The concept of PARPS
- Packet And Resource Plan Scheduling

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Abstract

Dynamic schemes for downlink packet radio resource management (RRM) are the topic of this paper.

The concept of PARPS (Packet And Resource Plan Scheduling) is introduced. PARPS reduces the combined problem of dynamic RRM, including statistical multiplex, dynamic channel allocation, power control, link adaptation, reuse partitioning, soft handover, admission control, etc, to a scheduling problem. PARPS makes it possible to achieve dynamic RRM individually for each data packet, without performing signal-to-interference ratio calculations for every single packet. A PARPS algorithm assigns a so-called resource plan to each timeslot, and assigns data packets to timeslots and transmitters. A resource plan is a combination of several radio parameters, e.g. transmitter power levels, coding rates and modulation schemes, for a group of centrally controlled and synchronised transmitters. We propose several optimised and heuristic PARPS algorithms. Optimised PARPS is NP hard, i.e. it is not realistic to solve in real time for a big system, but it can be used for finding an upper bound for the compound effect of several RRM techniques by means of computer simulations. The heuristic algorithms are realistic to implement in real systems. Our results show that some of the heuristic algorithms have delay performance very near an optimised algorithm, and that the capacity and coverage of a set of resource plans for 2D Poisson traffic can be evaluated with static analyses, i.e. without queuing system simulation.

We apply PARPS to cellular systems based on the COFDM modulation scheme. Especially, we have personal communication services in the MEMO system in mind, where the terrestrial digital audio or video broadcasting system (DAB or DVB-T) is used as a broadband downlink, in combination with some narrowband uplink, e.g. GSM.

1. Introduction

Due to the asymmetric communication mode of client-server applications, future cellular systems are expected to use much more bandwidth in the downlink than in the uplink. Efficient radio resource management (RRM) in the downlink is consequently increasing in importance. In this paper, we study downlink RRM schemes by assuming that a reliable uplink is already established.

Dynamic RRM techniques such as statistical multiplexing (i.e. packet mode multiple access), dynamic channel allocation, traffic adaptive handover, power control, reuse partitioning, link adaptation (i.e. dynamic modulation and forward error correction), soft handover and admission control are often handled by separate algorithms on different protocol layers. In this paper we introduce the concept of *Packet And Resource Plan Scheduling* (*PARPS*), which can be used to combine the above techniques in one algorithm.

We assume a system of centrally controlled synchronised transmitters (i.e. access ports), connected with a fast backbone network, and using the same frequency channel. We suppose that static cell planning avoids co-channel interference between neighbouring systems. We assume that some diversity scheme, e.g. COFDM modulation, avoids fast fading due to multi-path propagation.

The complexity of a centralised system is not as severe problem in the downlink case as in the uplink, and it is possible to make it very efficient from RRM point of view, since we have information about all packets in queue. We do not need to introduce any random RRM in the system to avoid collisions, such as random delays or frequency hopping.

We combine several radio resource parameters (e.g. the transmitter power levels, macro diversity grouping, forward error correction codes and modulation schemes) to a number of alternative *resource plans*. The system recurrently sends test transmissions of each resource plan, and each mobile terminal measures what resource plans it can capture, and reports the measurement results to the central system. Alternatively, the terminal measures the gain from each neighbouring transmitter, and perhaps also distortion measures such as the time spreading and Doppler shift. Based on these measurements the system centrally estimates what resource plans each terminal can capture. The overhead due to test transmissions and measurements can be very small in the first alternative, if the number of resource plans is restrained.

A PARPS algorithm dynamically assigns a resource plan to each timeslot, and assigns the incoming data packets to timeslots and transmitters. It aims e.g. at minimising the delay, maximising the throughput, and/or minimising the number of dropped packets due to time-to-live violation. In this paper we formulate several optimised and heuristic PARPS algorithms, and evaluate them.

Optimised PARPS algorithms give an upper bound on the performance of a given set of resource plans. We can use optimised PARPS with a large set of resource plans to study the combined effect of the dynamic RRM techniques above. Unfortunately, since the optimised PARPS is an assignment optimisation problem, it is NP hard, i.e. its computation time is a non-polynomial function of the size of the problem, and it is not realistic to solve it numerically in real-time for big systems. However, it can be used in computer simulations.

The heuristic algorithms use polynomial computation time, i.e. they are scalable and realistic for implementation in a real system.

