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Abstract

Recent developments in wireless networks have focused on improved data performance (e.g., 1xEV-DV [5], 1xEV-DO [1] and HSDPA). In these networks the forward packet data channel is time shared among the data users. In order to be able to take advantage of fast fading effects (i.e., schedule users when they are in good radio conditions), the scheduling of users is performed at the Base Station (BS). This implies that it is not possible to support soft handoff on this forward packet data channel since this would require that the BSs synchronize their schedules. However, macro-diversity gains can be achieved by fast cell switching. The mobile is served from the base station with the best forward link quality. This BS is reported through the reverse channel quality indicator channel. However, the BS with the best forward link quality is not necessarily the best BS to serve the mobile since it may be congested. In this paper we describe a procedure whereby a mobile switches to the cell that can provide it with the highest throughput rather than best channel conditions. We demonstrate why this approach is preferable and describe the framework necessary to support this mechanism.

1 Introduction

In a distributed system such as a wireless network, the resources available to each network component (e.g., BS) must be efficiently allocated among the corresponding users of the component. In addition, the loading of each component must be optimally balanced so as to maximize network resource utilization. We consider the problem of optimal balancing of load (data users) among BSs. Note that each mobile induces BS loading in both the Forward Packet Data Channel (F-PDCH) and Reverse Packet Data Channel (R-PDCH). In this paper we address the problem of forward link loading but a similar approach can be used for the reverse link. Note that loading in both directions must be computed before making a decision to switch.

The optimal allocation of users among the BSs can be solved by providing all relevant data to a centralized function that computes the allocation of BSs to Mobile Stations (MSs). However such an approach would be very signaling intensive. We instead focus on a distributed solution in which each mobile periodically determines if it should switch from its presently assigned BS (its serving BS) to any of the other BSs in its active set. This decision is based on local information as well as any information provided to it by the BSs in its active set.

This approach actually improves the overall system fairness because of the following. Consider any MS and assume that it is presently being served by $BS_s$ and is considering switching to $BS_t$. Assume that we can determine the forward link throughput of the mobile if it were to switch cells. Let $r_s$ denote the present throughput of the MS and let $r_t$ denote the throughput that the MS will achieve if it were to switch cells. Let $r_s < r_t$ then the mobile can increase its forward link throughput by switching. Furthermore, since $r_s < r_t$, then the loading of $BS_s$ is higher than that of $BS_t$. If the MS makes the switch then the loading on $BS_s$ decreases while the loading on $BS_t$ increases. Hence the switch reduces the difference in the loading between the two cells. Therefore, the system settles to a state where all cells running near capacity experience comparable loading. Note that the same argument can be used for the reverse link loading. Both forward link and reverse link loading must be considered in deciding if a MS should switch since link asymmetry may result in one increasing in throughput while the other may decrease.

Cell switching should not be performed too often because of the signaling overhead it induces. The forward link throughput of a MS depends on the amount of power allocated to the F-PDCH, the number of Walsh codes allocated to the F-PDCH, the number of active forward link users in the cell, the forward link radio conditions of these users, and the scheduler (which defines the tradeoff between fairness and sector throughput). Each of these factors need to be considered when predicting the achievable rate of the MS at the target cell. We first describe the present procedure for cell switching and highlight the problems with the approach. We next provide a method...
for predicting the throughput experienced by a MS if it were to switch to another BS. We demonstrate that the BS that provides the best throughput need not be the one with the best forward link channel conditions. We then discuss some practical and standardization issues.

2 Current Cell Switching Procedure

This section describes the current procedures for cell switching in the 1xEV-DV standards. We first describe the channel that is used to convey the information indicating that a cell switch is needed. Next we describe the procedure to determine if a MS should switch sectors and how this request is indicated to both the source and target sectors. We then discuss some of the limitations of the present standards. In particular the fact that more information needs to be taken into account for such a decision. In the final section of this paper we suggest possible ways for the dissemination of this information.

2.1 Channel Quality Information Feedback

The Reverse-Channel Quality Indicator Channel (R-CQICH) is a new reverse link channel added to support the fast link adaptation of the forward packet data channel (F-PDCH) in 1xEV-DV systems. Link adaptation allows the BS to track changes in the channel quality and select the optimal data rate. The MS subscribing to the F-PDCH service has to transmit an indication of the forward link quality in the R-CQICH. This indication of quality is the measured pilot strength seen at the MS from the best BS in the MS’s active set that contains all the pilots that the MS is in soft or softer handoff. Since the channel quality is only that of the strongest pilot seen at the MS, the MS must also indicate the identity of that best BS in the R-CQICH. Based upon the information on the R-CQICH, the BS determines the data rate of the F-PDCH and sends the data rate to the mobile via an explicit overhead message on the forward link using the F-PDCCH.

