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Transmission Timing - a Control Approach to Distributed Uplink Scheduling in WCDMA

David Törnqvist, Erik Geijer Lundin, Fredrik Gunnarsson, Fredrik Gustafsson
Div. of Control and Communication, Linköping University, SE-581 83 LINKÖPING, SWEDEN,
Email: {tornqvist,geijer,fred,fredrik}@isy.liu.se

***Abstract*— Centralized control and coordination of the connections in a wireless network is not possible in practice. To keep the delay from measurement instants to actuating the decisions, distributed control is required. This paper focuses on the uplink (from mobiles to base stations) and discusses distributing the decision of when and when not to transmit data (distributed scheduling) to the mobiles. The scheme, *uplink transmission timing*, utilizes mobile transmitter power control feedback from the base station receiver to determine whether the channel is favorable or not compared to the average channel condition. Thereby, the battery consumption and disturbing power to other connections are reduced. The algorithm can be described as a feedback control system. Some transient behaviors are analyzed using systems theory, and supported by wireless network simulations of a system with a WCDMA (Wideband Code Division Multiple Access) radio interface as in most 3G systems.**

I. INTRODUCTION

With limited availability of radio resources and an increasing interest in wireless data services, it is of utmost importance to utilize the resources efficiently in wireless networks. The performance could be much better if it would be possible to employ centralized coordination of the connections. However, this is not applicable, due to the required extensive signaling and the delays associated with centralizing the relevant information and distributing the decisions.

Recently, there has been a strong focus towards efficient downlink (from base stations to mobiles) radio resource utilization in 3G systems. The improvements significantly enhance both application and system performance. Much of the gain is due to time-sharing of base station radio resources among users and instead of all centralized resource control, some is distributed to the base stations. The uplink (from mobiles to base stations) situation is different, since resource coordination like time-sharing requires extensive signaling. The objectives with an enhanced uplink can therefore be flexible and efficient data transmission with minimal centralized coordination.

On the lowest uplink layer, the mobile sends a waveform according to selected coding and modulation over the established link to the base station(s). The channel quality is time-varying, and the link is best utilized by adapting coding and modulation to the channel state [15]. Several schemes are proposed to as tightly as possible meet the Shannon channel capacity, e.g., the water filling in [6]. However, in practice detailed information about the channel has to be fed back from the receiver to the transmitter, and this critically limits the performance [14]. An alternative is to update coding and modulation seldom, and to control the transmitter power to compensate for the varying channel [8] and to keep the received signal-to-noise ratio essentially constant, see Fig. 1. This strategy requires a very high power when the channel is infavorable, and limits the possible data rates that can be allocated to the user. It could thus be relevant to avoid transmitting data during bad channel states.

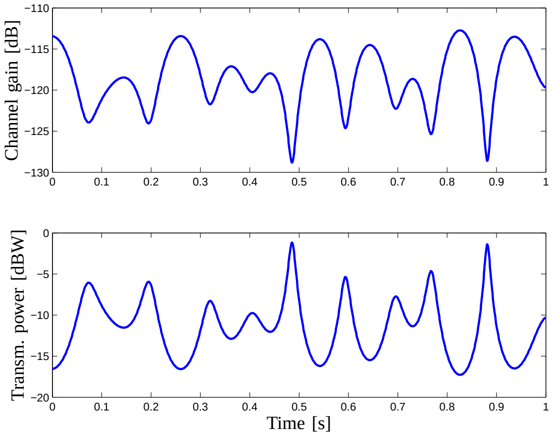

Fig. 1. Transmitter power control can be used to maintain the perceived quality despite a time-varying channel. The ideal power is essentially inverting (bottom) the channel gain (top).

In wireless networks, where the main source of disturbance originates from other connections, the situation is more delicate. Maximizing the resource utilization is not only a matter of optimizing the channel utilization of the individual links, but also to cater for the mutual interfering powers between connections. The individual transmitters need to compensate not only for the varying channel, but also the interference power. Consequently, the total received powers at the base station is related to the uplink load of the system [5], and whether it is possible to use power control to ensure an acceptable signal quality in the base station.

