i(t)$, while m maps onto $R_m(t)$. Time is slotted and in each slot a single connection is scheduled per radio frequency carrier. In a time slot t we assume that the $R_m(t)$'s are independent and identically distributed random variables, and that $R_m(t)$ remains fairly

Fig. 3. Illustration of the cross-layer nature of BLOT as an OS scheme.

constant within a time slot duration. The $R_m(t)$'s are also assumed to be available at the beginning of time slot t . However, mechanisms used to estimate the $R_m(t)$'s are not considered in this article. A time slot lasts a packet transmission time, which is variable as both $R_m(t)$ and $L_i(t)$ are variable. If the scheduling policy results in a tie, then we can pick among the ties, for example

- 1) a connection randomly.
- 2) the connection with the highest feasible data rate.
- 3) the connection with the tightest timing constraint.
- 4) the connection with the earliest packet delay violation to avoid global synchronization.

This article focuses on the downlink of the air interface. As Fig. 3 shows, the input parameters to the scheduler at time t for queue i are the: (a) feedback $B_i(t)$ to monitor fairness across queues and users, and (b) predicted instantaneous data transmission rate $R_m(t)$ of the channel between user m and the serving base station to monitor throughput maximization. We note that a complete radio resource manager in a packet-based wireless network includes an admission controller, a resource allocator and a packet scheduler. This article focuses on the packet scheduling functionality. Hence, it is presumed that packets operated on are already admitted into the system under study. The basic design principles of the scheduler for the downlink communications direction (a similar scenario occurs on the uplink) are:

- Packets belonging to the same application but to be scheduled to different users are queued in the same logical queue, as shown in Fig. 1. Packets in each queue are arranged in the order of arrival to the queue. Packet (re)ordering in a queue can also be based on (earliest) delay deadlines.
- Only the head-of-line packet in each queue is considered in each scheduling decision.
- Traffic parameters of the head-of-line packet in each queue and $R_m(t)$ of the corresponding users to send/receive the packets are jointly used in the scheduling policy (2). We expect the higher protocol layers to communicate to the MAC layer the traffic service feedback parameters in the Layer 3 packet header field.

TABLE I

PSEUDOCODE FOR BLOT ASSUMING THE AVAILABILITY OF THE R_m 'S BY SOME CHANNEL ESTIMATION TECHNIQUE.