Each frame (20 ms) is divided into 16 slots of 1.25 ms duration. The first slot contains the full CQI report and the following slots contain the differential CQI reports represented by 1 bit or full CQI reports represented by 4 bits in differential or full CQI reporting mode respectively during normal operation. The reporting pattern can change during cell switching, control hold and link imbalance.

2.2 Cell Selection and Soft Handoff

Soft handoff is not supported for F-PDCH, instead macro diversity in the F-PDCH is achieved through cell selection. The F-PDCH is not soft-combined at the MS, the MS indicates to the BS, on the R-CQICH, the sector from which the mobile station wishes to receive the F-PDCH. The R-CQICH indicates the desired sector by selecting a length-8 Walsh code (or R-CQICH cover) for Walsh spreading of coded symbols. Consequently, the cell selection information for a particular F-PDCH is also transmitted on the R-CQICH besides the channel-quality information. The MS is assumed to report the channel quality from the sector of the strongest pilot with the sector’s identification.

2.3 Cell Switching Process

In any cellular wireless system, the MS may move out of the coverage of any particular serving BS or the channel condition changes due to environment changes. A process by which the MS indicates to the BS that a different sector should now be its forward link serving sector is, therefore, necessary. The main goal of the cell switching process is to allow the best sector to serve the MS and make the transition robust. The MS sends a distinct switching pattern in the R-CQICH for a period of time known as the cell switching period. The length of the switching period is configurable and is dependent upon whether the source and target sectors belong to a single BS. The BS, furthermore, has the capability to terminate the switching period before the expiration of the configured switching period by sending a message to the MS on the F-PDCCH. At the termination of the switching period, the MS resumes non-cell switching (normal) operation of the R-CQICH with the selected target sector. During the cell switching period, the slots at the end of the frame are punctured and replaced with switching slots containing fixed data covered by the Walsh cover of the target sector whereas preceding slots carry the Walsh cover of the source sector. The switching slots are punctured at the end of the frame to minimize their impact upon the accuracy of CQI reports and the data is fixed to improve the detection of the target sector selected by the MS.

The number of switching frames and number of switching slots can be configured. When the number of switching frames is chosen to be large then the number of switching slots needed are small, and vice versa. Other factors such as repetition to increase the reliability of the cell switch detection and control hold generate the need for different (higher) cell switching slots.

2.4 Standards Limitations

In order for the MS to perform a meaningful cell switching process, basically, it needs to know whether it can receive better performance (throughput, delay, etc.) if switched to another sector in the active set. In order to know this, the MS needs information such as pilot strength, sector load, resource availability such as available Walsh codes and transmit power, and the type of scheduling algorithm used at the scheduler in the current and target sectors. Unfortunately, the MS knows only the pilot strength of current and the target sector; the rest are unknown at the mobile station. Currently, in the 1xEV-DV systems, the MS performs cell switching purely based on the pilot strength. The 1xEV-DV standard does not limit the MS in its cell switching decision except that the BS can provide the MS with an estimate of the delay and hence the degree of the service interruption if the MS were to initiate a cell switch.
The standards also allow a mechanism to reject cell switching. It is performed by sending a special control message on the F-PDCCCH. However, without knowing the needed information previously mentioned, the MS cannot perform an intelligent cell switch. As a result, the user may face unnecessary degradation in performance and the network may experience imbalance in load consequently leading to congestion.

3 Determination of Optimal Sector

In this section we propose a procedure for each MS to determine its best serving sector defined as the sector that provides the highest throughput in the forward link. On a periodic basis each BS broadcasts two parameters that represent the BS’s loading information. Each BS uses this information together with other local information to estimate the throughput it can achieve if it were to switch to any of the other BSs in its active set. If it can increase its throughput significantly by switching then it executes a switching procedure. First we compute the predicted forward link throughput for an arbitrary BS/MS pair.