The interference can be managed by a detailed time-coordination of the uplink, but it requires a substantial overhead signaling. The benefit is a reduced risk of uplink overload, but increased signaling overhead and reduced possibilities to adapt to channel variations [4], [12], [17],

[18]. Alternative approaches are to coordinate transmissions only within each base station or to rely on pure statistical multiplexing, where the decision to transmit is distributed to the mobiles [10], [11], [13], [19]. Advantages of such schemes are that the mobile can quickly adapt to variations in traffic demand, reducing initial delays, and adapt to rapid variations in channel quality. However, no or limited network coordination means that there is a risk of uplink overload when more users than the network can support transmit simultaneously.

To address this problem, *uplink transmission timing (UTT)* is proposed in [9], which is a scheme for uplink data transmission over wireless channels. It uses power control information to distributedly determine whether it is favorable to transmit or not. Some centralized control is also supported to allow control over the uplink load. This paper describes UTT as distributed feedback systems, which are utilized when analyzing the UTT behavior in some situations.

Section II describes the notation, models and algorithms that are central in the paper. Uplink transmission timing is introduced in Section III-A to utilize differential channel state feedback in the form of power control commands and to aim at transmitting when the channel is favorable relative the channel situation over a longer time frame. Section IV provides illustrative and comparative simulations, and Section V some concluding remarks. Appendix cover WCDMA-specific aspects of Uplink Transmission Timing.

II. SYSTEM MODEL

A specific mobile uses the transmitter power $p(t)$ [dBW] to compensate for the time-varying power gain $g(t)$ [dB] and interference power $I(t)$ [dBW], which is due to disturbing power from other connections and thermal noise. The power control objective is to maintain the *signal-to-interference ratio (SIR)*

$$\gamma(t) = p(t) + g(t) - I(t)$$

at the connected base station receiver to support the allocated data rate of the connection. This is typically implemented as feedback control [7] with a specified reference, SIR target, $\gamma^t(t)$ as illustrated in Fig. 2 (with the sample interval T_{pc} and update instants k). This results in a power,

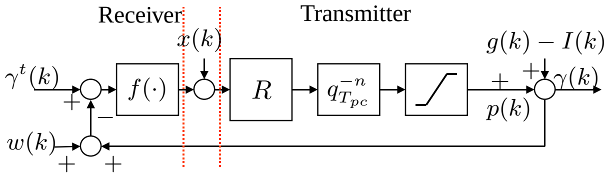

Fig. 2. Distributed power control. The receiver estimates SIR subject to noise $w(k)$ and compares to SIR target. The control error is coded $f(\cdot)$ and fed back (subject to control errors $x(k)$) to the transmitter, which uses the controller R to update the power. The performance is further limited by the sample interval T_{pc}, time delays and an output power saturation.

which can be separated into a slowly varying and a rapidly varying component

$$p(t) = p^{av}(t) + p^f(t)$$

In most wireless networks, e.g., WCDMA, the mobile always transmits control information such as information to the base station transmitter for downlink power control. The base station receiver also estimates the uplink SIR for this control information. Moreover, the mobile may transmit data in blocks with the sample interval T_s (*transmission time interval (TTI)* in WCDMA). Each time instant t, the mobile is thus either active $A(t) = 1$ or inactive $A(t) = 0$, where $A(t)$ is denoted the *activity* of the mobile.

III. DISTRIBUTED UPLINK SCHEDULING

A. Uplink Transmission Timing

When the uplink load increases, an alternative to disconnect users to maintain system stability is to use flexible services, which reduces the uplink activity on demand. One such approach could be to limit the time the mobiles transmit by assigning a fractional activity (*activity factor* A_f) to the mobiles, which transmits at *random* to meet this activity. The activity factor allows some slow centralized control of the uplink load. At time instant t, the mobile is therefore either active or inactive, such that $\mathrm{E}\{A(t)\} = A_f$. The uplink load contribution from the particular mobile is thus directly related to the activity factor. However, there is no correlation between transmission instants and when the channel is favorable. As discussed previously, it is highly interesting to avoid transmitting data during bad channel states.