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1. While time slot  $t \leq t_c$  do
  2. For  $m \in \mathcal{M}$  ( $\mathcal{M}$  is the set of backlogged users at time  $t$ )
    3. For  $i \in \mathcal{B}$  ( $\mathcal{B}$  is the set of non-empty queues at time  $t$ )
      compute  $f(x, t) = R_m(t)/[B_i(t) + \epsilon]$ ,  $x = (i, m)$ 
    end.
  4. Find connection  $x^* = \arg \max_x \{f(x, t)\}$ 
  5. If  $\max\{\text{size}\{x^*\} \neq 1\}$ , pick connection  $x^+ \in x^*$ 
     $B_{i^+}(t+1) = (1 - 1/t_c)B_{i^+}(t) + L_{i^+}(t)I_{i^+}(t)/t_c$ 
     $B_{i^*}(t+1) = (1 - 1/t_c)B_{i^*}(t) + L_{i^*}(t)I_{i^*}(t)/t_c$ 
    end
  6.  $t \rightarrow t + 1$ 
  7. Goto step 1
end

```

B. The BLOT Scheduling Rule

This section analyzes the objective function (1) when $f_1(x, t) = R_m(t)$ and $f_2(x, t) = 1/B_i(t)$. Hence, the problem to be solved, which we refer to as Best Link LOwest Throughput first (or *BLOT*) scheduling, reduces to

$$x_t^* = \arg \max_x f(x, t), \quad f(x, t) = R_m(t)/[B_i(t) + \epsilon] \quad (2)$$

where ϵ is a small positive number used to prevent division by zero and $B_i(t)$ evolves as $B_i(t+1) = (1 - 1/t_c)B_i(t) + 1/t_c L_i(t)I_i(t)$. Here, $I_k(t) = 1$ if queue k is scheduled at time t otherwise $I_k(t) = 0$. The *latency time scale* t_c determines how long a queue can wait for service. Too short t_c can penalize throughput maximization, while too long t_c increases the inter-service waiting times of queues. Hence, optimum trade-off between (short-term) fairness and throughput maximization is required, which is embedded in the proposed scheduler. A suitable value proposed for most data applications is 1000 time slots [11] with a slot duration of 1.667 ms, as used in the CDMA/HDR system. Table I contains the pseudocode for BLOT algorithm.

The connection scheduled in slot t at the transmission rate $R_{m^*}(t)$ is the solution to the optimization problem (2), which is a special case of (1). Note that there is a coupling between queue state and channel state. A high queue departure rate $R_m(t)$ prevents losses due to buffer overflow. However, $R_m(t)$ is limited by the instantaneous channel quality of users. The equity function embedded into the scheduler can be formulated to prevent queue starvation and thus ensure temporal fairness among competing queues over a given latency time scale t_c .

IV. SIMULATION AND RESULTS

In the following we compare the performance of BLOT with PF using the wireless channel and traffic models presented below. The classical round-robin (RR) and MaxSNR schemes are used as benchmarks for fairness and throughput, respectively.

A. Simulation Environment

We present wireless channel and traffic models and the performance metrics used for the simulations in this section.

1) *Wireless Channel Model*: In general wireless channels have varying characteristics depending on e.g. user mobility pattern, operating frequency, time, and the features of the operating environment such as topography. Usually, this varying feature is modeled by a concatenation of fast fading and slow fading models. We investigate and compare the performance of BLOT with PF in different wireless channel environments. We assume a flat Rayleigh fading channel with uncorrelated additive random noise and explore two different channel models: (a) Jakes' simulator model [12], and (b) autoregressive 1 (AR-1) model [13]. In the AR-1 model the signal-to-noise ratio on user m 's channel evolves as [13]

$$\gamma_m(t) = a\gamma_m(t-1) + (1-a)w_m(t).$$

Here, $a, |a| < 1$ is the channel correlation factor and the $w_m(t)$'s are independent and identically normal distributed random noise with mean and standard deviation μ_m and σ_m , respectively.

2) *Traffic Model*: It is assumed that traffic arrives in each active queue by an on/off source model. Each on/off source toggles between its two states in a time slot duration, and generates a single packet when it is in the *on*-state. Packet sizes are variable and are chosen from the bimodal probability mass function given in [1]. All queues are reset when the algorithm is first executed. We assume that packets are not fragmented at the MAC layer. Hence, as packets on data networks are in general of variable sizes and channel rates are inherently varying, we assume variable time slots. Once a connection is picked for scheduling its entire head-of-line packet is sent through before the next scheduling epoch begins. We focus on three non-real-time data applications in this discussion, namely, Email, file transfer and Web browsing.

3) *Performance Metrics*: The performance metrics of interest here are per-user and per-queue fairness, system throughput, and the stability of the scheduler to different channel models or environments. We define the average throughput for connection x up to time t by the sample mean $\frac{1}{t} \sum_{l=0}^t R_m(l)I_{im}(l)$. Hence, the average sum throughput for user m up to time t is

$$S_m(t) = \frac{1}{t} \sum_{i=1}^c \sum_{l=0}^t R_m(l)I_{im}(l)$$

where $I_{im}(t) = 1$ if queue i of user m is picked for service in slot t , otherwise $I_{im}(t) = 0$. Similarly, the average sum throughput for queue i up to time t is

$$S_i(t) = \frac{1}{t} \sum_{m=1}^M \sum_{l=0}^t R_m(l)I_{im}(l).$$

Thus the overall system throughput up to time t is

$$S(t) = \sum_{i=1}^c S_i(t) = \sum_{m=1}^M S_m(t). \quad (3)$$

Fig. 4. System throughput comparison under wireless Jakes' channel model [$c = 3$, $t_c = 1000$ time slots, $f_c = 2$ GHz, $E_b/N_0 = 0$ dB, 8 multipath signals, $v_m = 120$ km/hr].

B. System Throughput

