RVK 99: Adaptive Antennas in Spatial TDMA Multihop Packet Radio Networks

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Abstract

Multihop Packet Radio Networks (MHPRN) is an alternative for reliable rural data transmission where no telecommunication infrastructures exist. A key issue in designing such networks is the selection of Medium Access Control (MAC) strategy. Spatial TDMA is a MAC protocol proposed for MHPRN where links are pre-assigned time-slots according to a schedule in such way that interference is avoided allowing dense reuse of time slots within the network. Terrain obstacles act as shields to interference and may produce better performance. In this paper it is shown that use of simple adaptive directional antennas in rough terrain considerably improve the throughput and delay performance of MHPRN using STDMA. Using four-element linear antenna arrays at both transmitter and receiver ends of a link controlled to maximize the received power, provide a significantly reduction in the average packet delay and up to 70% capacity improvement respect to a reference system using omnidirectional antennas.

1 Introduction

Self-organizing store-and-forward packet radio networking is an interesting technique in many “ad-hoc” wireless communication systems, where a base station infrastructure cannot be provided. Rural communications in developing countries, military tactical networks and public safety systems are typical examples of such systems. Such a network consists of a number of communicating radio units, nodes dispersed in some more or less unknown pattern over some unknown terrain. Due to low power or poor propagation conditions the radio range of the nodes is limited and it may therefore in many cases be necessary to relay messagesmessages (packets) over multiple nodes before the final destination is reached. In such multihop packet radio networks[1], a message may travel long distances by means of the store-and-forward mechanism: a node transmits a packet on the wireless link to another node, which in turn forwards the packet. In the design of these networks one may identify three types of problems which are distinctly different from those found classical digital radio communications: the *multi-access* problem; how should we allocate of pertinent radio spectrum resources for the individual broadcast link transmissions such that the resource utilization and the collective performance is satisfactory, the *routing* problem; how can a message find its way to the final destination? (this is in particular difficult if the nodes are mobile), and finally, the *network control* problem; how can the network flows be controlled and the integrity of the network resources be maintained to allow for reliable operation as the network topology may change. In this paper we will focus on the first, the multiaccess problem.

The classic approach to multi-access in packet radio system is to use “contention” or Random TDMA protocols such as ALOHA and CSMA[2][3][4]. In these schemes the nodes make independent and randomized transmission decisions for each packet transmission. The advantage of these schemes is mainly their simplicity, that they require no other coordination between the nodes combined with rather acceptable performance at low traffic loads, i.e. when efficient resource utilization is not a major concern. The drawback is the unavoidable collisions at moderate and high traffic loads, i.e. the destructive contention for the radio channel, causing mutual interference to the receiving nodes resulting in packet loss, (excessive) retransmissions, delay and poor resource utilization.

Several *conflict free* MAC protocols have been proposed in the literature to remedy this situation. A simple way to provide conflict free access, would be Frequency or Time Division Multiple Access (F/TDMA), where every node would be assigned an exclusive frequency or time slot. For sparsely connected networks this is however highly inefficient since most time-slots would be perceived to be idle. In order to increase the capacity, Spatial TDMA (STDMA) has been proposed[5]. Here the capacity is increase by spatial reuse of time slots i.e. two or more nodes can transmit on the same time slot provided that the mutual interference is kept at bay.

In an STDMA system, time slots are assigned in a *schedule*, i.e. a repetitive pattern of time-slots of finite length. Slots can be assigned to transmitter (transmitter scheduling) or individual (unidirectional) links (link scheduling). Figure 1, illustrates a simple 5 node network with all possible radio links indicated by lines connecting the nodes. In this network it would, for example, seem feasible to reuse the time slots used for communication on the links 3→1 and 4→5, whereas 5→4 and 3→1 would probably not be able to share the same slot.

