System-Level Performance of Space-Time Scheduling for Non Real-Time Traffic in a 3G Network †

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***Abstract*—The implementation of third generation (3G) cellular networks in dense urban areas calls for more efficient use of radio resources. As network planning approaches unit frequency reuse, same cell reuse strategies arise as natural choices. One such strategy is spatial division multiple access (SDMA), which adds a new dimension to resource allocation in packet data networks. In this paper, we evaluate how SDMA together with channel allocation and space-time scheduling impact the performance of the packet data service of the GSM/EDGE Radio Access Network (GERAN).**

Keywords— space-time scheduling; SDMA; GERAN; EGPRS

I. INTRODUCTION

As mobile communications move into the third generation (3G), it is expected that mobile phone users surpass the one billion mark and packet-based multimedia services dominate wireless traffic, which will continue to push the ever increasing demand for capacity and bandwidth.

The Universal Mobile Telecommunications System (UMTS), one of the leading 3G standards, has been designed to work on both existing 2G and new 3G spectra. Packet-based 3G services may be provided in existing spectrum using the packet-switched service of the GSM/EDGE Radio Access Network (GERAN), called EGPRS.

There are several ways of increasing the capacity of a bandwidth constrained cellular system. Cell splitting is a common method. It achieves capacity improvement by rescaling the system and introducing smaller cells, called microcells. Macrocellular environments, characterized by medium to high-speed mobiles (50km/h and above), suffer from this approach due to the increased number of handovers required. Moreover, there are also the burdens of financing new cell site installations.

A better method for enhancing system capacity is increasing the reuse of the available bandwidth after taking the appropriate measures for reducing the interference levels. Interference reduction may be achieved through cell sectorization or, more efficiently, through the use of adaptive base station antennas. Adaptive antennas (AA) are a particular type of smart antenna technology which employ beam-forming algorithms in order to steer a narrow beam towards a desired apparent user position (a user's apparent position may not coincide with his actual location because of wave propagation effects).

Unlike circuit-switched systems, packet-switched systems are not limited by the number of available channels, but by the requirements of the users' quality of service (QoS) profiles. Therefore, packet data users may be able to share the available radio resources as long as their QoS constraints are respected. Channel sharing increases spectrum efficiency at the cost of higher queuing delays. In other words, in packet data systems, the ultimate capacity limitations are transmission and queuing delays.

Effective transmission delay, which accounts for any retransmissions requested by an ARQ (automatic repeat request) protocol, depends directly on the signal quality of the radio link. In a system which does not employ power control, the signal quality is a direct result of the interference distribution profile, which depends on several variables, including frequency plan, system load, and traffic nature, among others. EDGE's efficient link quality control (LQC) scheme is able to achieve optimum data transfer rates for a large range of radio link quality, thus guaranteeing the lowest achievable transmission delay in any interference scenario. Nonetheless, if the interference profile is too aggressive (e.g. in a tight reuse plan without interference counter-measures), the transmission delays may be high and there may not be much room left in the users' total delay requirement to account for additional queuing delays. Thus, it may not be feasible to push the system load any further.

A simple method for increasing the capacity of a packet data system which has reached the threshold of the delay requirements of its users is by parallel transmissions. Simultaneous access to the radio resources allows for higher offered loads without affecting queuing delays, i.e., without increasing channel queue lengths. Parallel transmission in the same radio channel means reusing channels in the same site. This is known as same cell reuse or SCR. There are different approaches to SCR. One of them is known as the channel allocation tiering (CHAT) concept [1]. Another approach is spatial division multiple access or SDMA.

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SDMA explores the spatial filtering advantages of adaptive antennas together with the diversity of user location within a site, allowing spatially separated users to transmit or receive data simultaneously. This adds a whole new dimension to packet scheduling, which then receives the denomination space-time scheduling or simply ST-scheduling. Recent works concerning SDMA include [2-6].

In this paper, we evaluate how SDMA together with channel allocation and ST-scheduling strategies impact the performance of GERAN networks. The paper is further organized as follows. Section 2 describes the effective adaptive antenna radiation pattern. Section 3 presents considerations on SDMA and radio resource allocation. Section 4 describes the simulation environment which was used to draw the results presented and commented in section 5. Finally, conclusions follow in section 6.

