THE EFFECT OF MOBILITY ON THE USER-LEVEL FAIRNESS OF A 3G WIRELESS TECHNOLOGY (EV-DO)

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ABSTRACT

In this work the behavior of a 3G wireless technology is evaluated. The analysis is done using a simulation tool, based on the Tangram-II platform, which incorporates a detailed propagation model and the relevant features of the CDMA20001x EVDO system. Internet access through web browsers was judged to be the key application to be provided. We are interested in analyzing the throughput, latency and fairness metrics for several scenarios, including cases considering only static users as well as cases where a fraction of terminals has mobility. Our experiments show that the introduction of mobile users severely compromises the fairness in respect to user's goodput and delay. A previous work of ours has shown that even if some parameters of the scheduling algorithm are varied, due to physical layer limitations it is difficult to improve performance of the technology with respect to fairness. In this article we show that the use of directional antennas can play an even more important role in improving EV-DO behavior for the envisioned application when some users are mobile.

I. INTRODUCTION

The initial motivation of this work was to evaluate the CDMA20001x EV-DO Rev.0 (IS-856) standard to be employed as a solution to implement the bi-directional return channel of the Brazilian Digital TV system. One assumption that was made is that a vast majority of the users will be stationary, at least for the first years of system deployment. Mobile users will be a minority and most will be moving at pedestrian speeds, i.e., at about 3Km/h.

The EV-DO [1, 2] is a third generation cellular technology conceived to serve an increasing demand for wireless packet data communications. In the uplink this technology operates as the CDMA20001x with all normal features of this technology such as soft hand-off. In the forward link the EV-DO is a time division multiplexing system designed to provide a high total sector throughput allowing a maximum bit rate of 2.4 Mbps in its revision 0 (3.1 Mbps in Rev.A).

In particular, the EV-DO has, as will be shown, one intrinsic difficulty (downlink variable packet duration) that leads to unfairness when the most commonly proposed downlink scheduling algorithm is adopted. Since the system should be used by a large population accessing the Internet, it is desirable that it should provide comparable (or at least good quality) services to all its subscribers. The quality of service obtained by users can not depend on their geographical location since they are paying the same price for the subscription. Note that in a highly mobile environment this is very hard to occur because users are changing their location constantly. However, in a common scenario where most terminals are stationary, this unwanted situation can happen.

There have been several papers published addressing the performance of EV-DO systems [2, 3, 4, 5]. In one of them [5] there is a focus on the user throughput fairness for a population of static users. However, except for our previous work [6], in none of them the average delay and bit rate achieved by users in different regions of the cell is addressed in detail. The results of [6] show that users in different points of a cell would have quite different QoS with respect to throughput and delay. Then, a simple solution is proposed to reduce the unfairness.

In this work we evaluate the effectiveness of the solution to circumvent this shortcoming of the EV-DO previously proposed by the authors [6] to a configuration that includes mobiles users.

It has been shown in [7] that, due to the high complexity nature of EVDO networks, the available analytical models are not accurate enough to correctly address EVDO system level performance. Consequently, it is extremely difficult to provide a good fit between analytical models results and the measured capacity values. Thus, we chose to build a detailed EVDO simulation model for our experiments.

We perform experiments considering a mix of static and mobile users which is a very common scenario for EV-DO networks. Furthermore, we show that: (1) user throughput unfairness increases when a subset of the population is mobile users and; (2) the simple solution proposed in [6] still works when mobile users are added to the system. It is shown that this solution can dramatically enhance the fairness characteristics of the service and also increase the total throughput of the cell site.

In the next section a brief review of the main features of the EV-DO technology is presented. In Section III the simulation, traffic and mobility models considered in this work are introduced. The results are discussed in Section IV and concluding remarks and suggestions for future work are in Section V.

