Minimum Length Scheduling in Wireless Networks with Successive Interference Cancellation

by

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This is to certify that I have examined this copy of a master's thesis by

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and have found that it is complete and satisfactory in all respects,
and that any and all revisions required by the final
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In human life, you will find players of religion until the knowledge and proficiency in religion will be cleansed from all superstitions, and will be purified and perfected by the enlightenment of real science.

Mustafa Kemal Atatürk

ABSTRACT

Scheduling in wireless 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 limits the capacity of wireless networks. 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, Successive Interference Cancellation (SIC) appears to be the most promising due to its simplicity, overall system robustness and existing prototypes. SIC is based on decoding and subtracting the signals successively from the composite received signal starting with the strongest signal.

In this thesis, we study the optimal scheduling problem for minimizing the length of the schedule required to satisfy the traffic demands of the links in single-hop variable rate multiple access wireless networks and multi-hop fixed rate wireless networks using SIC. The scheduling problems for both networks are proven to be NP-hard. In single-hop multiple access wireless networks, we propose a novel centralized algorithm based on Column Generation Method. This algorithm is based on decomposing the original problem into Restricted Master Problem (RMP) and Pricing Problem (PP), and approximating the exponentially complex PP by a greedy heuristic algorithm. In multi-hop wireless networks, we first propose a novel centralized algorithm that includes the feasible links in the scheduled link set one by one in the increasing order of a novel metric called Interference Effect (IE). IE number of a link is defined as the total Signal-to-Interference-plus-Noise Ratio (SINR) drop of scheduled links if the link is scheduled to the time slot. We then propose a novel distributed algorithm that extends the Request-to-Send (RTS)/Clear-to-Send (CTS) mechanism of Carrier Sense Multiple Access (CSMA) protocol to enable further transmissions exploiting SIC. We demonstrate via simulations that the proposed algorithms perform very close to the optimal solution and much better than the previously proposed algorithms with runtime robust to the increasing number of the links and much smaller than that of the optimal algorithm.

ÖZETÇE

Kablosuz ağlarda cihazların ağa erişim sıralamasını düzenlemenin önemi gitgide artmaktadır. Günümüzde kablosuz ağlara bağlanan cihazların sayısı, ağın sahip olduğu kaynakların (bu kaynağı hava olarak tanımlayabiliriz) tersine gitgide artmaktadır. Bu cihaz artışı aynı kanal üzerinde daha çok sinyal gönderim isteği anlamına gelmekte, dolayısıyla kapasite sorunları yaşanarak sinyal çözümlemeyi engellemektedir. Geleneksel ağlar bu problemi çözmek için enterferans imtina yolları kullanmakta, birbirine karışacak sinyalleri aynı anda göndermeyecek şekilde erişim sıralaması düzenlenmektedir. Fakat bu yöntem kanal kapasite kullanımı yüksek oranda düşürmekte ve simültane sinyal gönderimini kısıtlamaktadır. Son zamanlarda yeni yöntem olarak Ardışık Enterefans Silme (AES) yöntemi kapasite arttırımı için umut vadetmektedir. AES istenilen sinyale ulaşana kadar toplu gelen sinyalden en güçlü siynali çözümleyip çıkarır, dolayısıyla ardışık çözümleme uygulamasıdır. Bu yöntem ile birden çok sinyal aynı anda gönderilebilir ve gönderim kapasitesi arttırılabilir.

Bu tez, AES kapasiteli Zaman Bölmeli Çoklu Erişim (ZBÇE) sistemlerinde aynı kanalı kullanan cihazların kanala erişim çizelgesini ayarlayarak en kısa sürede iletim yapmalarını amaçlamaktadır. Tez iki fazdan oluşmakta olup ilki çoklu verici, tek alıcılı değişken iletim hızlı sistemleri kapsamaktadır. İkinci faz ise çok verici, çok alıcı sistemleri incelemekte olup, veri iletim hızı sabit olan durumları incelemektedir. Çizelgeleme problemi iki faz için de np problem kategorisine girdiğinden dolayı optimum çizelgeye yakın sonuç veren fakat düşük karmaşıklığı olan buluşsal metotlara ihtiyaç duymaktadır. Bu tezdeki amaç iki farklı ağ grubu için bu gereksinimleri karşılayarak hızlı ve optimuma yakın sonuçlar üreten metotlar üretmektir. Her iki faz için de ayrı ayrı çizelgeleme problem tanımları verilmekte, daha sonrasında da probleme uygun çözüm metotları aktarılmaktadır. Son olarak verilen metotlar simüle edilerek hem

teorik hem de hesaplama zamanı olarak optimum sonuçlarla karşılaştırılmıştır.

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NOMENCLATURE

ACK	:	Acknowledgment
CCR	:	Channel Condition Request
CGM	:	Column Generation Method
$CGM - HS$	:	CGM - Heuristic Scheduler
$CSMA$	:	Carrier Sense Multiple Access
CTS	:	Clear-to-Send
CW	:	Contention Window
DCF	:	Distributed Coordination Function
$DIFS$	:	Distributed Interframe Space
GHS	:	Greedy Heuristic Scheduler
IE	:	Interference Effect
$IEEE$	:	Institute of Electrical and Electronics Engineers
ILP	:	Integer LP
LIE	:	Least IE
LP	:	Linear Programming
LO	:	Link Ordering
NAV	:	Network Allocation Vector
OPT	:	Optimal Solution
PP	:	Pricing Problem
RLF	:	Recursive Largest First
RMP	:	Restricted Master Problem
RTS	:	Request-to-Send
SDF	:	Smallest Degree First
SIC	:	Successive Interference Cancellation
$SIFS$	:	Short Interframe Space
$SINR$	:	Signal to Interference plus Noise Ratio
$TDMA$	:	Time Division Multiple Access

Chapter 1

INTRODUCTION

1.1 Single-Hop Networks

Interference avoidance has been commonly used to deal with wireless channel interference in the design of network protocols. In interference avoidance, a receiver can only decode one transmission at a time by considering all other transmissions as interference and noise. The arrival of multiple transmissions at a receiver results in a collision so failure of reception. On the other hand, interference cancellation allows detecting multiple transmissions at a time by decomposing all the signals in a composite signal. Among many interference cancellation techniques, Successive Interference Cancellation (SIC) appears to be the most promising due to its simplicity, overall system robustness [1] and existing prototypes [2]. SIC is based on decoding the signals from multiple transmitters successively. Each time a signal is decoded, it is subtracted from the composite signal to improve the Signal-to-Interference-plus-Noise Ratio (SINR) of the remaining signals.

Time Division Multiple Access (TDMA), where only one transmission is scheduled at a time, has often been used as a conflict-free scheduling in single-hop multiple access wireless networks with interference avoidance. Although TDMA is simple and easy to implement, it leads to suboptimal channel usage since it doesn't exploit the capability of multiple transmission detection. On the other hand, SIC based single-hop multiple-access wireless networks still requires an efficient scheduling algorithm since in practice a receiver node may only decode a certain number of transmissions at a time [3].

First goal of this thesis is to study the joint optimization of the scheduling algorithm and rate allocation to minimize the completion time required to satisfy the given traffic demands of the links, defined as the schedule length, in SIC based single-hop multiple-access wireless networks. The resource allocation problem has received a lot of attention for interference avoidance based wireless networks in the past. However, the optimization problems formulated for these networks cannot be adapted to SIC based networks due to the difficulty of including the SINR requirement considering the ordering of the SIC decoding as a constraint in the optimization problem [4, 5]. In SIC based networks, the SINR of a link depends on the decoding order of simultaneous transmissions eliminating the previously decoded ones and considering the later decoded ones as interference. Including all possible SIC decoding orderings is only possible via assigning a variable to every possible subset of the links sorted according to their decoding order for SIC at the receiver [6]. Since such a formulation requires a high number of variables exponential in the decoding capability of the receiver, a greedy heuristic algorithm has been proposed in [6]. However, this heuristic algorithm has no relation to the optimal formulation so performs much worse than the optimal solution.

