Scheduling in Successive Interference Cancellation Based Wireless Ad Hoc Networks

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***Abstract*—Successive Interference Cancellation (SIC) allows multiple transmissions in the same neighborhood by enabling both concurrent reception and interference rejection via decoding and subtracting the signals successively from the composite received signal. In this letter, we study the scheduling problem for minimizing the schedule length required to satisfy the traffic demands of the links in SIC based wireless ad hoc networks. Upon proving the NP-hardness of the problem, we propose a novel efficient heuristic scheduling algorithm based on the greedy assignment of the links to each time slot by using a novel metric called Interference Effect (IE). The IE of a feasible link is defined as the total Signal-to-Interference-plus-Noise Ratio (SINR) drop of the links in the scheduled set with the addition of that link. We demonstrate via extensive simulations that the proposed algorithm performs better than the previous algorithms, with lower computational complexity.**

***Index Terms*—Wireless ad hoc networks, scheduling, successive interference cancellation.**

I. Introduction

SCHEDULING in wireless ad hoc networks determines the sets of transmitter-receiver pairs, i.e. links, to be activated at any given time. The interference model used in the simultaneous link activation specifies both the design and performance of the scheduling algorithm. Interference avoidance model that allows a receiver to only decode one transmission at a time by considering all other transmissions as interference has been widely used in link scheduling algorithms. When the neighboring transmissions overlap in time, collision occurs and reception is not successful. The scheduling algorithms avoiding such overlaps in time and space however limit the capacity of wireless ad hoc networks [1]. Interference cancellation model aims to solve this problem by allowing multiple transmissions in the same neighborhood at a time through the decomposition of all the signals in a composite signal at the receivers. Among many interference cancellation techniques, SIC appears to be the most promising due to its simplicity, overall system robustness and existing prototypes [2]. SIC is based on decoding and subtracting the signals successively from the composite received signal starting with the strongest signal, provided that the SINR is above a threshold at each stage. SIC improves the performance of wireless networks by enabling both concurrent receptions and interference rejection.

The scheduling algorithms proposed for SIC based wireless networks either use column generation method (CGM) or extends the protocol interference model previously used for interference avoidance based communication. CGM based heuristic algorithms are based on decomposing the large-scale Linear Programming (LP) problem with exponential number of variables, with each variable representing the time allocated to a subset of the links, into Restricted Master Problem (RMP) and Pricing Problem (PP) [3], [4]. The RMP starts with only a small subset of the feasible link sets and includes new link sets according to the solution of the PP iteratively as needed. The exponentially complex PP is approximated by a greedy heuristic algorithm or simulated annealing. CGM based heuristic algorithms however still have exponential worst case complexity due to the possibility of an exponential number of iterations. On the other hand, the heuristic algorithms extending the previously proposed protocol interference model need to consider not only the interference but also the concurrent transmission of the links [5], [6]. Protocol interference model in conventional networks describes the interference constraints among the active links according to a conflict graph, where every vertex corresponds to a link and two vertices are connected if the corresponding links are interfered. In SIC-based networks, this conflict graph is extended with a simultaneity graph that includes super vertices corresponding to two links requiring SIC for successful reception. The heuristic algorithms exploiting this extended model however do not take into account the cumulative effects of the interference, which may result in unexpected collisions, and have high computational complexity due to the consideration of each possible node subset in each iteration.

The goal of this letter is to propose a novel efficient heuristic scheduling algorithm with the goal of minimizing the completion time required to satisfy the given traffic demands of the links, defined as the schedule length, in SIC based wireless ad hoc networks. The proposed algorithm is based on including the feasible links in the scheduled link set one by one in the increasing order of a novel metric called Interference Effect (IE). The IE of a feasible link is defined as the total SINR drop of the links in the scheduled set with the addition of that link. This algorithm provides both higher accuracy by considering the cumulative effects of the interference and better performance with lower complexity compared to the previously proposed protocol interference based heuristic algorithms.

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II. System Model and Assumptions

The system model and assumptions are given as follows:

- The wireless ad hoc network comprises L directed links. Link i has traffic demand of f_i packets. The link traffic demands can be either given for single-hop networks or calculated by using end-to-end traffic demands in a multi-hop network with predetermined routing.
- A central controller executes the scheduling algorithm based on the given network topology, traffic demands and channel characteristics of the links. This centralized framework can be used in the communication of the mostly static routers with bandwidth requests typically slowly varying over time in wireless mesh networks (WMNs) [7] or as an upper bound on the performance of any distributed algorithm.
- Time Division Multiple Access (TDMA) is adopted as MAC protocol. The time is partitioned into frames, which are further partitioned into time slots. The traffic demand can be either defined as the number of packets to be transmitted in every frame or calculated from the long-run average data transfer rate as detailed in [8], [9].
- The transmission power and rate of the links are the same for all the links in the network. Let P_{ij} denote the received power at the receiver of the j-th link from the transmitter of the i-th link. We assume that the fading is slow such that the channel gain between every transmitter and receiver is fixed during the frame. This is a common assumption used in the prior formulations of the minimum length scheduling in wireless ad hoc networks [8].
- A node cannot receive and transmit simultaneously, and cannot transmit to more than one node simultaneously.
- The signal removal of SIC is perfect. This is a common assumption used in the prior formulations of SIC based wireless network scheduling since the residual interference does not change the scheduling algorithm framework [10].

