Distributed Medium Access Control Protocol for Successive Interference Cancellation-Based Wireless Ad Hoc Networks

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***Abstract*— Successive interference cancellation (SIC) enables the successful reception of multiple concurrent transmissions and elimination of interference through successive decoding. However, previously proposed distributed medium access control protocols have not exploited SIC. They mostly focused on either interference avoidance, based on the assumption that a receiver can only decode one transmission at a time, or self-interference cancellation, where a node can be a receiver and a transmitter at the same time. In this letter, we propose the first distributed communication protocol for SIC-based wireless networks, based on a novel message exchange and decision mechanism, to enable the simultaneous transmission of multiple neighboring nodes around the transmitter and receiver. The message exchange allows a random subset of neighboring nodes to test the feasibility of their simultaneous transmission. The decision mechanism evaluates the successive decoding capability of SIC receivers with the additional activation of neighboring nodes. We demonstrate the throughput improvement of the proposed algorithm via extensive simulations.**

***Index Terms*— Wireless ad hoc networks, successive interference cancellation, distributed algorithm, medium access control protocol.**

I. Introduction

DISTRIBUTED medium access control (MAC) protocols enable the communication of the nodes in a wireless ad hoc network in the absence of central controller units. Conventional distributed communication protocols adopt the well-known IEEE 802.11 Distributed Coordination Function (DCF) [1]. The nodes exchange Request-to-Send (RTS) and Clear-to-Send (CTS) control packets before data transmission to avoid interference around both transmitter and receiver. The communication protocols avoiding the overlap of neighboring transmissions in time, however, have been shown to limit the capacity of wireless ad hoc networks [2]. Distributed protocols adopting self-interference cancellation aim to increase the capacity of wireless networks by enabling dual links, with the transmitter of a link being the receiver of the other link. As soon as the receiver of a link decodes the header of the packet, it transmits either a packet to one of its neighboring nodes or a busy tone if it does not have any packets [3]. Self-interference cancellation, however, can at most double the feasible throughput [4].

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SIC has been demonstrated to increase the network capacity by enabling both concurrent reception and interference rejection [5]. Despite the existence of a large number of centralized scheduling algorithms developed for SIC based networks [6], there is no distributed MAC protocol proposed for these networks. Previous studies mostly analyze the performance of existing distributed protocols, such as slotted ALOHA [7] and IEEE 802.11 DCF [8], [9], without proposing any modification to further improve the throughput.

The goal of this letter is to propose a novel distributed MAC protocol that combines the RTS/CTS mechanism of the IEEE 802.11 DCF with a novel message exchange and decision making to enable further transmissions exploiting SIC. The novel message exchange happens before the data packet transmission to decide whether a subset of neighboring nodes can transmit simultaneously with the link. The decision making determines whether the simultaneous transmission of the nodes originating these extra messages allows the decoding of the packets received at the source and destination of the link.

II. System Model and Assumptions

The wireless ad hoc network comprises L links. The transmission rate is the same for all the links in the network. The transmit power of the links is fixed at the maximum level $P_t = P_{max}$. A node does not have the capability of simultaneous reception and transmission, and concurrent transmission to multiple nodes. The successive elimination of the signals in SIC decoding is assumed to be perfect, based on the fact that considering the residual interference keeps the same communication algorithm framework.

A. SIC Signal Detection

The successive decoding of multiple transmissions at an SIC capable receiver follows the order of decreasing received signal strength. Let P_{ji} denote the received power at the receiver of the i-th link from the transmitter of the j-th link. Let A be the set of simultaneously transmitting links. Let M be the number of links with received signal strength at the receiver of link i greater than P_{ii} ordered in decreasing received signal strength at the receiver of link i such that $P_{1i} > P_{2i} > \ldots > P_{Mi}$. The reception at link i is successful if the sequential signal-to-interference-plus-noise ratio (SINR) criteria

$$\frac{P_{ki}}{\sum_{j \in A \setminus [1,k]} P_{ji} + N_0} > \beta, \quad \forall k \in [1, M] \tag{1}$$

$$\frac{P_{ii}}{\sum_{j \in A \setminus \{1,2,\ldots,M,i\}} P_{ji} + N_0} > \beta \tag{2}$$

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are met, where N_0 is the background noise and β is SINR threshold.

