JOINT PHY-MAC LAYER DESIGN OF THE BROADCAST PROTOCOL IN AD-HOC NETWORKS

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ABSTRACT

Broadcast transmission mode in ad hoc networks is critical to support probing and routing procedures. In this paper, we present a novel topology-transparent protocol for broadcasting, which guarantees a minimum average throughput per neighbour. The scheme follows a physical-MAC cross-layer design based on retransmission combining. MAC layer performance is analysed. Coherent detection and separation of contending nodes is possible through training sequences which are selected at random from a reduced set. Guidelines for the design of this set are derived for a low impact on network performance and receiver complexity.

1. INTRODUCTION

The Network-Assisted Diversity Multiple Access (NDMA) protocol [1] provided an innovative signal processing-oriented solution for resolving collisions over the random access channel of cellular slotted systems. NDMA protocol does not discard colliding packets at the BS but combines them with conveniently scheduled retransmissions to extract the information of each individual user. Under the assumption of perfect multipacket reception, if the number of retransmissions equals the number of colliding users, the NDMA protocol radically enhances the throughput and delay performance in spite of the packet overhead needed to identify collisions multiplicity and the needed DL slots to schedule retransmissions.

The applicability of the NDMA protocol is not straightforward in the adhoc case and, to the best of our knowledge, there is no previous work addressing this topic. Two are the differences with respect to the cellular case making impossible the direct application of NDMA within in ad-hoc networks. First, transmissions over the random access channel in cellular systems have a unique intended receiver, the BS. Thus, all colliding packets must be demodulated and scheduled for retransmission. Contrarily, within ad-hoc systems, colliding packets at any receiving node are not always intended to this receiver, and thus, not all of them must be demodulated. Such is the case of transmissions over unicast channels. In broadcast ones, however, all received packets must be demodulated, so it follows that the use of retransmission combining in ad-hoc networks is more suitable for broadcast than for unicast channels.

This work has been carried out in the framework of the EC-funded project ROMANTIK (IST-2001-32549) and supported by Spanish and Catalan Government Grants: TIC2003-05482, TIC2002-04594, TIC2001-2356, TIC2000-1025 and 2001SGR-00268.

The second difference between ad-hoc and cellular systems also complicates the application of the NDMA protocol even for broadcast transmissions. In cellular systems, scheduling for retransmissions is performed over a contention free channel in the DL. Transmission of contention-free feedback is no longer possible for nodes within an ad-hoc network. By direct application of the NDMA protocol to the ad-hoc environment, scheduling information for retransmissions would also be exposed to collisions, which directly entails an intuitively high penalty in performance. This paper presents an alternative to NDMA, which takes advantage of retransmissions combining while eliminating the need for scheduling retransmissions. Compared to previous approaches for topology transparent scheduling using latin squares [3], significant gains in terms of average delay are obtained. The proposed scheme is specially designed and suited for the probing procedure in ad-hoc networks.

2. SYSTEM MODEL

The multi-access scheme assumed is slotted. The probing channel is defined by a set of particular timeslots within allocated radio frames. A timeslot in every frame or in a subset of all frames can be allocated. Nodes are half-duplex. In the phase of nodes discovery and maintenance all nodes transmit with a fixed power, which is the same for all neighbours. It follows that the number of neighbours any node has depends on the spatial distribution of nodes.

3. FF-NDMA PROTOCOL

Retransmission combining is possible if a receiving node detects collisions of the same neighbours during as many slots as the number of collided neighbours. NDMA protocol forces this situation by scheduling retransmissions. Such a situation without feedback is also achievable by forcing every node to transmit the same packet during a fixed number of R slots and thus, allowing resolving collisions of up to R packets at the receiver.