The main idea behind *uplink transmission timing (UTT)* [9] is to transmit data discontinuously to meet an assigned activity factor, but to utilize information about the transmission power to select the transmission instants carefully to avoid transmitting data when a high power is required. A plausible solution could be to only transmit data when the power level is less than a threshold h.

The fast transmission power gain variations, are typically independent between different mobiles. Therefore, data transmission decisions based on power level thresholding gives good statistical multiplexing properties. If the average power $p^{av}(t)$ would be constant, and the rapidly varying power $p^f(t)$ stationary, there is a direct link between the threshold, the activity factor A_f and the cumulative distribution function (CDF) of the rapidly varying power. The threshold h is implicitly given by

$$A_f(h - p^{av}) = \mathrm{CDF}(p^f) = \mathrm{P}(p^f < (h - p^{av})). \qquad (1)$$

In practice, the average power is not constant, and the varying power not stationary, partly due to a varying velocity.

Essentially, uplink transmission timing estimates the current activity $A_f^{est}(t)$ using recent transmission history $A(\tau), \tau \leq t$ and adjusts the threshold h so that $A_f^{est}(t) \approx A_f$. Algorithm 1 provides the detailed steps. The mobile either *fully transmit* both control information and data or *not fully transmit*, meaning that only control information is transmitted.

Algorithm 1 (Uplink Transmission Timing [9])

i) Monitor the transmission power $p(t)$.

ii) Fully transmit during time instant t if the transmission power $p(t)$ is lower than a threshold $h(t)$. The activity $A(t) = 1$ if fully transmitting during time instant t, and 0 if not fully transmitting.

iii) Estimate the current activity $A_f^{est}(t)$ using recent transmission history $A(\tau), \tau \leq t$.

$$A_f^{est}(t) = e^{rT_s} A_f^{est}(t-1) + (1 - e^{rT_s})A(t)$$

iv) Adapt the threshold $h(t)$ if the current activity estimate $A_f^{est}(t)$ is different from the desired activity A_f

$$h(t+1) = h(t) + \frac{T_s}{T_i}(A_f - A_f^{est}(t)).$$

The algorithm parameters are the integration time T_i and the continuous time filter pole r, and the parameters A_f and T_s are provided by the system and subject to changes.

B. UTT as Feedback Control

Uplink transmission timing in Algorithm 1 can be seen as a feedback system for threshold control and transmission decision. The block diagram in Fig. 3 describes the dynamics of UTT.

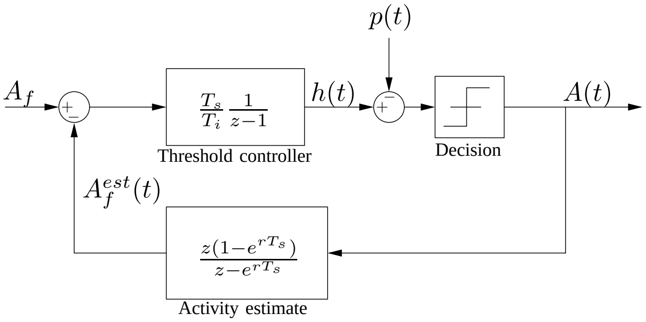

Fig. 3. Block diagram describing the dynamics of uplink transmission timing.

C. Corner-Effect Analysis

Since the same frequency spectrum is used by all connections, it is important to limit the interference to base stations other than the connected base station. Therefore, connections are handed over from one base station to another when the mobiles move in the service area. This *handover* takes some time due to network processing, and meanwhile, the mobile may create critical interference to the base station it approaches. The corner-effect is most critical, when the mobile suddenly experiences much worse link to the connected base station and much better propagation conditions to another base station - an intuitive scenario is when moving around a corner. However, UTT will handle the situation as analyzed below.

The power gain drop at $t = 0$ causes a corresponding power increase. This means that UTT will not fully transmit, and the activity becomes zero. Assume that $A_f^{est}(0) = A_f$, and that $A(0) = 1$. Then the block diagram in Fig. 3 can be rewritten as in Fig. 4 while the power is above the threshold $h(t)$.

