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Broadcast in Multirate Ad Hoc Networks

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Abstract

Transmission time on a single radio link decreases with increasing data rate. In a broadcasting setting in an entire ad hoc radio network, this is not necessary so, since the number of retransmissions needed may grow with increasing data rate due to reduced transmission range. Often there is a non-trivial optimum rate to be found.

We have studied the problem of optimizing the total time needed for broadcasting a message in an ad hoc radio network under the assumption that data rate can be traded for transmission range. We have analyzed this from a theoretical point of view and found optimal rates to use, given some model assumptions. Based on these finding we have proposed a rate choice algorithm and compared it to some other rate choice algorithms under realistic assumptions about the communication parameters. It was found that the proposed algorithm yields a good performance in most cases while at the same time being well suited for implementation in a distributed environment.

Keywords: Ad hoc networks, MPR, broadcast, multicast, adaptive data rate, multirate

Sammanfattning

Transmissionstiden på en enskild radiolänk minskar med ökande datatakt. I ett broadcastsammanhang i ett helt ad hoc-radionät är detta inte nödvändigtvis fallet, eftersom antalet vidaresändningar som behövs kan väsa med ökande datatakt på grund av minskad räckvidd. Ofta finns en icketrivial, optimal datatakt.

Vi har studerat problemet att optimera den totala tiden som behövs för att skicka ett meddelande som broadcast i ett ad hoc-radionät under antagandet att datatakt kan bytas mot räckvidd. We har gjort en teoretisk analys och funnit optimala datatakter, givet ett antal modellantaganden. Baserat på dessa fynd har vi föreslagit en algoritm för att välja datatakt och jämfört den med några andra sådana algoritmer under realistiska antaganden om nödvändiga kommunikationsparametrar. Vi fann att den föreslagna algoritmen ger bra prestanda i de flesta fall, samtidigt som den är väl lämpad för att användas i en distribuerad miljö.

Nyckelord: ad hoc-nät, MPR, broadcast, multicast, adaptiv datatakt, multipla datatakter

Contents

1 Introduction

Broadcasting is not as well studied as unicasting in the context of ad hoc networks, and the problems are in some senses very different. The trivial solution, using repeated unicasting to reach all nodes in the network, is inefficient. In military scenarios broadcasting is an essential mode of communication and an efficient implementation is important. Situation awareness data and orders are important examples of information that may need to be broadcast to all nodes in a network. Thus we believe that there is a need for a more thorough analysis of how broadcasting can be efficiently implemented in ad hoc networks.

The data rate is an important parameter in any communication situation, with higher rates usually being desired. However, in the case of radio based multi-hop networks it can sometimes be more efficient to use a lower data rate. The reason for this is that a lower data rate may allow a longer transmission range and thus fewer retransmissions to reach the destination node(s). In the case of broadcasting this effect can be very pronounced since with a low data rate (long range) very many nodes can be reached with each single transmission. However, for very low data rates the communication will be inefficient since we get longer ranges than are necessary. For very high data rates the transmission ranges will be insufficient to make the network connected even with the use of relaying. This means that for each network there exists an optimal assignment of data rates to the nodes in the network, somewhere in between the very high and the very low data rates.

We believe that more efficient broadcasting in ad hoc networks can be achieved using variable or multiple data rates in the network. With efficient broadcasting we mean that the network is kept connected and that the amount of broadcast data per time unit is large given the available bandwidth.

In Section 2 we describe the model and the assumptions used in the report. In Section 3 we treat broadcasting theoretically, modelling it as an area covering problem. The simplified model allows us to find an expression for the optimal data rate. In Section 4 we define a realistic rate choice algorithm based on the theoretical findings and compared it with three other rate choice algorithms. Section 5 contains conclusions and discussion.

2 Model and Assumptions

To see how communication cost and network data rate are related we will study broadcast transmissions in static, random networks with a given number of nodes, n, within a predefined, square area with sides of length L. The positions of the nodes are chosen uniformly at random on the predefined area. Each node will use one single data rate and the transmission range will follow from this choice, as will be described later in this section. Two nodes, a and b, are considered having a communication link between them if they are both within each other's transmission ranges. The set of all such links make up the network.