The design of STDMA scheduled has received some attention in the literature. Short (low delay) link schedules adapted to the traffic pattern have been discussed in[6][7][8]. Distributed implementation of SDTMA has also been an important subject[9]. Most early contributios in the field describe the network as a binary graph, i.e. two nodes are either connected and able to communicate reliable, or disconnected and not even able to disturb the transmissions of one another. Schedules were base on pairwise link compatibility. More realistic models taking radio propagation conditions have been proposed[3]. In particular the fact that combinations of "links" each not suitable for communication, still individually or as a group, may be capable of interfering with other links has be investigated in [7][10]. In the latter two references, schedules for mobile networks in actual (or simulated) terrains were studied. The investigations in [10] show that the character of the terrain has significant impact on the performance (in terms of delay and network capacity) of these networks. Rough (mountainous) terrain makes it more difficult to achieve a fully connected network, but when this is achieved, it has the advantage of "shielding" the nodes from interference yielding more efficient STDMA schedules. In this paper we will investigate, whether *directional antennas* could be used to further exaggerate this shielding effect in order to even more improve the performance of multihop STDMA networks. Earlier work on ALOHA-type multihop networks with directional transmitting antennas and very simple propagation models[11], indicate that considerable gains could be made. We will evaluate the performance in a random terrain network utilizing very simple, steerable (adaptive) directional antennas. We compare the results with the system using conventional omnidirectional antennas.

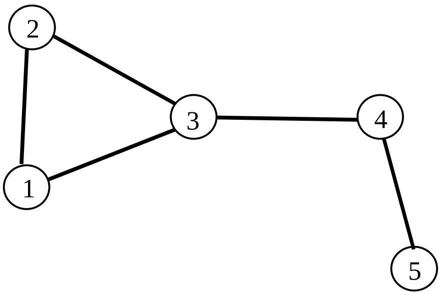

Figure 1: Multihop network example

2 System Models

2.1 Link quality modeling

The networks studied in this paper consists of a collection N of nodes spread randomly over a (synthetic) terrain. The terrain height variations are modeled by a stationary two-dimensional random process[10], H(x,y), in the locations (x,y)

$$H(x,y)=\sum_{k=-x_0}^{x_0}\sum_{l=-y_0}^{y_0}\left|H^*(x-k,y-l)\right|\cdot p(k,l),$$

where H*(x,y) is a two-dimensional white Gaussian process with zero mean and variance σ (height parameter), and where p(x,y) can be seen as the impulse response of a filter given by:

$$p(x,y)=\begin{cases}1+\cos\left(\pi\left(\frac{x^2}{(\rho+1)^2}+\frac{y^2}{(\rho-1)^2}\right)\right) & |x|\le(\rho+1),\quad |y|\le(\rho-1)\\ 0 \quad \textit{otherwise} & \end{cases}$$

where ρ is referred to as the smoothness parameter in meters. Figure 2 shows a realization of such a terrain.

The path gain between node i and node j is denoted Gij, which according to [12] can be split into three components: a distance dependent path loss, a plane earth propagation loss, and a (multiple knife-edge) diffraction loss due to the mountains in our terrain model. The path gains computed in this way are used to determine the total received power at node j when receiving a signal from node i as

$$P_{ij}=P_iG_{ij}A_T(\theta_{ij})A_R(\theta_{ji}) \qquad (1)$$

where A_T and A_R denote the (horizontal) antenna patterns of the transmitter and receiver antennas relative an isotropic radiator. $\theta_{\iota\varphi}$ denotes the angle to node j as seen from node i relative some given reference direction. We will assume that node i and j are connected if the propagation gain G_{ij} between them is higher than some threshold G_0 = -130dB in the sense that messages are correctly detected in absence of external interference from other nodes. Using this criterion the connectivity diagram for a sample networks is shown in figure 4. The study was confined to connected networks, i.e. networks where every node can be reached.