Figure 1 shows an example of the protocol transmission pattern for three users. The probing channel is divided into *contention periods* (CP) of length R. The *probing period* T_i is the number of slots a node i transmits the same packet. The length of the probing period may be different for each node and vary with time. Each node transmits the same packet R times within a CP with probability α (*transmission probability*) and listen to other nodes transmissions and demodulate them with probability $1-\alpha$. No coordinated scheduling among nodes is assumed. So, multiple neighbours may transmit within the same CP.

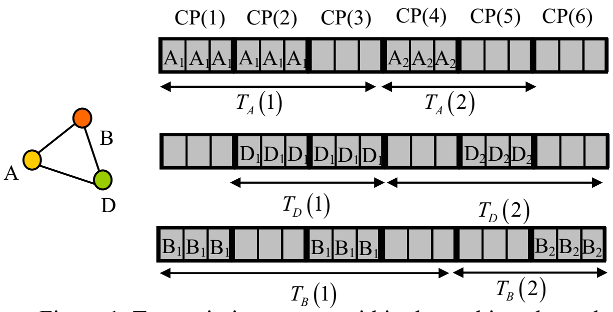

Figure 1. Transmission pattern within the probing channel

At every node, the received signal in a CP is combined when the receiver is listening. The received signal in a CP of length R slots, where K users are present, may be arranged in vector form

$$\begin{bmatrix} \mathbf{y}_1 \\ \vdots \\ \mathbf{y}_R \end{bmatrix} = \begin{bmatrix} \mathbf{A}_{11} & \cdots & \mathbf{A}_{1K} \\ \vdots & \ddots & \vdots \\ \mathbf{A}_{R1} & \cdots & \mathbf{A}_{RK} \end{bmatrix} \begin{bmatrix} \mathbf{x}_1 \\ \vdots \\ \mathbf{x}_K \end{bmatrix} + \begin{bmatrix} \mathbf{w}_1 \\ \vdots \\ \mathbf{w}_R \end{bmatrix} = \mathbf{Ax} + \mathbf{w} \qquad (1)$$

where $\mathbf{x}_k$ contain the L symbols of the k *th* user packet, $\mathbf{y}_r$ and $\mathbf{w}_k$ are the received signal and noise samples in the r *th* slot of a CP, and $\mathbf{A}_{rk} = P_T \; L_k e^{j\varphi_{rk}} \mathbf{H}_{rk}$ contains the transmitted power P_T, the propagation losses between the user k and the receiver L_k, a random phase uniformly distributed in r and k, $e^{j\varphi_{rk}}$, and the channel matrix in the slot r of user k, $\mathbf{H}_{rk}$.

The detection of users is possible if matrix $\mathbf{A}$ is invertible. When the propagation channel conditions are very static, this condition may be fulfilled by choosing a random phase in transmission, as was recognised in [1]. The coherent reception of multiple packets may be achieved through MMSE, BLUE or other receivers [2], and its probability of error affects the performance of the proposed protocol. The analysis of this aspect in fading propagation channels is deferred to a forthcoming publication.

For the coherent detection of colliding packets, nodes must be synchronized at CP level. Moreover, each node uses a single training sequence within a CP, so that the components of the mixing matrix $\mathbf{A}_{rk}$ may be estimated. If two or more users transmit in the same slot with the same training sequence, those users will collide and their packets will be lost. We refer this kind of collision as a *t-MPR collision* (Training-due Multi-Packet Reception Collision) and will be analysed in section 6.

4. ANALYSIS

Under the assumptions that the channel is error free and users may be uniquely identified, it is said that a *MAC MPR collision* occurs when the number of colliding users in a CP is greater than the number of slots in a CP. In this case all the packets in a CP are lost. For the protocol performance analysis only MAC MPR collisions are considered first.