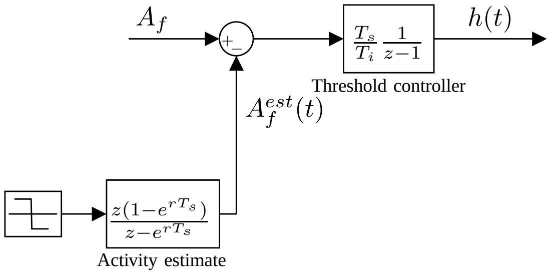

Fig. 4. Control loop in case of a rapid change in channel gain.

The dynamical relations are now all linear, and we get the Z-transforms of $A_f^{est}(t)$ and $h(t)$ respectively, as

$$A_f^{est}(z) = A_f \frac{e^{rT_s} z}{z - e^{rT_s}}$$
$$h(z) = \frac{T_s}{T_i}\frac{z}{z-1}\left(A_f \frac{z}{z-1} - A_f^{est}(z)\right)$$

Hence, the time domain threshold and activity estimate expressions are

$$A_f^{est}(t) = A_f e^{rT_s(t+1)} u(t) \tag{2}$$
$$h(t) = \frac{A_f T_s}{T_i}\left(tu(t) - \frac{e^{rT_s}}{1 - e^{rT_s}}\left(u(t) - e^{rT_s t}u(t)\right)\right) + h_0 \tag{3}$$

where $u(t)$ is the unit step, and h_0 the threshold value at $t = 0$. Fig. 5 illustrates the threshold (relative h_0) and activity estimate evolutions for the specific case $A_f = 0.5$, $T_i = 8.3 \cdot 10^{-3}$ and $r = -9$. For example, when the gain

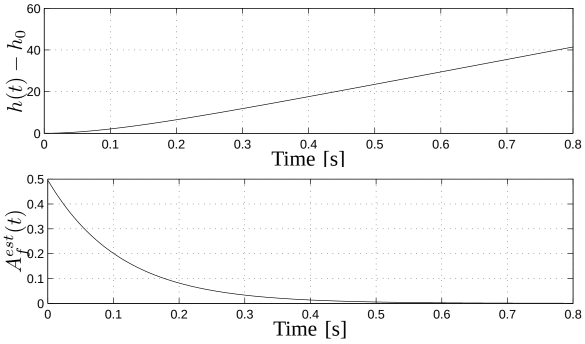

Fig. 5. Threshold (relative h_0) and estimated activity during rapid increase of the transmitter power.

abruptly drops 20 dB (the power increases by 20 dB), UTT will not fully transmit for slightly more than 0.4 s. Thereby, the network will most likely have time to complete the critical handover. Note that control signaling (for example to perform the handover) is still transmitted during this time.

IV. SIMULATIONS

Naturally, the behavior and adaptability of UTT depend on the parameters T_i and r. However, extensive simulations to analyze the required transmitter power indicate that the dependency is not critical. However, a sufficiently negative continuous time pole s is needed to obtain adequate activity averaging, and the parameters $r = -9$ and $T_i = 8.3 \cdot 10^{-3}$ are used in the simulations.

The simulations illustrate the behavior of UTT. Further evaluating simulations are provided in [9].

A. Simulation Environment

The simulated scenarios are sector cell WCDMA wireless networks. Only path loss (exponent $\alpha = 3.5$) and fast fading (ITU Pedestrian A and 3GPP Typical Urban) are included in the power gain model, since low to moderate velocities are considered, and the slow variation such as shadow fading are then fully compensated for by power control. The focus is primarily on the comparative behavior of UTT and not on the resulting capacity differences. Radio bearers for 64 kbps are parameterized according to the test configurations in [3], and 128 kbps are realized based on the former, but with appropriate power offset adjustments.

B. Illustrative Example

Fig. 6 illustrates the behavior of UTT. Clearly, bad channel states are avoided to a great extent. The activity A_f^{est} is estimated by lowpass filtering the activity $A(t)$ and used to adjust the threshold $h(t)$. Note the oscillatory behavior of the activity.

