A simulation study of Space and Time Reservation Multiple Access

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ABSTRACT. The paper introduces a new protocol for wireless cellular networks by combining a time reservation scheme with a dynamic space reservation scheme. The proposed new protocol, known as the Space and Time Reservation Multiple Access (STRMA) protocol, does not use a fixed reuse pattern but allows a dynamic reservation of bandwidth in both time and space. The performance of this protocol found by simulation is compared with the performance of a cellular network that uses PRMA with a fixed frequency reuse pattern. It is found that for homogenous traffic STRMA offers improved performance over a wide range of traffic loads. For inhomogenenous traffic the improvement is even more pronounced.

1 Introduction

In the attempts to solve the, by now almost classic, problem on how to make the most efficient use of the scarce bandwidth available for wireless communication systems, one can distinguish several tracks. On the one hand we have the attempts to diminish conflicts between several users accessing the same channel by using efficient multiple access protocols. For speech communication where the transmitted information is periodic in nature, multiple access protocols with reservation prove to be quite efficient. Examples of such protocols are the reservation ALOHA (r-ALOHA) protocol, the TDMA protocol and more recently the PRMA protocol [1]. On the other hand we see attempts to reuse the frequency band by dividing the area that our network should cover, into cells. Due to the propagation attenuation, two users can transmit at the same frequency in different cells provided the distance between these cells is adequate. This distance is determined by the reuse pattern, that is the number of different frequency bands into which the available bandwidth is divided.

For data communications with Poisson traffic it was shown in [2] that the reuse pattern providing the lowest delay was a reuse pattern of one, that is no reuse pattern at all, the whole bandwidth is available in every cell. So, assigning a reuse pattern to our networks might not provide the best spectrum efficiency.

What if we would employ the reuse pattern of one in a wireless communication system that is used to carry voice communications. Due to the periodic (non bursty) nature of packetised speech a direct implementation of a one cell reuse pattern does not work. We will have to do something smarter than that. If we look at the reservation multiple access protocols, we can see that these protocols reserve the bandwidth for a particular user part of the time. We could extend this reservation by including not just time but also space. This would mean that the bandwidth is reserved for a particular user part of the time in part of our network. The area of reservation is chosen such that users outside the reserved area will not interfere with the user for which the reservation is made. In practice this would mean that we would prohibit users in neighbouring cells (where the neighbours can include more than the first tier of cells) from transmitting during the timeslot that has been reserved for a particular user in the cell in which that user is located. This also creates a frequency reuse pattern but this pattern is no longer fixed. Instead it depends on the activity of the users. We call the scheme using both reservation techniques the Space and Time Reservation Multiple Access or STRMA protocol. The protocol is actually a new form of dynamic channel selection, an area in which a lot of research activities are going on at this moment (see e.g. [3], [4]).

2 The concept of Space and Time Reservation Multiple Access

As we explained in the introduction, STRMA combines a time reservation scheme with a dynamic space reservation (frequency reuse) scheme. Let us first look at the advantages such a scheme could offer compared to using a fixed frequency reuse pattern. In order to explain this lets just look at figures 1 and 2.
In figure 1 we have a cellular network with a fixed reuse pattern. The multiple access protocol that is used in each cell is the PRMA protocol. We assume that the entire channel contains 3 timeslots, so with a 3-cell reuse pattern each cell has 1 timeslot to its disposal. The active users are depicted as black dots in the cell. As we can see in cell C there are two active users. One (or both) of these users will fail to transmit

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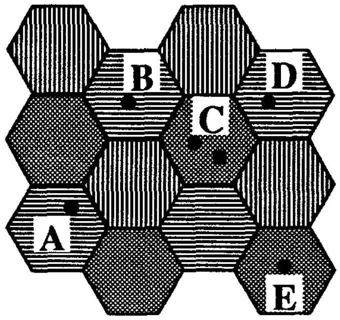

Figure 1: Transmission using a fixed reuse pattern

its packets since only one user can obtain a reservation for the one timeslot available in the cell. Now suppose that the entire channel can be used in each cell. This means that each cell has (in principal) 3 timeslots to its disposal. If we now have the same combination of active users as in figure 1, there is a possibility of all users transmitting all their packets, for example if the users transmit as depicted in figure 2. The users in the horizontally striped cells transmit while the users in the grey cells are prohibited from transmitting due to the reservation the transmitting cells make in space.