The probing *throughput* of a node with N neighbours $\tau_{N,\alpha,R}$, is defined as the ratio of the average number of successfully received packets from a given neighbour over the average number of packets this neighbour transmitted

$$\tau_{N,\alpha,R} = q_{N,\alpha,R} / \alpha R \qquad (2)$$

where $q_{N,\alpha,R}$ is the probability of receiving a packet from a given neighbour in a CP of length R. When considering only MAC MPR, $q_{N,\alpha,R}$ is the product of three factors

$$q_{N,\alpha,R} = (1-\alpha)\alpha \; \varepsilon_{N,\alpha,R} \qquad (3)$$

From left to right, the probability of the receiver being listening in the CP, the probability a given neighbour transmits, and the probability of up to R-1 other neighbours transmit

$$\varepsilon_{N,\alpha,R} = \sum_{t=0}^{\min(R-1,N-1)} \binom{N-1}{t} \alpha^t (1-\alpha)^{N-1-t}, \varepsilon_{1,\alpha,R} = 1 \qquad (4)$$

The *delay* $\lambda_{N,\alpha,R}$, is the average number of slots needed to receive a packet per neighbour. The number of CPs needed to receive a packet per neighbour x, has a geometric distribution of parameter $q_{N,\alpha,R}$ (3)

$$\chi_{N,\alpha,R,}(x) = q_{N,\alpha,R} (1-q_{N,\alpha,R})^{x-1} \qquad (5)$$

whose mean is $\bar{\chi}_{N,\alpha,R} = 1/q_{N,\alpha,R}$ and the average delay is

$$\lambda_{N,\alpha,R} = R / q_{N,\alpha,R} \qquad (6)$$

The *Effective Throughput* (ET) of a node with N neighbours $\xi_{N,\alpha,R}$, is defined as the average number of received packets per slot and neighbour, and is simply the inverse of the average delay

$$\zeta_{N,\alpha,R} = q_{N,\alpha,R} / R \qquad (7)$$

The probability of receiving a packet of any neighbour in T slots is given by

$$f_T(T) = 1 - (1-q_{N,\alpha,R})^{T/R} \qquad (8)$$

and measures the rate at which network topology may be communicated to neighbour nodes and propagation channel state estimated.

5. PROTOCOL OPTIMISATION

The objective of this section is to determine the optimum values of the transmission probability α and length of the contention period R, so as to distribute adequately the channel resources among users. It is assumed that the maximum number of neighbours of a given node is N_{max}.

The throughput function (2) decreases with increasing transmission probability. Thus, the protocol design parameters cannot be fixed in base to the throughput function. For a given value of the transmission probability α, the probability of receiving a packet from a neighbour ($q_{N,\alpha,R}$) grows with R (as any neighbour has more chances to be received) but at a slower rate than R (because not all neighbours are transmitting during the contention period). In consequence, the optimum R for equations (7) and (8) is not the same.

A meaningful network parameter to optimise is the ET in equation (7). Optimum values are obtained numerically. Figure 2 shows the ET for a node having 9 neighbours. The optimum ET is obtained for a contention period of 3 slots, and degrades as R increases. Note that the optimum value for R is lower than the number of neighbours, because the average number of users colliding at any contending period is only αN. Figure 3 depicts the ET with respect to the transmission probability for a different number of neighbours, and for a fixed contention period length R=3. Plots show that, for a non-homogeneous network, where different nodes may have different number of neighbours, the transmission probability has to be optimised for the most connected node (N=9 in the figure) so as to guarantee a given minimum ET for all nodes. It may be shown that (for a fixed α) the optimum R increases with N, since more slots are needed to demodulate more users.

For a network where the most connected node has 9 neighbours, α_o=0,22 and R_o=3 optimise the ET. The ET of the most connected node is τ_o=0,043 and the delay λ_o=24 slots. For the transparent scheduling based on latin squares [3], delay depends strongly on the number of nodes in the network (which is not the case for FF-NDMA). When the number of nodes is 100, the average delay λ_o is 121 slots, whilst for 1000 nodes, it increases up to 1369 slots.