II. Effective Adaptive Antenna Radiation Pattern

System-level performance evaluation of cellular systems requires a great deal of computational power in order to account for the most relevant characteristics of the actual communication scenario, such as propagation effects, user mobility, traffic generation, and resource management. Simplified models are commonly adopted to reduce simulation times, even though they may sometimes require large amounts of computer memory. Particularly, the adaptive antenna model is of major concern in system-level simulations because its spatial filtering characteristics deeply impact overall system performance.

In the past, we have used a simple “brick wall” model for the adaptive antenna system [7]. While this model is functional enough to support preliminary investigation involving adaptive antennas, it does not approximate a beam-forming antenna radiation pattern very well. One may use instead a fixed radiation pattern corresponding to the broadside of an antenna array using a beam-forming algorithm. This approach has been used in [4] for an 8-element uniform linear array (ULA), which is recommended for most GSM network layouts with sectorized cell configurations. Its limitations include the fact that it does not model the performance loss of the ULA according to the azimuth direction of the desired mobile and unrealistic interference rejection, particularly around the antenna pattern’s nulls, when even a modest azimuth spread (AS) is considered (e.g., an AS of 5º completely fills the antenna nulls).

In [8], a model has been described which includes both the azimuth dependency of the ULA and the AS effect over the adaptive antenna pattern. This model is simple and applies well for both urban and rural areas. It is based on a simple azimuth characterization of the multipath radio channel and it results in an effective radiation pattern of a narrow beam antenna taking the power azimuth spectrum (PAS) into account. Next, we define PAS and AS, and explain how the effective radiation pattern is obtained.

The PAS is defined in terms of the two-dimensional complex channel impulse response $h(\tau,\theta)$, where τ is the delay, and θ is the azimuth:

$$P(\theta) = \left\langle \int \left| h(\tau,\theta) \right|^2 d\tau \right\rangle \quad for\ \theta = \left] -\pi,\ \pi \right] \tag{1}$$

where $\langle\cdot\rangle$ denotes local average over short term fading.

The AS is defined as the standard deviation of the PAS. The PAS seen by a macrocellular base station antenna has been found to be accurately modeled by a Laplacian function for most measured routes, although there exist special cases where the shape is very different [8]:

$$p(\theta) = \frac{k}{\sqrt{2}\sigma_\theta} \exp\left(-\sqrt{2} \frac{|\theta - \mu_\theta|}{\sigma_\theta} \right) \tag{2}$$

where σ_θ is the AS, μ_θ is the mean azimuth direction, and k is a scaling factor equal to one for unit received power.

It should be noted that the AS is a stochastic quantity strongly correlated with the shadow fading component [8]. However, for practical reasons we have considered it to be constant throughout the simulations.

The adaptive antenna system consists of an M-element ULA using conventional beam-forming. Therefore, the complex response of the antenna array, with a steering direction θ_0 and a point source in the direction θ, is given by

$$Y(\theta,\theta_0) = \sum_{i=1}^{M} A_i \cdot w_i(\theta) \cdot w_i^*(\theta_0) \tag{3}$$

where $w_i(\theta)$ are the complex weights of the antenna array and A_i is an amplitude weight.

The amplitude weights A_i may be selected from a non-uniform window function in order to suppress the side lobe level at the expense of a broader main lobe and reduced gain [8]. In this work, a Kaiser window has been used with the weights given by

$$A_i = \frac{I_0\left(\alpha \cdot \sqrt{1 - \left(\frac{i}{N} \right)^2} \right)}{I_0(\alpha)} \tag{4}$$

where the value α controls the shape of the Kaiser window.

