Evaluation of Packet-by-Packet Downlink Radio Resource Management Schemes

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Abstract

The OFDM based terrestrial digital video broadcasting system (DVB-T) can be utilized for asymmetric Internet access with a downlink peak bit rate of 10-20Mbps. A narrow-band cellular communications system can be used as uplink. This paper is a comparison of centralized dynamic radio resource management schemes for this downlink packet radio system. Spectrum efficiency in bit/s/Hz/transmitter, and fairly shared spectrum efficiency in bit/s/Hz/transmitter, are evaluated for a best-effort traffic snapshot model. The Dynamic Packet Assignment (DPA) algorithm performs combined packet scheduling and rapid Dynamic Channel Allocation. Even better performance is achieved by the Dynamic Single Frequency Networks (DSFN) scheme. It exploits the macro-diversity capability of OFDM modulation. The base station transmitters are dynamically divided into groups that send the same information at the same channel frequency simultaneously.

1 Introduction

Popular Internet applications such as WWW and Internet radio are characterized by *asymmetric communication*, i.e. much higher data rate to the terminal host than from it. Especially in mobile communications, limited battery capacity makes high uplink data rates less interesting than high downlink data rates. However, cellular systems for wide-area coverage (e.g. GSM and WCDMA) are not designed with asymmetric communication in mind, since they use frequency division duplex, and the uplink and downlink frequency bands have equal widths.

To increase the downlink capacity in the GPRS cellular packet radio system, a broadband supplemental downlink is proposed by AT&T Labs in [1]. The proposal supports 2-5 Mbps peak bit rate over 5MHz wide channels in large cell environments. *Orthogonal Frequency Division Multiplex* (OFDM) modulation is chosen because of its ability to cope with multipath propagation.

An alternative is to use broadband OFDM radio technology existing on the market today. The *Terrestrial Digital Video Broadcasting system* (*DVB-T*) [2] can offer a net bit rate of between 6 and 31 Mbps over 8MHz channels. Teracom AB has demonstrated that DVB-T be turned into a cellular system by combining it with GSM and the Mobile IP protocol [3].

A major objective in the design of cellular systems is to achieve high *spectrum efficiency* (in bit/s/Hz/transmitter site) by means of high channel reuse, but avoid co-channel interference. This can be done by dynamic *radio resource management* (RRM) techniques, such as *dynamic channel allocation* (DCA).

The aim of this study is to find dynamic RRM schemes for OFDM based packet-oriented cellular downlink systems. The schemes are evaluated for the DVB-T case, regarding spectrum efficiency and fairness.

A challenging research topic is RRM for packet data cellular systems, because of the highly fluctuating nature of the co-channel interference. In modern cellular systems, interference fluctuations are handled by *interference averaging* by spread spectrum. However, it was shown by Pottie [4] that *interference avoidance* by DCA and power reservation can perform a factor 2 to 3 better spectrum efficiency than interference averaging techniques. Efficient interference avoidance for packet communication requires centralized resource reservation of each data packet individually. This packet-by-packet RRM is alluring in since we only deal with the downlink and easily can gather information about the destinations of all packets that are waiting in the system queues.

In this paper, two approaches to packet-by-packet RRM are evaluated: (i) The *Dynamic Packet Assignment* (DPA) scheme, which is proposed in the OFDM downlink proposal [1] mentioned in the beginning of this paper, and (ii) *Dynamic Single Frequency Networks* (DSFN), which were introduced in our previous work [5]. For reference, *Fixed Channel Allocation* (FCA) with (iii) static *handover* (HO) as well as (iv) traffic-adaptive HO are evaluated.

2 System model and assumptions

A *system* consists of N_{Tx} centrally controlled and synchronized base station transmitters. In this paper, no frequency channel assignment and no power control is considered, i.e. all transmitters send at the same frequency with the same power.

The following seven DVB-T transmission modes., i.e. combinations of modulation and error correction coding, are evaluated: QPSK modulation with code rate 1/2, QPSK 2/3, 16QAM 1/2, 16QAM 2/3, 64QAM 1/2 and 64QAM 5/6. These are referred to as scheme number m = 1 to 7. In this paper, no link adaptation is considered, i.e. m is the same for all transmitters.

A timeslot structure is introduced into the DVB-T system. RRM parameters, such as channel allocation and macro diversity grouping, can be changed between two timeslots but not during a timeslot. A DVB-T OFDM frame of 17.136 milliseconds is considered as the timeslot entity. Bit interleaving and error coding should not spread an IP packet over several timeslots.