Figure 4 shows the probability of receiving a packet of any neighbour (equation (8)) as a function of the number of probing slots T. Curves are grouped for different values of R and show different number of neighbours (from 1 to 9). In each curve, the optimum value of α is selected. When R=1 (no retransmissions combination) the most connected nodes actualising their probing information every 14 (30) slots, only have a probability of 81% (89%) of being received, while for R=3 (the optimum value for the most connected node) those probabilities are of the 95% (99%). The immediate conclusion is that retransmission combination allows higher dynamic topology changes.

From Figure 2, the throughput for R=3 is higher that for R=1. However, the optimum transmission probability for R=1 is half that for R=3. It does not necessarily imply that each node uses more power for a single packet. Note that, for each user, every symbol is spread in R retransmissions and hence, for a fixed received energy per symbol, the required power in each slot decreases as R increases. The investigation of this aspect implies the performance study of the receiver, which is currently being studied.

6. T-MPR COLLISIONS

In this section we quantify the degradation of the protocol performance as a function of the number of training sequences.

A network design in which every user has a unique training sequence (TS) is unrealistic. The number of the required training sequences S, and receiver complexity would increase linearly with the number of users. In a realistic environment S will be much lower than the number of users. Those TS will be allocated at random, and t-MPR collisions will occur. Assuming that a set of S training sequences are available and common to all the users, the probability that a given user does not collide because of a t-MPR collision and neither by a MAC MPR collision is

$$\tilde{q}_{N,\alpha,R} = \left(1-\alpha\right)\alpha\ \tilde{\varepsilon}_{N,\alpha,R} \tag{9}$$

where

$$\tilde{\varepsilon}_{N,\alpha,R} = \sum_{t=0}^{\min(R-1,N-1)} \binom{N-1}{t} \alpha^t \left(1-\alpha\right)^{N-1-t} f\left(t\right) \tag{10}$$

and

$$f\left(t\right) = \left(1-1/S\right)^t \quad t = 0..\min(R-1,N-1) \tag{11}$$

which is lower bounded by $\tilde{f} = (1-1/S)^{R-1}$ and thus

$$\tilde{q}_{N,\alpha,R} \geq q_{N,\alpha,R} \cdot \tilde{f} \tag{12}$$

Therefore, an upper bound of the number of training sequences for a loss in performance $1-\tilde{f}$ is given by:

$$S = 1\Big/\left(1-\tilde{f}^{\ 1/(R-1)}\right) \tag{13}$$

When R=2 (3, 4, 5) a maximum loss in performance of 5% yields S=20 (40, 59, 79). When the number of sequences is small, the ET of the network may be highly affected through equation (12), and the optimum value of R (as observed in section 5) may change (decrease). So, S is lower bounded not to reduce the performance.

Turning to receiver cost issues, note that it has to incorporate one correlator per training sequence, which makes the receiver complexity increasing linearly with S (this upper limits the value of S). A possible solution consists in using training sequences for different users which are cyclic shifted versions of one or several basic codes (as in UTRA-TDD [4]). This allows sequential channel estimation of all active users with the same basic code within one slot. The total number of available training sequences S is the product of the number of basic codes P and the number of possible shifts of each basic code S_t .

Loss of performance due to t-MPR collisions will decrease when decreasing both P and S_t but the receiver complexity only will increase as P increases. If we assume fixed the length of the used basic codes L_t, the number of possible different cyclic shifts to be used from a basic code is a function of L_t and the length of the channel delay profile τ_{ds}

$$S_t = L_t \big/ \tau_{ds} \tag{14}$$

Thus, the upper bound of the number of basic codes providing a loss in performance $1-\tilde{f}$, for a fixed R may be expressed as

$$P \geq \tau_{ds} \Big/ \left(L_t(1-\tilde{f}^{\ 1/(R-1)})\right) \tag{15}$$

7. SIMULATIONS

To evaluate the impact of the number of TS on the network performance, a network with 1000 nodes has been simulated, where the most connected node has 9 neighbours. The optimum value of R (=3) is chosen and different values of α have been tested. In Figure 5, the simulated ET is plotted. When the t-MPR collisions are not simulated (i.e. assumed an infinite number of TS available), the estimated value is the same as the one predicted theoretically (and plotted in Figure 2). Then, a finite number of TS (32 and 8) is considered. Closeness to the asymptotic performance may be verified when only 32 sequences are used. These may be obtained from cyclic versions of a single basic TS.