Consider now a mobile user whose apparent location is at an azimuth direction θ_I. The corresponding PAS is a function like (2) with mean azimuth direction θ_I. The received average power, when steering the beam towards θ_0 is given by

$$P(\theta_1,\theta_0) = \int \left| Y(\theta,\theta_0) \right|^2 \cdot p(\theta - \theta_1) d\theta \tag{5}$$

Note that (5) is a measure of received average power at the base station when the mobile is transmitting, i.e., in the uplink. If we consider the propagation effects in the downlink reciprocal to the uplink case, we may also use (5) to denote

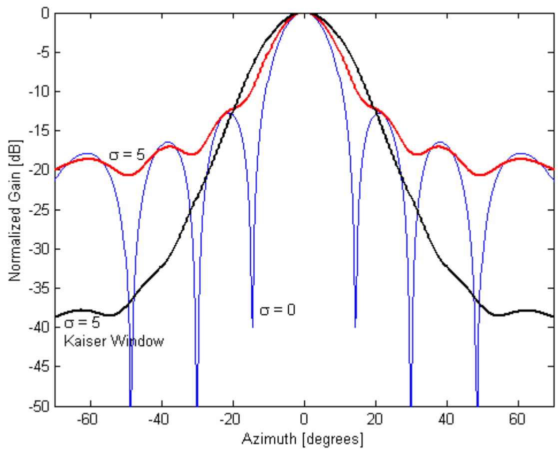

Fig.1 – Normalized effective radiation pattern of an 8-element ULA for a steering direction θ of 0º AS of 0º and 5º and with or without a Kaiser window function

transmitted average power as a function of the steering direction θ_0 and mobile user direction θ_1. The effective antenna radiation pattern for a given steering direction θ_0 may then be obtained by simply calculating the transmitted average power for several mobile user directions θ_1.

Fig. 1 shows the normalized effective adaptive antenna radiation pattern of an 8-element ULA for a steering direction θ_0 of 0^o, AS of 0º and 5º and with or without the use of the Kaiser window for side lobe level suppression. Note how the nulls fill up for an AS of 5º and how using a Kaiser window significantly reduces the side lobe level.

Finally, we must state that the above procedure was used to obtain a matrix of effective antenna gain indexed by the steering direction θ_0 and the mean mobile user direction θ_1 with an azimuth resolution of 1º, which resulted in a good compromise between precision and performance.

III. SDMA and Radio Resource Allocation

Multibeam packet-switched SDMA operation is highly dependent on the adopted radio resource allocation scheme. Before describing the SDMA strategies proposed in this work, we must present the concept of spatial compatibility testing. A user compatibility test is usually performed when forming groups of users that satisfy a common quality requirement. In our simulations, the compatibility test consists of a simple azimuth separation test, i.e., users are said to be compatible if they mutually guarantee a minimum angular distance. Fig. 1 shows that a minimum separation of 20^o guarantees an intra-cell interference level of at least 13dB below the user's signal level.

The SDMA strategies consist of the following functions:

- Channel allocation (CA), which designates a channel for users entering data transfer mode. CA may include a compatibility test to ensure that SDMA users will not mutually cause high levels of interference if scheduled for simultaneous transmission;
- ST-scheduling, which consists of
  - o Time-domain (TD) scheduling: sorts the channel queue according to some temporal criterion (e.g. first in first served);
  - o Compatibility test: draws spatially compatible groups of users from the sorted channel queue for immediate transmission.

Fig. 2 illustrates the possible states in which a mobile user may be found and the associated state transitions. A user is inactive when no data session has been established. In the downlink, as soon as the mobile acknowledges the paging procedure for session establishment, it enters active state, but has not yet an assigned channel. The network then establishes a temporary block flow (TBF), a means for transferring logical data units in one link direction, which requires a channel assignment performed by the CA function.

Two CA algorithms have been tested:

- Distributed channel load (DCL), which assigns the user to the channel with the lowest load measured in Kbit;
- Concentrated channel load (CCL), which attempts to fill channel queues up to a limited number of users before assigning new channels.

For best performance of the CCL algorithm, the channel assignment sequence is not chosen at random. Instead, each base station possesses a channel assignment plan, which minimizes the chances of interfering with major co-channel cells (note that sectorization plays an important role in defining this plan). In low offered load situations, the concentrated approach should limit channel queue lengths to a size M the ST-scheduler can handle optimally, i.e., simultaneously transmitting the whole queue. Naturally, this requires compatibility among all users allocated to the same channel. For this reason, unlike in the DCL algorithm, compatibility testing is mandatory in the CCL algorithm. Nevertheless, because of user mobility, spatially compatible users may eventually become incompatible.