3.1 Predicting Forward Link Throughput

Assume that a Proportional Fair scheduler is being used for the F-PDCH (a similar approach can be used for other schedulers). One can show that for each user \( i \), the ratio of the user’s average forward link throughput \( r_i \) and his average served rate \( d_i \) approaches some constant \( \theta \) (see [2]). Since this constant is the same for all MSs, we can update our estimate of it each time a new frame (not a retransmission) is transmitted. Let us index these new transmissions with \( k \) then our estimate of \( \theta \) is obtained as

\[
\theta(k) = \phi \theta(k-1) + (1 - \phi) \frac{r(k)}{d(k)}
\]

where \( r(k) \) is the average throughput and \( d(k) \) is the average served rate of the user who is scheduled in the time slot corresponding to index \( k \). Note that we are in fact averaging this quotient over all users being served since they all converge to the same value. This increases the rate of convergence. This ratio will allow us to estimate the throughput given the achievable rate of the MS.

This provides the present estimate of \( \theta \) but the addition of a new user to the cell will cause this metric to change. We next estimate the effect of a new user on this metric. One can show (see [3] for details) that for the case of Proportional Fair scheduling, the throughput of an individual user varies with the number of users in the system by the multiplicative factor \( g(N) \) given by

\[
g(N) = \int_0^\infty xe^{-x}(1 - e^{-x})^{N-1}dx.
\]

Therefore, if the MS were to switch, its throughput would be decreased due to the increase (by one) of the number of users in the target cell by the following multiplicative factor

\[
\gamma(N) = \frac{g(N+1)}{g(N)}.
\]

Note that in the case of a Round Robin scheduler this attenuation factor is simply \( N/(N+1) \). However, for Proportional Fair scheduling the user diversity gain increases with the number of users and hence the attenuation function decreases at a slower rate (see Figure 1 for attenuation plots for both Round Robin and Proportional Fair schedulers). Note that this attenuation factor is strictly dependent on \( N \) and can therefore be computed for various values of \( N \) and stored in a table. The attenuation factor \( \gamma(N) \) effectively takes into account the dependence on the number of active users in the system.

We now use this parameters to compute the expected value of the rate at which the MS would be served at the target cell. The served rate of the MS is determined by its channel quality (denoted by \( q \), the SINR of the pilot channel), the transmission power of the F-PDCH (denoted by \( P \)) and the number of Walsh codes used for the F-PDCH denoted by \( W \). The BS will have some look-up table that maps these three quantities to a rate. Since Turbo codes are used we can estimate the served rate \( d \) by the Shannon Capacity as follows:

\[
d = BW \log_2 \left( 1 + \frac{Pq}{pW} \right)
\]

where \( p \) is the transmission power of the pilot used by the MS to determine \( q \) and \( B \) is the channel bandwidth. We can combine this with the estimate of \( \theta \) as well as the attenuation factor due to an increase in the number of users to obtain the predicted rate as

\[
r = \theta \gamma(N)BW \log_2 \left( 1 + \frac{Pq}{pW} \right) = \alpha \log_2(1 + \beta q)
\]

Both \( \alpha \) and \( \beta \) are BS specific but independent of the MS. Note that all relevant information is accounted for, the
scheduler, the number of active users, the number of available Walsh codes, the power available to the F-PDCH and the only MS specific dependence, the pilot SINR, $q$. We assume that each BS periodically broadcasts its most recent estimate of $\alpha$ and $\beta$. Each MS can then use the above expression to determine its predicted throughput if it were to move to another cell. We assume that BS $j$ broadcasts $\alpha_j$ and $\beta_j$ every $\tau$ seconds (probably on the same broadcast channel that is used to broadcast the reverse link loading). We also assume that every $T$ seconds each MS determines the forward link channel quality $q_j$ for each BS $j$. Let $A$ denote the active set of the mobile. Every $T$ seconds each MS determines the predicted throughput for each BS in its active set (including its serving sector) and then determines the cell $j^*$ that can potentially provide the highest throughput.

$$j^* = \arg\{\max_{j \in A}[\alpha_j \log_2(1 + \beta_j q_j)]\}$$

Note that MSs will typically decide to switch near the cell edge. If this is the case then $q$ is small and we can make the approximation $\log_2(1 + x) \approx x$ to obtain

$$r \approx \frac{\theta\gamma(N)BPq}{p} \equiv \alpha'q$$

In this case only a single parameter needs to be broadcast by the BS. Note that this approach will tend to give the channel quality of a MS higher weighting over the other factors and hence may be preferable in some situations.

