FREQUENCY REUSE AND CODING FOR GPRS MULTI-SLOT OPERATION

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Abstract

Due to the growing interest in mobile data applications, the Global System for Mobile communications (GSM) has been extended by the General Packet Radio Service (GPRS). It allows the transmission of packet data at moderate bit rates using random access channels within the existing GSM infrastructure.

This paper analyses the impact of using multiple channels in a GSM system for GPRS packet transmission. Different combinations of frequency reuse and channel coding are evaluated for 1, 4 and 8 Packet Data Channels (PDCCHs) per cell.

A tight frequency reuse of 1, together with a strong error coding scheme was found to provide the highest capacity. The increased trunking efficiency for a system with 8 PDCCHs yields a capacity gain of about 64% over a system with only 1 channel.

The results indicate that mixing circuit and packet switched traffic causes inefficient use of system resources. Since GSM voice services usually require a frequency reuse of 3 or 7, a separate overlaying network for GPRS provides better resource utilization and maximizes the number of users fulfilling the specified Quality of Service (QoS) requirements.

1. Introduction

GPRS [1] provides the necessary functionality to handle packet data in GSM networks. Mobile terminals such as notebooks, personal digital assistants (PDAs), mobile phones and pagers can gain access to a wide range of new mobile data services. Many applications use the TCP/IP protocol architecture.

When GSM operators start to offer GPRS services, they can use their existing networks and gradually assign part of their resources from circuit-switched voice services to packet-switched data services. This allows a smooth transition from voice-only to multimedia service networks. Furthermore, the ratio between voice and data traffic can be changed dynamically according to the requested service type.

But packet and circuit switched networks are typically optimized for different objectives, resulting in different operation points, even if the underlying physical layer is very similar. Therefore, the efficiency of a network operating GSM voice and GPRS packet services in parallel is investigated in this paper.

The objective is to maximize the system capacity of a GPRS network. The performance measure is the average number of users per cell, normalized by the amount of spectrum used, under the assumption that each user generates packet traffic at the same rate. Three main parameters determine the link layer performance of a GPRS network:

- Frequency reuse factor;
- Error coding scheme (CS);
- Data packet delay.

An in-depth description of the influence of these three parameters on the system behavior is given in section 2 together with the background information about GSM and GPRS. The models, assumptions and performance measures for our analysis are described in detail in section 3. Simulation results are discussed in section 4. Conclusions and suggestions for further research complete this paper.

2. GPRS packet services in GSM networks

The coverage areas of cellular radio systems are often modeled as hexagonal cell patterns. Frequencies are assigned to a particular cell according to a K-color scheme [2]. The frequency reuse factor, or simply "re-use", in a cellular system is given by 1/K. Higher spectrum utilization can be achieved by increasing reuse. However, this worsens the interference problem.

The GSM system uses a combined F/TDMA air interface, where one TDMA frame is sent each 4.615 ms in a 200 kHz wide frequency band. Each TDMA frame is divided into eight slots. A mobile terminal is assigned to one slot and the sequence of these slots is called a channel. In GPRS, four TDMA frames are combined with additional control information from one Logical Link Control (LLC) frame. Each of the eight channels in a TDMA frame can be used for GPRS (see Fig. 1).

![Figure 1: Simplified GSM frame structure with GPRS packet data channels.](image)

At the link layer, there are consequently a maximum of eight GPRS packet data channels (PDCCH) per allocated frequency. Each of them can transfer one Radio Link Control (RLC) block every 20 ms, providing a raw bit
rate of 23 kbps per channel. All mobiles requiring data services in a particular cell share the available PDCCHs.

Two different methods are used to reduce transmission errors in the data packets:
- Forward error correction using punctured convolutional codes at different coding rates;
- Retransmission of RLC blocks containing unrecoverable errors, usually referred to as Automatic Repeat Request (ARQ).

The following four coding schemes can be used in GPRS [3]:

<table>
<thead>
<tr>
<th>Coding scheme</th>
<th>Punct. conv. code rate</th>
<th>Payload [bits]</th>
<th>Data rate [kbps]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS-1</td>
<td>1/2</td>
<td>181</td>
<td>8.8</td>
</tr>
<tr>
<td>CS-2</td>
<td>2/3</td>
<td>268</td>
<td>13.0</td>
</tr>
<tr>
<td>CS-3</td>
<td>3/4</td>
<td>312</td>
<td>15.2</td>
</tr>
<tr>
<td>CS-4</td>
<td>4</td>
<td>428</td>
<td>20.9</td>
</tr>
</tbody>
</table>

Table 1: GPRS error coding schemes.

The impact of channel coding and ARQ can be described by the following two scenarios:

**Strong channel coding** – The convolutional code recovers most of the transmission errors. However, the effective throughput of data packets is small due to the low code rate. Examples are CS-1 and CS-2.