Once a TBF is created, the mobile enters a channel queue managed by the ST-scheduling function. In a dynamic resource allocation scheme, the scheduling function is performed every period of four GSM frames, which corresponds to a GSM radio block period. This block period is

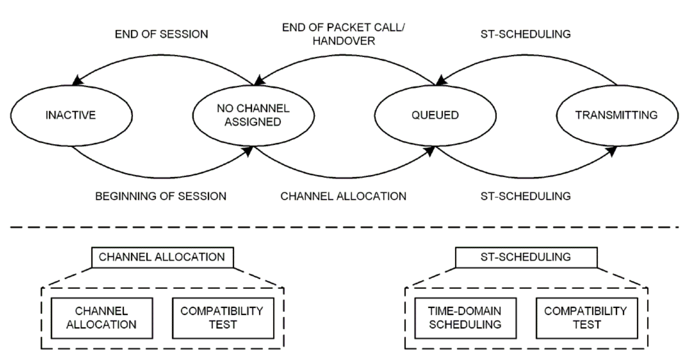

Fig. 2 – Mobile user state diagram and SDMA strategy functions

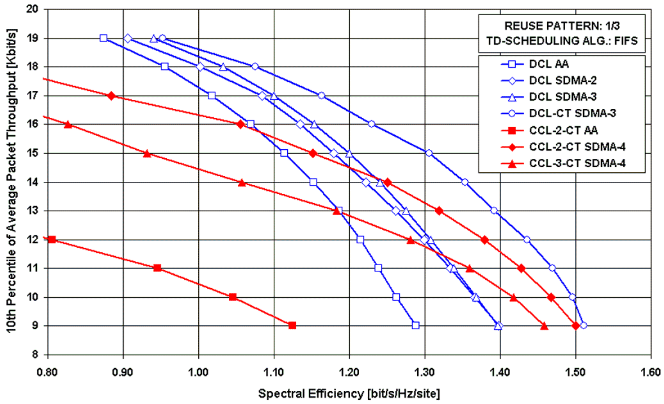

Fig. 3 – QoS level *versus* spectral efficiency for AA and SDMA in 1/3 reuse with the DCL and CCL algorithms and FIFS TD-scheduling

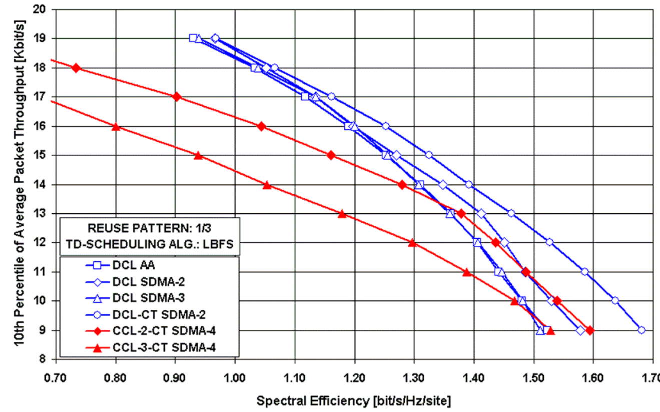

Fig. 4 – QoS level *versus* spectral efficiency for AA and SDMA in 1/3 reuse with the DCL and CCL algorithms and LBFS TD-scheduling

usually modeled as 20ms to account for the effect of idle frames in the logical structure of the packet data channel. The time-domain scheduler may sort the channel queue following either a First In First Served (FIFS) or a Least Bits left First Served (LBFS) algorithm.

The ST-scheduler then tries to form spatially compatible groups of users from the time-domain sorted channel queues using a low complexity search algorithm. The ST-scheduler is configured to simultaneously schedule a maximum of N users for transmission and the search algorithm simply forms the largest possible group of compatible users by drawing them from the sorted channel queue in their order of occurrence and testing them for spatial compatibility. Notice that while the compatibility test function may be optional in the channel allocation function, it is mandatory in the ST-scheduler.