II. CDMA2000 1xEVDO OVERVIEW

The cellular technology EV-DO, also known as TIA IS-856 standard [1], is optimized for packet data transmission and is part of a family of CDMA20001x third generation technologies. The EV-DO forward link operates on a Time Division Multiplexing (TDM) mode where at each 1.67 ms slot the data transmission is directed to a single user. This transmission is always made at peak access point (or cell site) power and the peak rate is 2.4 Mbps. As most modern wire-

less communication techniques, the EV-DO employs adaptive modulation/coding schemes in both forward and reverse links, although they are implemented in different ways depending on the direction considered. In the downlink, the choice of bit rate depends on the carrier-to-interference ratio (C/I) perceived by the access terminal (AT). The AT passes the instantaneous channel quality information to the access point (AP) through the bit field DRC (Data Rate Control) in the reverse link. Table 1 shows the available forward link modulation and coding schemes for the EV-DO (Rev.0) including respective bit rates, packet lengths and minimum SINR (signal-to-interference+noise ratio).

Congestion control in the reverse link is achieved by a reverse activity (RA) bit sent in the downlink by the AP. This bit is code multiplexed with the power control (RPC) logical channel to form the medium access control (MAC) signal. The MAC information is then time multiplexed with the pilot signal and the actual information bits.

The time multiplexed forward link signal spreading chip rate (1.2288Mc/s) and carrier spacing (1.25MHz) are compatible with other CDMA systems such as CDMA20001xRTT and IS-95.

From Table 1 it can be seen that the higher the downlink bit rate the lower the robustness to channel impairments hence the higher bit rate options will only be available when the propagation conditions are favorable and/or the system loading is low. Another interesting observation is that when the AP uses a low bit rate to transmit to a given user it will occupy larger number of slots to send a packet then when the bit rate employed is high. Hence, serving users in worst geographic/propagation condition will necessarily reduce the total bit rate achieved by the system. This characteristic will be addressed again when discussing system performance in Section IV. The EV-DO forward link behavior differs from those of typical TDMA systems. In traditional TDMA each active user gets exclusive use of one (or several) slot in each frame. In EV-DO each slot can be assigned for transmission to any terminal among those active. The choice of the terminal whose traffic will be sent in a given slot is made by a scheduling algorithm. This scheduling algorithm is not defined in the IS-856 standard. However, a scheme often suggested for use in the EV-DO AP is the *Proportional Fair Scheduling* (PFS) which is described in [8]. Following the PFS principle, the user with the best instantaneous condition in terms of propagation and interference, as determined by the set of DRCs received by the access point, is chosen to receive information in that slot. This policy would maximize the overall bit rate in the sector/cell but in practice it is necessary to include some fairness consideration to avoid completely starving some terminals. Indeed the PFS does include this concern in its design. The fairness level is controlled by a parameter $\alpha \in (0, 1)$ that determines for how long a terminal will be allowed to go without having a slot assigned to it. Hence α controls, to a certain extent, the degree of fairness in the system. A typical value for α is 0.001.

Bit Rate (Kb/s)	Packet length (slots)	FEC Rate	Modulation Scheme	Minimum SINR (dB)
38.4	16	1/4	QPSK	-11.5
76.8	8	1/4	QPSK	-9.2
102.6	6	1/4	QPSK	-6.5
153.6	4	1/4	QPSK	-3.5
204.8	3	1/4	QPSK	-3.5
307.2	2	1/4	QPSK	-0.6
614.4	1	1/4	QPSK	-0.5
921.6	1	3/8	QPSK	2.2
1228.8	1	1/2	QPSK	3.9
1843.2	1	1/2	8-PSK	8
2457.6	1	1/2	16-QAM	10.3

Table 1: Available transmission modes for EV-DO forward Link (Rev.0)

The EV-DO reverse link is based on the CDMA access method but with the flexibility of allowing different transmission bit rates. The actual bit rate achieved by a terminal depends on its propagation conditions and distance to the access point as well as on the cell/sector loading as determined by the AP. The congestion control mechanism implemented by the AP manages to keep the loading conditions within the cell below a given threshold. The bit rate adjustment due to changing loading conditions is done probabilistically [9], i.e., when the AT receives the appropriate RA bit command from the cell site it will change (or not) its rate in the requested direction with a given probability which can be a function of the rate the terminal is using at that moment.