**Weak channel coding** – Each RLC block carries a high payload and little redundancy. Transmission errors can therefore often not be corrected and the whole RLC block has to be retransmitted. Examples are CS-3 and CS-4.

The amount of coding, which yields the best performance, depends on the amount of noise and interference in the channel. The latter is directly related to the frequency reuse factor of the GSM network and the Doppler spread in the channel. In the simulations described in section 4, the coding scheme achieving the highest spectral capacity will be determined for different frequency reuse factors 1/K and a given delay constraint (QoS requirement).

### 2.1 Multi-slot GPRS

Up to 8 channels can be made available to GPRS traffic. The trunking gain due to the increased number of channels results in a lower queuing time for packets at the base station. In addition, the transmission of RLC blocks is not restricted to one slot per user [4] [5]. Employing multiple slots per user decreases the transmission time of a packet. The accumulated throughput of all 8 PDCCHs, excluding channel coding, yields 167.2 kbps at the link layer. System resources are hence more efficiently utilized when idle channels are dynamically reallocated to users with data queued.

However, the system becomes more loaded because of the reassignment of idle slots. Consequently, the interference level increases and a stronger coding scheme is needed. This effect can be observed in the simulation results described in section 4.

### 3. Models and Assumptions

The aim of this paper is to find the combination of network parameters that maximizes the spectral capacity of a GPRS network for a given QoS requirement. Maximizing the spectral capacity can stand for:

- achieving the highest possible throughput for a fixed user population, or
- aiming to serve as many users as possible at a given average data rate.

In this study, the model proposed in [6] is adopted. It reflects best the current practice of GSM operators: *Customers purchase a certain service, e.g. voice telephony, entailing access to the GSM network with a guaranteed minimum access probability and at a fixed transmission rate*. Operation revenues are then maximized by serving as many customers as possible.

Likewise, the average number of customers per cell, which fulfill the QoS requirement, is maximized for the GPRS services. The QoS requirement is an upper bound on the delay of each transmitted packet, i.e. the guaranteed time for a packet to be delivered, and the probability of fulfilling this requirement.

The focus of the analysis is to estimate the performance gain due to multi-slot operation of GPRS networks. Computer simulations were used to evaluate appropriate channel coding schemes that maximize the system throughput. Results were obtained in a three-step approach as follows:

1. Only one channel was allocated to GPRS traffic. The results served as a reference, since no performance gains due to trunking efficiency or multi-slot operation were included.
2. All eight channels were used for GPRS, but each user had only one channel available to transmit packets. The average number of users per cell was then expected to be more than 8-times larger, due to the trunking gain.
3. Like in the second step, all eight channels were available for GPRS. However, users were then allowed to transmit packets in multiple PDCCHs, provided idle channels were available in that cell.

It is reasonable to assume that future mobile terminals will be capable of processing up to eight channels. The strategies of reassigning the available resources and the results are discussed in detail in section 4.3.

The simulations generated hexagonal cell patterns and computed the Signal to Interference Ratio (SIR) between all base stations and mobiles, based on a free space propagation loss proportional to $R^{-3}$ and $\theta = 8 \text{ dB}$. The number of cells in the simulations was chosen sufficiently large, so that the co-channel interference was within 1 dB of the theoretical value.

The downlink was simulated, since mobile data applications, such as Internet browsing, usually generate more traffic from the network towards the terminal. Mobiles were uniformly distributed in the service area.
and remained stationary during the transmission of packets. Power control was applied [7], which compensates for the square root of the path loss \((b = \frac{3}{2})\). The same coding scheme was used throughout the network i.e. no link adaptation was available. After calculating the SIR for each RLC block, the according Block Error Rate (BLER) was obtained from link-level simulations [8]. Fig. 2 shows link level results for CS1-CS4 used to determine the block error probability for an RLC block received with a certain SIR. The results were obtained with frequency hopping in a typical urban environment.

![RLC block error rates for CS-1...4.](image)

Figure 2: RLC block error rates for CS-1...4.

As in [6], packet arrival was modeled as a Poisson random process with a rate of \(\lambda = 0.15\) packets/s. All packets had a fixed length of 275 Bytes, resulting in an offered traffic of 0.32 kbps per user. The maximum packet delay was set to 1.2 sec (60 RLC blocks) and at least 90% of a user's transmitted packets were required to arrive within this period. The relative low load per user together with short packets allows a large number of users in each cell. Moreover, the probability that a user has more than one packet waiting for transmission is very low. This avoids additional queuing delay on the network layer. The packets destined to the different users were queued at the base station. Queuing discipline was first-in-first-out (FIFO).

In the next section, results obtained for the system capacity are presented. Note that no additional queuing delays on the network layer have been considered as studied in [9].