In second chapter of the thesis, we propose a heuristic algorithm based on the Column Generation Method (CGM) [7] to solve the large-scale optimization problem efficiently by generating the variables of the optimization problem iteratively as needed. CGM based heuristic methods have been proposed for power controlled fixed rate wireless networks [4] and adaptive rate Ultra-Wideband (UWB) networks [8]. However, due to the difference in the SINR requirements of these networks, these previously proposed algorithms cannot be applied to SIC based networks. The main novelties of the chapter are the proposal of using CGM in the scheduling of the SIC based networks, the proposal of the heuristic algorithm following the proof of the hardness of the CGM method and the demonstration of the superior performance of the proposed CGM based heuristic algorithm compared to the previously proposed methods.

1.2 Multi-Hop Networks

Scheduling in wireless multi-hop networks determines the sets of transmitter-receiver pairs, i.e. links, to be activated at any given time for a variety of objectives such as maximizing total throughput [9], minimizing total transmit power [10] and minimizing schedule length [11]. The interference model used in the simultaneous link activation specifies both the design and performance of the scheduling algorithm [12]. 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 limits the capacity of wireless ad hoc networks [13]. 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. As stated previosuly, among many interference cancellation techniques, SIC appears to be the most promising due to its simplicity, overall system robustness [1] and existing prototypes [2] which is based on decoding and subtracting the signals successively from the composite received signal starting with the strongest signal.

SIC has been shown to improve the performance of wireless networks by enabling both concurrent receptions and interference rejection [14]. An SIC receiver is capable of decoding multiple packets from a composite signal. This allows concurrent packet reception if the packets reach the intended destination and interference rejection if the packet is from an unintended transmitter. To fully exploit these benefits on the other hand the scheduling algorithm should consider the sequential SINR constraint of SIC. SINR must be above a threshold when a receiver tries to decode the desired signal from the composite signal at any stage. If the current signal cannot be decoded, none of the remaining weaker signals can be decoded. The scheduling algorithms proposed for SIC based wireless networks fall into one of three categories: scheduling optimization, centralized heuristic scheduling algorithm design and distributed heuristic scheduling algorithm design.

Optimal SIC based scheduling in wireless networks has been shown to be NP-hard [15, 16]. For wireless multi-hop networks with fixed transmission power, fixed transmission rate and fixed length time slots, optimal scheduling of the transmission of the links has been formulated as an Integer Linear Programming (ILP) problem with $O(NL^2)$ variables, where N is the number of time slots and L is the number of the links [15]. The problem becomes Mixed Integer Linear Programming Problem when the continuous flow variables at the routing layer are included in the optimization problem [17, 18]. If additionally the power and rate of the links are considered as variables, the optimization problem becomes even harder formulated as a Mixed Integer Non-linear Programming Problem [19–21]. These formulations however can only be solved in exponential time.

Centralized heuristic scheduling algorithms proposed for SIC based wireless networks either use CGM or extends the protocol interference model previously used for interference avoidance based communication. CGM based heuristic algorithms are based on the formulation of the optimal scheduling as a Linear Programming (LP) problem where each variable represents the time allocated to a subset of the links sorted according to their decoding order for SIC at the receivers. Since the LP formulation requires a high number of variables exponential in the number of the links in the network, the CGM decomposes the large-scale original problem into Restricted Master Problem (RMP) and Pricing Problem (PP). 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 [16, 18, 19, 22]. 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 among different links but also the concurrent transmission of different sets of links. Protocol interference model in non-SIC based 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 due to the simultaneous transmission of more than three links since an edge between super and ordinary vertices allows us to consider only relationship of at most three links, which results in unexpected collisions [23–25]. Moreover, the performance of none of these centralized heuristic algorithms has been compared to that of the optimal scheduling algorithm.

Distributed heuristic scheduling algorithms proposed for SIC based wireless networks mostly employ Carrier Sense Multiple Access (CSMA) [2, 26]. In CSMA, the sender senses the channel to determine whether another transmission is in progress before the transmission of a packet. A threshold based process is usually adopted in assessing the channel state: The channel is considered busy if the received signal strength is greater than a threshold and idle otherwise. If the channel is idle, the sender transmits the packet. Otherwise, it waits for a random amount of time before attempting the next transmission. Conventional CSMA designed for single packet reception implicitly assumes that the transmission will fail if the interference is strong. However, this assumption is not valid for SIC based networks: If the interference is strong enough, it may be detected and subtracted from the composite signal to eliminate its effect on the remaining signal. Therefore, there is a trade-off between exploiting new transmission opportunities and capturing harmful interference for different carrier sense thresholds. [26] provides an analysis on the areas where simultaneous transmissions are allowed and the interference is harmful in a three-node network with SIC. [2] on the other hand provides an implementation of a CSMA algorithm for SIC receivers using software radios. However, none of the previous approaches analyze the effect of carrier sense threshold on the throughput or delay performance of the wireless networks nor propose any change on the CSMA mechanism proposed for conventional non-SIC based networks nor compare their performance to the optimal scheduling algorithms. Furthermore, none of the distributed scheduling algorithms proposed for non-SIC based networks that do not employ CSMA can be directly used in SIC based networks, e.g. [27] estimating accumulated interference power with the scheduling of additional links.

The second goal of this work is to study the optimization of the scheduling to minimize the completion time required to satisfy the given traffic demands of the links, defined as the schedule length, in SIC based multi-hop wireless networks, propose novel centralized and distributed scheduling algorithms and compare their performance to that of the optimal scheduling algorithm. The original contributions of third chapter are listed as follows:

- The minimum length scheduling problem for SIC based wireless multi-hop networks has been shown to be NP-hard and formulated as an ILP problem.

- The proposed centralized scheduling algorithm is a greedy algorithm that includes the feasible links in the scheduled link set one by one in the increasing order of a novel metric called Interference Effect (IE). 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 heuristic algorithms. The performance of the proposed and previous centralized scheduling algorithms are compared to that of the optimal schedule for the first time in the literature.

- The proposed distributed scheduling algorithm is based on the extension of the RTS/CTS mechanism of the IEEE 802.11 DCF [28] with a novel messaging exchange and decision making to enable further transmissions exploiting SIC. The novel messaging exchange happens after the RTS/CTS and before the data packet transmission to decide whether a subset of neighboring nodes are allowed to transmit simultaneously with the link. The decision making includes decoding the extra messaging using SIC and determining whether the simultaneous transmission of the nodes originating these extra messages allow the decoding of the source and destination of the link. The performance of the proposed and previous distributed scheduling algorithms are compared to that of the optimal schedule and centralized scheduling algorithms for the first time in the literature.

Chapter 2

SINGLE-HOP NETWORKS

2.1 System Model and Assumptions

The system model and assumptions are detailed as follows:

- The wireless network consists of a set of L directed links corresponding to L transmitters and a common receiver node. Let us denote the link set by $\mathcal{L} = \{1, 2, ..., L\}$.

- The links in the set $\mathcal{L}$ have positive traffic demands. Let us call the $L \times 1$ demand vector F such that $F = [f_1, f_2, ..., f_L]^T$ where f_i is the traffic demand of the i-th link.

- The time is partitioned into slots of possibly variable lengths.

- We assume that the signal removal of SIC is perfect but the receiver can only decode a certain number of simultaneous transmissions, which is denoted by K, considering the practical limitations as shown in [3, 6, 29].

- The transmitters in the network transmit at the maximum power level p_{max}. The set of received powers is denoted by $\mathcal{P}$ such that $\mathcal{P} = \{P_1, P_2, ..., P_L\}$ where P_i is the received power corresponding to the transmission at maximum power level at the i-th link.

2.2 SIC for Single-Hop Networks

Let us denote the set of active links in a time slot by S. Let $r_i(S)$ be the transmission rate of link $i \in S$ when simultaneously transmitting with the links in S. The capacity region of the multiple access channel determines the feasible rates of the links in the set and is defined as the closure of the convex hull of the rate vectors satisfying

$$\sum_{i \in S'} r_i(S') \leq W log_2(1 + \frac{\sum_{i \in S'} P_i}{N_0}) \tag{2.1}$$

for all $S' \subseteq S$, where W is the channel bandwidth and N_0 is the power of the background noise [30]. Minimizing the schedule length requires maximum transfer of information such that the sum of the transmission rates of the links in S is maximized as

$$\sum_{i \in S} r_i(S) = W log_2(1 + \frac{\sum_{i \in S} P_i}{N_0}) \tag{2.2}$$

This maximum information transfer can be achieved by SIC using any decoding order. There are $|S|!$ possible orderings of the links in S. For each decoding order, the rates of the links are determined by eliminating the previously decoded signals from the composite signal and treating the remaining signals as interference. The capacity region achieved by SIC is larger than that achieved with TDMA.