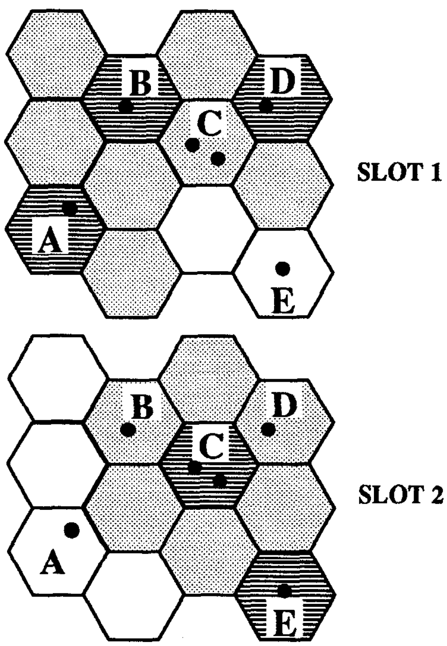

Figure 2: Transmission using the STRMA protocol

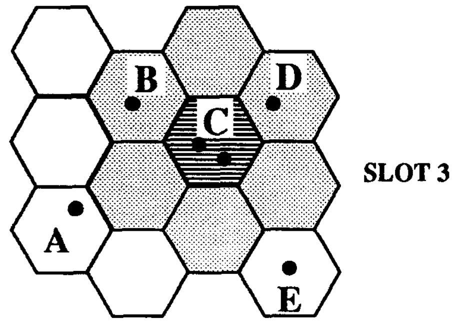

Figure 2: Transmission using the STRMA protocol (continued)

In the first timeslot the users in cells A, B and D transmit their packets. In the second timeslot one of the users in cell C and the user in cell E transmit their packets while in the third timeslot the second user in cell C transmits its packet. Because the reservation process is dynamic, we can not be sure that the pattern as sketched in figure 2 will arise. It may very well be that a pattern like the one in figure 3 occurs. In this case in slot one the users in cells A, B and E transmit (so the users in cell C are prohibited from transmitting), in the second timeslot the user in cell D transmits (so again the users in cell C are prohibited from transmitting) and in the third timeslot one user in cell C transmits.

To investigate the STRMA system, to see if it can improve the performance of our multiple access protocol, a simulation study has been performed. We compare the simulation results to the performance of a system using PRMA and a fixed frequency reuse pattern. In the next section we describe the STRMA and the fixed reuse PRMA system and the way in which we calculate the performance of the latter. In section 4 we present the results of the comparison.

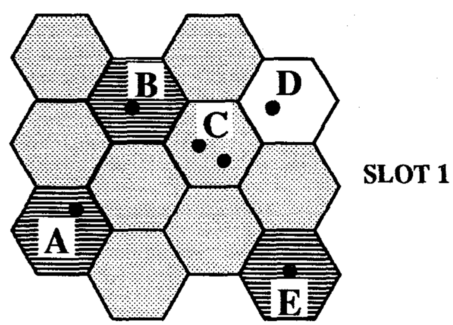

Figure 3: Undesirable transmission pattern in STRMA

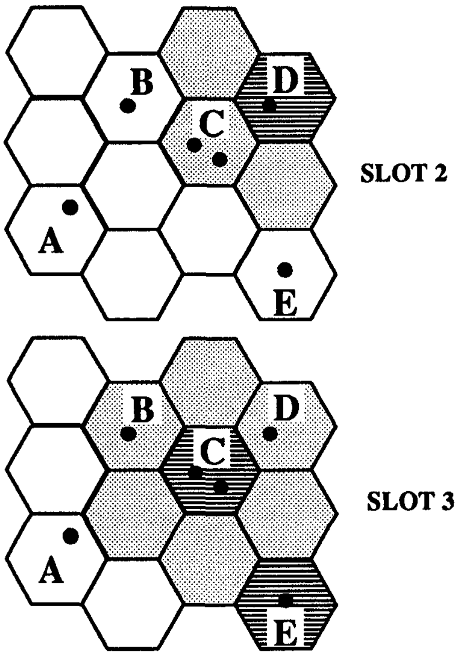

Figure 3: Undesirable transmission pattern in STRMA (continued)