8. CONCLUSIONS

We have presented a novel distributed MAC protocol for broadcasting suited for the probing procedure. The protocol is topology transparent and its performance is independent of network size, but depends on the number of neighbours of the most connected node in the network (N_{max}).

The MAC layer analysis shows that the throughput may only be slightly increased by transmitting the same packet in several slots. This does not imply increased transmitted power, as the combination of several instances of the same packet at the receiver provides coding gain (and diversity gain in fading channel). Physical layer performance of the proposed method is under study and will be published in a forthcoming paper.

Loss of performance due to the random allocation of training sequences (TS) is linked with the number of available TSs and the receiver complexity. A solution for reducing receiver complexity is proposed. It is shown that the loss in performance when the number of TSs is limited is small.

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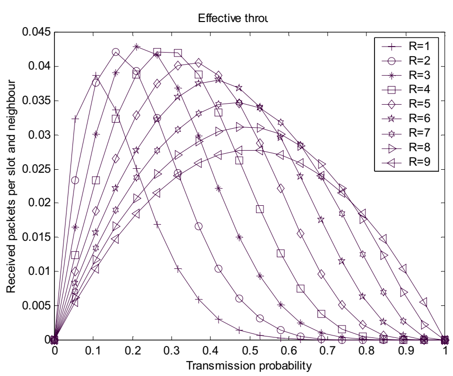

Figure 2. ET for different values of the transmission probability (α) and contention period (*R*) length for nodes with 9 neighbours

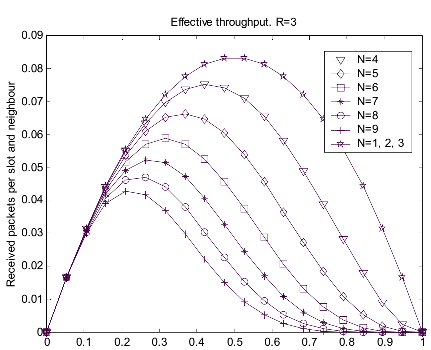

Figure 3. Effective throughput for different number of neighbouring nodes and a contention period of length 3.

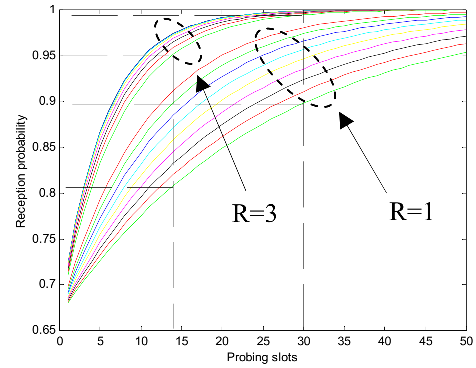

Figure 4. Reception probability vs. number of probing slots for optimum values of α. For two values of *R,* different number of neighbours are chosen (1 for upper curves, 9 for lower curves).

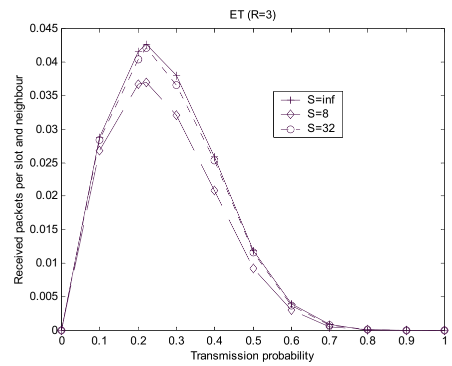

Figure 5. Effective throughput in a network of 1000 nodes, for different values of α, when t-MPR collisions are considered. Plots show the cases of 8, 32 and infinite number of available TS.