2.3 Scheduling for Delay Minimization

2.3.1 Optimal LP Formulation

The optimal transmission rate for any subset S of the link set $\mathcal{L}$ is a linear combination of the transmission rates obtained by using SIC in $|S|!$ decoding orderings of this subset. The scheduling problem can therefore be formulated as an LP problem given the transmission rates of the SIC in $|S|!$ decoding orderings for all $S \subseteq \mathcal{L}$.

Let $\mathcal{E} = \{\mathcal{E}_k : 1 \leq k \leq |\mathcal{E}|\}$ be the set of all ordered subsets of the link set $\mathcal{L}$ of maximum size K due to the decodability limit stated in Section 2.1. Let R denote an $L \times |\mathcal{E}|$ matrix such that the element in the i-th row and k-th column of R is the transmission rate of link i when the transmission of link i is decoded in the order specified in $\mathcal{E}_k$ by using SIC if link i is within $\mathcal{E}_k$ and 0 otherwise.

The optimal minimum length scheduling problem is then formulated as an LP problem as

$$\min_{t} \quad \mathbf{1}^T t \tag{2.3a}$$

$$\text{s.t.} \quad Rt \geq F\,, \tag{2.3b}$$

$$t \geq \mathbf{0}\,, \tag{2.3c}$$

where $\mathbf{1}$ is $|\mathcal{E}| \times 1$ all-ones vector, $\mathbf{0}$ is $|\mathcal{E}| \times 1$ all-zeros vector. The variable of the LP problem is the $|\mathcal{E}| \times 1$ vector $t = [t^{(1)}, t^{(2)}, ..., t^{(|\mathcal{E}|)}]^T$, where $t^{(k)}$ is the time slot length allocated to the ordered subset $\mathcal{E}_k$. Equation (2.3a) represents the objective of minimum schedule length. Equation (2.3b) represents the requirement of meeting the traffic demands of the links in the set $\mathcal{L}$. Equation (2.3c) represents the nonnegativity requirement for the slot lengths.

The complexity of the solution based on this LP formulation mainly comes from the large number of variables in the LP problem. Since $\mathcal{E}$ contains all ordered subsets of the link set $\mathcal{L}$ of maximum size K, the number of variables in the LP problem is $O(L^K)$. The worst case complexity of the LP problem is then $O(L^{4K+1}d)$, where d is the maximum number of bits to record one parameter among all parameters of the problem, using Interior Point Method [31]. On the other hand, by virtue of Caratheodory theorem, the number of non-zero variables in the optimal solution of this LP problem is at most L suggesting the use of the CGM where the most useful columns of R are generated iteratively as needed.

2.3.2 Column Generation Method (CGM) based Heuristic Algorithm

CGM decomposes the large scale original LP problem into two subproblems, a Restricted Master Problem and a Pricing Problem, and solves them iteratively.

2.3.2.1 Restricted Master Problem (RMP)

The RMP is similar to the original problem except that only a small subset of the feasible ordered subsets of $\mathcal{L}$ denoted by $\mathcal{E}^p$ is considered. The LP problem is formulated as

$$\begin{aligned} \min_{t} \quad & \mathbf{1}^T t && (2.4a) \\ \text{s.t.} \quad & R^p t \geq F\,, && (2.4b) \\ & t \geq \mathbf{0}\,, && (2.4c) \end{aligned}$$

where R^p denotes the transmission rate matrix corresponding to the set $\mathcal{E}^p$ and the length of all-ones vector $\mathbf{1}$, all-zeros vector $\mathbf{0}$ and variable t is $|\mathcal{E}^p| \times 1$.

The set $\mathcal{E}^p$ and the corresponding R^p matrix can be chosen arbitrarily in the first iteration of the CGM as long as the feasibility of the LP problem is guaranteed. An example feasible initial set is $\mathcal{E}^p = \{(i, i+1, ..., i+K-1) | 1 \leq i \leq L-K+1\}$. The R^p matrix is then extended by including a column that improves the objective function in Equation (2.4a) in the following iterations until no such column can be found. To determine which column to include, we define the reduced cost of a column, which leads to the formulation of the PP, next.

We can obtain the primal and dual optimal solution of the RMP denoted by t^p and t^d respectively in polynomial time [32]. Since we consider only an arbitrary subset $\mathcal{E}^p \subset \mathcal{E}$, t^p is not necessarily the optimal solution to the original problem (2.3). In the original problem, the cost coefficient of every variable in the objective is 1. The reduced cost of a column $r^{(k)}$ in the matrix R is denoted by $c^{(k)}$ and given by

$$c^{(k)} = 1 - \left(t^d\right)^T r^{(k)} \tag{2.5}$$

If the reduced cost $c^{(k)}$ of every column $r^{(k)}$ of the matrix R is greater than 0 then the optimal solution t^p in the current iteration is the optimal solution to the original problem. Otherwise, the objective of the RMP can be reduced by including a column $r^{(k)}$ of negative $c^{(k)}$ in the matrix R^p [7]. Instead of calculating the reduced cost of each column $r^{(k)}$ in the matrix R but not in R^p, which requires an exponential effort, the following PP aims to find the best column with minimum $c^{(k)}$ value among all columns in R matrix as described next.

2.3.2.2 Pricing Problem (PP)

The PP aims to find the ordered subset $(l_1, l_2, ..., l_K)$ that minimizes the reduced cost as formulated in Equation (2.5) so maximizes the price defined as

$$p_{(l_1,l_2,...,l_K)} = \sum_{u=1}^{K} t^d_{l_u} W log_2(1 + \frac{P_{l_u}}{N_0 + \sum_{v=u+1}^{K} P_{l_v}}) \tag{2.6}$$

where t^d_l is the l-th element of the vector t^d representing the dual optimal solution of the RMP in the current iteration. The PP is harder than the problem that aims to find the subset that maximizes the price formulated in Equation (2.6), which is an Integer Programming Problem, due to the removal of the ordering. Solving the PP therefore requires exponential effort [32]. We propose the following heuristic algorithm to efficiently and rapidly solve the PP.

2.3.2.3 Heuristic Algorithm for PP

The heuristic algorithm is based on iteratively including the links one at a time such that the price of the resulting ordered set is maximized. The algorithm starts with the empty set. In each iteration, the set is extended with the link that maximizes the price when included as the last element of the set. The algorithm stops when the set contains K links or the addition of a link does not increase the price of the set.

Algorithm 1 Heuristic Algorithm for PP

```
G = ∅; D = ℒ;
while |G| < K do
  if max_{i∈D} p_(G,i) > p_G then
    k = arg max_{i∈D} p_(G,i);
    G = (G, k); D = D − k;
  else
    break;
  end if
end while
```

The ordered subset is included as a new column of R^p in the RMP problem if its price is higher than 1 so its reduced cost is negative. Otherwise, the CGM stops.

2.3.2.4 Complexity of CGM based Heuristic Algorithm

Let Z be the number of iterations in the CGM algorithm. In each iteration of the CGM, the RMP solves an LP problem of at most $L+Z$ variables resulting in the worst case complexity of $O(L(L+Z)^4 d)$ using Interior Point Method [31]. The heuristic algorithm for PP on the other hand has complexity of $O(LK)$. Therefore, the overall complexity of the CGM based heuristic algorithm is $O(ZL(L+Z)^4 d)$. Since the complexity of Z is $O(L^K)$ in the worst case, the worst case complexity of the CGM based heuristic algorithm is worse than that of the optimal LP solution as expected [7]. However, its average runtime is much better than that of the optimal LP solution due to the average Z value much lower than $O(L^K)$ as demonstrated in Section 2.4.

