Radio Resource Management - an overview

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Abstract — Comparing market estimates for wireless personal communication and considering recent proposals for wide band multimedia services with the existing spectrum allocations for these types of systems show that spectrum resource management remains an important topic in the near and distant future. In this paper we present a quite general formulation of the radio resource management problem and review some the work previously published. Finally, an outlook over some of the key problems in resource management in third generation PCS is given.

1. Introduction

The rapid increase of the size of wireless mobile community and their demands for high speed, multimedia communications stands in clear contrast to the rather limited spectrum resource that have been allocated in international agreements. Efficient spectrum resource management is of paramount importance puts increasing demands. Fig 1 illustrates the principles of wireless network design. The network consists of a fixed network part and a wireless system. The fixed network provides connections between base stations or Radio Access Ports(RAP), which in turn provide the wireless "connections" to the mobiles. The RAPs are distributed over the geographical area where we wish to provide the mobile users with communication services. We will refer to this area as simply as the service area. The area around a RAP where the transmission conditions are favorable enough to maintain a connection of the required quality between a mobile and the RAP, is denoted the coverage area of the RAP. The transmission quality and thus the shape of these regions will, as we may expect depend heavily on the propagation conditions and the current interference form other users in the system. The coverage areas are therefore usually of highly irregular shape.

The fraction of the service area where communication with some required quality is possible is called the coverage or the area availability of the system. In two-way communication systems(such as mobile telephone systems), links have to be establish both from the RAP to the mobile (down- or forward link) and between the mobile terminal and the RAP (up- or reverse link). At first glance these to link seem to have very similar properties, but there are some definite differences from a radio communication perspective. The propagation situation is quite different, in particular in wide area cellular phone systems, where the RAP (base station) usually has its antennas at some elevated location, free of obstacles. The terminals on the other hand are usually located amidst buildings and other obstacles creating shadowing and multipath reflections. Also the interference situation in the up and downlink will be different since there are many terminals and varying locations and quite few RAP:s at fixed locations.

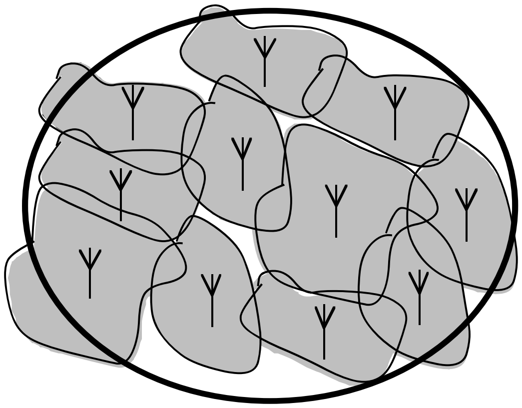

Fig 1. Wireless area communication system

For obvious economical reasons, we would like our wireless network to provide ample coverage with as few RAP:s as possible. Clearly this would not only minimize the cost of the RAP hardware and installation, but also limit the extent of the fixed wired part of the infrastructure. Coverage problems due to various propagation effects puts a lower limit to the number of RAP that are required. However not quite correct, one could say that the range of the RAPs is to small, compare to the inter-RAP distance. Such a system where this type of problem is dominant is called a *range limited* system. As the number of transmitters in the system becomes large compared to the available bandwidth, the number of simultaneous connections (links) will become larger that the number of orthogonal signals that the available bandwidth may produce. In order to provide service for such a large population of users, it is obvious that the bandwidth used by the RAP:s and terminals has to be reused in some clever way at the cost of mutual interference. The systems is said to be *bandwidth or interference- limited*.

In the remainder of the paper we will know formulate our version of the resource management and review some of the ideas and results from the litterature. The references mentioned are chosen as examples of work done in certain areas. The literature list should thus tbe considered to be complete in any way.