A web browsing session is composed of several packet calls. Each packet call may be thought of as a web page. After receiving a web page, the user reads it and may then request another one or end the session. In our work, after complete delivery of a packet call, radio resources are released and so is the TBF. If another packet call should arrive, a new TBF is established and a new channel assignment is performed. When the session ends, the user returns to the inactive state. We must stress that control signaling has not been modeled herein.

IV. Simulation Environment

Performance evaluation of SDMA in EGPRS has been done using a dynamic discrete-time system-level simulation tool called EdgeSim [7]. The program simulates downlink data communication (no control signaling), which is expected to be the limiting communication direction due to restricted signal-processing capability in the mobile station side (constrained by size and power consumption) and the expected amount of asymmetrical data traffic.

A macrocellular environment was considered [9]. We have used link-level results (block error rate *versus* signal-to-interference ratio tables) of a TU50 scenario without frequency hopping from [10]. Simulations did not include power control. Perfect knowledge of the signal quality was assumed and link quality control was considered in pure link adaptation mode (no incremental redundancy). Following the procedure described in section 2, we have modeled an adaptive antenna system consisting of eight 90° sector antenna elements and assuming an azimuth spread of 5°. The SDMA strategies were as described in section 3. SDMA operation was tested for a single packet data service, 8Kbps web browsing. For a more complete description of the simulator and other specific parameters, refer to [6].

V. Results

Fig. 3 presents a comparison between both CA strategies for the 1/3 reuse pattern considering the FIFS TD-scheduling algorithm. Using the DCL algorithm without the compatibility test, the introduction of SDMA with N simultaneous users (SDMA-N) in a pure spatial filtering scenario (AA) produces a capacity gain of approximately 9% at the 10Kbps QoS level or a QoS gain of 35%. When the CA's compatibility test (CT) is activated, the SDMA algorithm achieves a better performance, this time with a capacity gain of 19% and a QoS gain of 56% over the AA scenario. The CCL algorithm with channel queue lengths equal to 2 (CCL-2) or 3 (CCL-3) had worse performance than DCL for both the AA and the SDMA scenarios.

In Fig. 4 the same comparison is done, but this time adopting the LBFS TD-scheduling algorithm. The impact of SDMA is not so pronounced in this situation, reaching a capacity gain of merely 5%, even when the CA's compatibility test is employed. Once again the concentrated channel load scheme proved to be inferior to the distributed one.

A comparison between both TD-scheduling algorithms is shown in Fig. 5. The LBFS scheme presented the best performance for all considered CA strategies. Note that LBFS introduction in both systems employing SDMA provides lower gains than those achieved in the AA system (compare the curves with the same markers). The SDMA system configuration with DCL-CT and LBFS achieved a capacity gain of 23% over the scenario without SDMA using FIFS.

The performance of different reuse patterns is presented in Fig. 6. As previously demonstrated in [7], the tighter the reuse pattern, the more spectral efficient the system becomes when adaptive antennas are employed. The 1/1 reuse pattern achieved a huge capacity leap compared to the other systems,

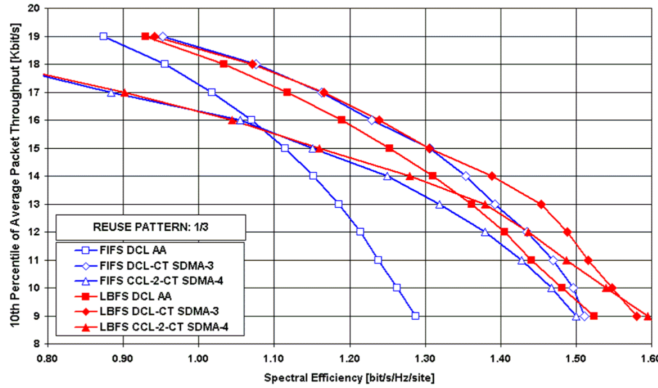

Fig. 5 – Performance comparison of SDMA strategies using FIFS and LBFS TD-scheduling in 1/3 reuse