In STDMA system two or more stations may transmit in the same time slot provided that the Signal-to-Interference Ratio (SIR) in all these links is above a certain threshold γ_0. Let us assume that transmissions are in progress in a set of links *L*. Computing the SIR in link (*i*,*j*) in this set yields the requirement

$$\Gamma_{ij}=\frac{P_iG_{ij}A_i(\theta_{ij})A_j(\theta_{ji})}{\sum\limits_{\forall(k,l)\in L\backslash(i,j)}P_kG_{kj}A_k(\theta_{kj})A_j(\theta_{jk})}\ge\gamma_0 \qquad (2)$$

where A_i is the radiation pattern (relative intensity) of the antenna at node i.

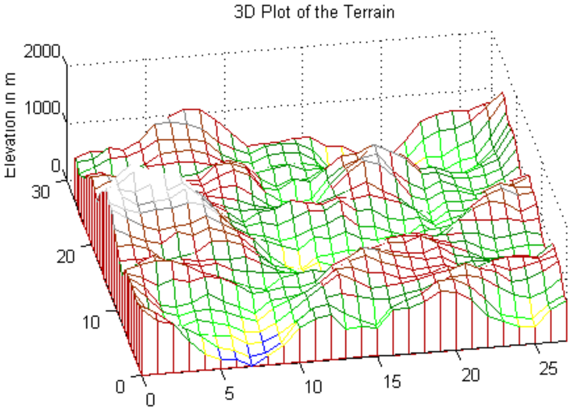

Figure 2: Plot of terrain realization. σ = 40 meters, ρ = 5 meters. Heights vary between 0 and 1200 meters, and the area is 28x28 km2. (Vertical scale strongly exaggerated)

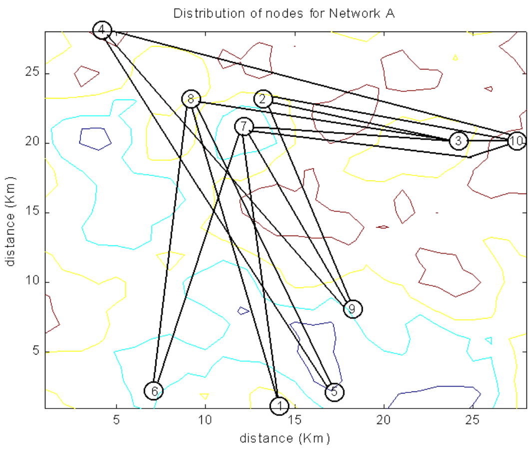

Figure 3: Typical network realization in terrain in figure 2. N=10. Lines indicated possible communication link (with received power exceeding noise threshold)

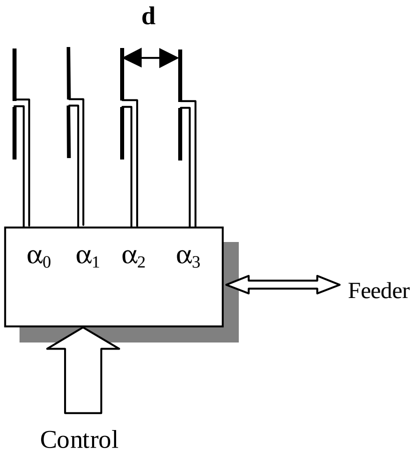

Figure 4: Antenna array

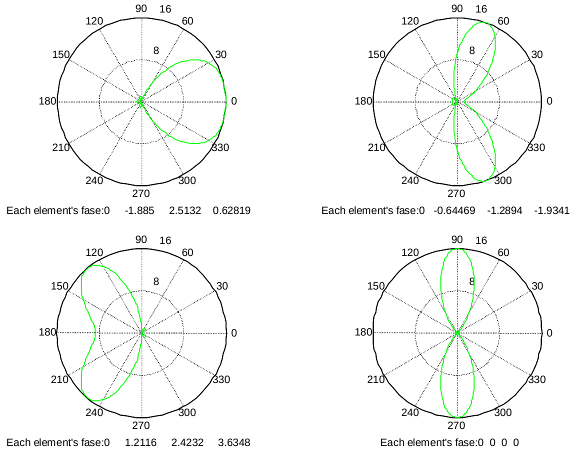

Figure 5: Typical antenna radiation patterns

2.2 Antenna adaption scheme

Now, each of the nodes is equipped with an electronicly steerable antenna that is used both for transmission and reception. The antenna can be adapted for every individual timeslot, independently of prior control settings. Since the antenna size and complexity are important constrains, without loss of generality, we limit the study to a simple four-element vertical antennas array as shown in Figure 4. This array consists of 4 uniformly spaced vertical dipoles separated by distance d. In order to control the radiation patter of the array, the phases □i of the signals fed to it are controlled by the node.