2. The radio resource management problem

Assume that M mobiles are served by access ports (base stations), numbered from the set

$$\mathbb{B} = \{1,2,3,...B\}.$$

Now, let us assume that there are C (pairs of) waveforms (in conventional schemes these can be seen as orthogonal channels (channel pairs)) numbered from the set

$$\mathbb{C} = \{1,2,3,...C\}$$

available for establishing links between access ports and mobile terminals. To establish radio links the system has to each mobile has to assign

a) an access port from the set $\mathbb{B}$,

b) a waveform (channel) from the set $\mathbb{C}$,

c) a transmitter power for the access port and the terminal.

This assignment (of access port, channel and power) is performed according to the *resource allocation algorithm* (RAA) of the wireless communication system. The assignment is restricted by the interference caused by the access ports and mobiles as soon as they are assigned a "channel" and when they start using it. Another common restriction is that access ports are in many case restricted to use only a certain subset of the available channels. Good allocation schemes will aim at assigning links with adequate SIR to as many (possibly all) mobiles as possible. Note that the RAA may well (should) opt for not assigning a channel to an active mobile if this assignment would cause excessive interference to other mobiles.

Let us now study the interference constraints on resource allocations in somewhat more detail. We now may compute the signal and interference power levels in all access ports and mobiles, given the *link (power) gains,* G_{ij}, between access port *i* and mobile terminal *j*. For the sake of simplicity we will here consider only rather wideband modulation schemes which will make the link gains virtually independent of the frequency. Collecting all link gains in matrix form, we get a BxM rectangular matrix the *link gain matrix*

$$\boldsymbol{G} = \begin{pmatrix} G_{11} & G_{12} & .. & .. & G_{1M} \\ G_{21} & G_{22} & .. & .. & G_{2M} \\ .. & .. & .. & .. & .. \\ .. & .. & .. & .. & .. \\ G_{B1} & G_{B2} & .. & .. & G_{BM} \end{pmatrix} \qquad (1)$$

The link gain matrix describes the (instantaneous) propagation conditions in the system. Note that in a mobile system both the individual components (mobile motion) and the dimension of the matrix (traffic pattern) may vary over time.

The task of the Resource allocation scheme is to find assignments for which the SIR (or actually the Signal-to-interference+noise ratio) is large enough (exceeds the threshold γ_o in as many links as possible (preferably all). This means that the following inequality must hold

$$\Gamma_i = \frac{P_j G_{ij}}{\sum_m P_m G_{im} \theta_{jm} + N} \geq \gamma_o \qquad (2)$$

where Γ_j denotes the SIR in the up (mobile-to-access port) and down (access port-to-mobile) link of the connection and *N* denotes the receiver (thermal) noise power at the access port. P_j denotes the transmitter power used by terminal j. The quantity θ_{jm} is the normalized crosscorrelation between the signals from mobiles j and m at the access port receiver. If the waveforms are chosen to be orthogonal(as in FDMA and TDMA) these correlations are either zero or one depending on if the station has been assigned the same frequency (time slot) or not.

Note that we may not be certain that it is possible to comply with all the constraints (2) for all the *M* mobiles, in particular if *M* happens to be a large number. As system designer we may have to settle for finding resource allocation schemes that assign channels with adequate quality to as many mobiles as possible. The largest number of users that may be handled by the systems is a measure of the *system capacity.* Since the number of mobiles is random quantity and the constraints (2) depend on the link matrix, i.e. on the relative position of the mobiles, such a capacity measure is not a well defined quantity.

The classical approach of telegraphic theory is to use as capacity measure the maximal relative arrival rate of calls ρ for which the *blocking probability* (the probability that a newly arrived call is denied service) can be kept below some predetermined level. Due to the mobility of the mobiles this is not an entirely satisfying measure. A call may be lost due to adverse propagation conditions. To include such phenomena in to our capacity would require detailed specification of call handling procedures (e.g. handling of new vs. old calls, hand-off procedures as a mobile moves from one access port to another etc.). It may therefore be practical to choose a simpler and more fundamental capacity measure that will reflect the performance of the resource allocation scheme as such. For this purpose, let us recollect that the number of active calls is the random number *M.* Assume that at some given instant, our RAA has succeeded to provide adequate links to *Y* of these mobiles. *Y* will of course also be a stochastic variable. Let us by *Z* denote the remaining number of mobiles, the assignment failures, i.e.