2.4 Simulation Results

The goal of this section is to compare the performance of the proposed CGM based heuristic algorithm with that of the optimal LP solution, the TDMA algorithm and the only previously proposed heuristic algorithm in the literature [6], which is based on scheduling any K links from the link set $\mathcal{L}$ in an arbitrary order at any time until all the links have satisfied their traffic demands. We denote the optimal LP formulation, the TDMA algorithm, the proposed CGM based heuristic algorithm and the previously proposed greedy heuristic algorithm by "OPT", "TDMA", "CGM-HS" and "GHS" respectively.

We used MATLAB on a computer with a 2.5 GHz CPU and 4 GB RAM to run the simulations. Simulation results are obtained by averaging over 1000 independent random network topologies where the nodes are randomly distributed within a square of length 100m and the receiver is placed in the middle of the square. The traffic demands of the links are assigned randomly between 1 and 10 Mbits. The attenuation of the links is determined by using Rayleigh fading with scale parameter Ω set to the mean power level determined by using the path loss and shadowing model given 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, γ is the path loss exponent and Z is a Gaussian random variable with zero mean and σ_z^2 variance. The parameters of the model used in the simulations are $\gamma = 3$, $\sigma_z^2 = 2$, $PL(d_0) = 1dB$, $d_0 = 1m$, $N_0 = 10^{-5}W/Hz$, $W = 1\text{MHz}$, $p_{max} = 1W$.

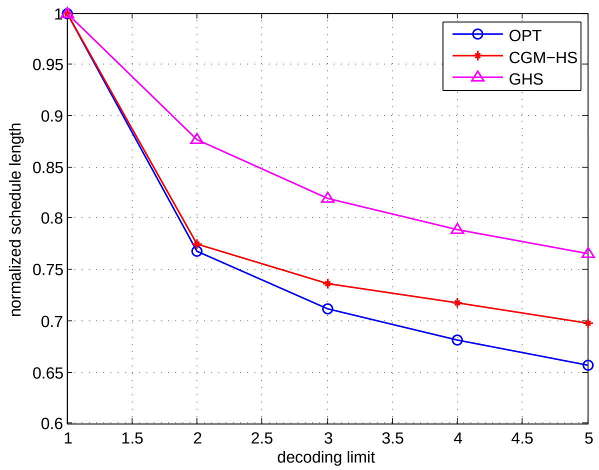

Figure 2.1: Normalized schedule length for different decoding limits in a 20-link network.

Figs. 3.7 and 3.8 show the schedule length normalized by that of the OPT solution at $K = 1$ and the average runtime respectively for OPT, CGM-HS and GHS algorithms with different decoding limits in a 20-link network. The TDMA corresponds to the decoding limit of 1. We observe that the decoding limit of even 2 decreases the schedule length of the TDMA by 25%. The schedule length then further decreases as the decoding capability of the receiver increases but with diminishing improvements. CGM-HS performs very close to the OPT and considerably better than the GHS. On the other hand, the average runtime of the CGM-HS is stable as the decoding capability increases compared to the exponential increase of that of the OPT. Although the average runtime of the CGM-HS is worse than that of the OPT at small values of the decoding limit, increasing the decoding limit results in an exponential increase in the number of the ordered link subsets making the solution of the OPT intractable for large values of the decoding limit.

Figs. 3.9 and 3.10 show the schedule length normalized by that of the OPT solution

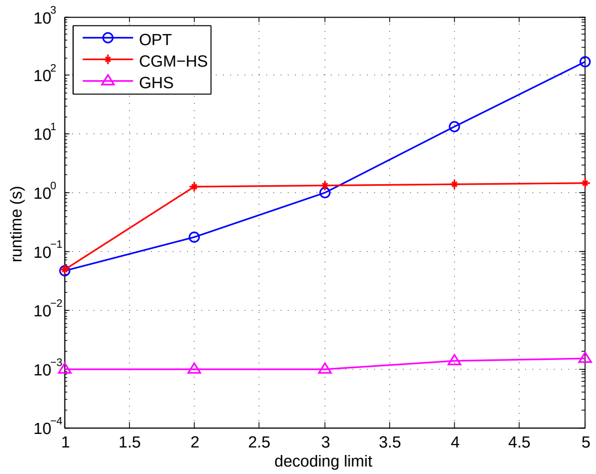

Figure 2.2: Average runtime for different decoding limits in a 20-link network.

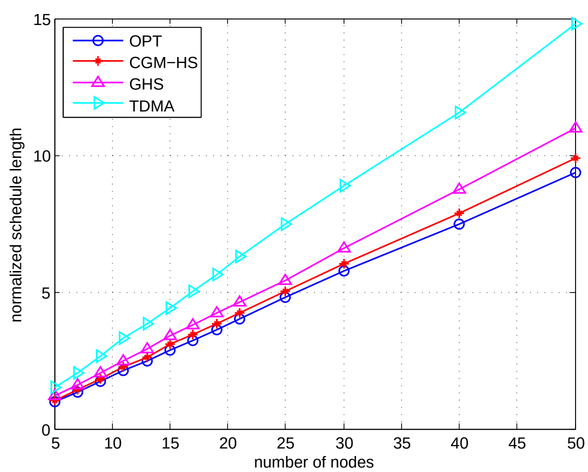

Figure 2.3: Normalized schedule length with the decoding limit $K = 5$ for different number of nodes.

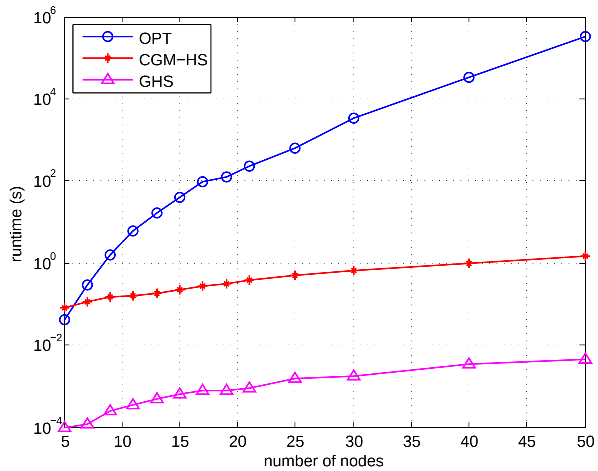

Figure 2.4: Average runtime with the decoding limit $K = 5$ for different number of nodes.

in a 5-link network and the average runtime respectively for OPT, TDMA, CGM-HS and GHS algorithms with the decoding limit $K = 5$ for different number of nodes. We observe that OPT, CGM-HS and GHS decreases the schedule length of TDMA considerably. Moreover, CGM-HS again performs much closer to the OPT than the GHS. The runtime of the CGM-HS on the other hand is robust to the increasing number of the links.

Chapter 3

MULTI-HOP NETWORKS

3.1 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. The proposed framework can be extended to include routing via flow-balance equations that map the end-to-end flow demands to the link traffic demands [33,34]. To avoid complexity in the first step of the study and better focus on the scheduling, the inclusion of the routing in the optimization problem is out of scope of this work and subject to future studies.

- The transmit power of the links is fixed at the maximum level p_{max}. 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 schedule. This is a common assumption used in the prior formulations of the minimum length scheduling in wireless ad hoc networks [5,35]. Extending this work for fast fading wireless networks requires a lot of overhead for collecting the channel information at the granularity of the packet transmission time [36] and is beyond the scope of this thesis.

- The transmission rate is the same for all the links in the network. To avoid the complexity in the first step of the study, the inclusion of the variable rate in the optimization problem and scheduling algorithms is out of scope of this work and subject to future studies.

- A node cannot receive and transmit simultaneously, and cannot transmit to more than one node simultaneously.

- The signal removal of SIC is perfect. The effect of residual interference [37] on the performance of scheduling algorithm is out of scope of this work and subject to future studies.