We compare the achievable system throughputs over the simulation runs of 1000 time slots under the OS policies BLOT, PF, OCASD, MaxSNR and RR as a function of the number of users competing for service. If we assume a time slot duration of 1.667 ms as in the CDMA/HDR system then the total simulation time is 1.667 seconds. The results are shown in Fig. 4. Here, we observe that BLOT, PF, OCASD and MaxSNR have the similar throughput performance, and that they perform much better than round-robin. It is also observed that the throughput increases with number of mobile users sharing the wireless resource, except for RR which does not exploit multiuser diversity. This is attributed to multiuser diversity whereby the chance of the OS picking a user at a good channel state in a time slot is enhanced as the number of simultaneous users increases. Figure 5 compares the achievable system throughput under varying latency time scales t_c . Again, BLOT and PF achieves the same performance. Both BLOT and PF converge to a stable throughput after as few as 40 time slot durations.

C. Sensitivity of Scheduler to Channel Environments

We consider the effects of wireless channel model on the throughput performance of BLOT and PF using the channel models described above. Similarly to [13] we set $\mu_m \in \{-4, -2, 0, 2, 4, 0\}$, $\sigma_m = 15.0$ and $a \in \{0.1, 0.9\}$. Figure 6 compares the throughput performance of BLOT and PF under AR-1 channel environment. There are interesting scenarios to be observed here. Let us remark again that the autoregressive coefficient a denotes how correlated the channel states in neighboring time slots are, and the higher the value of a , the higher the correlation. When $a = 0.1$ we observe that BLOT and PF once again show similar performance. However, as a increases to 0.9 we observe that BLOT performs better than PF. One other interesting observation is that PF seems rather unstable when the channel states are very correlated. Hence, BLOT is robust and stable in different channel environments.

Fig. 5. Snapshot of simulation results with $t_c = 1000$ timeslots, $c = 3$, $f_c = 2$ GHz, $E_b/N_0 = 0$ dB, 8 multipath signals, $v_m = 120$ km/hr.

Fig. 6. Effects of wireless channel model on the throughput performance of opportunistic schedulers [$c = 3$, $f_c = 2$ GHz, $t_c = 1000$ time slots, $E_b/N_0 = 0$ dB, 8 multipath signals, $v_m = 120$ km/hr, $\sigma_m = 15$, $\mu_m = 0$].

Fig. 6 also shows that the throughput performance is better when the channel states are more correlated.

D. Per-User Fairness

In this section too, we compare the cumulative throughput received by each of M mobile users competing for the shared wireless resource over a given time window t_c for the OS schemes: MaxSNR, BLOT, PF and RR. As Fig. 7 shows, BLOT, MaxSNR, OCASD and PF achieves the same throughput across all M mobile users. Also, all M mobile users receive similar throughput under BLOT, MaxSNR, OCASD and PF. We define the throughput fairness metric as the difference between the users that receive the highest and the minimum throughputs for each scheme. These are 10 bits/sec/Hz for RR and 36 bits/sec/Hz for PF, BLOT and MaxSNR. The average throughput (AvgT) for RR is 140 bits/sec/Hz, while that for PF, BLOT and MaxSNR is 209 bits/sec/Hz. While RR achieves the worst throughput across

Fig. 7. Comparison of per-user throughput under Jakes' channel model [$M = 8, c = 3, t_c = 1000$ time slots, $f_c = 2$ GHz, $E_b/N_0 = 0$ dB, 8 multipath signals, $v_m = 120$ km/hr].

Fig. 8. Illustration of BLOT's per-queue fairness for three concurrent queues active at the same user terminal [$M = 8, c = 3, f_c = 2$ GHz, $E_b/N_0 = 0$ dB, 8 multipath signals, $v_m = 120$ km/hr, $m = 15, \mu_m = 0, t_c = 1000$ time slots].

all the M users, it is the fairest scheme.

E. Per-Queue Fairness

We illustrate the multiservice nature of BLOT in this section. Besides per-user fairness, BLOT provides per-queue fairness (Fig. 8). This is because BLOT guarantees a minimum service level to each of the multiple applications that may be active simultaneously on a single mobile device. Queue isolation is a feature that an OS scheme such as PF lacks, although BLOT is quite similar to PF. We compare the fraction of time slots received by each of the three concurrent queues active at a given user over the simulation runs of t_c time slots under BLOT. Figure 8 compares the per-queue fairness of BLOT under three different wireless channel conditions. As can be observed, none of the three queues is starved of service under any of the three channel environments. It is also interesting to note that BLOT provides a fair service to all the three queues. Figure 8 also shows that BLOT is stable under different channel models and environments, and achieves almost the optimum fairness of a round-robin scheduling, which ideally assigns equal service to the three queues.

V. CONCLUSION

This article considered the problem of scheduling traffic of multiple users in a cellular wireless network whereby each active user can be backlogged with multiple non-real-time data traffic requiring similar service. Among others, an opportunistic scheduling scheme called BLOT is presented. BLOT achieves similar throughput performance as PF, and it is similar to the latter. However, unlike PF, BLOT can serve multiple queues active at the same user concurrently and guarantee a minimum service level to the individual queues. Simulation analysis also confirms that BLOT is stable in different wireless channel environments, unlike PF. BLOT can be adopted in any time-slotted wireless data network. For

example, BLOT can be an alternative to PF in CDMA/HDR networks.

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