We assume that the BS broadcasts are much more frequent than the MS cell switching determination and that each MS performs this operation at time instances that are uncorrelated with those of other MSs. In this way the effects due to the simultaneous switching of two MSs into a cell are minimized. This effect is also minimized since we will only allow a MS to switch if its predicted throughput in the new cell is significantly larger (not simply larger) than its present throughput.

### 3.2 Illustrative Examples

In this section we provide some illustrative examples to demonstrate that the proposed approach in fact results in a more efficient network as opposed to the present procedure based solely on channel conditions.

The ratio $\theta$ will vary with the number and distribution of users in the sector. Typically it will decrease monotonically with the number of users in the system. The next factor is the attenuation factor $\gamma(N)$. Consider two BSs that only differ in the number of users. In one case there are 5 users and in the other there are 10 users. We determine the expected value of the product $\theta\gamma(N)$ for these two cases and plot (in Figure 2) the resulting predicted throughput as a function of the channel conditions (SINR of the pilot).

Note that even if the forward link channel conditions for the 5 user BS is worse than that of the 10 user BS it may still be better, from a throughput perspective, to have the MS switch to the 5 user BS because of its lower loading.

Next we consider what happens if there are differences in the number of Walsh codes available to the F-PDCH. We consider the case of 10 users and keep everything identical except that one BS has 16 available Walsh codes for the F-PDCH while the other has 32. In this case (Figure 3) the 32 Walsh code BS provides better throughput but the difference is relatively small.

Finally we consider the effect of the power available to the F-PDCH. We repeat the case of 10 users but this time we assume that one BS has 14 watts available to the F-PDCH while the other has 7 Watts. Here we see (Figure 4) a significant throughput difference between the two cases and so it is preferable to have the MS switch to the BS with the higher available power.
3.3 Proposed Cell Switching Algorithm

In this section we describe a simple algorithm for cell switching using the above procedure for determining the expected throughput when switched. One simple embodiment of the algorithm is as follows. On a periodic basis the MS determines $j^*$. If this is the serving BS then nothing is done. If this is a non-serving BS and the predicted throughput is at least $\varepsilon$ greater than the present throughput and the predicted reverse link throughput is also greater than the present reverse link throughput then the MS switches to $j^*$.

Note that the estimate of the forward link throughput of the serving BS is used in the algorithm and not a smoothed measurement of the actual throughput. The latter quantity can in fact be used to fine tune the algorithm to obtain better predicted throughputs.

4 Information Dissemination Options

Recall that two parameters ($\alpha$ and $\beta$) must be reported to the MSs in a periodic fashion. We provide several (non-standardized) alternatives for accomplishing this in the following paragraphs.

The sectors could periodically send the sector information via the F-PDCCH message. This is a broadcast message that all MSs can monitor. The MS knows the predefined time instance that the serving sector and the other sectors in the active set will send this information. Hence, the MS can acquire this information from its serving and other sectors by locking onto their transmission at the predefined times slots. The disadvantage of this method is that multiple RF channels need to be decoded at the MS.

The sector information could be distributed among other sectors via the backhaul connections, and each sector places the necessary information in a MS directed F-PDCCH message. The disadvantage of this method is that the overhead will be high because of the mobile specific message.

The sector information could be distributed among other sectors via the backhaul connections, and each sector puts a subset of the information of itself and its neighboring sectors in a F-PDCCH broadcast message. If a single F-PDCCH message is used, the amount of information that can be conveyed may be too little, on the other hand, if multiple F-PDCCH messages are used, then there could be a long interruption in serving MSs.

The sector information could be distributed among other sectors via the backhaul connections, and each sector broadcast this information to all the MSs in the sector via the F-PDCH with a low rate to maintain high reliability. This in-traffic broadcast via the F-PDCH channel can be made possible through a common identifier in the associated F-PDCCH message. This allows for sufficient granularity in representing the sector information of each neighbor sectors.

5 Conclusions

We considered the problem of assigning MSs to their serving BSs. We described the present distributed procedure for making these assignments and show that, in terms of system data throughput, the procedure was non-optimal. We then presented an approach that switches MSs based on the throughput that the MS is expected to experience if it were to switch. In this way each MS is always served by the BS that can provide it with the highest expected throughput. We provided illustrative examples that demonstrate why the proposed approach was better than the present procedure. Finally we described various options for disseminating the information that is required for the operation of the proposed procedure.

References