III. SIC Signal Detection

An SIC capable receiver can decode multiple transmissions at a time in the order of decreasing signal strength from a composite signal. Let S denote the set of concurrently transmitting links. Let us order the links in the set S in decreasing received signal strength at the receiver of link i such that $P_{1i} \geq P_{2i} \geq \ldots \geq P_{Mi}$ and M is the number of the links with received signal strength at the receiver of link i higher than P_{ii}. For successful reception of link i, the sequential SINR criteria are then given as

$$\frac{P_{ki}}{\sum_{j \in S \backslash [1,k]} P_{ji} + N_0} > \beta, \tag{1}$$

for all $k \in [1, M]$ and

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

where N_0 is the background noise and β is the SINR threshold corresponding to a certain packet error probability as a function of packet length, modulation, channel coding, diversity and receiver design [11].

IV. Minimum Length Scheduling Problem

The scheduling problem aims to minimize the schedule length while satisfying the traffic demands and sequential SINR constraints of the links.

A. NP-Hardness of the Problem

Theorem 1: The minimum length scheduling problem for SIC based wireless ad hoc networks is NP-hard.

Proof: Let us consider the network instance in which no two links share a common node; the received power at every link $i \in [1, L]$, i.e. P_{ii}, is greater than the received power at the receiver of link i from the transmitters of the remaining links, i.e. $P_{ji}, j \neq i$, such that no SIC needs to be activated; every link has one packet to transmit. The minimum length scheduling is then equivalent to the minimum length scheduling problem in [12], which is shown to be NP-hard by reducing the problem instance to the NP-hard graph coloring problem. □

B. Least Interference Effect (LIE) Algorithm

The proposed scheduling algorithm is a greedy algorithm that generates the maximal feasible set of links in each time slot by including the link that minimally affects the transmission of the already scheduled links iteratively. The decision for the minimal effect on the set of already scheduled links is made based on a novel metric called Interference Effect (IE). The IE of a feasible link is defined as the total SINR drop of the links already included in the scheduled set when that link is included. Choosing the feasible link with minimum IE at each iteration allows the inclusion of a larger number of links decreasing the schedule length.

Let S denote the set of the links already included in the scheduled set for a time slot. Let i denote the link that is considered for inclusion in the scheduled set S. First, the feasibility of the inclusion of link i in S is tested. The feasibility test starts by checking the sequential SINR constraints given in Eqs. (1) and (2) for link i by ordering the received powers at the receiver of link i from the transmitter of the links in S. If these constraints are satisfied then for every link $j \in S$, the satisfaction of the sequential SINR constraints is checked by including P_{ij} in their received power set. If the constraints are not satisfied for at least one link, link i is considered not feasible for inclusion in the set S. Otherwise, the IE of the feasible link i for inclusion in the set S is defined as

$$IE_i^S = \sum_{j \in S} \frac{P_{jj}}{\sum\limits_{\substack{l \in S \\ P_{lj} < P_{jj}}} P_{lj} + N_0} - \frac{P_{jj}}{\sum\limits_{\substack{l \in S \cup \{i\} \\ P_{lj} < P_{jj}}} P_{lj} + N_0} \tag{3}$$

The IE of an infeasible link is set to ∞ in the algorithm.

Algorithm 1 Least Interference Effect (LIE) Algorithm

Input: Links in $[1, L], f_i, P_{ij}$ for $i, j \in [1, L]$
Output: Schedule of link transmissions

1: $L_S = [1, L]$;
2: **while** $L_S \neq \emptyset$ **do**
3: $S = \emptyset$; $U = L_S$;
4: pick an arbitrary link $i \in U$;
5: $S = S + i$; $U = U - i$;
6: **while** $U \neq \emptyset$ **do**
7: **if** $\min_{i \in U} IE_i^S < \infty$ **then**
8: $k = \arg\min_{i \in U} IE_i^S$;
9: $S = S + k$; $U = U - k$;
10: **else**
11: break;
12: **end if**
13: **end while**
14: include S in the schedule;
15: for every $i \in S, f_i = f_i - 1$;
16: remove all $i \in S$ with $f_i = 0$ from L_S;
17: **end while**