2.1 Broadcasting Cost Measure

In order to evaluate performance we need a communication cost measure. The one we have chosen is the sum of the inverted rates, $1/R$, of all transmissions (the transmissions of the source and the relaying nodes) used in a broadcast. Using this cost measure, the cost of a broadcast is directly proportional to the total amount of network resources it uses, which we define as the time the network spends on the transmissions. Notice that this measure is not necessarily the same thing as the network latency.

2.2 Radio Interface

For each pair of nodes a, b in the network, the maximum possible data rate R_{max} will be taken as the channel capacity for an Additive White Gaussian Noise (AWGN) channel, taken from [1]:

$$R_{max} = W \log_2(1 + S/N). \tag{1}$$

If both a and b use a rate of at most R_{max} they are assumed able to communicate directly, without any relaying.

The capacity of an AWGN channel is defined by the signal-to-noise ratio (SNR), which can be found using a link budget for the radio channel:

$$\frac{S}{N} = \frac{P_t G_t G_r}{L_b F k T_0 W}, \tag{2}$$

where S is the signal level, N is the noise level, P_t is the transmitted power, G_t and G_r are the gains of the transmitter and receiver, L_b is the elementary path loss (signal attenuation between the transmitting and the receiving antenna), F is the noise factor of the receiver, kT_0 is the noise level at reference temperature $T_0 = 290$K and W is the bandwidth.

We first turn to L_b, the elementary path loss. The path loss is often modeled as proportional to the distance d raised to some power α. Free-space propagation gives $\alpha = 2$, while the plane-earth model [4] gives $\alpha = 4$. We will use the plane-earth model throughout this report, yielding $L_b = d^4/(h_1 h_2)^2$, where d is the distance between transmitter and receiver, and h_1 and h_2 are the elevations of the antennas. We will further use the following parameter values: $P_t = 1$, $G_t = G_r = 1$, $kT_0 = 4 \times 10^{-21}$, $F = 25$ and $(h_1 h_2)^2 = 40$ (i.e. $h_1 = h_2 \approx 2.51$). We let W be a variable and d will be given by the placements of the nodes. Taken together we get the SNR as:

$$\frac{S}{N} = \frac{4 \times 10^{20}}{W d^4}. \tag{3}$$

Using (3) in (1) yields the following upper bound on R, for the radio channel:

$$R \leq W \log_2(1 + \frac{4 \times 10^{20}}{W d^4}), \tag{4}$$

which is the expression we will use, with equality, for linking data rate to transmission range in this report.

In a real system the actual data rate will never reach the channel capacity, but we need a relation between the data rate and the transmission range, and for simplicity we use the capacity expression combined with the link budget to get this relation. This means that in reality the cost measure values will be greater than what we find in our analyses and simulations.

3 Optimal Transmission Range

In this section we will make a theoretical analysis to find an efficient transmission rate to use for broadcasting. To do so we make the assumption that broadcasting to all nodes in the network is equivalent to covering the entire surface with receivable radio transmissions. Each transmitting node will contribute a disk-shaped area with a radius given by the d in (4). The set of transmitting nodes must be such that the union of the disks forms a superset of the network surface. This model is reasonable if the number of nodes is large so that no point on the surface is far from a node. We also have to take into account that each relaying node has to receive the message from at least one other node, yielding disks that are very much overlapping. We further assume that all nodes have the same transmission range and that the network surface is large compared to the disks, so that their relative geometry does not change significantly with different transmission ranges. Under these assumptions we will derive an expression for the optimal transmission range.

3.1 Analysis

We express the transmission cost per covered area as $T(d) = (1/R)/k_3 d^2 = 1/k_3 d^2 R$, where k_3 is a constant depending on the covering efficiency (the average fraction of each transmission that is not overlapping any other transmission), d is the transmission range and R is the data rate. The constant k_3 will depend on the broadcast algorithm and the exact placement of the nodes in the specific scenario, but assuming we have a dense set of nodes and a large area (compared to the transmission range) over which the nodes are scattered, k_3 will be relatively stable between different setups. We use (4) to express R in d, change to natural logarithm base, finding the following expression for the transmission cost per covered area:

$$T(d) = \frac{\ln(2)}{k_2 k_3 W d^2 \ln(1 + \frac{4\times 10^{20}}{W d^4})}. \tag{5}$$

