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Performance analysis of topology-unaware TDMA MAC schemes for ad hoc networks with topology control☆

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Abstract

Traditional omni-directional antennas result in increased mutliuser interference and are known to limit the performance of Medium Access Control (MAC) protocols for ad hoc networks. *Topology control* is the capability of a node to control the set of neighbor nodes. In this paper, the impact of using smart antennas and/or power control for topology control is investigated and the performance of TDMA MAC schemes with common frame, for which the assignment of time slots to a node is not aware of the time slots assigned to the neighbor nodes (*topology-unaware*), is studied. A comparison based on analytical models reveals the advantages of topology control, as well as its dependence on the *mobility* of the nodes and its resolution. Simulation results support the claims and the expectations of the analysis and show how the performance under topology control can be increased and how mobility affects it.

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1. Introduction

Ad hoc networks require no infrastructure and nodes are free to enter, leave or move inside the network without prior configuration, thus making the design of an efficient Medium Access Control (MAC) a challenging problem. CSMA/CA-based MAC protocols have been proposed [1–5], as well as TDMA-based MAC protocols have also been proposed for ad hoc networks [6–10].

Topology-Unaware TDMA MAC schemes, under which the assignment of time slots to nodes does not consider the time slots assigned to the neighbor nodes (nodes that a direct transmission is possible), have also been proposed [11,12,15]. In particular, Chlamtac and Farago proposed the *Deterministic Policy* [11], whereas the *Probabilistic Policy* has been proposed and analyzed in [13–15]. This analysis has shown that the Probabilistic Policy outperforms the Deterministic Policy under certain conditions. The aforementioned analysis was based on traditional *omni-directional* antennas, where the transmitting node did not have any *topology control* capabilities. Topology control is a node's capability of controlling the set of neighbor nodes and it may be achieved by adjusting the *angle* of the transmission beam and/or the transmission power and thus, control the interference caused to neighbor nodes when transmitting.

The use of *directional antennas* for topology control is not a new idea and has been proposed in the past [16]. Nowadays, more sophisticated *smart antennas* can be used to adjust the angle of the transmission beam and even be incorporated into portable devices. Several MAC protocols have been proposed for ad hoc networks that exploit the capabilities of smart antennas. The majority of them is based on random access schemes (e.g. ALOHA or CSMA/CA)

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and enhancements of the RTS/CTS mechanism [17–19]. *Power control* may also be used for topology control. The transmission power can be adjusted according to the location of the receiver, reducing the interference caused to neighbor nodes by the transmitting node [20–24]. *Resolution* is an important factor of topology control. The higher the resolution of the topology control, the narrower the transmission beam of the smart antennas and/or the smaller the transmission range corresponding to a particular transmission.

In this work, both the Deterministic Policy and the Probabilistic Policy are considered when topology control is applied (use of smart antennas and/or power control) and their performance is compared against that induced when no topology control is present (use of traditional omni-directional antennas). This comparison is based on an analytical approach and is supported by simulation results. The nodes' *mobility* is also taken into account, since it is expected to impact the performance especially under topology control. The (mobility) conditions under which topology control (for a given resolution) improves performance are also established here.

Topology control is presented in Section 2. In Section 3, an ad hoc network is described and some key definitions are introduced. The Deterministic Policy and the Probabilistic Policy are presented in Section 4. In Section 5, expressions for the *system throughput* under both policies are derived with and without topology control. The mobility aspects are considered in Section 6, where the conditions, under which topology control with a certain resolution is beneficial for the system performance, are also established. Simulation results for network topologies with different characteristics are presented in Section 7. These results support the claims and the expectations introduced by the analytical comparison and show that the system throughput achieved under the Probabilistic Policy and under topology control can be rather high. On the other hand, it is shown that mobility degrades the system throughput especially under topology control with high resolution and therefore, topology control may not be desirable under certain conditions. Finally, Section 8 presents the conclusions.

2. Topology control

Traditional omni-directional antennas transmit and receive from all directions. Consequently, the receiver is not benefited by the entire power of the transmitter since this power is scattered in the 360° pattern. Furthermore, as it will be seen in the following section, the interference caused by neighbor nodes may be high and spatial reuse of the network resources becomes a difficult task. In Fig. 1(a), an omni-directional antenna example is shown.

Directional antennas have been introduced with fixed transmission and reception directions. The advantage is that the power of the transmitter is 'directed' to the receiver.

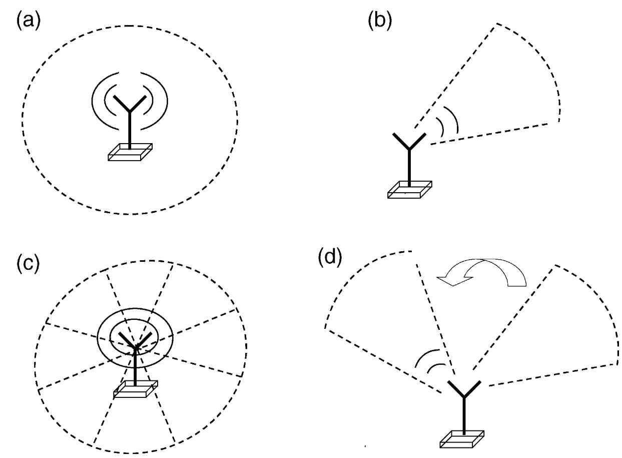

Fig. 1. Various antenna types.

In Fig. 1(b), a directional antenna example is presented while in Fig. 1(c) several directive antennas are used to cover the 360° pattern.

Smart antennas are considered as one of the more promising technologies for reducing interference and increasing the utilization of the network resources. They are composed of an array of antennas and their 'smartness' is due to the efficient combination of incorporated Digital Signal Processing (DSP) capabilities and an antenna array [26]. A special subset of smart antennas, the *adaptive array antennas*, are capable of focusing the main lobe of the transmission power towards a certain direction (the receiver's direction). This case is depicted in Fig. 1(d). Another subset of smart antennas are the *switched-beam antennas* which choose to switch between predefined directions. For the rest, when smart antennas are considered, it is assumed that they can adjust the transmission angle towards the receiver, as it is depicted in Fig. 1(d).

From the above discussion is clear that the transmitting node is able to 'control the topology', if smart antennas are used. Topology control may also be achieved by adjusting the transmission power. The transmission power plays an important role regarding the existence of a link between two nodes as well as the *quality* of the link [25]. In general, the higher the power of a transmission the more likely a node to receive it successfully. Let $Power_t$ be the transmission power at the transmitting node u and a be the distance between node u and node v. In order for node v to be able to receive successfully a transmission from node u, the reception power $Power_r$ has to be above a certain threshold. It is shown that $Power_r \sim Power_t/a^n$, where n is a positive constant that depends on the particular environment [25]. This relation reveals the fact that an exponential increment of the transmitting power is required as the distance between two nodes increases.

An example is depicted in Fig. 2, where u is the transmitting node and v the receiver. If the transmission power of node u is $Power_t(a_1)$ ($Power_t(a_2)$), then a transmission is possible at a distance a_1 (a_2). If $a_2 = 2a_1$