All IP packets have equal length of 1500 bytes (the maximum payload of Ethernet frames) in our simulations. The seven transmission modes can transfer 7, 10, 15, 20, 23, 30 and 38 IP packets per timeslot respectively.

Each receiver terminal j can measure the received power $P_{i,j}$ from each nearby base station transmitter i, and report changes of this level to a base station controller.

A Single Frequency Network (SFN) is a set of one or several transmitter sending the same information simultaneously over the same frequency channel. The OFDM modulation scheme is robust to this kind of multipath propagation.

The measured or calculated *Signal-to-Interference ratio* (SIR) must be above a SIR threshold γ_m of mode m for sufficiently low bit error ratio. A receiver is said to be in a state of *outage* if the RRM scheme is not able to assign resources to the receiver for sufficient SIR. Only modes that gives outage probability $\chi<5\%$ are considered.

For further details, we refer to [5].

3 Traffic model and performance measures

At a certain instant there is a density of w *active* or *backlogged* receiver terminals per transmitter in the system, i.e. receivers that have at least one data packet waiting for transmission in the queues. Note that this figure includes receivers that are in outage.

Only *best-effort* traffic is considered, i.e. communication without differentiated priorities or quality of service guarantees. During a period of receiver activity a data burst is transferred to receiver j with the maximum allowed data rate r_j (the user throughput).

A steady state snapshot simulation model is used, meaning that during a simulation, no data bursts are initiated or terminated, and no user terminals are moved.

The *spectrum efficiency* $\eta(w)$ in bit/s/Hz/transmitter is a normalized measure of the total throughput:

$$h(w) \triangleq \frac{1}{N_{Tx}B} \mathrm{E}\left[\sum_{j\in\mathbb{RX}} r_j\right], \qquad (1)$$

where $\mathbb{RX}$ is the set of active receivers that are not in outage, and B is the channel bandwidth.

We propose a combined measure of the fairness and the spectrum efficiency, which we call the *Fairly shared spectrum efficiency* $F(w)$ in bit/s/Hz/transmitter. It is a normalized measure of the minimum user throughput times the number of active non-outage receivers:

$$F(w) \triangleq \frac{w(1-c)}{B} \mathrm{E}\left[\min_{j\in\mathbb{RX}} r_j\right]. \qquad (2)$$

Dynamic RRM can maximize $\eta(w)$ by letting some "expensive" users starve such that $F(w)$=0. That is an unreasonably high unfairness. On the other hand, it is absolute fairness such that $\eta(w)$= $F(w)$ is not desirable.

We strive at *max-min fairness* [6], which is a widely accepted compromise between these two extreme strategies. The first priority is to maximize the lowest r_j, i.e. maximize $F(w)$, second priority to maximize the second lowest r_j, etc. The data rates are max-min fair if no data rate r_j can be increased without forcing a decrease in another rate of equal or lower value.

4 Evaluated schemes

4.1 Fixed Channel Allocation reference system (FCA)

For reference, conventional cellular Fixed Channel Allocation (FCA) is evaluated. Each transmitter is assigned to one of K TDMA channels, and transmits during the corresponding timeslot independently of if it has something to send or not. Reuse factors of K=3, 4, 7, 9 and 12 are considered.

Two handover schemes are evaluated: (i) **SIR based static HO**, which assigns each receiver to the transmitter that gives maximum SIR. (ii) **Traffic adaptive HO**. If a receiver belongs to overlapping cells, (i.e. the SIR > γ_m for several transmitters), the receiver always re-assigned to the transmitter i with lowest number of active receivers L_i if L_i are differing by two or more. If L_i differ by one, then the receiver is reassigned to the other cell with a certain probability, in view to make room for HO from more loaded cells. After each iteration of this algorithm the variance var(L_i) is either unchanged or decreased, and converges to the minimum possible value.

4.2 Dynamic Packet Assignment (DPA)

The AT&T Labs *Dynamic Packet Assignment* (**DPA**) [1] is a combination of DCA and statistical multiplexing, i.e. data packet scheduling. The algorithm assigns transmitters and data packets to timeslots.

The following modified DPA scheme, adapted to the DVB-T case, is evaluated: A traditional HO scheme assigns each terminal to a transmitter. We use the SIR based static HO scheme above. The base station transmitters belong to K groups, where the transmitters in one group are non-adjacent. See figure 1. During timeslot n, the algorithm checks if it will be possible for the transmitters in group n mod K to transmit during timeslot n+1, n+2,... n+K without causing outage of already scheduled terminals. The purpose with the K groups is to facilitate a distributed execution of the scheduling algorithm in each base station, without contention among adjacent transmitters. The base stations inform each other about the scheduling by a fast backbone network.