$$Z = M - Y \qquad (3)$$

We define the *assignment failure rate* ν as

$$\nu = \frac{E[Z]}{E[M]} = \frac{E[Z]}{\omega A} \qquad (4)$$

In the last expression we have assumed the (active) mobiles to be uniformly (2-D Poisson) distributed over the service area *A* with ω mobiles per area unit. The quantity ν is a measure of to which average proportion the allocation scheme has been successful in providing the mobiles with links of adequate quality. For moderate to large ωA, ν is also a good approximation of the probability that a randomly chosen active mobile at some given instant is not provide with a channel. The *instantaneous capacity* $\omega^*(\nu_o)$ of a wireless system is the maximum allowed traffic load in order to keep the assignment failure rate below some threshold level ν_o, i.e..

$$\omega^*(\nu_o) = \{ \max \omega : \nu \leq \nu_o \} \qquad (5)$$

As we have seen above, finding the optimum resource allocation, i.e. for each mobile determining

i) a waveform assignment (determining theθ_{jm})

ii) an access port assigment (of one or more(!) ports)

iii) a transmitter power assignment

that maximizes Y for a given link gain matrix, is a formidable problem. No efficient general algorithm that is capable of doing such an optimal assignment for arbitrary link gain matrices and mobile sets is known. Instead, partial solution and a number of more less complex heuristic schemes have been proposed (and are used in the wireless systems of today). These schemes are usually characterized by low complexity and by using simple heuristic design rules. The capacity ω^* achieved by these schemes is, as expected, often considerably lower that can be expected to be achieved by optimum channel assignment.

3. Waveform (Channel) Allocation

The subproblem that has attracted most of the interested so far in the literature is the choice and allocation of waveforms. Orthogonal waveforms such as frequency division multiplexing (FDMA) and time division (TDMA) that provide a "channelization" of the spectrum have not doubt been the most popular ones, although considerable interest has recently been devoted to non-orthogonal waveforms, e.g. the IS-95 DS-CDMA waveforms[25]. Given the set of signaling waveforms $\mathbb{C}$, the next problem is the allocation of waveforms to the different terminal-access port links. This allocation can be done in a lot of different ways depending on the amount and quality of the information available regarding the matrix **G** another the traffic situation (activity of different terminals). Another important issue is the time scale on which resource (re-)allocation is feasible.

Channel allocation in early FDMA cellular radio systems operates on a long term basis. Based on average type statistical information regarding **G** (i.e. large scale propagation predictions), frequencies are on a more or less permanent basis assigned to different access ports. Such a "cell plan" provides a sufficient reuse distance between RAP:s providing a reasonably low probability of outage (to low SIR)[1]. Inhomogenuities in the traffic load can also be taken care of be adapting the number of channels in each RAP to the expected traffic carried by that access port. To minimize the planning effort, adaptive cell planning strategies (e.g. "channel segregation"[2]) have been devised using long-term average measurements of the interference and traffic to automatically allocate channels to the access port
These "static" (or "quasi-static") channel allocation schemes work quite well when employed in macrocellular systems with high traffic loads. In short range (microcellular) systems and in multimedia traffic scenarios, "static" channel allocation schemes require considerable design margins to cope with the large variations in propagation conditions and traffic load. Large path loss variations are countered with large reuse distances, unfortunately at a substantial capacity penalty. In the same way microcellular traffic variations are handled by assigning excess capacity to handle traffic peeks. In recent years two principally different methods to approach this problem have been devised: *Dynamic* channel allocation (DCA) and *Random* Channel Allocation (RCA).