3.2 SIC Processing

3.2.1 SIC Signal Detection

In the classical interference avoidance, a receiver decodes only one transmission at a time treating all other concurrent transmissions as noise. Let S denote the set of concurrently transmitting links. The signal of link i in the set S is successfully decoded if its SINR is above a fixed threshold as

$$\frac{P_{ii}}{\sum_{j\in S, j\neq i} P_{ji} + N_0} > \beta \tag{3.1}$$

where N_0 is the background noise and β is the SINR threshold to be kept to satisfy a certain packet error probability as a function of packet length, modulation, channel coding, diversity and receiver design [38].

An SIC capable receiver can decode multiple transmissions at a time in the order of decreasing signal strength from a composite signal. Let us order the links in the set S in decreasing received signal strength at the receiver of link i such that $P_{1i} > P_{2i} > ... > P_{Mi}$ and M is the number of links with received signal strength at the receiver of link i higher than P_{ii}. Receiver of link i first decodes the strongest signal. If the strongest signal is decoded successfully, i.e. its SINR is above a fixed threshold, then it can be subtracted from the composite signal. Receiver of link i then decodes the second strongest signal from the remaining composite signal. If this signal is decoded successfully, it is again subtracted from the composite signal. The process continues until either all the stronger signals and the signal of link i are successfully decoded or one of the stronger signals or the signal of link i does not satisfy the SINR criterion. For successful reception of link i, the sequential SINR criteria are then given as follows:

$$\frac{P_{1i}}{\sum_{j \in S \setminus \{1\}} P_{ji} + N_0} > \beta \tag{3.2}$$

$$\frac{P_{2i}}{\sum_{j \in S \setminus \{1,2\}} P_{ji} + N_0} > \beta \tag{3.3}$$

$$\vdots$$

$$\frac{P_{Mi}}{\sum_{j \in S \setminus \{1,2,\ldots,M-1\}} P_{ji} + N_0} > \beta \tag{3.4}$$

$$\frac{P_{ii}}{\sum_{j \in S \setminus \{1,2,\ldots,M\}} P_{ji} + N_0} > \beta \tag{3.5}$$

3.2.2 SIC Packet Detection

SIC packet detection requires the following steps [39]:

1. *Detecting the beginning and end of a packet*: The beginning and end of a packet are detected by searching for sharp changes in the amplitude of the received signal. When there is a jump in the energy of the received signal, the detector synchronizes with the new stronger signal determining the beginning of the packet. A corresponding decrease in the amplitude of the signal indicates the end of the packet.

2. *Decoding the strongest signal*: If the SINR of the stronger signal is sufficient, the standard single packet reception techniques can be used to decode the corresponding packet.

3. *Canceling the strong interferer*: Once the packet with stronger received signal power is detected, it can be subtracted from the composite received signal to eliminate its effect.

4. *Iterate to decode remaining packets*: The remaining signal is again scanned for sharp changes in the received signal amplitude to detect the beginning and end of the packets and decode the remaining signals.

3.3 Minimum Length Scheduling Problem

3.3.1 Integer Linear Programming Formulation (ILP)

The minimum length scheduling problem given the packet traffic demands of the links is formulated as

minimize

$$\sum_{n=1}^{N} t^{(n)} \tag{3.6}$$

subject to

$$\sum_{n=1}^{N} x_i^{(n)} \geq f_i, \quad i \in [1, L] \tag{3.7}$$

$$\frac{P_{ji} + M_{ji}(1 - y_{ij}^{(n)})}{\sum\limits_{l=1, P_{li} < P_{ji}}^{L} P_{li} x_l^{(n)} + N_0} > \beta, \quad P_{ji} > P_{ii}, i, j \in [1, L] \tag{3.8}$$

$$y_{ij}^{(n)} \leq x_i^{(n)}, \quad i, j \in [1, L], n \in [1, N] \tag{3.9}$$

$$y_{ij}^{(n)} \leq x_j^{(n)}, \quad i, j \in [1, L], n \in [1, N] \tag{3.10}$$

$$y_{ij}^{(n)} \geq x_i^{(n)} + x_j^{(n)} - 1, \quad i, j \in [1, L], n \in [1, N] \tag{3.11}$$

$$\frac{P_{ii} + M_{ii}(1 - x_i^{(n)})}{\sum_{l=1, P_{li} < P_{ii}}^{L} P_{li} x_l^{(n)} + N_0} > \beta, \quad i \in [1, L] \tag{3.12}$$

$$t^{(n)} \geq x_i^{(n)}, \quad i \in [1, L], n \in [1, N] \tag{3.13}$$

$$a_{ij} + x_i^{(n)} + x_j^{(n)} \leq 2, \quad i, j \in [1, L], n \in [1, N] \tag{3.14}$$

variables

$$x_i^{(n)}, y_{ij}^{(n)}, t^{(n)} \in \{0, 1\}, i, j \in [1, L], n \in [1, N] \tag{3.15}$$

where N is the number of time slots, M_{ji} is a constant equal to $\sum_{l=1, P_{li} < P_{ji}}^{L} P_{li}\beta + N_0\beta - P_{ji}$, a_{ij} takes value 1 if links i and j share a common transmitter or the transmitter of link i is the receiver of link j and vice versa and 0 otherwise. The variables of the optimization problem are $t^{(n)}$, which takes value 1 if the n-th time slot is included in the schedule and 0 otherwise; $x_i^{(n)}$, which takes value 1 if the i-th link transmits a packet in the n-th time slot; $y_{ij}^{(n)}$, which takes value 1 if and only if both $x_i^{(n)}$ and $x_j^{(n)}$ take value 1 and 0 otherwise.

The goal of the optimization problem is to minimize the length of the schedule. Eqn. (3.7) represents the packet demand requirement of link i. Eqn. (3.8) gives the sequential SINR constraint of SIC for the links with higher received power at link i than P_{ii}. If $y_{ij}^{(n)}$ is 1, i.e. both links i and j are transmitting in the n-th slot, then the stronger links must satisfy the SINR requirement by considering the links with lower received power at link i as interference. If $y_{ij}^{(n)}$ is 0, then there is no SINR requirement so the inequality is satisfied independent of the value of the problem variables since M_{ji} is chosen accordingly. Eqns. (3.9), (3.10) and (3.11) are used to guarantee that $y_{ij}^{(n)}$ takes value 1 if and only if both $x_i^{(n)}$ and $x_j^{(n)}$ take value 1 and 0 otherwise. Similarly, Eqn. (3.12) represents the SINR requirement of link i after all the stronger simultaneous receptions have been eliminated by SIC. Eqn. (3.13) states that the n-th time slot is active only if there is at least one transmission in that slot. Eqn. (3.14) represents the requirement that a node cannot receive and transmit simultaneously, and cannot transmit to more than one node simultaneously.

This optimization problem is an ILP with $O(NL^2)$ variables so cannot be solved in polynomial time [40].

3.3.2 NP-Hardness of the Problem

Theorem 1. *The minimum length scheduling problem for SIC based wireless multi-hop 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 as formulated in Eqs. (3.6)-(3.14) is then equivalent to the scheduling problem in [41], which is shown to be NP-hard. □

3.4 Centralized Heuristic Scheduling Algorithm

The proposed centralized heuristic 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). IE of a 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 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 Eqns. (3.2)-(3.5) 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

$$IE_i^S = \sum_{j \in S} \frac{P_{jj}}{\sum\limits_{\substack{l \in S \\ P_{lj} < P_{jj}}} P_{lj} + N_0} - \frac{P_{jj}}{\sum\limits_{\substack{l \in S \cup \{i\} \\ P_{lj} < P_{jj}}} P_{lj} + N_0} \tag{3.16}$$

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

Algorithm 2 Least Interference Effect (LIE) Algorithm

Require: Links in $[1, L]$, f_i, P_{ij} for $i, j \in [1, L]$
Ensure: 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 (Line 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 with the update of the traffic demands of the scheduled links, initialization of S and U. The algorithm stops when all the packets are scheduled, i.e. $L_S = \emptyset$ (Line 2).

The complexity of the algorithm is $O(NL)$.

3.5 Distributed Heuristic Scheduling Algorithm

The centralized scheduling algorithms require collecting complete topology information at a central controller, which then performs the slot assignment and sends it back to the nodes in the network, and frequent synchronization among the nodes to align the slot times at each node. This requires a lot of communication among the nodes and may become inappropriate in large networks. One way to bring scalability to the network is through distributed algorithms, in which the schedules are generated based on the local topology information in each node.