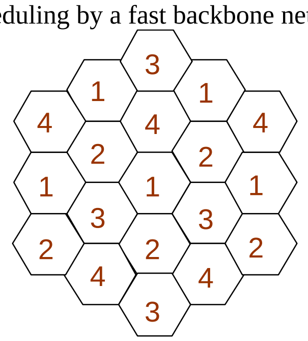

Figure 1: DPA with *K*=4 groups of transmitters.

A drawback is that DPA requires a SIR bound margin for interference among transmitters in the same group.

In the original proposal, K = 4, but we evaluate other values. In the original DPA, only one receiver is assigned to each timeslot and transmitter. Since our system can transfer many IP packets per timeslot, we modify DPA to allow several different receivers to share the same slot, to restrict the packet delay. We simulate *fair scheduling* of each transmitter queue, which gives scheduling priority to the user j that have achieved lowest data rate r_j.

4.3 Dynamic Single Frequency Networks (DSFN)

Dynamic Single Frequency Networks (DSFN) exploits the macro diversity capability of OFDM. For a comprehensive description, see our previous paper [5].

The transmitters are divided into *single frequency networks* (SFNs), i.e. groups of transmitters that send the same data at the same channel frequency simultaneously. By using big SFNs (with a large number of transmitters), co-channel interference is avoided, but on the other hand the spectrum efficiency is reduced. (The term SFN originates from the broadcasting world, where a network is a group of transmitters that send the same TV or radio program. In the cellular systems tradition, SFNs are sometimes referred to as *transmitter macro diversity* or *simulcasting*.) If *inter-symbol interference* (ISI) is neglected, the SIR at receiver j averaged over all OFDM sub-carriers is, according to [7],

$$\Gamma_j = \frac{\sum\limits_{i \in \mathbb{U}_j} P_{i,j}}{I_{Ext} + \sum\limits_{i \in \mathbb{TX} \setminus \mathbb{U}_j} P_{i,j}}, \qquad (3)$$

where $\mathbb{TX}$ is the set of transmitters that are sending for the moment, $\mathbb{U}_j \subseteq \mathbb{TX}$ is the set of transmitters in the SFN (the useful signals) assigned to receiver j, $\mathbb{TX} \setminus \mathbb{U}_j$ is the set of co-channel interferers in the same centrally controlled system, and I_{Ext} is the external interference power including noise and signals from transmitters outside the centralized system. I_{Ext} is further discussed in section 5.

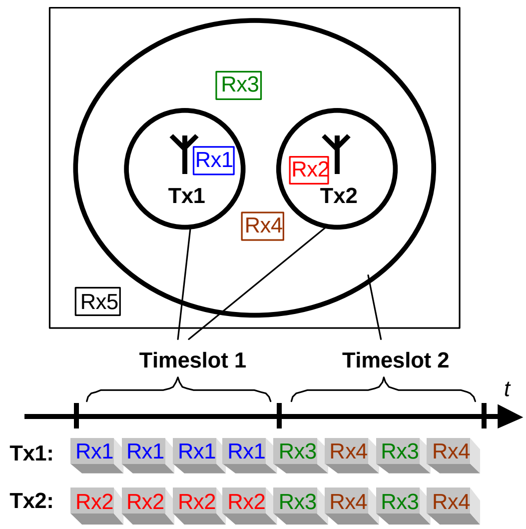

Figure 2: A simple example. Top: Coverage map. Below: Data packet schedule, stating the packet destinations.

A scheduling algorithm changes the SFN grouping from timeslot to timeslot, and assigns data packets to timeslots and SFNs. DSFN is a way of introducing timeslots and DCA into DVB-T, without keying of the transmitter power. Thus, receiver and transmitter circuits existing on the market today may be used.