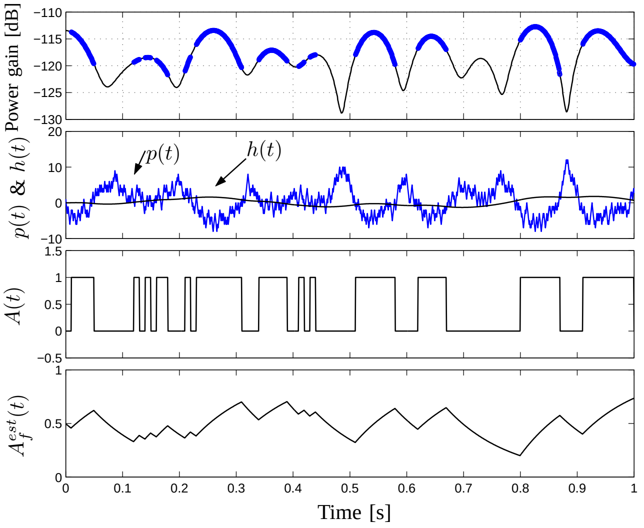

Fig. 6. Uplink transmission timing example. The power gain plot indicates datatransmission with thicker sections.

C. Corner Effects

The critical problems with corner-effects were addressed in Section III-C. As shown, UTT will reduce the interference in such a scenario. This is simulated for an abrupt power gain change of 20 dB, and Fig. 7 illustrates that the simulated behavior is in accordance with the theory in Section III-C. The transmitter does not fully transmit until after 0.4 s.

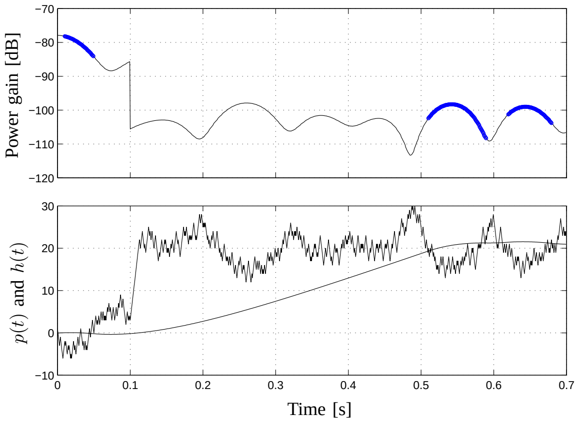

Fig. 7. UTT and an abrupt change in channel gain by 20 dB. Top: Power gain (thick sections indicate the time instants when fully transmitting). Bottom: Uplink power $p(t)$ and threshold $h(t)$.

D. Abrupt Change in System Load

The graceful degradation seen above for the drastic power gain change is also obtained at an abrupt change in system load. Consider a case with 21 cells, 8 users/cell with 128 kbps, $A_f = 0.5$. At 5 s, another 4 identical users/cell but with $A_f = 1$ are admitted to the network. As seen in Fig. 8, the abrupt interference increase causes essentially all initial connections to back off to give room for the newly admitted mobiles. This gives the RNC more time to employ appropriate resource management to handle the situation.

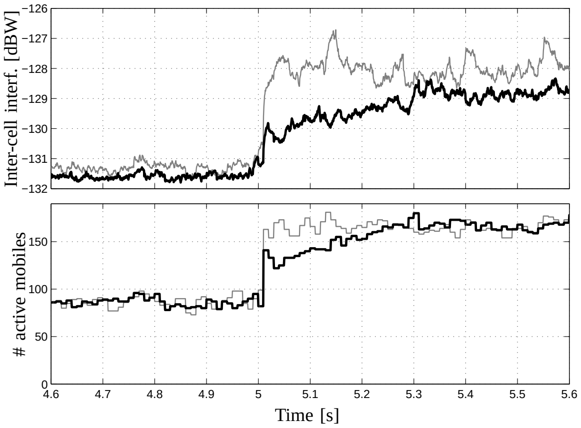

Fig. 8. Simulation of an abrupt change in load.