The proposed distributed scheduling algorithm is based on the extension of the RTS/CTS mechanism of the IEEE 802.11 DCF with a novel messaging exchange and decision making to enable further transmissions exploiting SIC. DCF is a random access scheme based on CSMA protocol. Conventional CSMA designed for single packet reception assumes that the transmission fails if the interference is strong [28]. Therefore, a carrier sense threshold is used to determine the channel state: The channel is considered idle if the received signal strength is below the threshold and busy otherwise. In SIC based wireless networks however the strong interference can be detected and canceled by using SIC. Therefore, ordinary carrier sensing is not efficient in SIC based networks, which necessitates coordination among the neighboring nodes to decide whether the interference is tolerable. If the interference of additional links still allows the decoding of the actual data transmission then they can be activated simultaneously.

In the basic access of DCF, a station with a new packet to transmit monitors the channel activity [28]. If the channel is idle for a period of time equal to a distributed interframe space (DIFS), the station transmits. Otherwise, the station persists to monitor the channel until it is measured idle for a DIFS. The station then generates a random backoff interval before transmitting to minimize the probability of collision with packets being transmitted by other stations. DCF adopts an exponential backoff scheme on a discrete-time backoff scale. The time immediately following an idle DIFS is slotted, and a station is allowed to transmit only at the beginning of each slot time. The slot time is set equal to the time needed at any station to detect the transmission of a packet from any other station. At each packet transmission, the backoff time is uniformly chosen in the range $(0, w-1)$. The value w is called contention window, and depends on the number of transmissions failed for the packet. At the first transmission attempt, w is set equal to a value CW_{min} called minimum contention window. After each unsuccessful transmission, w is doubled, up to a maximum value CW_{max}. The backoff time counter is decremented as long as the channel is sensed idle, frozen when a transmission is detected on the channel, and reactivated when the channel is sensed idle again for more than a DIFS. The successful reception of a packet is followed by the transmission of a positive acknowledgment (ACK) by the destination after a period of time called short interframe space (SIFS). As the SIFS (plus the propagation delay) is shorter than a DIFS, no other station is able to detect the channel idle for a DIFS until the end of the ACK. Explicit transmission of an ACK is needed to inform the transmitter of the successful reception of the packet.

In the RTS/CTS access of DCF, before transmitting a packet, a node reserves the channel by sending a special RTS short packet. The destination node acknowledges the receipt of an RTS packet by sending back CTS packet. Following the successful reception of the CTS, the normal data packet transmission and ACK response occurs. The RTS/CTS mechanism allows to increase the system performance by reducing the duration of a collision when long messages are transmitted. Moreover, RTS and CTS packets carry the information of the length of the packet to be transmitted. The nodes that receive either RTS or CTS packet update a network allocation vector (NAV) containing the information of the period of time during which the channel will remain busy. Therefore, a node that is hidden from either the transmitting or receiving node can suitably delay further transmission, and thus avoid collision.

The proposed extension of RTS/CTS mechanism includes extra messaging between the RTS/CTS and DATA/ACK packet exchanges to decide whether a subset of neighboring nodes are allowed to transmit simultaneously as illustrated in Fig. 3.1. In the pure RTS/CTS mechanism, the nodes that hear either the RTS or CTS packet stay silent until the end of the corresponding ACK packet. This decreases the number of simultaneous transmissions considerably. On the contrary, advanced decoding mechanism of 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.

In the proposed extension of RTS/CTS mechanism for SIC, instead of remaining silent for the NAV period, a randomly selected subset of neighboring transmitters who 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 p_a. p_a is a function of the number of neighboring nodes and will be extensively studied in Section 3.6. 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. 3.1(a)). Otherwise, they don't send any packet implying the suitability of their simultaneous transmission (Fig. 3.1(b)).

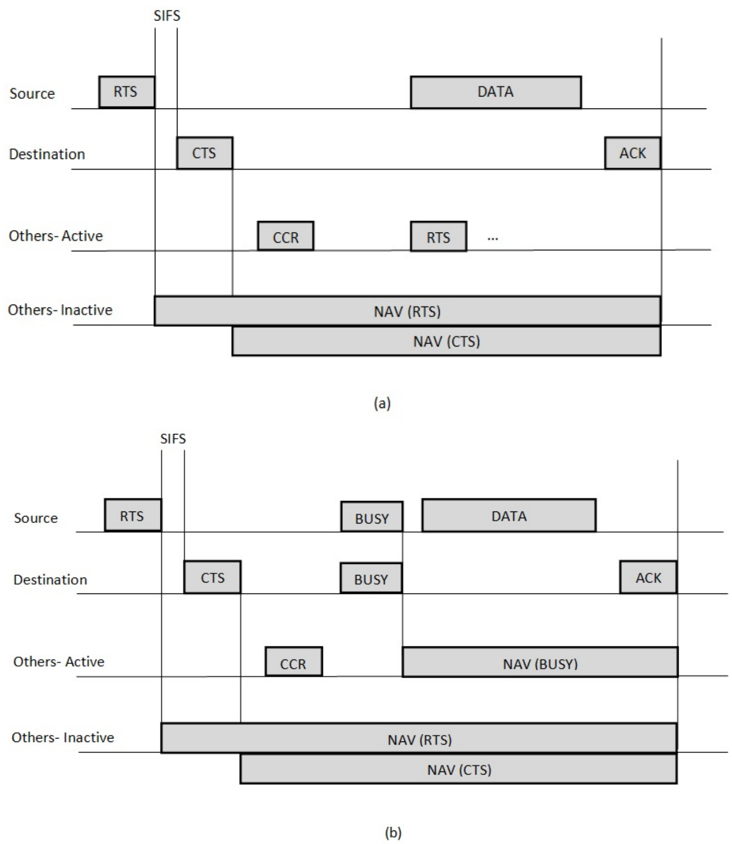

Figure 3.1: Proposed channel access mechanism. a) The randomly selected subset of neighboring transmitters can transmit simultaneously with the link. b) The randomly selected subset of neighboring transmitters cannot transmit simultaneously with the link.

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 packet detection mechanism described in Section 3.2.2. 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 $\{P_1, P_2, ..., P_M\}$, where M is the number of decoded transmissions with received power greater than P_r and P_i is the received power of the i-th strongest transmitter. 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 $\{P_1, P_2, ..., P_M, P_r\}$ are decodable in the presence of noise N_0 and interference I_r by checking the sequential SINR criteria given in Section 3.2.1. 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. 3.2 provides a network instance for the explanation of the proposed algorithm. Let us denote the source and destination of the link by S and D respectively and the set of their neighboring nodes by $\{N_1, N_2, ..., N_7\}$. The transmission ranges of S and D are shown by the dashed circles around them: Neighbors N_1, N_2 and N_3 hear only from S, neighbors N_4, N_5 and N_6 hear only from D and N_7 hears from both S and D. The proposed algorithm runs as follows: T sends an RTS packet, N_1, N_2, N_3 and N_7 overhear the message and wait until CTS ends. After receiving the RTS message, D sends CTS response, which is overheard by N_4, N_5, N_6 and N_7. After CTS is delivered, the neighbors who receive RTS or CTS send CCR message with probability p_a otherwise put their radio in sleep mode until the end of the corresponding DATA/ACK packets. 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 a composite CCR from N_1 and N_7, S checks sequential SINR criteria for the successful reception of the ACK packet from D in the presence of the simultaneous transmission of these neighbors. Likewise D checks this criteria for the successful reception of the DATA packet from S in the presence of the simultaneous transmission of N_6 and N_7. 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.

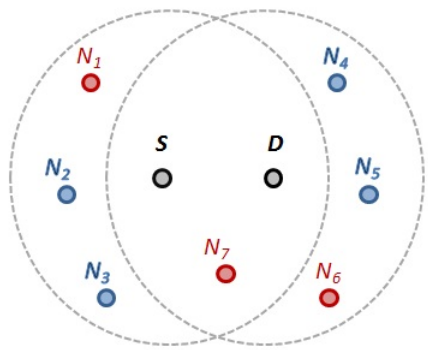

Figure 3.2: Network instance for the proposed algorithm.