We would like to minimize (5) with regard to d. We note that $T(d) \to \infty$ both when $d \to 0$ and when $d \to \infty$. Since $T(d)$ is continous and finite for positive d it has at least one minimum. Differentiating and equating with zero will, after some tedious work, yield (numerically) a unique transmission range value:

$$d_{opt} \approx 1.005 \times 10^5 / W^{1/4}. \tag{6}$$

Using (6) it is easy to express the optimal transmission range (and thereby data rate) for a given bandwidth, and it is this we use in Section 4 and compare to some other ways of choosing the data rate in a broadcasting scenario. In Figure 1 below is shown the relations between optimal transmission range/data rate and bandwidth

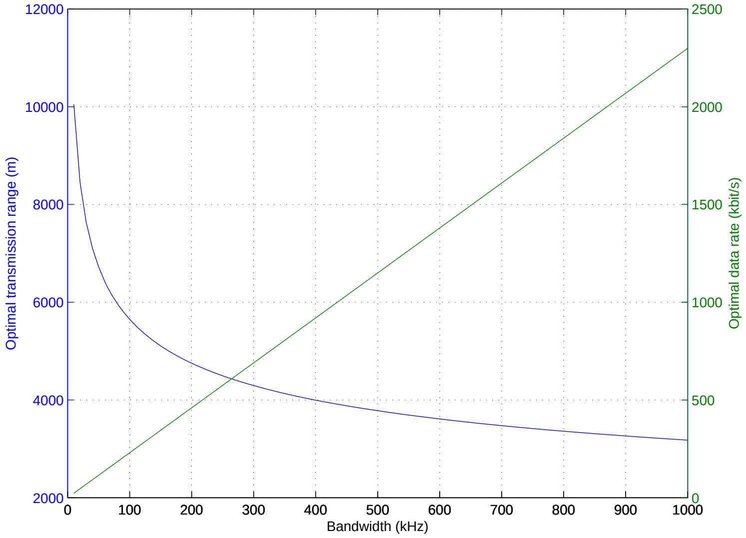

Figure 1: Optimal transmission range (blue) and data rate (green) as a function of bandwidth. Note that the intersection between the curves has no special interpretation.

4 Experiments with Rate Choice Algorithms

In this section we evaluate a number of algorithms for choosing the data rates of the nodes. None of the algorithms are very complex, since we are interested mainly in such that are realistic to implement in a real system. We will do simulations with the different algorithms for a number of different parameter settings to better to be able to compare the algorithms.

4.1 MPR Broadcast Algorithm

The rate choice algorithms decide the data rate (and thus the transmission range) for each node in the network. This results in a set of links which can be used for enabling the message broadcasting. Two of the rate choice algorithms we will compare need an underlying, general broadcast algorithm to work. For this we have chosen the multipoint relay (MPR) flooding algorithm [2, 3, 5]. This is a distributed broadcast algorithm which has proven to be both robust and efficient in ad hoc networks.

The MPR broadcast algorithm works in the following way, using graph theoretical notation: Two nodes are considered *neighbours* if they are distinct and can communicate directly with each other in both directions, without need for relaying. Two nodes are considered *second-neighbours* if they are distinct and have a neighbor in common. For each node ν we define a set of neighbors N_1^ν and a set of second-neighbors N_2^ν, where $\nu \notin N_1^\nu$, $\nu \notin N_2^\nu$ and $N_1^\nu \cap N_2^\nu = \emptyset$. The MPR set ν_{MPR} of the node ν is then chosen as a subset of N_1^ν such that the neighbors of the nodes in ν_{MPR} form a superset of N_2^ν. How ν_{MPR} is chosen will affect the communication cost.

In our experiments ν_{MPR} has been chosen in the following, heuristically minimizing way, taken from [5]:

- Let $\nu_{MPR} = \emptyset$ at the beginning.
- First add to the MPR set ν_{MPR} all neighbors of ν that are unique in reaching some second-neighbors of ν.
- Add other neighbors in order of how many further (previously unreached) second-neighbors are reached. If there are several neighbors reaching the same number of previously unreached second-neighbors, add the one reaching more second-neighbors of ν,regardless of whether they are already reached or not.
- The heuristic is stopped as soon as the neighbors of the nodes in ν_{MPR} becomes a superset of N_2^ν.