Least IE (LIE) algorithm is described next. L_S is the set of links containing at least one packet to be scheduled. U is the set of links considered for concurrent transmission in each time slot. S is the link set that includes all the links that can concurrently transmit chosen from the set U. L_S is initialized to $[1, L]$ to include all the links in the network with at least one packet to transmit (Line 1) and updated to remove the links with no remaining packets once the schedule is formed for each time slot (Lines 15–16). For the scheduling of each time slot, U is initialized to the set of links with at least one packet to transmit, i.e. L_S, and S is initialized to $\emptyset$ (Line 3). The first link to be included in the scheduled set S is chosen arbitrarily (Lines 4–5). The remaining links are chosen considering the IE of the feasible links. If no feasible link can be included in the set S, the scheduling of the current time slot is finalized (Lines 10–11). If there exists at least one feasible link, the one with minimum IE is chosen for inclusion in S (Lines 7–9). Once no more links can be included in the set S, S is included in the schedule for the current time slot and the scheduling of the next time slot starts following the update of the traffic demands of the scheduled links (Lines 14–16). The algorithm stops when all the packets are scheduled, i.e. $L_S = \emptyset$ (Line 2).

Let the transmit-receive pairs $T1 - R1$, $T2 - R2$, $T3 - R3$ and $T4 - R4$ be denoted by links 1, 2, 3 and 4, respectively. Fig. 1 shows an example iteration of the LIE algorithm in which the next link to be included in the link set $S = \{2\}$ is determined. Let the SINR of link 2 be 100 and $\beta = 1$. The inclusion of link 3 is not feasible. The inclusion of link 1 is feasible resulting in the SINR drop of link 2 by 30 due to the interference caused by link 1, whereas the inclusion of link 4 does not cause any decrease in the SINR of link 2 thanks to SIC. Therefore, link 4 is included in S in this iteration of the algorithm.

The complexity of the algorithm is $O(L^3 \sum_{i=1}^{L} f_i)$ since the number of times the link of minimum IE is determined has complexity $O(\sum_{i=1}^{L} f_i)$ and the complexity of determining the link

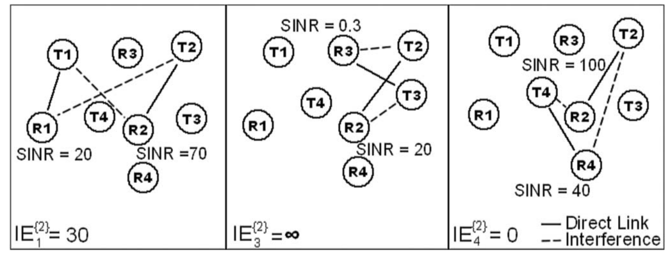

Fig. 1. Example iteration of the LIE algorithm.

of minimum IE is the maximum number of possible links evaluated for inclusion, i.e. L, times the complexity for determining the feasibility, and if so, the IE of the link given by $O(L^2)$.

V. Simulation Results

The goal of this section is to evaluate the performance of the proposed scheduling algorithm for different network sizes and environments in comparison to the optimal scheduling and previously proposed algorithms. The optimal scheduling is obtained by the Integer Linear Programming formulation with exponential number of variables with each variable corresponding to the time allocated to a feasible subset of the links and denoted by OPT. The scheduling algorithms previously proposed for SIC based wireless networks are greedy algorithms that generate a link subset for each time slot considering the interaction of each link with others on a simultaneity graph. The order in which the links are chosen determines the type of the algorithm. The interference number of each link is defined as the total number of incoming and outgoing edges in the simultaneity graph. Once a link is chosen, it is included in the scheduled set, the links that interfere with that link are included in the interference set and the links that can potentially be included in the scheduled set remain in the candidate set. Smallest Degree First (SDF), Recursive Largest First (RLF) and Link Ordering (LO) algorithms then favor the link with minimum interference number in the candidate set, maximum interference number in the interference set, and difference of the outgoing and incoming interference numbers in the candidate set, respectively [5]. Since this simultaneity graph does not consider the cumulative effects of the interference, we also include an additional mechanism to check the feasibility of the final scheduled set in the algorithm.

We used MATLAB on a computer with a 2.5 GHz CPU and 4 GB RAM to run the simulations. Simulation results are obtained based on 100 independent random network topologies, where the nodes are distributed randomly within a square of 100 m × 100 m area. The packet demand of each link in the network is chosen randomly from [1,10]. The attenuation of the links is 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, γ is the path loss exponent, $PL(d)$ 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, $\beta = 1$ and the transmit power given by $p_{max} = 0.2$ W.