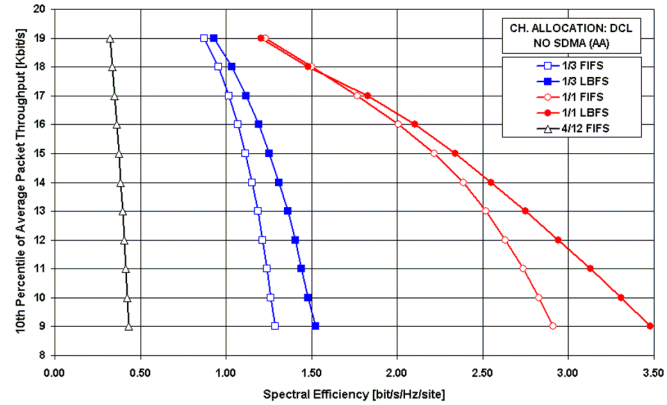

Fig. 6 – Performance of 1/3 and 1/1 frequency reuses with the AA system using FIFS and LBFS (4/12 FIFS is a reference scenario)

reaching spectral efficiencies of up to 3.31 bit/s/Hz/site. The adaptive antenna model considered in this work played an essential role in producing such optimistic results for the 1/1 reuse pattern, since it models the beam-forming network more accurately than the “brick wall” model used in [7].

The capacity gains that SDMA provided when considering the 1/3 reuse pattern were not perceived in the 1/1 reuse pattern, as it can be seen in Fig. 7. Instead of improving capacity, SDMA had a performance worse than the case with only adaptive antennas, even when the CA’s compatibility test was activated (a capacity reduction of 33%). In such a tight reuse pattern the generation of another beam within the sector increases the inter-cell interference considerably, although SDMA attempts to reduce queuing delays, causing the system to lose plenty of the performance gained from spatial filtering.

VI. Conclusions

This work has evaluated the performance of SDMA with the packet data service of GERAN. SDMA was implemented exploring the spatial filtering property of an adaptive antenna system using traditional beam-forming and the impact of its introduction was evaluated with diverse combinations of channel allocation and time-domain scheduling algorithms in 1/1 and 1/3 frequency reuse scenarios.

We have demonstrated that SDMA introduction in a system previously equipped with adaptive antennas may or may not result in performance improvement, depending on the trade-off between the reduction of queuing delays provided by simultaneous transmission of SDMA users and the increase of transmission delays due to the reduced spatial filtering gains when multiple antenna beams are generated. For instance, in 1/3 reuse SDMA provides gains of up to 19% in capacity over the corresponding AA system. In contrast, 1/1 reuse perceives at least a 33% reduction in capacity.

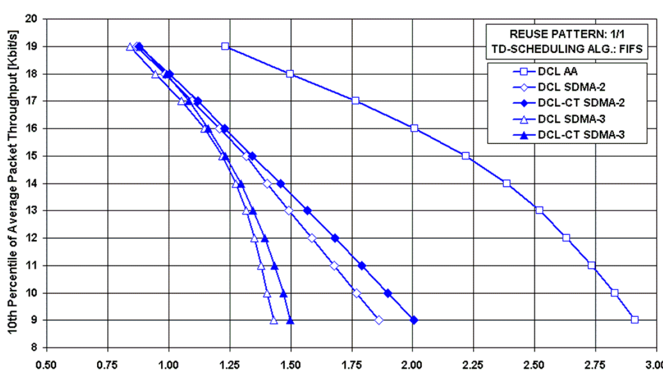

Fig. 7 – Impact of SDMA strategies in 1/1 reuse with DCL and FIFS

Finally, although SDMA provides reasonable capacity gains in a 1/3 reuse, it is still more advantageous to increase the frequency reuse to 1/1 rather than to settle for the SDMA upgrade. In fact, 1/1 reuse with adaptive antennas achieves a spectral efficiency of 3.31 bps/Hz/site whereas 1/3 using SDMA provides only 1.55 bps/Hz/site.

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