3 Performance of an STRMA and fixed reuse PRMA system

We consider a cellular system consisting of N_c hexadiagonal cells. In the system we have a fixed number of users N_u. Each user generates telephone calls where the duration of the call is a negative exponentially distributed variable with an average of t_h seconds. The time between two telephone calls of one user is also a negative exponentially distributed variable but with an average of t_b seconds. These negative exponential distributions are commonly used to model speech traffic. When a user starts a conversation, its location is a random variable with a probability density function that is either:

1. uniformly distributed over the area of the network.
2. uniformly distributed over the area of the network with the exception of one cell, the hot-spot. The probability of a user being located within the hot-spot cell is a factor H_f (the hot-spot factor) larger than the probability of being located within another cell. Such a distribution allows us to see how the STRMA protocol copes with inhomogenous traffic.

We further assume that during the conversation the position of the user will not change, which for an indoor wireless environment would be a very reasonable assumption. The communication channel is slotted and the slots are grouped into frames. The duration of a frame is chosen such that speech users generate one packet per frame time.

In each cell we use the PRMA protocol as multiple access protocol. So if a user has initiated a telephone call and is in a talkspurt, he will transmit in every available (non-reserved) timeslot with probability P_s. If successful in one slot, this slot will be reserved for that user in future frames. If a user has transmitted all the packets of his current spurt, he will give up its reservation so the slot is free to be used by other users. If a new talkspurt is started, the user has to gain access to the channel once more. If a packet awaiting transmission is delayed for more than some predefined time, it is discarded (dropped). The performance of the protocol can be measured from the percentage of packets that are dropped (the packet dropping probability or pdp).

The observations made so far are the same for the system using the STRMA protocol and the system using PRMA in each cell and a fixed reuse pattern among the cells. There are only two differences between the two systems:

1) In the STRMA protocol the reservation of the timeslot is not restricted to the cell in which the user is located. The timeslot will also be reserved in surrounding cells to avoid collisions of packets transmitted in those surrounding cells in the same timeslot.
2) For the STRMA system a frame consist of N_s timeslots. When a reservation is made only the cells in the first tier surrounding the user obtaining the reservation, are also reserved. So two active users are always separated by one cell. In a fixed reuse pattern such a separation compares to a 3-cell reuse pattern. So in every cell we have 1/3 of the available bandwidth which compares to having $N_s/3$ timeslots per frame.

The performance of the STRMA protocol will be obtained by computer simulation. The performance of the system using a fixed reuse pattern with PRMA can be calculated. For this calculation we assume that the rate at which the number of active users in a cell (= the number of users having a telephone conversation) changes, is slow enough so that the cell is constantly in a steady-state (steady state for the particular number of active users). In this case we can write for the packet dropping probability of the fixed reuse PRMA system:

$$\text{pdp} = \frac{\sum_{n=0}^{N_u} n.\Pr\{n \text{ act. users in cell}\}.\text{pdp}\{n \text{ act. users in cell}\}}{\text{average number of active users in cell}} \qquad (1)$$

where $\Pr\{n$ act. users in cell$\}$ is the probability of n active users within a cell and pdp$\{n$ act. users in cell$\}$ is the steady-state packet dropping probability for a single cell with n active users. The calculation of this packet dropping probability can be found in [5].

The probability of n active users within a cell is, with an assumed uniform distribution over the entire system area, equal to:

$$\Pr\{n \text{ act. users in cell}\} = \binom{N_u}{n}\left(\frac{P_a}{N_c}\right)^n \cdot \left(1-\frac{P_a}{N_c}\right)^{N_u-n} \quad (2)$$

where P_a is the probability of a user being active. With the average number of active users per cell being equal to $N_u{*}P_a/N_c$ equations 1 and 2 can be combined to:

$$\text{pdp} = \sum_{n=0}^{N_u}\left[n.\binom{N_u}{n}\left(\frac{P_a}{N_c}\right)^n \cdot \left(1-\frac{P_a}{N_c}\right)^{N_u-n} * \text{pdp}\{n \text{ act. users per cell}\}\right] * \frac{N_c}{N_u * P_a} \quad (3)$$

For the case where we have one hot-spot cell the probability of n active users within any of the non hot-spot cells becomes:

$$\Pr\{n \text{ act. users in non hotspot cell}\} = \binom{N_u}{n}\left(\frac{P_a}{N_c-1+Hf}\right)^n \cdot \left(1-\frac{P_a}{N_c-1+Hf}\right)^{N_u-n} \quad (4)$$

while for the hot-spot cell we have

$$\Pr\{n \text{ act. users in hotspot cell}\} = \binom{N_u}{n}\left(\frac{Hf * P_a}{N_c-1+Hf}\right)^n \cdot \left(1-\frac{Hf * P_a}{N_c-1+Hf}\right)^{N_u-n} \quad (5)$$

combining equation 1 with equation 4 or 5 gives us the packet dropping probability for a non-hot-spot cell and a hot-spot cell for the case of inhomogenous traffic.

