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Throughput-oriented MAC for mobile ad hoc networks: A game-theoretic approach ☆

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Abstract

The conservative nature of the 802.11 channel access scheme has instigated extensive research whose goal is to improve the spatial reuse and/or energy consumption of a mobile ad hoc network. Transmission power control (TPC) was shown to be effective in achieving this goal. Despite their demonstrated performance gains, previously proposed power-controlled channel access protocols often incur extra hardware cost (e.g., require multiple transceivers). Furthermore, they do not fully exploit the potential of power control due to the heuristic nature of power allocation. In this paper, we propose a distributed, single-channel MAC protocol (GMAC) that is inspired by game theory. In GMAC, each transmitter computes a utility function that maximizes the link's achievable throughput. The utility function includes a pricing factor that accounts for energy consumption. GMAC allows multiple potential transmitters to contend through an admission phase that enables them to determine the transmission powers that achieve the Nash equilibrium (NE). Simulation results indicate that GMAC significantly improves the network throughput over the 802.11 scheme and over another single-channel power-controlled MAC protocol (POWMAC). These gains are achieved at no extra energy cost. Our results also indicate that GMAC performs best under high node densities and large data packet sizes.

Keywords: Mobile ad hoc networks; MAC protocol; IEEE 802.11; Game theory; Power control; Throughput

1. Introduction

Mobile ad hoc networks (MANETs) are self-organizing networks that provide an efficient solution when centralized control is infeasible (e.g., emergency and rescue operations, disaster-relief efforts, etc.). A key design objective in MANETs is to achieve high network throughput while maintaining energy-efficient wireless communications for mobile terminals [1,20]. To achieve this objective, efficient design of the MAC layer is necessary

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in order to resolve channel-contention and reduce packet collisions.

The “ad hoc” mode of the IEEE 802.11 standard [9] has so far been used as the *de facto* MAC protocol for MANETs. This standard is based on CSMA/CA with an optional RTS/CTS (request-to-send/clear-to-send) handshake to coordinate channel access and resolve contention. Several studies documented the inadequate performance of this protocol, which is attributed to its conservative treatment of potential interferers (the RTS/CTS packets are used to silence all overhearing terminals), its use of fixed transmission powers (TPs), and its inefficient handling of ACK packets (the exposed terminal problem). These problems are particularly acute in dense networks, where the transmitter–receiver distances are relatively small.

To overcome these problems, researchers considered the use of power control at the MAC layer as a way to improve spatial reuse (e.g., [14,25,16]) and/or reduce energy consumption (e.g., [3,11]). Our emphasis in this paper is on the first objective, i.e., to improve the network throughput. In throughput-oriented power-controlled MAC schemes, terminals broadcast some *collision avoidance information* (CAI) to neighboring terminals. This information is used to *bound* the transmission powers of potential future transmitters in the neighborhood. For example, CAI may include information about the maximum tolerable interference (MTI), defined as the amount of interference power that a receiver of a data or ACK packet is able to tolerate from one future interferer [16]. Future transmitters use the overheard MTI values along with other information (e.g., channel gains, load tolerance, etc.) to determine their TPs. This way, multiple interference-limited transmissions can take place concurrently in the vicinity of the same receiver.

Motivation and contributions. Despite their demonstrated performance gains, previously proposed TPC schemes suffer from several problems, including incompatibility with the 802.11 architecture, extra hardware, and lack of ACK protection. For instance, many of them offer dual-channel solutions, which often require two transceivers per terminal. In [16], the authors presented a single-channel, single-transceiver power-controlled MAC protocol called POWMAC, which allows for multiple concurrent interference-limited transmissions and provides protection for ACK packets. Simulations indicate that POWMAC achieves good performance improvement (up to 40%) over the classic (fixed-power) CSMA/CA. However, because it relies on heuristics for determining the MTI value (and hence the TPs), the protocol does not fully exploit the potential of power control and may sometimes unnecessarily silence some possible transmissions.

The following simple example illustrates the impact of heuristically setting the MTI in the POWMAC protocol. Consider a MANET of four terminals: A, B, C, and D, as depicted in Fig. 1, where $P_{\max}$ denotes the maximum transmission power. Let G_{ij} and d_{ij} denote, respectively, the channel gain and distance between any two terminals i and j. Suppose that terminals A and C wish to transmit to terminals B and D, respectively, and suppose that A succeeds in transmitting its RTS before C sends its RTS. Assume that $G_{AB} = G_{CD}$, and that A and C are within the maximum transmission range of each other. Let $\mathrm{SNR_{th}} = 6$ dB be the required signal-to-noise ratio for both receivers. Assume a two-ray channel propagation model with a path loss factor of 4. For simplicity, we ignore the thermal noise. Clearly, the spatial reuse is maximized when both transmissions $A \to B$ and $C \to D$ are allowed to proceed concurrently. The necessary conditions for that are $\frac{G_{AB}p_A}{G_{CB}p_C} \geqslant \mathrm{SNR_{th}}$ and $\frac{G_{CD}p_C}{G_{AD}p_A} \geqslant \mathrm{SNR_{th}}$, where p_A and p_C are the transmission powers of terminals A and C, respectively. Combining these two inequalities, we get $\frac{G_{AD}}{G_{CD}} p_A \mathrm{SNR_{th}} \leqslant p_C \leqslant \frac{G_{AB}}{G_{CB}} \frac{p_A}{\mathrm{SNR_{th}}}$. Thus, it is necessary to have $\frac{G_{AD}}{G_{CD}} \mathrm{SNR_{th}} \leqslant \frac{G_{AB}}{G_{CB}} \frac{1}{\mathrm{SNR_{th}}}$. Since we assume $G_{AD} = G_{CB}$ and $G_{AB} = G_{CD}$, the above condition becomes

$$\left(\frac{G_{AD}}{G_{AB}} \mathrm{SNR_{th}}\right)^2 \leqslant 1,$$

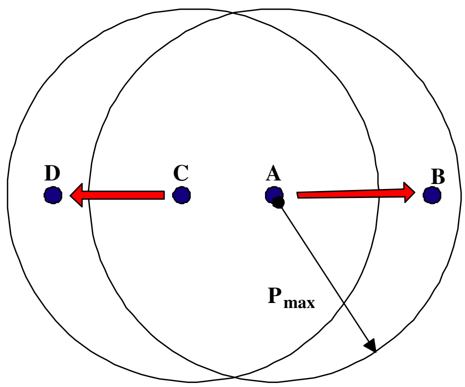

Fig. 1. Example of two transmissions that can proceed simultaneously if transmission powers are computed appropriately ($G_{AD} = G_{CB}$ and $G_{AB} = G_{CD}$).