There are 5 bit rates available in Revision 0 uplink, namely, 9.6, 19.2, 38.4, 76.8 and 153.6 Kbps. The modulation scheme is the same (BPSK) for all rates as well as the packet duration (53.3ms). The transmit power for each of the bit rates is different with higher rates obviously requiring a higher received power for the same level of packet error rate (PER). Consequently users located at the edge of the cell/sector will experience an average bit rate lower than those at close range. The specific rate achieved by a terminal, as stated before, will depend on the instantaneous system loading.

The reverse link allows for the adoption of an Early Termination mechanism [2, 4] where there is a gradual transmission of redundancy bits. However the significant benefits afforded by this mechanism are derived when the terminals are very mobile, which is not the case in the application considered in this paper. Therefore Early Termination was not implemented to obtain the results described in the sequel.

III. Simulation Model

The proposed simulation model was developed to evaluate the users´ delay and goodput as a function of the user population and of their distance to the AP. The model is composed of a web user population accessing the Internet through the EV-DO system. The simulation results were obtained using the Tangram-II [10] modeling environment. The adopted EV-DO model takes into account the most relevant physical and link layer characteristics of the CDMA2000-1xEVDO standard, such as the propagation model, the power control, the packet scheduling algorithm, and the inter-cell and intra-cell interferences. The implementation of these features produced

an open-source network-level model. The simulation model is based on the following assumptions: (i) there are static and mobile users in the population. Mobile users are represented using the Random Waypoint model [11]. (ii) users generate load to the system according to an associated traffic model; (iii) there is only one AP with a single omnidirectional antenna (i.e. no sectorization), therefore there is no virtual soft-handoff; (iv) *Proportional Fair Schedule* is used at the AP for downlink access control; (v) downlink interference is computed through straightforward geometrical calculations; (vi) the uplink total inter-cell interference is made equal to 40 % of the value of the intra-cell interference; (vii) *Early Termination* mechanism was not included in the model since most of the terminals are stationary or moving at a low speed.

A. Physical Layer Model

Three mechanisms are represented in this layer: the propagation loss, the reverse link power control and the congestion control. Let $L_{total}[dB]$ be the total loss between the user and the access point. It is given by:

$$L_{total}[dB] = L_{prop}[dB] + L_{pen}[dB] + D[dB], \quad (1)$$

where L_{prop} is the propagation loss, L_{pen} is the building penetration loss, and D is the flat fading.

The propagation loss model is based on [12]. In this work we consider only the dense urban scenario. The model parameters we considered are: the carrier frequency is equal to $450MHz$, the terminal height is $1.5m$, the height of the AP antenna is $40m$, and the penetration loss is equal to $10dB$. The flat fading is modeled using a log-normal random variable with mean $0dB$ and standard deviation equal to $8dB$. For the mobile users, there is no penetration loss.

Similarly to other CDMA technologies, the reverse link power control is implemented in three steps. The first step is the inner-loop power control. The closed-loop power control is the second step. The model used for the closed-loop power control is based on [13], which recommends a 1% PER. We do not model the third step, i.e. the outer-loop power control.

Let P_{pilot} be the value obtained from the reverse link power control described above. If the condition $P_{pilot} > P_{MAX} - DataGain[CurrentRate]$ is satisfied, the terminal decides that it has sufficient power to transmit the next message, where (P_{MAX} is the maximum available power and $DataGain[CurrentRate]$ is the data gain given the transmission rate. Note that the terminal will try to satisfy this condition with the highest possible rate (which is the $CurrentRate$).

Finally, the third mechanism we model is the congestion control described in Section II which is based on [1, 13].

B. Link Layer Model

The main feature of the link layer is the forward link packet scheduling algorithm known as *Proportional Fair Scheduling* (PFS). The main objective of PFS is to give some priority to users in favorable conditions while keeping other users from starving. To achieve this goal, cross-layer concepts are used, that is, from the link layer, PFS reads values (i.e. SINR) which are available in 1G, 2G and 2.5G standards only at the physical layer.