V. CONCLUSIONS

Schemes for full coordination of the WCDMA uplink suffers from extensive signaling, whereas no coordination means a risk of causing system overload. A simple distributed solution with minimal centralized control is random transmission decisions to meet an activity factor provided by the network. Uplink transmission timing (UTT) is proposed to aim at a provided activity factor, while carefully selecting transmission instants to transmit when the channel is favorable. The scheme is associated with a feedback control system, and the specific scenario of abruptly changing propagation conditions or interference levels is studied, both in theory and in simulations. It is concluded that UTT has the property of discontinuing the transmission, which facilitates handover without critical interference problems when the channel gain is changing abruptly. Moreover, a system with services based on UTT, degrades more gracefully, when the system load increases dramatically.

ACKNOWLEDGMENT

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APPENDIX
DEDICATED CHANNELS IN WCDMA

One possible realization of a data service in WCDMA is over a dedicated radio bearer [2], [3], with transmitter power control to mitigate fast channel variations.

A. Dedicated Channels

The focus here is on services, which are allocated resources dedicated to a specific mobile. Fig. 9 illustrates how dedicated channels are realized in WCDMA.

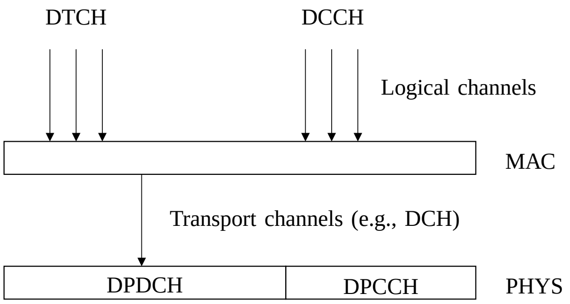

Fig. 9. The logical channels DTCH (data) and DCCH (control) are mapped onto the transport channel DCH.

There are two types of dedicated physical channels in WCDMA – *Dedicated Physical Data Channel (DPDCH)* and *Dedicated Physical Control Channel (DPCCH)*. The former carries data and control information from higher layers, whereas the latter carries physical control information and is therefore always transmitted. In the uplink these two physical channels are I/Q multiplexed (i.e., phase-shifted 90 degrees) and transmitted in parallel (as opposed to the downlink with time-multiplexed dedicated physical channels). The physical layer (PHYS) offers information transfer services to higher layers, and the *transport channel* dedicated to a specific mobile is the *Dedicated Channel (DCH)*. The medium access control (MAC) layer provides data transfer services on *logical channels* for control information (e.g., *Dedicated Control Channel, DCCH*) and user data (e.g., *Dedicated Traffic Channel, DTCH*). Both DCCH and DTCH can be mapped onto DCH.

A specific service is thus realized as one or several traffic channels (DTCH's) and supported by one or several control channels (DCCH's). In a multi-service situation (for example speech and web-browsing), some DTCH's transfer the delay-sensitive services, while others transfer services less sensitive to delays.

The data units (data blocks) transferred over the dedicated transport channels occupy at most the *transmission time interval (TTI)*, which is 10, 20, 40 or 80 ms in WCDMA (and 2 ms in evolved WCDMA for high data rates in the downlink) These are either received correctly or erroneously (block errors). For further information on dedicated channels, see for example [2] and references. During TTI's when there are no data units to transmit over the DTCH's and DCCH's, there is no need to transmit over DPDCH at all. This is referred to as *discontinuous transmission, DTX*. This is similar to UTT, but in the latter data transmission is not avoided due to lack of data, but due to a bad channel state. Furthermore, not all data transport can be discontinued. The delay-sensitive control and data on DCCH's and DTCH's should not be discontinued. This means that for Algorithm, 1, *fully transmit* is equivalent to transmitting all channels including less delay-sensitive information, whereas *not fully transmit* means that only delay-sensitive control information and data are transmitted.