3.6 Simulation Results

The goal of this section is to evaluate the performance of the proposed centralized and distributed scheduling algorithms for different network size, network density and environment in comparison to the optimal scheduling and previously proposed algorithms. The optimal scheduling is obtained by the ILP formulation given in Section 3.3.1 and denoted by OPT. The centralized 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, difference of the outgoing and incoming interference numbers in the candidate set respectively [23]. 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. The distributed algorithms previously analyzed for SIC based wireless networks are basic access and RTS/CTS mechanism of DCF, which are denoted by basic-DCF and RTS/CTS-DCF respectively.

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 1000 independent random network topologies. The packet demand of each link in the network is chosen randomly from $[1, 10]$. 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, 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, $W = 1$ MHz, $p_{max} = 1.25$ W, $\beta = 1$, $CW_{min} = 16$, $CW_{max} = 256$, slot time= 50μs, DATA packet transmission time= 8.2 ms, RTS, CTS and ACK packet transmission time= 245μs, DIFS= 500μs, SIFS=50μs.

3.6.1 Performance of Proposed Centralized Scheduling Algorithm

In this section, we compare the performance of the proposed centralized scheduling algorithm, called LIE, to the optimal scheduling and previously proposed centralized algorithms SDF, RLF and LO, for different network size, network density and environments.

Figs. 3.3 and 3.4 show the schedule length and average runtime of centralized scheduling algorithms for different number of links respectively. Nodes are distributed randomly within a square area of 100×100 meters and $\gamma = 3$. The proposed LIE algorithm performs very close to the optimal scheduling with much lower schedule length than the previously proposed centralized 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.

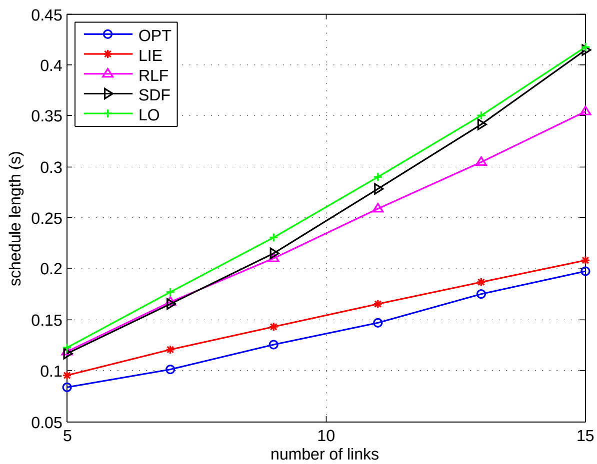

Figure 3.3: Schedule length of centralized scheduling algorithms for different number of links.

Fig. 3.5 shows the schedule length of centralized scheduling algorithms in a 10-link network for different path loss exponents. Nodes are distributed randomly within a square area of 20×20 meters. 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.

Fig. 3.6 shows the schedule length of of centralized scheduling algorithms for different network densities. 10 links are distributed randomly within a square of side length varying from 10 to 100 m and $\gamma = 3$. The schedule length is almost constant at varying network density. The proposed LIE algorithm still performs much closer

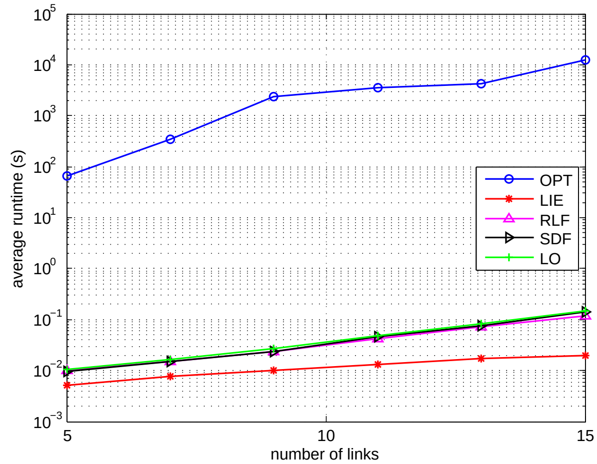

Figure 3.4: Average runtime of centralized scheduling algorithms for different number of links.

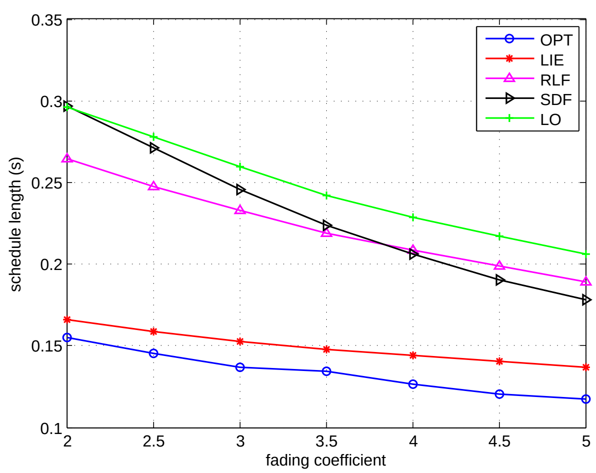

Figure 3.5: Schedule length of centralized scheduling algorithms in a 10-link network for different path loss exponents.

to the optimal solution and much better than previously proposed algorithms for all network densities.

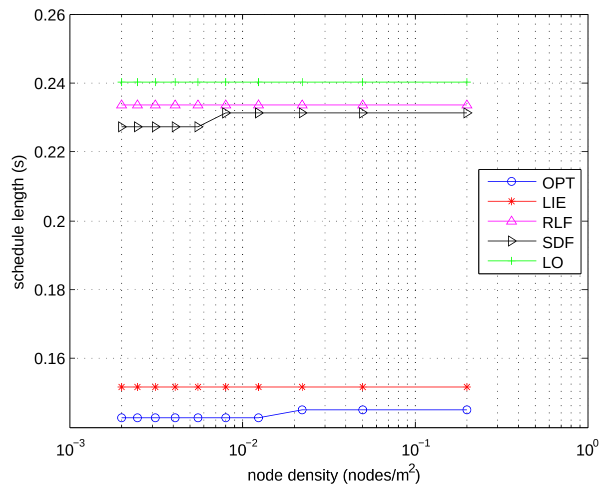

Figure 3.6: Schedule length of centralized scheduling algorithms for different network densities.

3.6.2 Parameter Analysis of Distributed Algorithms

In this section, we analyze the performance of the proposed distributed algorithm, called SIC-CCR-RTS/CTS, the previously proposed 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, for different values of carrier sense thresholds and activation probabilities.

Fig. 3.7 shows the schedule length of CCR-RTS/CTS-DCF for different activation probabilities. The carrier sense threshold is set to 25 dB since it provides close to minimum schedule length under different scenarios including different number of links and different activation probabilities as illustrated later in Figs. 3.9 and 3.10. We observe that there is an optimum activation probability corresponding to each value of the number of links. If the activation probability is very large then a large subset

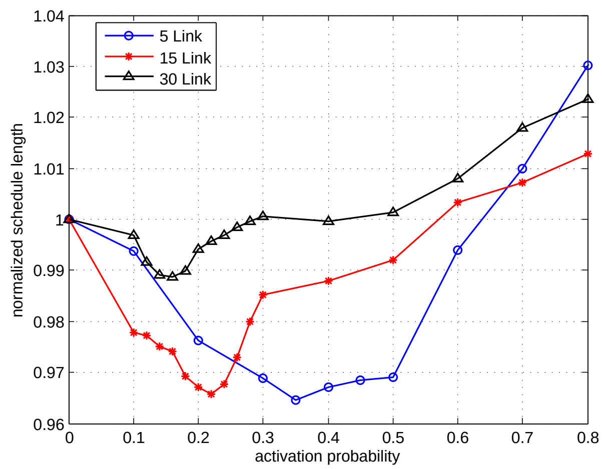

Figure 3.7: Schedule length of distributed scheduling algorithms for different activation probabilities.

of neighboring transmitters receiving an RTS or CTS packet sends the CCR packet, resulting in the unsuitability of their simultaneous transmission. On the other hand, if the activation probability is too small, then a very small subset of neighboring transmitters attempt simultaneous transmission, not exploiting the capability of SIC adequately.