PFS is divided into two steps. In the first the user with the highest $\frac{DRC_i(t)}{R_i(t)}$ is selected, where $DRC_i(t)$ is the rate requested by user i and $R_i(t)$ is the mean rate at which user i has been receiving data:

$$j = \underset{i}{arg\,max} \left[\frac{DRC_i(t)}{R_i(t)} \right] \quad (2)$$

In the second step, the average data rate of user i (for all i) is updated as follows:

$$R_i(t+1) = (1-\alpha) * R_i(t) + \alpha * CRT_i(t) \quad (3)$$

$$\begin{cases} CRT_i(t) = DRC_i(t) & \text{if } i = j \\ CRT_i(t) = 0 & \text{if } i \neq j \end{cases} \quad (4)$$

where CRT_i is the current user i data rate at time t. Parameter α regulates the trade-off between the aggregate throughput and user fairness.

Each terminal obtains the maximum allowed bit rate to transmit ($DRC_i(t)$) according to its downlink signal to interference noise ratio (SINR), and send the $DRC_i(t)$ to the AP. Table 1 shows in the fifth column the minimum required SINR for a given bit rate (first column).

C. User Model

As already mentioned in Section I, we assume that all services are web based. The behavior of a web application can be described as follows. When a user clicks in a HTTP link, several web requests are generated. The first corresponds to the main object request. When the main object arrives at the terminal, it is parsed and a new web request is generated for each in-line object reference found. After all objects of the main web page are received, the users spends some time (called reading time), browsing through the downloaded material before clicking in another HTTP link. We use distributions and parameter values from [14]. The reading time distribution is Pareto. The number of objects referenced by the main page is a Pareto truncated at 53 objects. An important characteristics of the HTTP model are the distributions of the main and in-line object sizes. Note that these sizes tend to be quite different, since the main object is typically a HTML file, and the in-line objects may be components of a multimedia content, such as an audio or a video file. The main and in-line object sizes are given by Lognormal distributions with average 10.7 KB and 7.7 KB, respectively, as suggested by [15]. Finally, each uplink request has a fix size equal to 200 bytes.

D. User Mobility Model

We use the Random Waypoint model of [11] to represent the mobility of users and suppose a constant speed of 3km/h. In our experiments, we update the node's position once every second in order to keep track of the user's coordinate even if it has not reached the next waypoint.

As stated by [11], the random waypoint model does not reach the stationary regime in some scenarios because of several factors such as the speed decay and speed changes as the simulation progresses. To solve this problem, the authors of [11] propose the *Perfect Sampling* procedure, where the initial simulation state is sampled from the stationary regime. We use this procedure in our mobility model The sampling algorithm guarantees the stationarity of the mobility model and has another advantage: there is no need to discard the initial simulation period since the mobility model is at the steady state at the beginning of the simulation run. In our experiments, we discard the initial period of the simulations runs because of the EV-DO transient period. No further discarding was required for the mobility scenario.

E. Model Overview

Figure 1 shows a high level graphical description of the simulation model. The figure is divided into different sections. Section *A* is the web user model, section *B* represents the Internet delay, and section *C* models the EV-DO protocol (reverse channel in the left and forward channel in the right).

When a user generates a web request, the request waits in the transmission queue of the terminal until it is granted access to the reverse channel and transmitted. In the reverse channel model we consider the following subchannels: the power control subchannel pilot, the RRI (Reverse Rate Indicator), DRC, DATA and ACK.

The web requests eventually reach the Internet (Internet object). This object emulates the Internet Round Trip Time (RTT) delay. After one RTT, the requested web object arrives at the BS queue and waits for the forward channel (proportional fair scheduling discipline).