B. Carrier Sense Multiple Access of IEEE 802.11 DCF

In the basic access of IEEE 802.11 DCF, upon the arrival of a new packet, a station first listens to the channel. If the channel is idle for a time duration of distributed interframe space (DIFS) length, the station sends the packet. Otherwise, the station generates a random backoff time, uniformly chosen in the range $(0, w-1)$, to eliminate collisions with the packets of nearby transmitting stations, where w refers to contention window size. w is initially set to CW_{min}, called minimum contention window size; doubled up to a maximum value CW_{max}, after each unsuccessful transmission; and reset to CW_{min} upon a successful transmission. If the channel is detected idle for a DIFS, the time is slotted. The value of the generated random back off value is decremented by one at each slot if the channel is idle for the past DIFS time interval up to that slot. When the back off value reaches zero, the packet is transmitted. If the packet is successfully received, the destination node sends an acknowledgement (ACK) after a time duration of short interframe space (SIFS) length. If the transmitter does not receive an ACK packet, the process of packet transmission restarts.

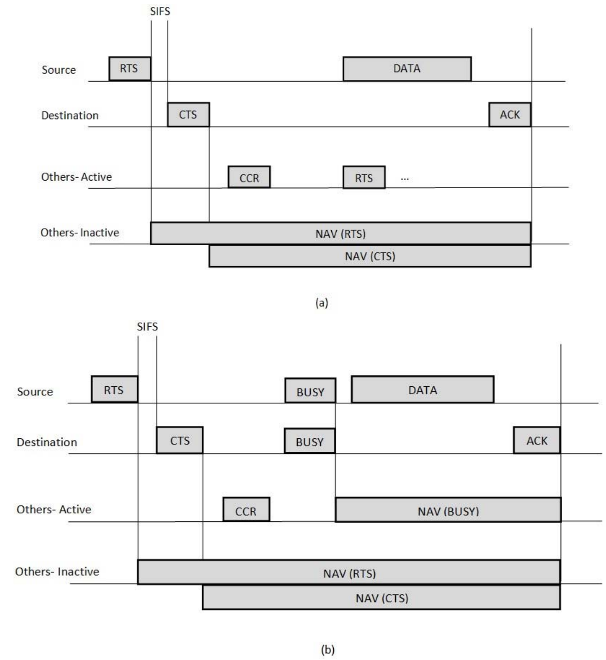

Fig. 1. Proposed channel access mechanism. a) No busy tone. b) Busy tone.

III. Proposed Distributed MAC Protocol

A. Motivation

The proposed MAC protocol is based on combining the RTS/CTS mechanism of the IEEE 802.11 DCF with a novel message exchange. In the RTS/CTS mechanism, upon the arrival of a new packet, a node first sends a short RTS packet. If RTS packet is successfully received at the destination node, a short CTS packet is transmitted. The nodes that receive RTS and CTS packets defer their transmissions for the time period equal to network allocation vector (NAV), containing the information of the time duration until the end of the data and ACK packets. If the source receives the CTS packet successfully, the data packet is transmitted, followed by the ACK response. RTS and CTS packet transmissions reserve the channel in the neighborhood of both source and destination nodes until the end of the transmission of the corresponding data and ACK packets, which decreases the number of simultaneous transmissions considerably. On the contrary, SIC may support simultaneous transmission of some of the neighboring links but links have insufficient information on the channel condition to exploit this. We therefore include the additional messaging to check the feasibility of the simultaneous transmission of a subset of the neighboring links receiving RTS or CTS packet.