The PARPS concept has the benefit that it can perform power control, link adaptation, etc, for packets and timeslots individually, but the signal-to-interference ratio (SIR) does not have to be calculated for every single packet and timeslot.

In practical systems, the set of alternative resource plans must be limited. The set of resource plans may be changed by means of a slow adaptive process. This process can be a genetic algorithm, which combines the most popular resource plans to new resource plans, and abandons the least popular plans. It may also use conventional algorithms for static radio network planning, power control, etc, which uses measurement data to optimise the radio parameters. In this paper, we do not consider adaptive evolution of resource plans further.

2. System model

To be able to evaluate the PARPS concept numerically, we must apply it on a specific system model and problem area. We chose to study cellular packet radio systems based on the COFDM modulation scheme. Specifically, we have interactive services in the new terrestrial digital video and audio broadcasting systems (DVB-T [3] and DAB [2]) in mind. The broadcasting system is supplemented by a narrow-band return channel or *interaction channel* [4]. E.g. in the ACT's MEMO (Multimedia Environment for Mobiles) project [5], [6], the DAB system is combined with the GSM system. Examples of applications are interactive radio and TV programmes, and mobile Internet access with a broadband downlink.

A new RRM method which we have proposed [1] is to dynamically group the transmitters into *Single Frequency Networks* (SFNs). An SFN is a group of M=1 transmitters sending the same information simultaneously over the same channel [7]. The COFDM modulation scheme avoids self-interference due to this macro diversity. Our approach is to have different SFN formations in different timeslots. These *dynamic SFNs* facilitate *soft handover,* and efficient multicasting (one-to-many) and broadcasting (one-to-all) communication.

We assume that the COFDM guard interval is sufficient for avoiding inter-symbol interference. This gives an average signal-to-interference ratio (SIR) of

$$\Gamma = \frac{\sum_{i \in \mathcal{U}} G_i P_i}{N_0 + \sum_{j \in \mathcal{I}} G_j P_j}, \tag{2.1}$$

where $\mathcal{U}$ is the set of M transmitters in the SFN (the useful signals), $\mathcal{I}$ is the set of co-channel interferers, P_i the power from transmitter i, G_i the propagation gain from transmitter i to the terminal, and N_0 the noise power [7]. Due to shadow fading, $10\log G_i$ is $\mathrm{No}(10\log(F/d_i^{\,a}),\ s_S)$, where d_i is the distance, F is the antenna gain and s_S is the standard deviation in dB.

Non-overlapping timeslots are introduced in the broadcasting system. We assume that the resource plan can be changed between two timeslots, and that the timeslots have the same duration in time, independently of the modulation and coding scheme. These assumptions are simplifications of the problem, and are not fully in accordance with today's DAB and DVB-T standards.

We neglect the traffic load due to automatic repeat request (ARQ) retransmissions, and test transmissions.

3. Resource plans

The coverage (capture) area of each SFN or a single transmitter, such that G>g_0, is here called a *zone*. The SIR bound g_0 includes a margin for measurement data inaccuracy, e.g. due to terminal motion since last measurement. The margin is based on the measured variance of the SIR, and chosen for a desired probability of ARQ.

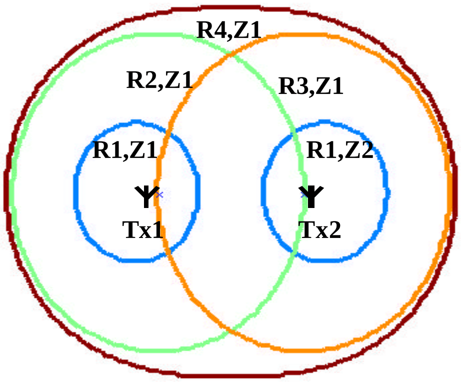

Fig 1: A simple example. Zone borders for four resource plans. (The system is noise limited. a=3, SP_i=1 in every plan, g_0=12dB, s_S=0dB, N_0/F=0.03.)

Figure 1 shows a simple example with two transmitters Tx1 and Tx2, and a set of four resource plans R1, R2, R3 and R4. In plan R1, both transmitters send different information to two zones (Z1 and Z2), resulting in high co-channel interference level and small zones. In R2 and R3 one transmitter is blocked, resulting in bigger zones. In R4, the transmitters are grouped to one SFN, resulting in an increased total coverage area. R2, R3 and R4 have one zone each (Z1).