In the following evaluation, the antenna adaption algorithm will be simple; for each link (i,j) we maximize the received signal power such that both the transmitter and receiver adjust their antennas to achieve:

$$A_i^*(\theta) = A_i(\theta;\alpha_1^*,...\alpha_4^*)$$

$$\text{where} \qquad (3)$$

$$(\alpha_1^*,...\alpha_4^*) = \arg\max_{\alpha_1,...\alpha_4} A_i(\theta_{ij};\alpha_1,...\alpha_4)$$

The antenna pattern of the receiving antenna in node j is computed in same manner.

2.3 Traffic, Routing & STDMA Scheduling

We assume that packets are of constant length and arrived according to a Poisson process with total (external) arrival rate λ packets/time slot. Further we assume the traffic load to be even, i.e. onthe average each node

$\lambda_i = \lambda/N$ i ∈ {1, 2, .. N}

The traffic originated at node i destined to node j, is denoted μ_{ij}. Assuming the destinations to be random and uniformly distributed, we have

$$\mu_{ij} = \begin{cases} \dfrac{\lambda_i}{N-1} & i \neq j \\ 0 & i = j \end{cases}$$

The μ_{ij}:s can also be seen as the elements of the traffic matrix. The routing scheme used is a simple minimum hop routing scheme, i.e. minimizing the number of hops in a multihop "connection". The routing is performed in advance ("table routing") and is independent of the access schedule and the actual traffic flows. Nodes are assumed to have infinite buffer size for intermediate storage of packets.

In this work we use the algorithm presented by Grönkvist [7]as a method to derive the STDMA schedule in our network. The positive thing in this algorithm respect to others is that the scheduling combine the relative traffic load over each link and the signal interference ratio in order to decide which links are allow to transmit during one slot.

2.4 Performance measure

The primary performance measure is the average expected end-to -end packet delay. The end-to-end packet delay is defined as the time between the arrival of a packet at the buffer of the originating station and the end of the slot in which is successfully received at the final destination. In a network of N nodes, in general, a randomly selected packet to be transmitted from node i to node j has the delay D_{ij}, expressed in timeslots. Since D_{ij}, is a random variable, why we chose to study its expected value $E[D_{ij}]$.The average expected delay for all source-destination pairs is given by

$$\overline{D} = \frac{1}{\binom{N}{2}} \sum_{j=1}^{N} \sum_{i=j+1}^{N} E[D_{ij}] \qquad (4)$$

In general, $\overline{D}$ is a function of the traffic load and the terrain parameters, which influence the connectivity of the network.

3 Numerical Results

Simulations have been used to evaluate the expected packet delay in the same terrain that with a vaying height scale to simulate different terrain roughness. 10 nodes have been randomly dispersed over this terrain until a connected network was found, i.e a network where every node is reachable at least in a finite number of hops. Two such networks, denoted A and B are used in the numerical examples below. Since the schedule is collision free, we further assume that all message are perfectly received.