4. Results and Conclusions

The results are obtained for a system with $N_c = 50$ cells, the number of users N_u varies with the traffic load according to $N_u{=}N_c{*}m/P_a$ where m is the traffic load. The probability P_a of a user being active is chosen as 0.2. The probability P_s of transmitting in an unreserved timeslot is 0.5, the number of timeslots per frame N_s is equal to 21 for the STRMA system and thus 7 for the PRMA system.

In figure 4 we show the packet dropping probability versus the traffic (per cell) for both the STRMA protocol and the PRMA protocol with fixed reuse pattern. This figure is for the case where we have uniformly distributed traffic over the whole system area. As we can see from the figure the STRMA protocols offers an improved performance over the whole range of traffic load.

If we would take the 1% pdp as the limit for an acceptable voice connection, the fixed reuse PRMA system can handle a traffic load of about 7 Erlang per cell while the STRMA system can handle about 10 Erlang/cell.

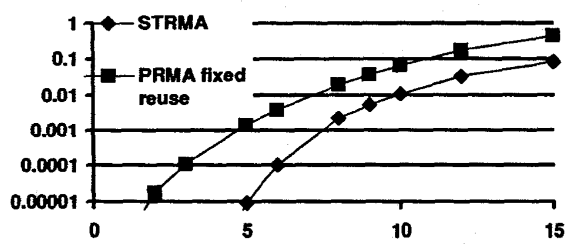

Figure 4: The packet dropping probability versus traffic for the STRMA and fixed reuse PRMA system, homogenous traffic

We can explain the improved performance of STRMA by observing the following:
If, for the fixed reuse system, a cell is highly loaded and has all its 7 timeslots occupied, new active users cannot be served in that cell. In the STRMA system however a highly loaded cell can 'borrow' timeslots from neighbouring cells up to the maximum of 21 timeslots, provided the neighbouring cells are less loaded.

From the observation above, we expect the STRMA protocol to perform even better (compared to the fixed reuse PRMA system) with inhomogenous traffic where there is a higher probability of a particular cell (or small group of cells) having a high traffic load while the surrounding cells have a much lower load. To study this we have also performed simulations where one cell, the so-called hot-spot cell, has a traffic load that is a factor H_f (the hot-spot factor) higher than the traffic load in the other cells.
For the STRMA protocol the introduction of a hot-spot cell will result in a higher dropping probability for this cell, due to the higher traffic load. But the dropping probability in surrounding cells will also be higher because voice channels will be borrowed from these cells so the number of available channels in the cells will decrease. If we assume that the borrowing effect does not stretch out much further than the first tier of cells surrounding the hot-spot cell, the interesting performance measures for the STRMA protocol with inhomogenous traffic are: the packet dropping probability in the hot-spot cell, the packet dropping probability in the first tier of cells surrounding the hot-spot cell and the packet dropping probability in the rest of the network.
For the PRMA protocol the effect of a hot-spot cell does not extend beyond the hot-spot cell itself because there is no channel borrowing. So there is no difference in the packet dropping probability among any of the non hot-spot cells.

Figure 5 shows the packet dropping probability versus the traffic (per non hot-spot cell) for the STRMA protocol and the PRMA protocol with fixed reuse pattern, using inhomogenous traffic with a hot-spot factor of 1.8. The figure shows the pdp for the hot-spot cell, the first tier surrounding the hot-spot and the rest of the system. Figure 6 shows the same pdp's but now for a hot-spot factor of 1.4.