The transmitter plan matrix **P** specifies the transmitter power levels and the assignment of transmitters to zones and resource plans:

$$(\mathbf{P})_{\mathrm{r,z,i}} = \begin{cases} \text{power from transmitter } i\text{, if it belongs to zone } z \text{ of plan } r, \\ 0, \quad \text{otherwise,} \end{cases} \tag{3.1}$$

where $r \in \mathcal{R} = \{R1, R2, \ldots\}$, $z \in \mathcal{Z}_r = \{Z1, Z2, \ldots\}$ and $i \in \mathcal{TX} = \{Tx1, Tx2, \ldots\}$.

The example above is generated from the following transmitter plan matrix:

$$\mathbf{P} = \left[\underbrace{\begin{bmatrix} 0.5 & 0 \\ 1 & 0 \\ 0 & 0 \\ 0.5 & 0 \end{bmatrix}}_{\substack{\underbrace{\quad}_{Z1}\;\underbrace{\quad}_{Z2} \\ Tx1}} \underbrace{\begin{bmatrix} 0 & 0.5 \\ 0 & 0 \\ 1 & 0 \\ 0.5 & 0 \end{bmatrix}}_{\substack{\underbrace{\quad}_{Z1}\;\underbrace{\quad}_{Z2} \\ Tx2}} \right] \begin{matrix} \}R1 \\ \}R2 \\ \}R3 \\ \}R4 \end{matrix} . \tag{3.2}$$

K_r is the *channel reuse factor* for plan r, here defined as the number of transmitters per reuse cluster, i.e.

$$K_r = \frac{|\mathcal{TX}|}{|\mathcal{Z}_r|} = \frac{\#\text{ of transmitters in the system}}{\#\text{ of zones in plan } r} . \tag{3.3}$$

In this paper, only symmetrical resource plans are considered, implying that all zones in plan r has the same SFN size M_r transmitters per SFN. In the example above, $M_{R1}=M_{R2}=M_{R3}=1$, $M_{R4}=2$, $|\mathcal{TX}|=2$, $|\mathcal{Z}_{R1}|=2$, $|\mathcal{Z}_{R2}|=|\mathcal{Z}_{R3}|=|\mathcal{Z}_{R4}|=1$, $K_{R1}=1$ and $K_{R2}=K_{R3}=K_{R4}=2$.

If link adaptation is facilitated, we use the *SIR bound matrix* $(\mathrm{g})_{r,z}$, which is the SIR threshold of the modulation and coding scheme used in zone z of plan r. The *data rate matrix* $(\mathbf{R})_{r,z}$ specifies the number of data packets which can be transmitted per timeslot, for the modulation and coding scheme used in zone z of plan r. **P** and g are used to calculate if a terminal can capture a certain zone and resource plan. **R** is input to the PARPS algorithm.

The *capacity* h_r of a resource plan is the *maximum transmitter utilisation*, or the *maximum throughput*, i.e. the number of data packets that can be sent per timeslot and transmitter, and is

$$h_r = \frac{\sum_{z \in \mathcal{Z}_r} R_{r,z}}{|\mathcal{TX}|} . \tag{3.4}$$

If link adaptation is not used, and a timeslot has the same duration length as one packet, $h_r = 1/K_r$.

4. *A static analysis method*

In this section, we assume a very simple PARPS algorithm, which uses *static handover*. We use the term handover for the packet to zone and resource plan assignment. Static handover implies that we do not utilise that the zones are overlapping. The handover decisions are always the same for a specific terminal position, regardless of the traffic load.

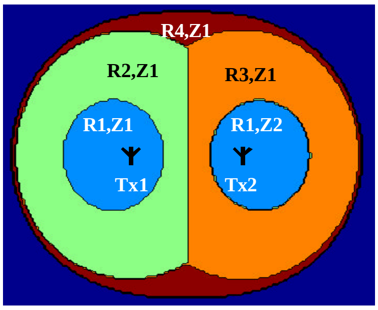

Fig 2: Static handover borders for the example in figure 1. Plan R1 has priority over the other plans.

The handover borders are statically defined by the set of resource plans.