### 4. GPRS Link Layer Simulations

The following results are based on a number of snapshots, during which the mobiles remained stationary. After each snapshot, all the mobiles were repositioned. Finally, the average delay and throughput over all snapshots was calculated. The performance measure, the average number of users per cell, is in all following results normalized by the amount of spectrum a particular frequency reuse requires and the number of channels used per cell. Thus, the spectral capacity \(\eta\) in user per MHz per cell is obtained. The spectral efficiency \(\lambda\) in kbps per cell per MHz can be derived directly from \(\eta\) by multiplying it with the offered traffic per user, i.e. 0.32 kbps. The spectral efficiency denotes the amount of GPRS packet traffic, which 8 PDCHs can carry in one cell.

#### 4.1 System capacity

As the average number of users per cell increases, the fraction of users meeting the delay requirement drops significantly. Fig. 3 shows the percentage of users fulfilling the QoS requirement in a GSM system where only one channel per cell is used for GPRS.

![QoS-achievement vs. spectral capacity \(\eta\) for 1 PDCH per cell.](image)

Figure 3: QoS-achievement vs. spectral capacity \(\eta\) for 1 PDCH per cell.

These results allow identifying the best reuse/coding combinations that will be used in the next simulations. The four best alternatives are: Reuse 1 \((K=1)\) with CS-1 and CS-2 as well as reuse 1/3 \((K=3)\) with CS-2 and CS-3. The graphs for CS-4 are omitted, since this coding scheme performs poorly in tight frequency reuse patterns. CS-4 actually provides no error protection and therefore requires very low interference levels. All further discussions now focus on the four best-performing combinations.

When eight channels are made available for GPRS packet transmission, the performance is significantly better due to higher trunking efficiency. Fig. 4 and Table 1 below compare a 1 and 8 PDCHs/cell system.

![QoS-achievement vs. spectral capacity \(\eta\) for 1 and 8 PDCHs per cell.](image)

Figure 4: QoS-achievement vs. spectral capacity \(\eta\) for 1 and 8 PDCHs per cell.
However, reassigning idle slots can significantly reduce the channel access delay. This is discussed in the following section.

Figure 5: QoS-achievement vs. spectral capacity \( \eta \) for 8 PDCCHs per cell with random reassignment of free slots.

Graphs for reuse 1 and CS-1 with 1 PDCCH and 8 PDCCHs without reassignment are shown as a reference.

Figure 6: Average delay per packet vs. spectral capacity \( \eta \) for reuse 1 and CS-1.

For a low system load, the graphs converge since the queuing probability tends to zero. Reassigning free slots significantly decreases the packet transmission delay. In

### Table 2: Spectral capacity \( \eta \) and spectral efficiency \( \lambda \) at 90% QoS-fulfilment for 1 and 8 PDCCHs per cell.

<p>| ( K=1 ) | ( K=1 ) | ( K=3 ) | ( K=3 ) |</p>
<table>
<thead>
<tr>
<th>CS-1</th>
<th>CS-2</th>
<th>CS-2</th>
<th>CS-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 PDCCH</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \eta ) [user/cell/MHz]</td>
<td>226</td>
<td>195</td>
<td>214</td>
</tr>
<tr>
<td>( \lambda ) [kbps/cell/MHz]</td>
<td>72.8</td>
<td>62.8</td>
<td>69.0</td>
</tr>
<tr>
<td>8 PDCCHs, 1 PDCCH per user</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \eta ) [user/cell/MHz]</td>
<td>371</td>
<td>274</td>
<td>312</td>
</tr>
<tr>
<td>( \lambda ) [kbps/cell/MHz]</td>
<td>119.6</td>
<td>88.3</td>
<td>100.6</td>
</tr>
</tbody>
</table>

4.2 Reassigning free resources

At the 90% QoS-fulfilment points, the system is almost fully loaded. However, not always all eight slots in a cell are utilized. These free resources could be used by the active users. At system loads below the 90% target, a significant decrease in the packet delay can be expected, since more slots become available for reassignment.

Different strategies are possible when deciding which user should get the idle PDCCHs. By assigning free channels to users enjoying a good link quality, the system capacity is improved. However, resources are unfairly distributed in that case, since the variance in packet delay is further increased. On the other hand, allocating the free channels to users with poor link quality yields a fairer system—by reducing the variance in throughput and delay, users experience a more balanced QoS—at the cost of peak system performance. We chose to compromise between these two strategies: One user per cell is selected randomly, among all active, each RLC block interval (20 ms) to use the idle channel(s).

The following reasoning should further support the choice made: The estimation of the radio-link quality, i.e. the SIR, is not trivial in packet data systems. Hence, a deliberate decision of devoting free slots to a user with a particular good or poor link quality is not very realistic. Even if such a SIR estimate would be available, the continuously changing interference situation due to the random packet transmission would make link quality prediction relative unreliable.