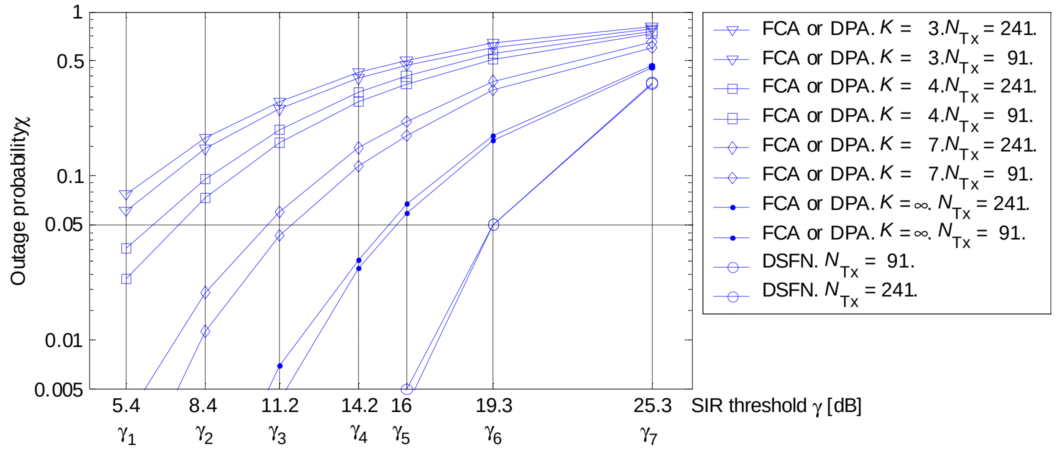

Figure 3: Outage probability c as function of the SIR bound g_m of the 7 modes *m*. Solid and dashed curve represent large and a small system size N_{Tx} respectively. FCA and DPA have the same outage for the same *K*. The lower bound for DPA and FCA is denoted with K=¥.

A simple example: (See Figure 2.) A system consists of two base station transmitters, Tx1 and Tx2, and five receiver terminals, Rx1 to Rx5, all assigned to the same frequency channel. During the first time slot, Tx1 and Tx2 send different information, which only can be received within the two inner circles, since the co-channel interference level is too high outside the circles. The schedule shows that during time slot 1, Tx1 and Tx2 send data packets destined to terminal Rx1 and Rx2 respectively. During next time slot, both transmitters send the same information simultaneously, i.e. they are grouped to an SFN. The SFN covers the whole ellipse, and can therefore send data packets destined to terminal Rx3 and Rx4. Terminal Rx5 cannot be covered, and is in a state of outage. During the first and the second time slot, the spectrum efficiency is R/B and $R/2B$ bps/Hz/transmitter respectively, where R is the transmitter useful bit rate, and B is the channel bandwidth. The spectrum efficiency η averaged over the whole period is $3R/4B$.

Two *fair scheduling* algorithms are evaluated. Algorithm A gives scheduling priority to users that have achieved low data rate r_j, and algorithm B to users that have waited long time since last packet transmission.

5 External Interference and Outage

In our previous work noise and interference from transmitters outside the centralized system, were neglected. However, it has extensive effect on the behavior of dynamic RRM schemes. The DSFN scheme can avoid all internal interference to vulnerable receivers, resulting in χ=0 and infinite SIR if I_{Ext} were neglected.

In this paper we assume a homogenous external interference level I_{Ext}, i.e. the same to all receivers in the system. We set I_{Ext} to a level corresponding to an *outage probability c* of 5% for the DSFN case for a certain *reference SIR bound* $\gamma_{Ref} = \gamma_6$ = 19.3dB.

If the external interference is varying in time, I_{Ext} is defined as the maximum external interference that can occur, rather than the average external interference. The reason is that we do not average the interference level by spread spectrum technology, and thus RRM scheme has to calculate SIR for the worst case. Consequently, the I_{Ext} produced by an adjacent system of transmitters is the same independently of if it uses TDMA, DPA or DSFN.

6 Simulation results

6.1 Outage

Figure 3 shows that DSFN has considerably better outage probability χ than the other schemes. It is allowed to use any of the transmission modes m = 1 to 6 for χ < 5%.

DPA with K groups has the same outage as FCA with reuse factor K. The lower bound for DPA and FCA is denoted with K=∞. DPA and FCA can use mode 1 to 4.

The figure shows that our I_{Ext} model makes χ quite insensitive to the number of transmitters N_{Tx} in the system.

6.2 Spectrum efficiency and fairness

The highest spectrum efficiency $h(w)$ that is achieved in our simulations is 0.88 bit/s/Hz/site by DSFN algorithm B. This should be compared with a maximum $h(w)$ of 0.17bit/s/Hz/site by FCA with fixed HO. However, this *maximum spectrum efficiency policy* for choosing mode m and (in the DPA and FCA cases) the factor K, may result in impaired fairly shared spectrum efficiency $F(w)$ of DSFN and DPA in comparison to FCA.