Figure 6 and Figure 7 show the delay results for network A (in Figure 3) and a different network realization in the same terrain (network B) respectively using three different height parameters. As expected, respect to the omnidirectional antenna case. A reduction in the average packet delay of 50-70% a low to moderate traffic loads is achieved in both sample networks. The main reason of this is that the frame duration decreases as illustrated by table 1. In both networks, the increasing the terrain roughness parameter reduces the connectivity, i.e. the average number of neighboring nodes a node can reach by means of a one hop transmission. Note for instance that in the (almost) flat terrain case (σ=1m), network A is "fully" connected, i.e. all nodes can be reached in a single hop. As expected, the improvement by using the directional antennas is as most pronounced here. For more rough terrain the number of neighbors goes down, and thus also the interference experienced. Nevertheless, the directional antennas still provide quite significant gains in network A as can be seen in the frame length column for the case σ=40m. In other networks, the limited connectivity may limit the gains by using the adaptive antennas. This can be seen in network B for σ=40m and σ=20m, where in fact a significant improvement is reached using adaptive antennas the frame lengths are the same for the adaptive antenna case. The result is approximately equal performance for relative low traffic. For higher loads, however, better performance is achieved for the case σ=20m due to the improved connectivity, providing more links to be actually scheduled.

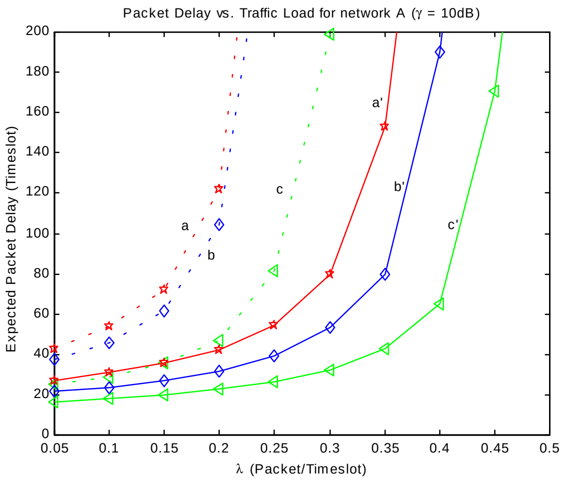

Figure 6: Packet Delay vs. traffic load(Network A, γ_0= 10dB. Omnidirectional antennas a : σ = 1m, b : σ = 20m, c : σ = 40m. Adaptive antennas a', b', c' with corresponding parameter settings.

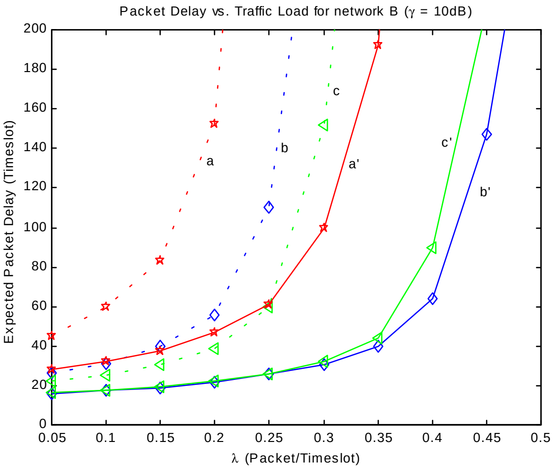

Figure 7: Packet Delay vs. traffic load for a different network (Network B) realization in the same terrain as in Figure 6.

4 Conclusions

The study presented in this paper demostrates that the performance of multihop packet radio networks can be considerable improved by using adaptive directional antennas. Significant gains (50-70% in capacity) compared to a system with omnidirectional antennas can be achieved already for a four-element antenna and a simple maximum-gain array processing scheme.

Considering some of the implementation aspects, achieving antenna adaptivity in a fixed or slowly mobile network does not require any complex arrangements. The antenna parameters for each time slot can be determined at the same time the schedule is determined.

The same parameters are used for the respective timeslot until the schedule is changed due to significant topology changes in the network. Further work would include studying more advanced array processing, jointly optimizing the scheduling and maximizing the signal-to-interference ratios.

σ (m)	Frame Size Omni	Frame Size Adaptive	Avg. # eighbors	Avg #hops
1	71	48	9	1
20	62	39	4.8	1.47
40	34	23	3.2	1.8

Table 1: STDMA frame size and characteristics of sample Network A for various terrain characteristics. A "neighbor" is a node reachable in one hop.

5 References

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