B. Detailed Description

In the proposed distributed MAC protocol, instead of remaining silent for the NAV period, a randomly selected subset of neighboring transmitters that receive RTS or CTS packet send a channel-condition-request (CCR) message. The neighboring transmitters decide to send CCR message with a certain activation probability, denoted by p_i for node i. p_i is chosen as $min(\frac{k}{N(i)}, 1)$, where k is the probability constant and $N(i)$ is the number of neighbors of node i. Following the period of time allocated for CCR transmissions, the source and destination of the link executes the decision procedure to determine whether the transmission of this randomly selected subset of transmitters would interfere with their transmission. If so, they send a busy tone so that these neighboring transmitters are not activated (Fig. 1(b)). Otherwise, they don't send any packet implying the suitability of their simultaneous transmission (Fig. 1(a)).

The decision procedure executed in the source and destination of a link for the simultaneous activation of a subset of neighboring nodes includes both the decoding of their CCR transmission and computation of the suitability of their simultaneous transmission with the link. The decoding of the CCR transmission relies on the SIC signal detection mechanism described in Section II. The source and destination of the link decode the CCR transmissions in the order of decreasing received power until no more transmissions can be decoded. Let us call the received power over the link P_r. Let us denote the received power of the decoded neighboring transmissions greater than P_r by $\{P_1, P_2, \ldots, P_M\}$, where M is the number of decoded transmissions with received power greater than P_r and P_i is the i-th strongest received power. Let us denote the total received power of the links remaining from the SIC subtraction of the M-th link by I_r. Then the source and destination of the link checks whether the received powers $\{P_1, P_2, \ldots, P_M, P_r\}$ are decodable in the presence of noise N_0 and interference I_r by checking the sequential SINR criteria given in Section II. If the sequential SINR criteria are satisfied, the subset of neighboring transmitters can transmit simultaneously with the link. Otherwise, they are not allowed for simultaneous transmission hence busy tone is sent.

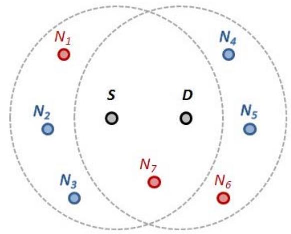

Fig. 2. Network instance for the proposed algorithm.

C. Illustration by Example

Let us denote the source and destination of the link by S and D, respectively, and the set of their neighboring nodes by $\{N_1, N_2, \ldots, N_7\}$, as shown in Fig. 2. The transmission ranges of S and D are shown by the dashed circles around them. The proposed algorithm runs as follows: S sends an RTS packet. After receiving the RTS message, D sends CTS response. Assume that N_1, N_6 and N_7 choose to send the CCR message and other neighbors get into sleep mode. Upon reception of the CCR, S and D check sequential SINR criteria for the successful reception of the ACK and DATA packet, respectively, in the presence of the simultaneous transmission of these neighbors. If both S and D decide to send busy tones, then all N_1, N_6 and N_7 go into sleep mode. If busy tone is sent only by S, N_1 and N_7 put their radio in sleep mode, and since N_6 has received no busy signal, the channel is idle for it. If busy tone is sent only by D, N_6 and N_7 put their radio in sleep mode, and the channel is considered idle for N_1. If no busy tone is generated, all the neighbors who send CCR consider the channel idle and start transmitting their own packets.

D. Performance Analysis

The proposed MAC protocol increases the throughput of the RTS/CTS mechanism of the IEEE 802.11 DCF by a factor proportional to the number of simultaneously transmitting nodes enabled by SIC. Next, we derive the mathematical expression for the expected number of simultaneously transmitting nodes enabled by the proposed protocol, then validate the proposed formulation for the activation probability.

Let d_{SD} be the distance between source node S and destination node D. Let the received power at distance d be expressed as $P_r(d) = P_t d^{-\gamma}$, where γ is the path loss exponent, for simplicity of mathematical expressions (We adopt a more accurate path loss model in Section IV). Let D_{min} and D_{max} be minimum and maximum communication distance between the nodes. D_{max} is the distance at which successful communication can occur in the absence of interference with SINR greater than β, so $D_{max} = (\frac{P_t}{\beta N_0})^{1/\gamma}$.