We also use *reuse partitioning* (*RP*) without borrowing, which implies that the plans may have different capacity h_r, and that resource plans with big h_r (small reuse factor K_r or big data rate R_r) are prioritised in view to maximise the throughput. A packet is sent over the zone of the resource plan which gives sufficient $G>g_0$ with, firstly, maximum capacity h_r, and secondly, maximum *SIR*.

Figure 2 shows the cell borders and the coverage area for the combination of R1, R2, R3 and R4 in the example above. Resource plan R1 has priority over the other plans, because $h_r = 1$ for R1, and 0.5 for R2, R3 and R4, resulting in that R1 has priority over R2, R3 and R4.

In this static case the bandwidth B_r assigned to resource plan r (in bps unit or timeslots/time unit) is fixed. For maximum capacity, it should be proportional to the expected traffic load λ_r to plan r. If we assume uniform geographic traffic distribution, B_r is proportional to the area of the cells of plan r. E.g. if B_{R1}=0.5 and B_{R2}=B_{R3}=0.25, we use the sequence R1-R2-R1-R3-R1-R2-R1-R3, etc.

If we study link adaptation, and all zones of resource plan r are using the same modulation and coding scheme, B_r should be proportional to λ_r/R_r, where R_r is the link bit rate.

The *capacity* of the system is defined as the *maximum transmitter utilisation* (the *maximum throughput*), i.e. the maximum number of transmitted packets per timeslot and transmitter and frequency channel, is for Poisson traffic

$$\eta_{\max} = \frac{\sum_r B_r \eta_r}{\sum_r B_r}. \tag{4.1}$$

Thus, we can evaluate the capacity and coverage of this static algorithm and a certain set of resource plans, for 2D Poisson traffic, numerically without a queuing system simulation.

5. Scheduling algorithms

Figure 3 shows the previous example with 6 packets in queue, destined to 5 terminal positions. E.g. packet P2 and P6 are destined to a mobile which can capture zone Z2 in plan R1, Z1 in R2, Z1 in R3, and Z1 in R4. Figure 4 shows a conceivable schedule for this example. The packet length is equal to the timeslot length in this example. This schedule has minimal average delay, because we start with plan R1 in the first timeslot, which allows us to transfer two packets simultaneously.

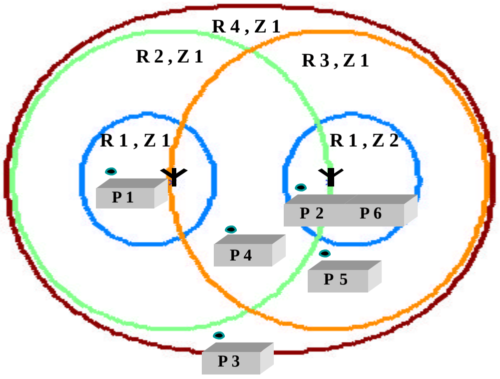

Fig 3: The example in figure 1, with 6 packets (P1-P6) in queue, destined to 5 terminal positions.

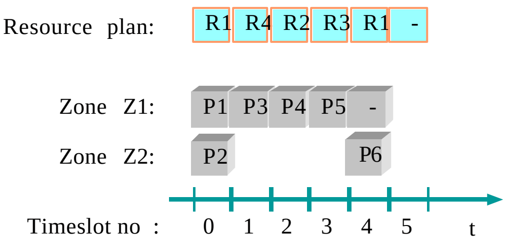

Fig 4: A conceivable schedule.

In this section, we propose a number of dynamic PARPS algorithms, which utilise that the zones are overlapping.

5.1 Optimised scheduling

We define the compatibility matrix **C** as:

$$(\mathbf{C})_{r,z,p} = \begin{cases} 1, & \text{if packet } p \text{ can be captured in zone } z \text{ of plan } r, \\ 0, & \text{otherwise,} \end{cases} \tag{5.1}$$

where p belongs to the set of packets {P1, P2, ...} that have arrived to the system and can be captured in at least one resource plan.