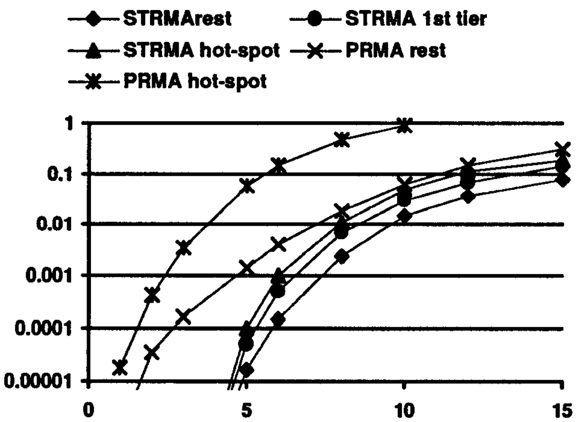

Figure 5: The packet dropping probability versus traffic for the STRMA and fixed reuse PRMA system, non-homogenous traffic, hot-spot factor of 1.8

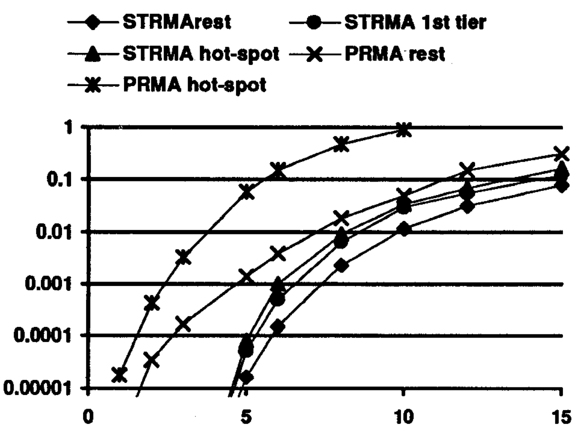

Figure 6: The packet dropping probability versus traffic for the STRMA and fixed reuse PRMA system, non-homogenous traffic, hot-spot factor of 1.4

What we can see from the figures is that the packet dropping probability in the hot-spot cell is much lower for the STRMA protocol than for the PRMA fixed reuse protocol. Even if the hot-spot factor is 1.8. The packet dropping in the hot-spot cells and the first tier surrounding the hot-spot cell is almost the same, while the packet dropping in the rest of the system is not much different from the homogenous case (compare figures 5 and 6 with figure 4). So the channel borrowing spreads the effect of one highly loaded cell over an entire tier of cells. Because of this the pdp in this entire tier becomes somewhat larger although it still stays below the pdp of a non hot-spot cell using the PRMA fixed reuse protocol.
The difference between the hot-spot factor of 1.8 and 1.4 is a slightly higher pdp in the hot-spot cell and the first tier for the factor of 1.8.
All in all we can conclude that STRMA is highly tolerable to high traffic in a single cell.

This simulation study is intended as a first look at the STRMA protocol. Further simulation studies are being performed for STRMA systems transmitting both speech and data and for more elaborate models of inhomogenous traffic. Future research will concentrate on the modelling of STRMA systems. Work in this direction is in progress at Delft and at U.C. Berkeley (J. Davis, [6]).

5 Acknowledgement

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6 References

[1] D.J. Goodman, R. A. Valenzuela, K.T. Gayliard and B. Ramamurthi, "Packet Reservation Multiple Access for Local Wireless Communications", Proceedings 38th IEEE Vehicular Technology Conference, Philadelphia, US., June 1988, pp. 701-706

[2] J.P.M.G. Linnartz, "Contiguous frequency assignment in wireless packets switched networks", Proceedings IEEE Personal Indoor and Mobile Radio Communications (PIMRC) Int. Conf. , Sept. 1993, Yokohama, Japan, pp. 327-331

[3] J. Chuang, "Performance issues and algorithms for dynamic channel assignment", IEEE journal Select. Areas Comm., Aug. 93, pp. 955-963

[4] D.J. Goodman et al, "Distributed channel assignment schemes", IEEE proceedings Vehicular Technology Conference", New York, U.S.A, May 1993, pp.

[5] Casper van den Broek and Ramjee Prasad, "Effect of capture on the performance of the PRMA protocol in an indoor radio environment with BPSK modulation", Proceedings 44th IEEE Vehicular technology Conference, Stockholm, Sweden, June 1994, pp. 1223-1227

[6] J.Davis, "Space Time Reservation Multiple Access", World Wide web, http://infopad.eecs.berkeley.edu/~davisj/STRMA/strma.htm, Feb. 1995.