In the following Fig. 5 and Table 3, the results for a system with 8 PDCCHs and random reassignment of free slots are shown. The improvement in spectral capacity is negligible compared to the case without reassignment. In fact, for reuse 1 and CS-2, a decrease in the spectral capacity can be found. The coding cannot cope with the increased interference due to the reassigned slots. Then, the system becomes overloaded, since more retransmissions per packet are necessary.

### Table 3: Spectral capacity \( \eta \) and spectral efficiency \( \lambda \) at 90% QoS-fulfilment for 8 PDCCHs and reassignment of free slots.

<p>| ( K=1 ) | ( K=1 ) | ( K=3 ) | ( K=3 ) |</p>
<table>
<thead>
<tr>
<th>CS-1</th>
<th>CS-2</th>
<th>CS-2</th>
<th>CS-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 PDCCHs with random reassignment of free slots</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \eta ) [user/cell/MHz]</td>
<td>381</td>
<td>212</td>
<td>307</td>
</tr>
<tr>
<td>( \lambda ) [kbps/cell/MHz]</td>
<td>122.8</td>
<td>68.3</td>
<td>98.9</td>
</tr>
</tbody>
</table>

4.3 Delay considerations

The use of multiple PDCCHs per cell increases the probability of getting instantaneous access to a channel. This results in a reduced queuing time and lower packet delay perceived by the user. Fig. 6 shows the decreased delay for 8 PDCCHs compared to 1 PDCCH.
particular at loads somewhat below the 90% QoS target, users can almost certainly find free slots in a cell and reduce the packet transmission time.

4.4 System capacity for mixed traffic cases

The results in the previous sections show that the highest capacity is reached when all 8 channels in the GSM system are used for packet transmission. However, for an operator it might not be realistic to dedicate a complete 200 kHz band to data traffic only. Therefore, we also simulated a system with 4 PDCCHs, representing mixed traffic with resources divided equally for voice and data channels.

Performance gains are still considerable (36% for reuse 3 and CS-2, see Table 4 below) compared to using 1 PDCCH per cell (see Table 2). A GSM/GPRS network with four data and four voice traffic channels is consequently an acceptable compromise between efficiency and deployment cost. Particularly during the introduction phase of GPRS, existing GSM networks can be upgraded to provide GPRS services.

<table>
<thead>
<tr>
<th></th>
<th>K=3</th>
<th>K=3</th>
<th>K=3</th>
<th>K=3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CS-2</td>
<td>CS-3</td>
<td>CS-2</td>
<td>CS-3</td>
</tr>
<tr>
<td>4 PDCCHs</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 PDCCH per user</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>random reassign. of free slots</td>
<td>281</td>
<td>271</td>
<td>292</td>
<td>269</td>
</tr>
<tr>
<td>η [user/cell/MHz]</td>
<td>90.6</td>
<td>87.3</td>
<td>94.1</td>
<td>86.7</td>
</tr>
</tbody>
</table>

Table 4: Spectral capacity η and spectral efficiency λ at 90% QoS-fulfilment for 4 PDCCHs per cell, with and without reassignment of free slots.

5. Conclusions

In this paper, the performance gain due to higher trunking efficiency in GPRS networks using multiple GSM channels was studied. Results were obtained by link layer simulation of semi-static snapshots with a large number of mobiles. Downlink traffic was considered and different combinations of frequency reuse and coding were analyzed in networks with 1, 4 and 8 PDCCHs.

GPRS allows generally a tighter frequency reuse than GSM voice services, due to the additional channel coding with four different code rates (CS-1...4) and the ARQ scheme. In principle, the same frequency can be used in all cells when the strongest coding scheme is applied. The better resource utilization compensates for the lower net throughput of the low-rate coding scheme and outperforms the other reuse/coding combinations.

Assigning all 8 channels in a GSM system to GPRS results in up to 64% increase in spectral capacity due to the higher trunking efficiency and the tighter frequency reuse. The spectral efficiency improves from 73 to 120 kbps/cell/MHz. GPRS should therefore be operated as a separate overlaying network instead of sharing the resources between voice and data services.

In practice, it might not be realistic to assign a 200 kHz band only for GPRS. Using 4 channels per cell for packet transmission still achieves a good trunking efficiency compared to 1 PDCCH, but the low frequency reuse required for voice services, and consequently also for mixed traffic networks, reduces the performance slightly. A spectral efficiency of 94 kbps/cell/MHz can still be achieved with a frequency reuse of 1/3 and CS-2.

A simple reallocation scheme was proposed to improve the resource utilization and reduce the packet transmission delay. Average packet delay was substantially reduced by reassigning idle slots to a randomly selected user.

GPRS is a useful extension to the GSM system. It can provide packet data services within existing GSM networks. However, the performance is optimized by employing a high frequency reuse. Hence, it is preferably operated as a separate overlay network.

References