Fig. 3.8 shows the optimum activation probability for different average number of neighboring nodes in the network. We observe that the optimal probability decreases as the number of neighbors increases. This is expected since as the number of neighbors increases, the neighboring transmitters should refrain more from transmission to balance the total number of nodes transmitting CCR messages improving the probability of the suitability of their simultaneous transmission.

Figs. 3.9 and 3.10 show the schedule length of distributed scheduling algorithms in a 15 and 30 link networks respectively for different carrier sense thresholds. The activation probability is chosen based on the number of neighboring nodes at each node according to the function plotted in Fig. 3.8. We observe that there is an optimal carrier sense threshold for all the algorithms. If the carrier sense threshold is too high, the number of attempted simultaneous transmissions is very large preventing

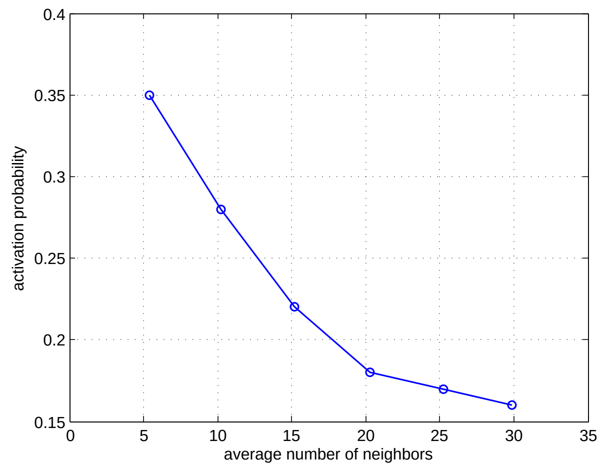

Figure 3.8: Optimum activation probability as a function of the average number of neighbors.

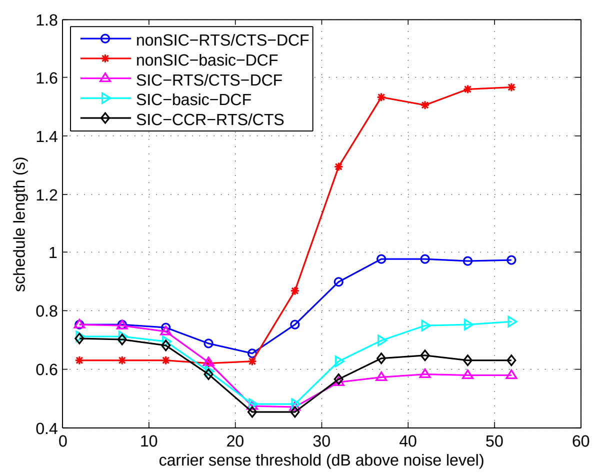

Figure 3.9: Schedule length of distributed scheduling algorithms in a 15-link network for different carrier sense thresholds.

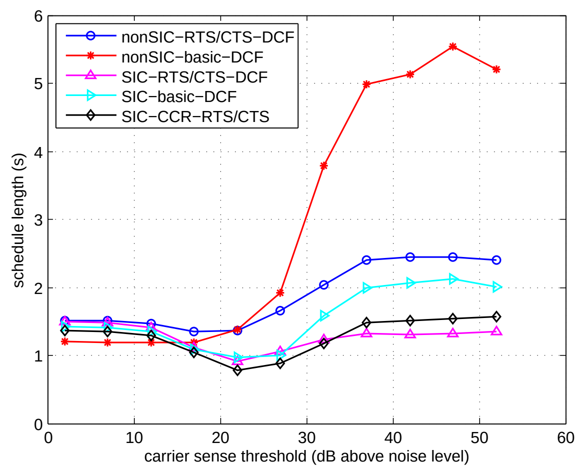

Figure 3.10: Schedule length of distributed scheduling algorithms in a 30-link network for different carrier sense thresholds.

their decodability. If the carrier sense threshold is too low, then the nodes assume the channel is busy most of the time and do not attempt transmission although it is suitable. Moreover, the carrier sense threshold of 25 dB provides close to minimum schedule length under all scenarios. Furthermore, we observe the minimum schedule length of the proposed algorithm is smaller than previously proposed algorithms used in both non-SIC and SIC enabled networks. This is because of the increase in the number of simultaneous transmissions thanks to the extra messaging.

3.6.3 Performance of Proposed Distributed Scheduling Algorithm

In this section, we compare the performance of the proposed distributed scheduling algorithm to the previously proposed distributed algorithms, proposed centralized scheduling algorithm and optimal algorithm for different network sizes.

Fig. 3.11 shows the schedule length of distributed scheduling algorithms, proposed centralized scheduling algorithm and optimal algorithm for different number of links. The activation probability is chosen based on the number of neighboring nodes at each node according to the function plotted in Fig. 3.8. The carrier sense threshold is set to 25 dB since it provides close to minimum schedule length under different scenarios. We

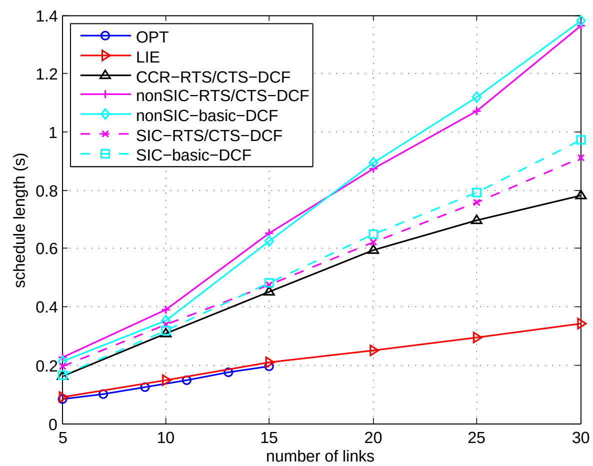

Figure 3.11: Schedule length of distributed scheduling algorithms in comparison to the LIE and optimal centralized algorithms for different number of links.

observe that the proposed distributed scheduling algorithm performs better than the basic and RTS/CTS access mechanisms of DCF. The difference between the schedule length of the algorithms increases as the number of links increases. The difference between the proposed distributed and centralized algorithms arises mainly from the lack of central coordination.

Chapter 4

CONCLUSION

Initially in this thesis, we propose a heuristic algorithm based on the CGM to solve the optimal scheduling problem to minimize the schedule length given the traffic demands of the links in SIC based single-hop multiple access networks. Simulations show that this algorithm performs very close to the optimal formulation with runtime robust to the increasing number of the links and decoding capability of the receiver and much smaller than that of the optimal algorithm enabling its usage in large networks.

Then we study the optimization of the scheduling and design of centralized and distributed heuristic scheduling algorithms with the goal of minimizing the schedule length given the traffic demands of the links in wireless multi-hop networks with SIC.

In this part, we first formulate the optimization problem as an ILP, prove it to be NP-hard and then propose a centralized scheduling algorithm based on the definition of a novel metric called IE. 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. The algorithm includes the feasible links in the scheduled link set one by one in the increasing order of IE. We show that this algorithm performs very close to the optimal scheduling with much lower schedule length than the previously proposed centralized scheduling algorithms adopting extended protocol interference model for SIC at much smaller average runtime via extensive simulations.

We next propose a distributed algorithm based on extending the RTS/CTS mechanism of the IEEE 802.11 DCF with a novel messaging exchange and decision making to enable further transmissions exploiting SIC. The nodes that receive RTS or CTS packet, instead of remaining silent during the transmission, transmit a control packet with a certain activation probability to check whether their simultaneous transmission is suitable. This allows increasing the number of concurrent transmissions if the right subset of nodes are activated. We demonstrate that the proposed distributed scheduling algorithm performs very close to the centralized and optimal one, and much better than the basic and RTS/CTS access mechanisms of DCF via extensive simulations.

In the future, we plan to extend these algorithms for variable rate and variable power multi-hop wireless networks.

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