An additional node T_1 activated by the protocol may be closer to or further away from the destination than node S. If T_1 is closer, the destination node needs to first decode the transmission of T_1 successfully by considering node S as interferer. This puts an upper bound on the distance between T_1 and D as a function of d_{SD}, which is given by $u_{1,D} = (\beta d_{SD}^{-\gamma} + \beta N_0/P_t)^{-\frac{1}{\gamma}}$. On the other hand, if T_1 is further away from the destination than S, then S needs to decode its own signal while considering T_1 as interferer. This forces a lower bound on the distance between T_1 and D, which is expressed as $l_{1,D} = (\frac{d_{SD}^{-\gamma}}{\beta} - \frac{N_0}{P_t})^{-\frac{1}{\gamma}}$. This results in two rings with radius ranges $(D_{min}, u_{1,D})$ and $(l_{1,D}, D_{max})$ around the destination for the feasible region of the additional transmitter. Let us call the union of these two rings as the feasible region around the destination, denoted by F_D. We can similarly construct the feasible region around the source and call it F_S. Since the additional transmitter should not interfere with neither source nor destination, it should be in the intersection of these regions, i.e. $F_S \cap F_D$.

If there are many additional nodes activated around the source and destination, then building the feasible regions requires updating the radius of both inner and outer rings of the corresponding feasible regions recursively with the addition of each node. Assume there exist N additional nodes within distance D_{max} of either source or destination. The distances to the destination are ordered such that there exist J_D nodes further from the destination than node S with distances $d_{SD} \leq d'_{1,D} \leq \ldots \leq d'_{J_D,D}$ and $N - J_D$ nodes closer to the destination than S with distances $d_{N-J_D,D} \leq \ldots \leq d_{1,D} \leq d_{SD}$. Similarly, the distances to the source are ordered such that there exist J_S nodes further from the source than node D with distances $d_{SD} \leq d'_{1,S} \leq \ldots \leq d'_{J_S,S}$ and $N - J_S$ nodes closer to the source than D with distances $d_{N-J_S,S} \leq \ldots \leq d_{1,S} \leq d_{SD}$. Given these distances, these N nodes are successfully decoded together with the original source-destination transmission if they are in $F_S \cap F_D$, where

$$F_Z = \{l_{j,Z} \leq d'_{j,Z},\ j \in [1, J_Z];\ \ D_{min} \leq d_{i,Z} \leq u_{i,Z},\ i \in [1, N - J_Z]\}, \quad Z \in \{S, D\}, \tag{3}$$

such that

$$l_{j,Z} = (\frac{d_{SD}^{-\gamma}}{\beta} - \frac{N_0}{P_t} - \sum_{p=1}^{j-1} d'^{-\gamma}_{p,Z})^{-\frac{1}{\gamma}}, \tag{4}$$

with $l_{j,Z} \geq 0$, and

$$u_{i,Z} = (\beta d_{SD}^{-\gamma} + \beta \sum_{p=1}^{J_Z} d'^{-\gamma}_{p,Z} + \beta \sum_{k=1}^{i-1} d_{k,Z}^{-\gamma} + \beta N_0/P_t)^{-\frac{1}{\gamma}}. \tag{5}$$

Then the expected number of simultaneously transmitting nodes, denoted by N_t, for N activated nodes is given by

$$E[N_t] = N. \int_{a_1} \ldots \int_{a_N} 1((a_1, \ldots, a_N) \in F_S \cap F_D | (a_1, \ldots, a_N)) f_{A_1,\ldots,A_N}(a_1, \ldots, a_N) da_1 \ldots da_N, \tag{6}$$

where A_i is the random location of the i-th node and $f_{A_1,\ldots,A_N}$ is the joint distribution of the location of N nodes. We observe that as the number of activated nodes N increases, the feasible region rings around both source and destination shrink further for each additional node, based on Eqns. (4) and (5). This results in a lower probability of successful decoding at the destination and source, which is the second term in Eqn. (6). Therefore, an optimal N that maximizes the expected number of simultaneously transmitting nodes exists. Keeping the

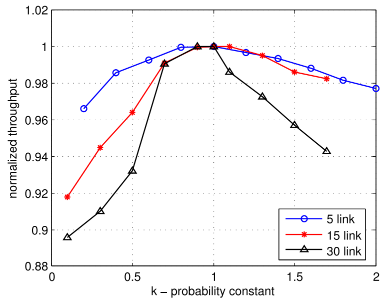

Fig. 3. Normalized throughput for different values of probability constant parameter in networks of different sizes.

