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A channel-access protocol to utilize multiple heterogeneous channels for ad hoc networks

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ABSTRACT

We introduce a new approach to channel access for ad hoc networks that utilize multiple heterogeneous channels. The radios of the ad hoc networks we investigate are frequency-agile allowing them the ability to change their carrier frequency and transmission rate over a wide range of possibilities. Our approach to channel access takes advantage of the multiple frequency bands available to the network to increase network-layer performance. We have previously found that in some network scenarios, the best network-layer performance is achieved if the channel-access protocol always selects the channel with the fastest data rate that is immediately available. However, in other network scenarios it is preferable to always wait for a channel with a faster data rate that is temporarily unavailable to become available rather than select a channel with a slower data rate that is immediately available. We show that our new channel-access protocol is able to adapt the strategy for selecting channels so that high network-layer performance is maintained in all scenarios compared to channel-access protocols that utilize either fixed strategy.

1. Introduction

An ad hoc network is comprised of wireless terminals that self-configure to form a network without an established or centralized infrastructure. Because these networks can be quickly deployed and require minimal configuration, they are advantageous in emergency situations and for military applications. Without an established infrastructure, it is the responsibility of these wireless terminals to cooperate such that packets are forwarded to their destination in a distributed manner. The channel-access protocol is responsible for controlling access to the channels available to the network and for ensuring that these packets are received successfully. It is the responsibility of the network layer to correctly determine how a packet is to be routed through the network from its source to its destination [1].

In a software-defined radio, components that have typically been implemented in hardware have been replaced by software-based systems allowing the radio to transmit and receive on a variety of different frequencies. This leads to increased flexibility in specifying the carrier frequency, transmission rate, and receiver bandwidth over a wide range of possible configurations at the time the network is deployed or as the operating conditions change [2]. Our work assumes that multiple nonoverlapping channels have been identified and made available to the terminals in a mobile ad hoc network. Furthermore, the channels are *heterogeneous*, that is, the center frequencies and bandwidths for each channel differ widely. Consequently, the communication ranges and data rates for the channels are significantly different from each other.

In [3], the authors compare four categories of multichannel MAC protocols: dedicated control channel, common hopping, split phase, and parallel rendezvous. The dedicated control channel protocol uses two radios. One radio is used to constantly monitor the control channel, and the other radio can tune to any other channel. The

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Dynamic Channel Assignment (DCA) algorithm [4] and the protocols of [5,6] are examples of this approach, which assume that each data channel is equivalent and has the same bandwidth. For the DCA algorithm, channel negotiation occurs on the control channel, and the switchable interface switches to one of the data channels to transmit data packets and acknowledgments. The protocol of [5] extends this approach by allowing for the transmission of multiple frames on the data channel after channel negotiation on the control channel. The protocol of [6] also extends DCA by only using the control channel for channel negotiation and using CSMA/CA on the data channels before transmitting data packets to avoid collisions. The switchable interface of this protocol also employs independent slow hopping over the data channels to maximize the utilization of the data channels.

For the common hopping protocol, a device has a single radio, and each device hops through all the channels synchronously until a pair of devices make an agreement for transmission. The devices pause hopping to exchange data on the current channel and return to the common hopping pattern after the transmission. For the Channel Hopping Multiple Access (CHMA) protocol [7], a time slot is just long enough for a single control packet. In [8], Improved CHMA (ICHMA) introduces schemes to alleviate the multichannel hidden terminal problem and deaf node problem present when CSMA/CA is used with the common hopping protocol. Both protocols assume homogeneous channels.

Devices employing the split phase protocol use a single radio, and time is divided into an alternating control phase and data phase. During the control phase, all nodes tune to the common control channel for data channel negotiation. Multiple pairs of devices can select the same channel due to the possibility that a single pair may not have enough data to fill the entire data phase. These nodes then tune to their negotiated channels to schedule themselves or to contend for a data transmission in the following data phase. For the multichannel MAC protocol introduced in [9], the split phase protocol is utilized to enable simultaneous transmissions on different channels in the same region. For their approach, the time interval for the data and control phase is fixed. However, in [10], the control phase has a fixed-time interval, but the duration of the data phase varies based on the reservation schedule determined in the control phase. The authors of [11] implement a power-control algorithm for which the minimum required transmission power is used during the data phase. The protocols also assume homogeneous channels.

Lastly, devices using the parallel rendezvous protocol use a single radio, and multiple device pairs can make agreements simultaneously on distinct channels. Each device follows its default hopping pattern to hop and listen to a channel. A sending device determines the receiver device's hopping sequence and hops into its channel. Examples such as Slotted Seeded Channel Hopping (SSCH) [12], and McMAC [13] do not account for heterogeneous channels, but DataRate-Aware MAC (DRA-MAC) [14], accounts for channels with different data rates by adjusting a portion of the hopping sequence to hop more frequently onto channels with a higher data rate. Other examples of devices adjusting their hopping sequence include [15], where the adjustment is based on a device's traffic load and [16], where the adjustment is based on channel quality.

Other research involving networks with multiple traffic channels assume that the terminals of these networks are equipped with multiple radios or network interface cards (NICs) tuned to a particular channel. The Multi-radio Unification Protocol (MUP) [17] is a link-layer protocol that coordinates the multiple NICs tuned to pre-assigned non-overlapping channels by monitoring the channel quality on each interface to each of its neighbors. The protocol uses this locally-available load information to select the interface on which the packet should be forwarded. For their study, the network is assumed to be composed of NICs with approximately the same range, bandwidth, etc. In [18], a joint channel-assignment, scheduling and routing algorithm is developed. This algorithm is fully distributed and addresses channel diversity by considering different capacity channels. The authors of [19] assume homogeneous channels and present a joint channel assignment and cross-layer routing protocol that achieves load balancing.

Our work follows the split phase protocol described above in which each terminal is equipped with a single half-duplex frequency-agile radio. For each transmission, the radio can be tuned to a particular carrier frequency and its associated channel-symbol rate corresponding to either a common control channel or one of the multiple traffic channels available to the network. Similar to the system model of [20,21], the control and data phases of our channel-access protocol are not fixed and are independently determined by each terminal. For example, a pair of terminals may be in their control phase negotiating access to a traffic channel while a different pair of terminals is simultaneously transmitting a data packet during their data phase. Unlike many of the above-mentioned protocols and the uniform approach to channel access introduced in [20], we consider a network consisting of multiple heterogeneous traffic channels. The highest good and highest/deferred protocols of [21] also consider heterogeneous channels, but channel selection is based solely on the transmission time associated with a particular traffic channel. For the highest good protocol, the channel with the fastest data rate that is immediately available is always selected. If the channel with the fastest data rate is not available, the highest/deferred protocol will wait for the channel to become available rather than select a channel with a slower data rate that is immediately available. In [21], we found that the highest/deferred strategy outperforms the highest/good protocol when the parameters of the routing protocol are tuned to the particular network scenario but results in poor performance when the parameters are not properly matched.

For this work, we introduce a channel-access protocol that extends the work of [20,21] such that a traffic channel is selected based on its current channel conditions and characteristics. We improve the performance of this protocol as well as that of those introduced in [20,21] by applying a randomization and a forward progress protocol. We show that our new channel-access protocol provides better