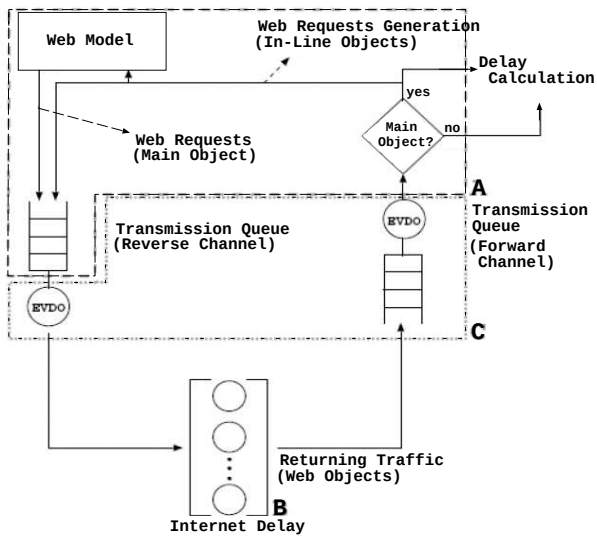

Figure 1: Model Overview

IV. Numerical Results and Discussion

The following parameter values are used in the simulations performed: (i) the other-cell interference perceived by the AP is equal to 40% of the intra-cell interference; (ii) the population varies from 10 to 80 users; (iii) the cell radius is equal to 1Km; (iv) the users are randomly positioned in the cell; (v) the congestion control parameters p and q are based on [1]; (vi) the AT and AP maximum transmission power are 23dBm and 55.8dBm, respectively; (vii) the thermal noise is -165dBm; (viii) the cable loss is 3dB; (ix) the AP gain is 17dB; (x) the client's receiver sensibility is -119dBm; (xi) the parameter α of the PFS is equal to 0.001; (xii) the speed for the mobile users is 3kmh. In all simulations we used a 95% confidence level and, for all results, the confidence intervals where smaller than 20%. (We choose not to show the confidence intervals in the figures to make the plots more readable.)

In the first set of experiments, we focus on the average user delay (d) and goodput. We define goodput as the ratio L/d, where L is the mean size of a complete web page and d is the average delay measured from the instant the user clicks on a link till the requested web pages are completely received.

Four scenarios were considered for each experiment: (scenario 1) only static users are modeled, (scenario 2) 30% of mobile users traveling within the cell; (scenario 3) only static users with antennas; (scenario 4) static users with antennas and 30% of mobile users traveling within the cell. In the scenarios 3 and 4 we consider that the terminals located in the two farthest zones use a 8dB directional antenna. Mobile terminals continue to use omnidirectional antennas

Figures 2 and 3 show the average user goodput and delay for scenarios 1 and 2. One can note that when there are 30% of mobile users in the system, the goodput decreases in all population scenarios. Our experiments have shown that the system is underloaded for a population varying from 30 to 40 users. For a population of 80 users the load approaches 95% and for 60 users the load is approximately 84%. We define the *system load* as the fraction of forward link data slots used for transmission. With 30 to 40 users, when some idle data slots are observed, the perturbation caused by the mobile terminals is not as significant as when there are 60 users and the load is high. Therefore, there is a clear significant loss of service quality for a population of 60 users, both in terms of the goodput and the delay metrics. However, when the system is heavily loaded (80 users), the mobile users do not impact the average user goodput and delay as for a population of 60 users. This occurs because for a population of 80 users (in both scenarios 1 and 2), the PFS scheduler gives priority to serve the (now numerous) static users geographically located near the AP.

We now focus at the 60 user population configuration, as shown in Figures 4 and 5. User-level average delay and Forward link goodput are plotted in these figures for all scenarios. If we compare scenario 1 (only static users, no directional antennas) with scenario 2 (30% mobile users, no directional antennas for the static users), we note that the average delay has increased from 2 to almost 8 seconds.

An analogous behavior is shown in Figure 5, where the av-

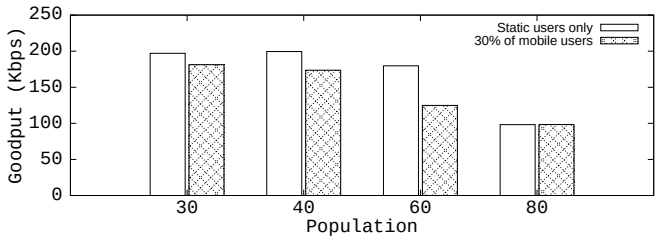

Figure 2: Average goodput perceived by users as a function of the population

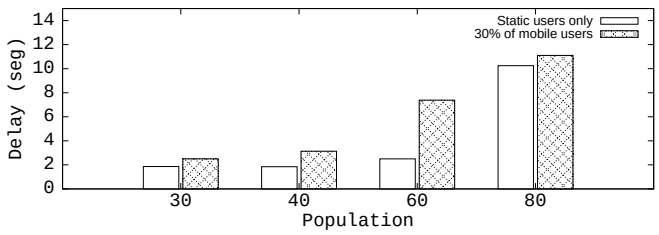

Figure 3: Average delay perceived by users as a function of the population

erage goodput is equal to 175Kbps for scenario 1 and reduced to 125kbps for scenario 2. It is easy to see that the introduction of mobile users decreases significantly goodput and increases delay.