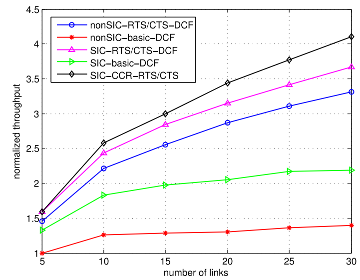

Fig. 4. Throughput of the proposed algorithm in comparison to previous algorithms for different number of links.

number of nodes activated around source and destination at this optimal value validates choosing the activation probability inversely proportional to the node density, measured by the number of neighboring nodes.

IV. Simulation Results

The goal of this section is to analyze the dependence of the performance of the proposed algorithm on the probability constant k parameter, defined in Section III, and compare the performance of the proposed algorithm, called SIC-CCR-RTS/CTS to the previously proposed algorithms, including basic and RTS/CTS access of DCF in non-SIC based wireless networks, called nonSIC-basic-DCF and nonSIC-RTS/CTS-DCF, respectively; and the usage of these basic and RTS/CTS accesses in SIC based networks, called SIC-basic-DCF and SIC-RTS/CTS-DCF, respectively.

We implemented an event-driven simulator in MATLAB for the simulations. Simulation results are obtained by taking the average of the performance metrics over 1000 independent random network topologies, where the nodes are distributed randomly within a square of 100×100 meters. The attenuation of the links are determined by using Rayleigh fading with scale parameter set to the mean path loss value calculated by $PL(d) = PL(d_0) - 10\gamma \log_{10}\left(\frac{d}{d_0}\right) + Z$, where d is the distance between the transmitter and receiver, d_0 is the reference distance, $PL(d)$ is the path loss at distance d in decibels and Z is a Gaussian random variable with zero mean and σ_z^2 variance. The parameters used in the simulations are $\sigma_z^2 = 2$ dB^2, $PL(d_0) = 1$ dB, $d_0 = 1$ m, $N_0 = 10^{-5}$ W/Hz, $W = 1$ MHz, $P_{max} = 0.2$ W, $\gamma = 3$, $\beta = 1$, $CW_{min} = 16$, $CW_{max} = 256$, slot time$= 50\mu$s, DATA packet length $=$ 1 kbytes, RTS, CTS and ACK packet length $=$ 250 bits, DIFS$= 500\mu$s, SIFS$=50\mu$s, carrier sense threshold over which the channel is determined to be busy is set to 22 dB above noise level.

Fig. 3 shows the normalized throughput for different values of probability constant parameter in networks of different sizes. The normalized throughput is obtained by normalizing the throughput of the network by that obtained using optimal value of the probability constant. We observe that the optimal value of the probability constant is independent of the number of nodes in the network, as validated in Section III-D. The decrease in the normalized throughput with the deviation of the probability constant from the optimal value is steeper for networks containing higher number of nodes. This is mainly due to faster change in the average number of activated nodes around each transmission with higher number of neighboring nodes.

Fig. 4 shows the normalized throughput of the proposed algorithm in comparison to the previous algorithms for different number of links. The throughput is normalized by that of the nonSIC-basic-DCF in a 5-link network. The proposed distributed scheduling algorithm performs better than the basic and RTS/CTS access mechanisms of DCF. The increase in the throughput by the usage of the RTS/CTS mechanism is larger than that by the exploitation of the SIC capability. The difference between our proposed algorithm and SIC-RTS/CTS-DCF increases as the number of links increases.

V. Conclusion and Future Work

We propose a novel distributed MAC protocol for SIC based wireless networks based on a novel message exchange and decision making to enable further transmissions exploiting SIC. In the future, we plan to extend these algorithms for variable rate, variable power and multi-channel multi-hop wireless networks.

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