In the example in figure 4, the compatibility matrix becomes:

$$\mathbf{C} = \left[\underbrace{\begin{bmatrix} \underbrace{\begin{matrix}1\\1\\0\\1\end{matrix}}_{Z1} & \underbrace{\begin{matrix}0\\0\\0\\0\end{matrix}}_{Z2} \end{bmatrix}}_{P1} \underbrace{\begin{bmatrix} \underbrace{\begin{matrix}0\\1\\1\\1\end{matrix}}_{Z1} & \underbrace{\begin{matrix}1\\0\\0\\0\end{matrix}}_{Z2} \end{bmatrix}}_{P2} \underbrace{\begin{bmatrix} \underbrace{\begin{matrix}0\\0\\0\\1\end{matrix}}_{Z1} & \underbrace{\begin{matrix}0\\0\\0\\0\end{matrix}}_{Z2} \end{bmatrix}}_{P3} \underbrace{\begin{bmatrix} \underbrace{\begin{matrix}0\\1\\1\\1\end{matrix}}_{Z1} & \underbrace{\begin{matrix}0\\0\\0\\0\end{matrix}}_{Z2} \end{bmatrix}}_{P4} \underbrace{\begin{bmatrix} \underbrace{\begin{matrix}0\\0\\1\\1\end{matrix}}_{Z1} & \underbrace{\begin{matrix}0\\0\\0\\0\end{matrix}}_{Z2} \end{bmatrix}}_{P5} \underbrace{\begin{bmatrix} \underbrace{\begin{matrix}0\\1\\1\\1\end{matrix}}_{Z1} & \underbrace{\begin{matrix}1\\0\\0\\0\end{matrix}}_{Z2} \end{bmatrix}}_{P6} \right] \begin{matrix}R1\\R2\\R3\\R4\end{matrix}. \tag{5.2}$$

The *resource plan to timeslot assignment matrix* is defined according to:

$$(\mathbf{R2T})_{t,r} = \begin{cases} 1, & \text{if resource plan } r \text{ is assigned to timeslot } t. \\ 0, & \text{otherwise.} \end{cases} \tag{5.3}$$

The *packet to timeslot and zone assignment matrix* is:

$$(\mathbf{P2TZ})_{t,z,p} = \begin{cases} 1, & \text{if packet } p \text{ is assigned to timeslot } t \text{ and zone } z \text{ .} \\ 0, & \text{otherwise.} \end{cases} \tag{5.4}$$

The schedule in our example corresponds to:

$$\mathbf{R2T} = \begin{pmatrix} \underbrace{\begin{matrix}1\\0\\0\\0\\1\\0\end{matrix}}_{R1} & \underbrace{\begin{matrix}0\\0\\1\\0\\0\\0\end{matrix}}_{R2} & \underbrace{\begin{matrix}0\\0\\0\\1\\0\\0\end{matrix}}_{R3} & \underbrace{\begin{matrix}0\\1\\0\\0\\0\\0\end{matrix}}_{R4} \end{pmatrix} \begin{matrix} \}t=0 \\ \}t=1 \\ \}t=2 \\ \}t=3 \\ \}t=4 \\ \}t=5 \end{matrix} \tag{5.5}$$

$$\mathbf{P2TZ} = \left[\underbrace{\begin{bmatrix} \underbrace{\begin{matrix}1\\0\\0\\0\\0\\0\end{matrix}}_{Z1} & \underbrace{\begin{matrix}0\\0\\0\\0\\0\\0\end{matrix}}_{Z2} \end{bmatrix}}_{P1} \underbrace{\begin{bmatrix} \underbrace{\begin{matrix}0\\0\\0\\0\\0\\0\end{matrix}}_{Z1} & \underbrace{\begin{matrix}1\\0\\0\\0\\0\\0\end{matrix}}_{Z2} \end{bmatrix}}_{P2} \underbrace{\begin{bmatrix} \underbrace{\begin{matrix}0\\1\\0\\0\\0\\0\end{matrix}}_{Z1} & \underbrace{\begin{matrix}0\\0\\0\\0\\0\\0\end{matrix}}_{Z2} \end{bmatrix}}_{P3} \underbrace{\begin{bmatrix} \underbrace{\begin{matrix}0\\0\\1\\0\\0\\0\end{matrix}}_{Z1} & \underbrace{\begin{matrix}0\\0\\0\\0\\0\\0\end{matrix}}_{Z2} \end{bmatrix}}_{P4} \underbrace{\begin{bmatrix} \underbrace{\begin{matrix}0\\0\\0\\1\\0\\0\end{matrix}}_{Z1} & \underbrace{\begin{matrix}0\\0\\0\\0\\0\\0\end{matrix}}_{Z2} \end{bmatrix}}_{P5} \underbrace{\begin{bmatrix} \underbrace{\begin{matrix}0\\0\\0\\0\\0\\0\end{matrix}}_{Z1} & \underbrace{\begin{matrix}0\\0\\0\\0\\1\\0\end{matrix}}_{Z2} \end{bmatrix}}_{P6} \right] \begin{matrix} \}t=0 \\ \}t=1 \\ \}t=2 \\ \}t=3 \\ \}t=4 \\ \}t=5 \end{matrix} \tag{5.6}$$