B. Wireless Networks and Power Control

Some quantities will be expressed both in linear and logarithmic scale (dB). Linear scale is indicated by the bar notation $\bar{g}(t)$. With a simple model, the communication channel can be seen as a time varying power gain $\bar{g}(t)$. It is instructive to separate the power gain into a slowly varying $\bar{g}^{av}(t)$ and a rapidly varying component $\bar{g}^{f}(t)$ such that $\bar{g}(t) = \bar{g}^{av}(t)\bar{g}^{f}(t)$ [16]. The power gain from mobile $i,\ i = 1, \ldots, M$ to base station $j,\ j = 1, \ldots, B$ is denoted $\bar{g}_{ij}(t)$. If the transmitter power of mobile i is $\bar{p}_i(t)$ and the connected base station j_i is interfered from other connections and thermal noise by the power $\bar{I}_i(t)$, the *signal-to-interference ratio (SIR)* at the receiver is given by

$$\bar{\gamma}_i(t) = \frac{\bar{p}_i(t)\bar{g}_{ij_i}(t)}{\bar{I}_i(t)} = \frac{\bar{g}_{ij_i}(t)\bar{p}_i(t)}{\sum_{k\neq i} \bar{g}_{ij_k}(t)\bar{p}_k(t) + \bar{\nu}_i(t)}, \tag{4}$$

where $\bar{\nu}_i(t)$ is thermal noise at receiver. In logarithmic scale, the SIR expression becomes

$$\gamma_i(t) = p_i(t) + g_{ij_i}(t) - I_i(t). \tag{5}$$

In the uplink, the connections are separated by code-correlation. This only works if all connections are received with a SIR, that is motivated by the associated data rate. Therefore, power control is an important means to prevent mobiles close to the base station to be received with much better SIR than more distant mobiles. The QoS requirements can approximately be associated to a desired *block error rate, BLER*, which in turn can be related to a required target SIR level, $\bar{\gamma}_i^t(t)$. To ensure that the desired BLER is met, target SIR is regularly re-assigned based on block error statistics. This is referred to as *outer loop power control*. The distributed power control algorithms are based on local feedback information, typically to meet SIR, $\bar{\gamma}_i(t) \approx \bar{\gamma}_i^t(t)$, despite time-varying channels. The *inner loop power control* [1] operates at 1500 Hz and is faster than the outer loop. The power level is increased/decreased depending whether the measured SIR is below or above target SIR, and implemented as:

$$\begin{aligned} \text{Receiver}: \quad & e_i(t) = \gamma_i^t(t) - \gamma_i(t) && \text{(6a)} \\ & s_i(t) = \text{sign}\,(e_i(t)) && \text{(6b)} \\ \text{Transmitter}: \quad & p_{TPC,i}(t) = \Delta_i s_i(t) && \text{(6c)} \\ & p_i(t+1) = p_i(t) + p_{TPC,i}(t) && \text{(6d)} \end{aligned}$$

where Δ_i is the step size. The base station feeds back the power control commands $s_i(t)$ to the mobile using the downlink DPCCH. Then, the mobile updates the transmitter power $p_i(t)$ based on the demodulated and decoded power control commands. This scheme gives acceptable SIR provided that the channel variations are not too fast, and that the system is not overloaded [7]. In WCDMA, inner loop power control is applied to DPCCH, which is continuously transmitted. The DPDCH power is obtained as

$$p_{DPDCH} = \beta \cdot p_{DPCCH}, \tag{7}$$

where β is a configurable *power offset* which depend on the amount of data transmitted over DPDCH [1]. This means that UTT should monitor and utilize p_{DPCCH} in Algorithm 1 for the transmission decisions.

If power control is perfect ($\gamma_i(t) = \gamma_i^t(t)$), the mobile transmission power is given by (5)

$$p_i(t) = \underbrace{\left(\gamma_i^t(t) + I_i(t) - g_{ij_i}^{av}(t)\right)}_{p_i^{av}(t)} + \underbrace{\left(-g_{ij_i}^f(t)\right)}_{p_i^f(t)}, \tag{8}$$

where the notation of local average power $p_i^{av}(t)$ (slowly varying) and rapidly varying power $p_i^f(t)$ is intuitive if assuming that the power variations are mainly due to power gain variations. The fast variations are characterized by deep fades, meaning that temporary high power levels are needed to fully compensate for such fades.

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