In dynamic (Real-time) channel allocation, real-time measurements of propagation and/or traffic conditions are used to (re-)allocate spectrum resources. Early, graph theoretic schemes, adapted only to traffic variations[4,5]] yielding only moderate capacity gains (<50 %) compared to static systems in microcellular environments. Other schemes adapt their channel allocation to the received wanted signal strength. One example of the latter type of schemes is the class of Reuse-partitioning schemes[6,8]. Here, several overlaid cell plans with different reuse distances are used. Terminals with a high received signal level are tolerant to interference and can be allocated a channel from a dense reuse cell plan whereas the "weaker" terminals get channels with a large reuse distance and lower interference levels. Capacity gains in the order of up to 100% have been reported for these schemes[7]. Also schemes directly estimating the C/I and thereby in a distributed way finding channels with adequate quality have been proposed[2,9]. Similar gains a in the reuse partitioning are found in the literature.

The performance of the DCA schemes is critically dependent on the rate at which allocation or reallocation occurs. Purely traffic adaptive schemes act on incoming user request and users releasing capacity. Channel reallocation have to occur at these rates to fully utilize the potential of such a DCA scheme. For speech traffic this means that reallocations typically occur at second rates. Path loss and interference adaptive schemes will have to "track" (at least slow fading) signal level variations and reallocation rates in the 10's of millisecond range may be required.

An alternative class of allocation schemes are the random channel allocation schemes. The principle is most easily explained using fig 2. The graph 2a) shows a typical set of C/I-trajectories of five terminals in a cellular system. As we can see, 4 of the 5 terminals achieve an adequate C/I, corresponding to an (ensemble) outage rate of 20%. Compare this situation to the one in figure 2b) exhibiting the same outage rate. In contrast to the situation in a) where 20% of the terminals where finding a to low C/I, here each terminal will experience insufficient quality 20% of the time. In case a) channel coding is a waste of capacity since 4 terminals have sufficient quality and the last unlucky terminal is probably "beyond salvage". In case b) however, there are probably a sufficient number of reliable channel symbols in all terminals to make reception possible, provided suitable constraint lengths & interleaving is used.

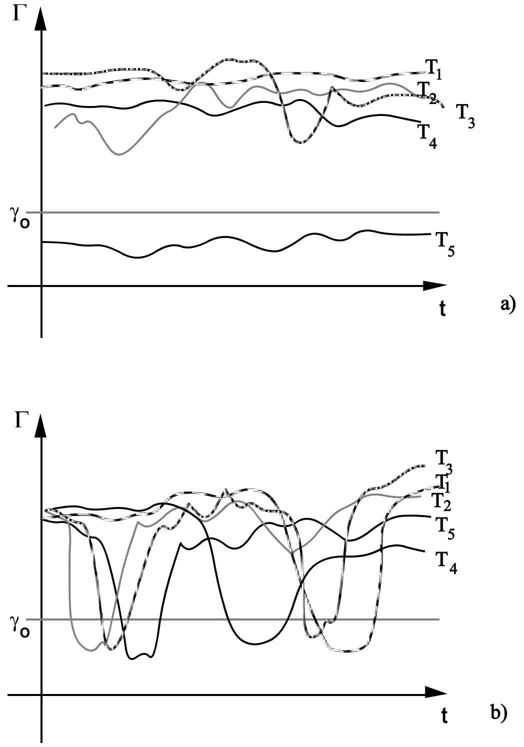

Fig 2. Typical realizations of terminal SIR:s in cellular systems with slowly moving terminals (a) and with rapidly moving terminals(b).

The obvious way to achieve the latter situation irregardless of the mobile speed, is to permute channel allocations in a random fashion. The simplest way is to use (orthogonal) frequency hopping which can be seen as a static channel allocation where terminals allocated to a certain access port swap channels with each other[28]. Frequency hopping occurs typically 100-1000 times/second. Also non-orthogonal waveforms can be used as in the DS-CDMA based IS-95 scheme[25]. Effectively, a new random waveform is used for every transmitted bit. DS-CDMA schemes require only very low level of synchronization and no cell planning which has made them attractive. Regarding capacity the comparison between DS and FH schemes is not obvious although orthogonal schemes seem to have advantages in mixed cell environments[26]. Comparing the performance of (deterministic) DCA to the performance of the Random allocation schemes is even more complex and stands out as one of the more fundamental research topics of the near future.