A *PARPS optimisation problem* is solved for every timeslot during which new packets have arrived to the system. **C** is the input to the problem, and **R2T** and **P2TZ** are the result.

Before the problem is solved, a sufficient number N_T of timeslots $t \in \{0,1,\ldots,N_T-1\}$ in the schedule (number of rows in P2TZ and R2T) must be presumed. In the example above, N_T=6.

We have formulated the following four alternative PARPS optimisation problems:

Opt problem 1: Minimise the sum of the packet delays:

$$\text{Minimise } D = \sum_p \sum_t t \cdot \sum_z (\mathbf{P2TZ})_{t,z,p} \tag{5.7}$$

$$\begin{array}{llll}
\text{subject to} & \displaystyle\sum_z \sum_t (\mathbf{P2TZ})_{t,z,p} = 1, & \forall p & \text{(All packets must be scheduled.)} \\
& \displaystyle\sum_t (\mathbf{P2TZ})_{t,z,p} \cdot (\mathbf{R2T})_{t,r} \le (\mathbf{C})_{r,z,p}, & \forall z,p,r & \text{(The compatibility matrix constraint.)} \\
& \displaystyle\sum_p (\mathbf{P2TZ})_{t,z,p} - \sum_r (\mathbf{R2T})_{t,r} \cdot (\mathbf{R})_{r,z} \le 0, & \forall t,z & \text{(Max } (\mathbf{R})_{r,z} \text{ packets per zone and slot.)} \\
& \displaystyle\sum_r (\mathbf{R2T})_{t,r} = 1, & \forall t & \text{(One resource plan per timeslot.)} \\
& (\mathbf{P2TZ})_{t,z,p} \in \{0,1\}, & \forall t,z,p & \\
& (\mathbf{R2T})_{t,r} \in \{0,1\}, & \forall z,r. &
\end{array} \tag{5.8}$$

Optimisation problem 2: Minimise the maximum packet delay.

$$\text{Minimise } D_{\max} = \max_p \left(\sum_t t \cdot \sum_z (\mathbf{P2TZ})_{t,z,p} + \left(\mathbf{T}_{age}\right)_p \right), \tag{5.9}$$

under the same constraints as in (4.8).

Optimisation problem 3: Maximise the number of scheduled packets.

This is an admission control problem. We minimise the number of skipped packets due to age exceeding the time to live. Thus old packets are automatically prioritised, as well as packets to terminals near the transmitters:

$$\text{Maximise } h_{tot} = \sum_t \sum_z \sum_p (\mathbf{P2TZ})_{t,z,p}\, , \tag{5.10}$$

under the same constraints as in (4.8) except the first, as well as under the constraints

$$\sum_z \sum_t (\mathbf{P2TZ})_{t,z,p} \le 1, \qquad \forall p \ \text{(Packets are scheduled max once)} \tag{5.11}$$

$$\sum_t t \cdot \sum_z (\mathbf{P2TZ})_{t,z,p} < \left(\mathbf{T}_{lifetime}\right)_p - \left(\mathbf{T}_{age}\right)_p, \quad \forall p \ \text{(Time constraints)} \tag{5.12}$$

where element p of the vectors $\mathbf{T}_{age}$ and $\mathbf{T}_{lifetime}$ specifies the number of timeslots since the arrival of packet p, and its time to live in timeslots, respectively.

Optimisation problem 4: Combination of problem 3 (firstly) and 2.

$$\text{Minimise} \quad aD_{\max} - \eta_{tot}\, , \tag{5.13}$$

where a is a very small positive weight. In a non-overload situation, this acts as problem 2.

These problems are optimal scheduling problems if we lack knowledge to predict future packet arrivals. In this paper, we only evaluate problem 1.