In Figure 4, a *max-min fairness policy* is adopted, such that m and K and are chosen for maximum $h(w)$. In this case $h(w)$ of up to 0.37 bit/s/Hz/site is achieved by DSFN algorithm B, while a maximum $F(w)$ of 0.21 bit/s/Hz/site is achieved by DSFN algorithm A.

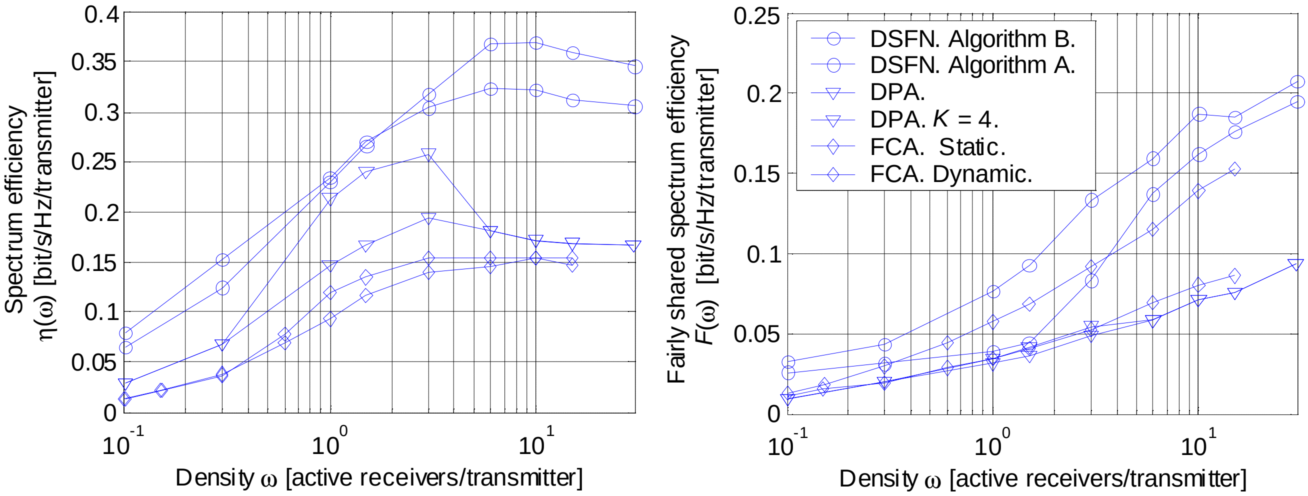

Figure 4: Max-min fairness policy for selection of transmission mode *m* and reuse factor *K*. N_{Tx} = 241.

The decreased DPA performance for high densities is caused by that we have modified DPA to allow several users to share a timeslot.

Table 1 shows the performance improvement span of the schemes relative to FCA with static HO, for the maximum throughput (M) and max-min fairness (F) policies, for all evaluated values of ω and N_{Tx}.

		Adaptive HO	DPA	DSFN Alg A
M	η(ω)	0 to 25%	3 to 197%	16 to 651%
M	*F*(ω)	0 to 87%	-39 to +30%	-7 to +309%
F	η(ω)	-5 to +51%	3 to 159%	76% to 651%
F	*F*(ω)	20 to 78%	-17% to +30%	90% to 309%

Table 1: Improvement relative to FCA with static HO.

7 Conclusions

Dynamic RRM should be utilized with care for best-effort traffic. If fairness is not considered, large average user throughput in bit/s may be achieved, but several users may suffer from “starvation” and might be locked out from the system. Although fair scheduling is included in our algorithms and starvation is avoided, some users may achieve worse performance with the dynamic schemes than with Fixed Channel Allocation with static handover if the system parameters are chosen for maximum spectrum efficiency.

If modulation and coding are chosen according to a max min fairness policy, the DSFN algorithm A not only achieves considerably higher average throughput than FCA and DPA, but also higher throughput every user. Further improvement of the performance is expected by link adaptation and directional antennas.

A major contribution of this paper is the analysis of the Fairly shared spectrum efficiency. By maximizing this measure, max min fairness is achieved. However, the plots are a little bit “jittery”, because the statistics is based on only one user. Further research should investigate if e.g. the 5:th percentile of the user throughputs is a more stable measure. Maximization of that objective function would give combined control over the spectrum efficiency, fairness and outage.

The DPA algorithm attacks the problem of efficient computation in an interesting way, by avoiding contention. Further research should be devoted to analyzing the computational complexity of the schemes, as well as the packet delay.

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