In the sequel, we show that the observed decrease in service quality when comparing scenarios 1 and 2 is followed by a serious degradation in both goodput and delay fairness. Note that, for the mobility scenarios, there is an additional zone called "mob." which aggregates the results for the group of mobile users. In addition, to evaluate the effect of both type of users (mobile and static) and the user population on fairness, we consider a scenario with only one static user in the system.

When the static user is at the first distance zone, her average delay is 0.68s. If this user is placed at zones 8, 9 and 10, her average delay is 2.1s, 2.4s and 3.6s, respectively. We note that the average delay of a user in the last zone is approximately five times greater than the user delay in the first zone. From Figure 6, we observe that, for a population of 60 static users, the delay of a user in the last zone increases 10 times when compared with that of a user in the first zone. If 30% of the population are mobile users, the delay increases 15 times. These results show that both the growth of the population and mobile

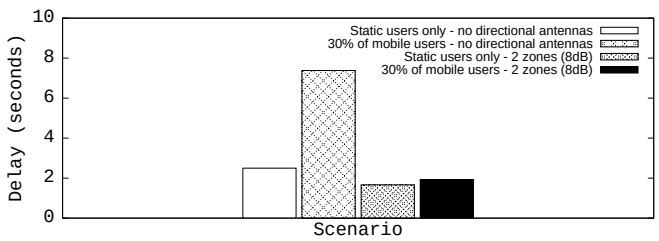

Figure 4: Average delay (60 users)

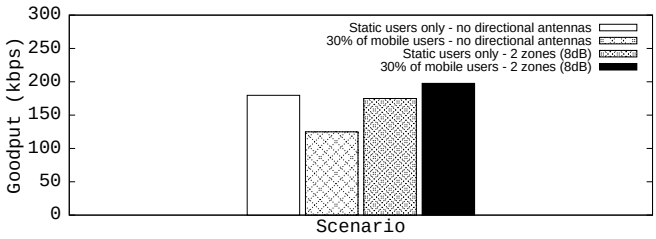

Figure 5: Average goodput (60 users) for scenarios 1, 2, 3 and 4.

users increases user unfairness.

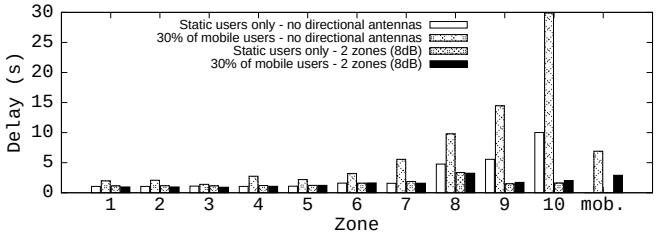

Figure 6: Average delay vs. distance zone for each scenario considered

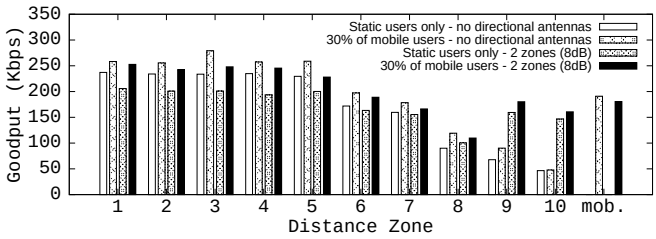

Figure 7: Average goodput vs. distance zone for each scenario considered

In this work we also propose to reduce the intrinsic unfairness of the scheduling algorithm by allowing users that are located towards the cell border to use directional antennas. These antennas can be inexpensive, as for example a Yagi. Also it is sufficient that the gain provided by the antenna be as modest as 8dB.