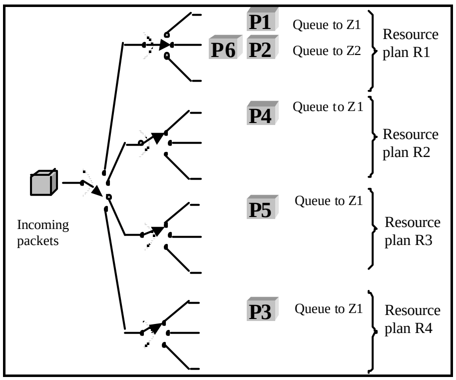

Fig 5: *Local FIFO queue algorithms for the exampel in figure 3.*

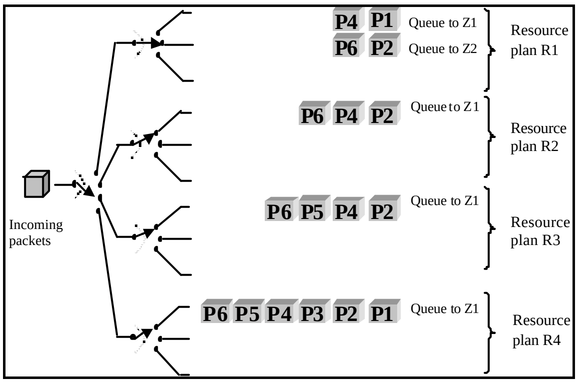

Fig 6: *Centrally controlled queue algorithms. A packet can be in several queues.*

5.2 Heuristic scheduling algorithms

We propose ten heuristic scheduling algorithms. They have similar objective functions as the optimisation problems, but they have a smaller set of feasible solutions. These algorithms can only schedule one packet per timeslot, i.e. they can not handle link adaptation.

Algorithm 1 and 2 are static schemes based on fixed values of B_r, and static handover with reuse partitioning without borrowing, as described in section 4. Algorithm 3, 4, 5, 8, 9 and 10 dynamically adopts the resource plan sequence (the *R2T*=resource-plan-to-timeslot assignment) to the traffic. Algorithm 6, 7, 8, 9 and 10 dynamically utilises that the zones are overlapping.

We categorise the algorithms according to the following hierarchy:

Local FIFO queue algorithms: There is a queue to each zone in each resource plan. The handover decision (the packet to zone and resource plan assignment decision) is taken immediately when a packet arrives. See the example in figure 5.

- **Static handover algorithms** put incoming packets in the queue of each cell, according to the static handover criteria in section 4.
    - **Static R2T**: The handover is defined by the static cell borders and reuse partitioning handover rule in section 4.
        1. *Cyclic R2T.* The plan sequence may be R1-R2-R3-R1-R2-R3, etc. B_r is equal for all r.
        2. *Weighted R2T.* B_r is proportional to the probability that a packet uses plan r. E.g. if B_{R1}=0.5 and B_{R2}=B_{R3}=0.25, the sequence R1-R2-R1-R3-R1-R2-R1-R3, etc is used.
    - **Dynamic R2T:** Chooses the resource plan for the next timeslot which has
        3. most packets in the queues.
        4. longest queue.
        5. the oldest packet in queue.
- **Traffic adaptive handover:** Utilises that the zones are overlapping. Incoming packets are put in the zone with
        6. shortest queue.
        7. shortest waiting time queue.

Centrally controlled queue algorithms: All incoming packets are put in several queues, one to each overlapping zone. See the example in figure 6. When a packet is sent from one queue, it is removed from all the queues. Thus, the handover decision is taken in the moment immediately before the transmission. In the next timeslot, the algorithm uses the resource plan which

8. can send most packets during next timeslot.
9. can send the packets with the highest age sum.
10. firstly can send the oldest packet, and secondly, can send most packets.

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6. Simulation results and conclusions

The simulations only consider PARPS algorithms for a fixed set of symmetric resource plans with different channel reuse (i.e. reuse partitioning) and SFN grouping. We do not evaluate power control, link adaptation and adaptive evolution of the set of resource plans at this stage. The duration of a data packet is a timeslot.

From figure 6 we can draw the conclusion that the *centrally controlled queue algorithms (cq)* have better mean delay performance than the *local FIFO queue algorithms (lq)* for 2D Poisson traffic. It is better to take the handover decision immediately before a packet is transmitted, than to take it when a packet arrives to the system.