Broadcasting of messages to all nodes has been performed in the following way, also taken from [5]:

- **When ν is the source of the message:** ν transmits the message once. Other nodes will retransmit the message so that every node receives it.
- **When ν is not the source of the message:** if ν hears another node μ (which may or may not be the source of the message) transmitting a broadcast, and if ν has not heard the message previously, and if ν is an MPR-node of μ ($\nu \in \mu_{MPR}$) then ν will retransmit the message.

With this algorithm messages that are broadcast are guaranteed to reach all nodes in the network, as long as the network is connected.

4.2 Description of Rate Choice Algorithms

The rate choice algorithms that will be evaluated are the following:

- *Covering Optimal*, meaning that every node will use the same rate, namely that which is optimal in the sense of transmission cost per covered area, as described in Section 3.

- *Direct Broadcast*, meaning that each node chooses the highest rate such that it reaches every other node. This means that each broadcast results in only one transmission.
- *Central Relay*, meaning that the most centrally located node will act as a broadcasting station, using the highest rate such that it reaches every other node. Other nodes will unicast to the central node using the route with the lowest cost, using the highest possible rate, R_{max}, on each link in the route.
- *Optimal Samerate*, meaning that every node will use the same rate, namely that which minimizes the total broadcast cost. The minimization is done individually for each randomly created network. This rate is not possible to find in a distributed manner, and thus this algorithm is not realistic using in a real system. Its value lies in it being a relevant comparison to the covering optimal algorithm.

We note that the covering optimal and optimal same-rate algorithms only differ in the choice of the rate assigned to the nodes in the network.

4.3 Simulation Comparison of Rate Choice Algorithms

In this subsection we present the results of a number of simulations. We have used two standard values for each of the parameters *size* (10 km and 20 km), *bandwidth* (100 kHz and 500 kHz) and *number of nodes* (50 and 200 nodes). We have used every combination of two parameters while varying the third, free parameter over a relatively wide range of values. In total 12 parameter combinations have been simulated, each simulation consisting of five or six values for the free parameter, each of which has been evaluated using 500 randomly created networks. The results are shown in Figures 2, 3 and 4.

We can see that the central relay algorithm becomes worse with increasing bandwidth compared to the covering optimal and optimal same-rate algorithms, which is congruent with the fact that difference between the covering optimal transmission range and the range needed by the central relay increases with increasing bandwidth.

In general the direct broadcast algorithm is worse than the other algorithms. The central relay algorithm is never very bad, and is sometimes even the least costly in the comparison. The optimal same-rate and the covering optimal algorithms are very similar. In a few places the optimal same-rate is worse than the covering optimal algorithm, an anomaly due to the fact that it is difficult to find the exact optimal rate since for a single network the broadcast cost is not continous and often differ wildly even for similar data rates. However, the simulation results show that there is very little to gain from trying to find the single optimal rate to use in the entire network. Instead it is simpler, and probably good enough, to use the covering optimal data rate in all nodes instead.

In the choice between using the central relay algorithm and the covering optimal algorithm, it is much harder to find a single recommendation. In smaller networks the central relay algorithm yields the lower costs, but the difference is not that great.

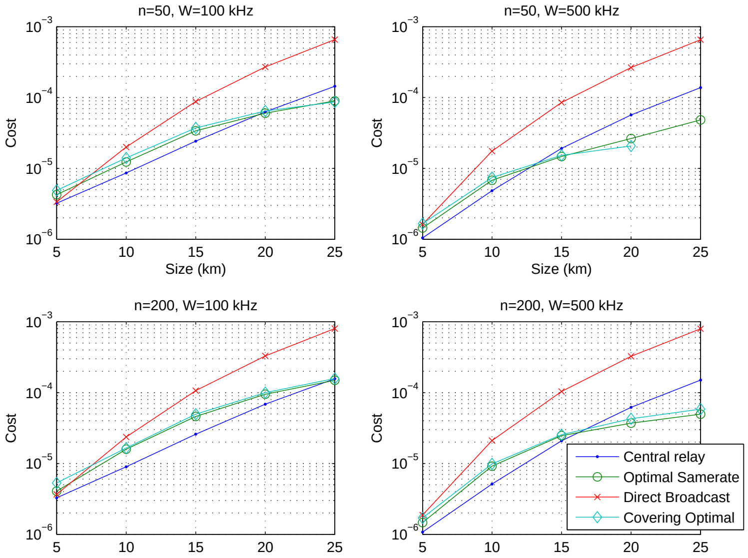

Figure 2: Cost as a function of network size for the different rate choice algorithms.