4. Transmitter power control

The selection of the proper transmitter power in terminals and access port is another topic that has attracted considerable interest in recent years. There can be several objectives for this: to suppress adjacent channel (cross correlation) interference in non-orthogonal schemes, to minimize power consumption in order to extend terminal battery life and to control cochannel interference (in schemes with orthogonal waveforms). In resource allocation problem context, it can be shown that the maximum number terminals is supported under a power control (PC) regime that *balances* the C/I of all terminals that can be supported and shuts of the rest[10]. Finding the optimum set of non-supported terminals is a problem closely related to the design of DCA schemes.

Distributed implementations and different implementational constraints[11,12] have been studied. Results show that very robust near-optimum power control schemes can be devised at very low complexity. Performance result indicate that in static channel allocations substantial (>100%) capacity gains can be achieved using optimum power control. These gains are, of course, not additive with the gains obtained by DCA schemes. However, preliminary results regarding combined DCA/PC schemes show substantial capacity gains[13,15].

5. Mobility and implementation aspects

As terminals move about in the service area, the propagation and interference situation may turn such that the terminal cannot be supported by the same access port on any waveform. In this case an *inter-port* ("inter-cell") *handoff* is required (in contrast to waveform reallocations, intra-port handoffs). In early cellular systems which are mainly noise-limited systems the handoff were basically triggered by to low received signal level. The handoff mechanism may be seen as a selection (macro-) diversity scheme where the terminals is assigned to the access port with the highest received signal level. This situation where hand-offs occur at more or less well defined "cell-borders" has been extensively studied[].

In high density wireless systems, the coverage areas of the access port overlap to a large extent. Low signal levels is rarely a problem since normally several access ports provide sufficient signal levels. In these cases the variations in the interference and not cell boundary crossings is to most probable cause of a handoff. When several access ports may provide sufficient C/I, the system is also able to handle traffic variations be means of *load sharing,* i.e. by letting less loaded access ports support terminals even though they are providing less C/I than the best (often the closest) port[20]. Combinations of power control and access port selection also show promising results[21,22]. Instead of conventional handoff schemes ("switching diversity"), also continuos combining schemes ("soft handoff") have been studied quite extensively[19].

Keeping track of the mobile terminals in a large (possibly global) wireless system, the *mobility management*, is a formidable task. Although this is handled mainly on the fixed network end, there are important implications to the resource management. The tradeoff between the capacity required for the air signaling to monitor the whereabouts of the terminals (the "locating" procedures) and the capacity required for finding, or paging, a terminal when a communication request comes from the network end, has received quite some attention[23,24].

6. Resource management issues in future wideband wireless systems

In conclusion, a few remarks regarding what we believe to be future trends in radio resource allocation. Wideband and mixed rate traffic in small cell environments will exhibit very large peek to average capacity demands. Dynamic channel allocation (statistical multiplexing) will provide even larger capacity gains in these situations. Conventional single cell traffic multiplexing/averaging will surely not be sufficient making dynamic spatial resource reuse of paramount importance[27].

Traditionally we consider the frequency spectrum to be the resource to be shared. Since there, in fact, does not exist any upper limit on the capacity that can be provided (with an dense enough infrastructure), it is important that we widen the resource management perspective. Parameters such as infrastructure density costs and terminal power consumption play important roles. One could easily identify tradeoffs such as where the signal processing load should be put in a wireless system - in the terminal where power is scarce or in the fixed infrastructure. The key question here is: Should the access port infrastructure be very dense (and costly) allowing for "dumb", cheap, low power terminals or should terminals be more complex allowing for the rapid deployment of a cheap infrastructure at the expense of battery life and terminal cost ?

7. References

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