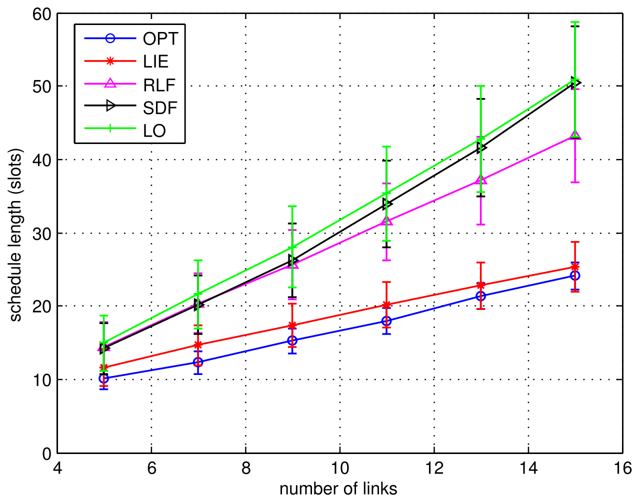

Fig. 2. Schedule length of scheduling algorithms for different number of links.

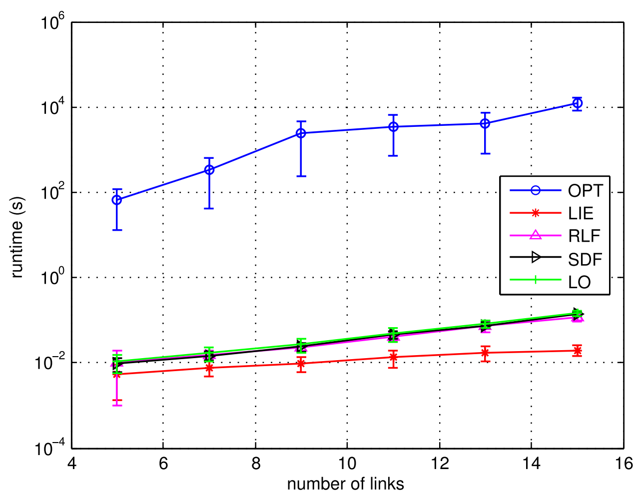

Fig. 3. Runtime of scheduling algorithms for different number of links.

Figs. 2 and 3 show the average and the standard deviation of the schedule length and runtime of the scheduling algorithms for different number of links, respectively. The value of γ is set to 3. The proposed LIE algorithm performs very close to the optimal scheduling with much lower schedule length than the previously proposed scheduling algorithms at much smaller average runtime. The average runtime of the algorithms adopting extended protocol interference model is larger than that of the LIE algorithm due to the requirement of checking the suitability of each possible node subset in each iteration.

Fig. 4 shows the average and the standard deviation of the schedule length of the scheduling algorithms in a 10-link network for different path loss exponents. As the path loss exponent increases, the schedule length of all the algorithms decreases due to the decrease in the interference among the links with larger attenuation. The proposed LIE algorithm still performs much closer to the optimal solution and much better than previously proposed algorithms for all path loss exponents.

VI. Conclusion

We study the design of an efficient heuristic scheduling algorithm with the goal of minimizing the schedule length given the traffic demands of the links in wireless ad hoc networks with SIC. We show that the proposed algorithm performs very close to the optimal scheduling with much lower schedule length than the previously proposed heuristic algorithms adopting extended protocol interference model for SIC at much smaller average runtime via extensive simulations. In the future, we plan to extend this algorithm for variable rate and variable power wireless ad hoc networks.

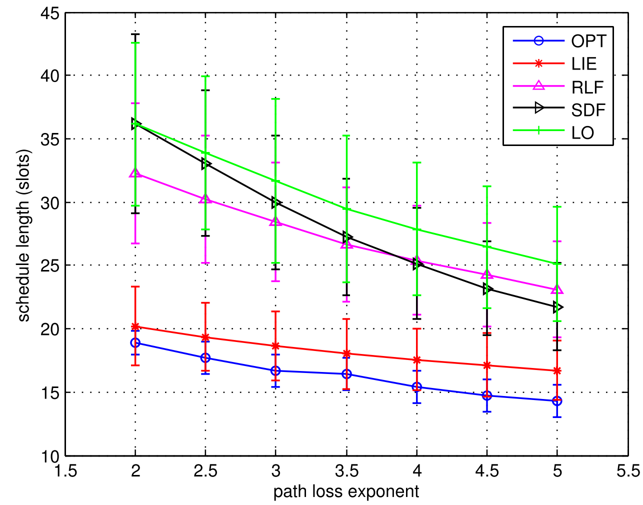

Fig. 4. Schedule length of scheduling algorithms in a 10–link network for different path loss exponents.

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