Figure 7 shows that for bursty traffic, centrally controlled queue algorithms give a substantial delay and capacity perfomance improvement in comparison to local FIFO queue algorithms.

We have numerical results showing that centrally controlled queue algorithms have packet delay performance very near an optimised PARPS algorithm. E.g. the mean packet delay is 2.13 timeslots of heuristic algorithm 8, and 2.11 of optimisation problem 1, when h=0.12, $K \in \{1,3,4\}$, $M \in \{1,2,3,4\}$, g_0=12dB, s_S=12dB and $N_0 = 0$.

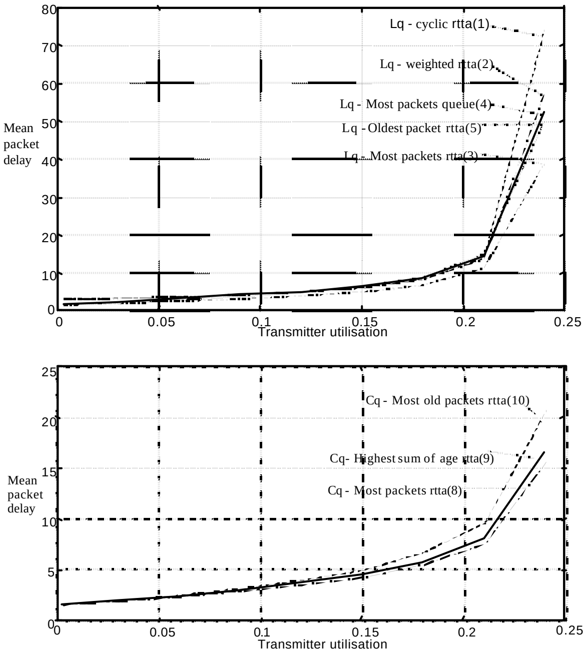

Fig 6: 2D Poisson traffic. Comparison of the average packet delay in timeslots, as function of the transmitter utilisation (i.e. the arrival intensity) h, in packets per timeslot and transmitter, for nine heuristic algorithms. (K=4. M=1. g_0 = 12dB. s_S=12dB. N_0 = 0. a=4.)

Preliminary numerical results indicate that for a 2D Poisson traffic model, all the PARPS algorithms have the same capacity h_{max} (maximum arrival rate with stable queue length). Thus, the static analysis method developed in section 4 gives the coverage and capacity of a certain combination of resource plans for any PARPS algorithm, for 2D Poisson traffic, without queuing system simulation. However, for bursty traffic the dynamic algorithms give a substantial improvement of the capacity in comparison to a static handover algorithm.

Further research activities will be devoted to

- adaptation of the PARPS concept to the MEMO system and the DAB and DVB-T protocols.
- evaluation of schemes for adaptation of the set of resource plans.
- the trade-off between the number of resource plans, and the overhead for test transmissions and measurement data.
- comparison of the performance and complexity of the PARPS concept with other state-of-the-art RRM schemes.

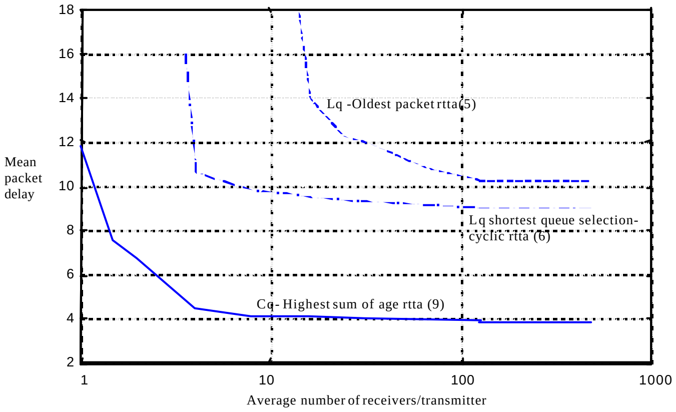

Fig 7: Bursty traffic. (Poisson traffic to geometrically distributed teminals.) Average packet delay vs the average number of receivers per transmitters. (Total arrival rate $h=0.2$ packets per transmiter and timeslot. Reuse partitioning with $K=1, 3, 4$ and $M=1, 2, 3, 4$. $g_0=12$dB. $s_S=12$dB. $N_0 = 0$. $a=4$.)

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