The effectiveness of our proposed solution is shown in Figures 6 and 7. We plot the average delay in Figure 6 for the 4 scenarios we consider. Note that the difference among the average delays in the most distant zones significantly decreases if we compare scenario 1 with 3 and scenario 2 with 4. For example, the delay of a user in zone 10 decreases from 29s (scenario 2) to 2s (scenario 4). This is due to the directional antenna that is used in the last two zones. Additionally, the delay for the mobile users (last two bars) decreases in half from scenario 2 to scenario 4.

In Figure 7, the results for scenarios 3 and 4 show that the users' goodput in zone 9 and 10 is significantly improved when compared to scenarios 1 and 2, respectively. The value of the user's goodput in the zones 9 and 10 (with a directional an-

tenna) is approximately 75% of that for a user in the zone 1 (this value was 20% for the scenarios 1 and 2).

Furthermore, we define the following metrics in order to quantify the fairness improvement: (a) σ_g^2 is the variance of the average goodput of a distance zone; (b) σ_d^2 is the variance of the average delay of a distance zone; (c) d_g is the difference between the smallest and the greatest average goodput measured for each distance zone; and (d) d_d is the difference between the smallest and the greatest average delay measured for each distance zone. All the metrics above include zones 1 to 10 and zone *mob*.

By comparing scenario 1 with 3 and scenario 2 with 4 in Table 2, one can clearly note that the previously observed unfairness has significantly decreased even when there are 30% of mobile users.

Scenario	σ_g^2	σ_d^2	d_g	d_d
1 - Static users: no antennas	5844.49	9.05	190.57	8.97
2 - Mobility: no antennas	6142.96	72.55	231.45	28.48
3 - Static: antennas in 2 zones	1149.62	0.45	105.39	0.45
4 - Mobility: antennas in 2 zones	2144.12	0.62	142.86	2.34

Table 2: Fairness represented through σ_g,σ_d, d_g and d_d

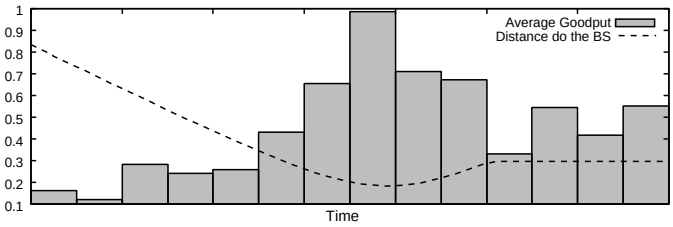

Figure 8: A simulation sample path: distance vs. goodput of a mobile user

Finally, Figure 8 shows what happens to the goodput (normalized by the greatest value - 250kbps) of a user as it travels through the cell (distance is normalized by the cell radius). This result was obtained under the scenario which we call "scenario 4". It is important to note that the mobile users also suffers from the same quality of service variation observed in static users due to the physical layer limitations of the technology.

V. Conclusions

The experiments allowed us to make a set of observations with respect to the effect of the Proportional Fair Scheduler and the physical Layer limitations in the system's quality of service. To the best of our knowledge, these observations have not appeared in related works. One of them is the fact that we quantify the variations in the users quality of service and fairness metrics due to their geographic position for both static and mobile user scenarios.

Although the average goodput and delay provided by the EV-DO for web based services was generally adequate, its fairness profile is not ideal for the considered scenarios. Our experiments have also shown that the fairness decreases when there is a mix of mobile and static users. This shortcoming is due to intrinsic characteristics of the technology. Furthermore, it is difficult to overcome this deficiency just by adjusting the scheduling algorithm without unduly reducing the overall cell site throughput, which is also undesirable.

In this paper it was shown that even for the mobility scenarios the fairness can be efficiently improved if a small fraction of the subscribers employs inexpensive directive antennas in order to attenuate the SINR difference among users located in different distant zones. Furthermore, even the mobile benefit from improved delay, while their goodput remain unchanged. Additionally, one can note that the intrinsic limitations of the physical layer play an important role to the system unfairness. Thus, by attacking these limitations, we are trying a different approach when compared with the available literature.

We suggest that future work should investigate the effect of the use of smart antennas that could vary its gain while the terminal moves through the cell to improve overall quality.

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