Instead other factors may be more important. One important example of this is that the covering optimal algorithm is probably simpler to implement since there is no need to find the most central node, and no node has to take on such a special role.

5 Conclusions and Discussion

We have studied some different ways of approaching multiple data rates in mobile ad-hoc networks. Using a theoretical analysis we have found an algorith for choosing the data rate, which is optimal under some simplifying assumptions. This algorithm has been compared to a number of other algorithms for choosing the nodes' data rates. The comparison has been done using simulations, and we have found that the proposed algorithm from the theoretical analysis is a likely candidate for use in a real system. It performs well in most situations and should be straight-forward to implement in a real scenario if the number of nodes is sufficient to keep the network connected.

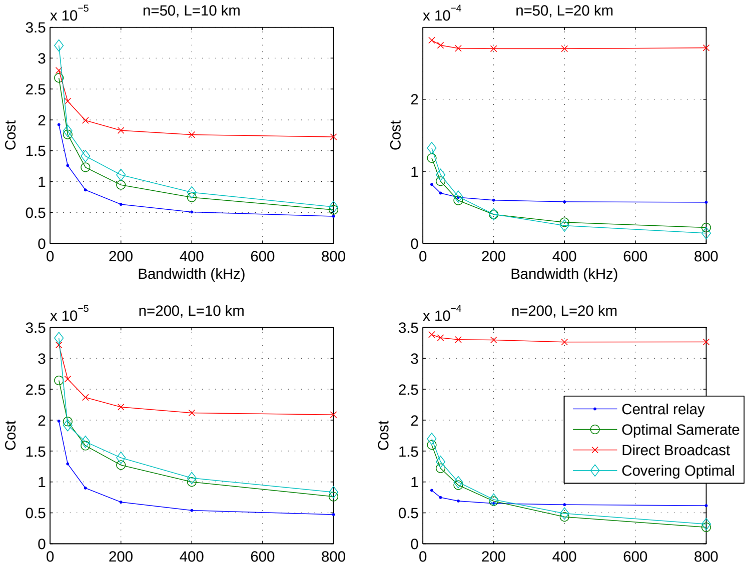

Figure 3: Cost as a function of bandwidth for the different rate choice algorithms. Note that the scales differ on the y axes.

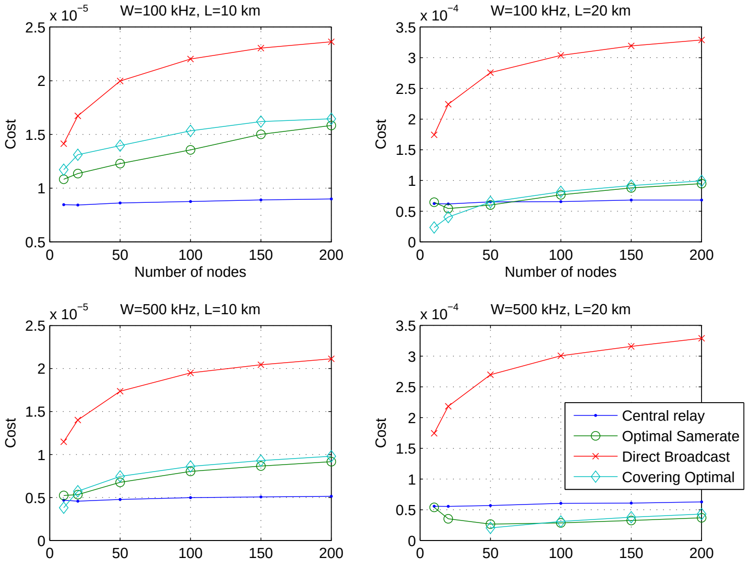

Figure 4: Cost as a function of the number of nodes for the different rate choice algorithms. Note that the scales differ on the y axes.

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