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EXPLOITING GEOMETRICAL NODE LOCATION FOR IMPROVING SPATIAL REUSE IN SINR-BASED STDMA MULTI-HOP LINK SCHEDULING ALGORITHM

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ABSTRACT

This paper proposes a novel approximation for a Spatial Time Division Multiple Access (STDMA) link-scheduling algorithm based on geometrical node exploitation to improve spatial reuse performance. The geometrical location of nodes was exploited in order to reduce computational complexity and to achieve higher accuracy in transmission to satisfy the Signal to Interference and Noise Ratio (SINR) requirement. The process of SINR global checking is a main constraint in the SINR based interference model but is reduced through geometrical partition and interference approximations based on geometrical node locations. Simulation results show that the proposed algorithm increases the spatial reuse performance in comparison to the greedy physical interference model in similar scenarios. The model utilizing geometrical partition exhibits lower complexity compared to the pure physical interference model that includes SINR global checking.

Keywords: Approximation algorithm; Geometrical node location exploitation; Link scheduling; Mesh network; STDMA

1. INTRODUCTION

Various developments regarding resource allocation algorithms have been widely reviewed by researchers in efforts to utilize the information to improve the performance of wireless communication networks (Shariat et al., 2009). Of special interest are mesh or multi-hop topologies which are important candidates for use in realizing ubiquitous networks in the future era (Akyildiz et al., 2005) and as potential networks for various applications (Bruno et al., 2005). There is a resource allocation opportunity for achieving higher efficiency of mesh network capacity through exploiting the possibility of using the same timeslot for different communication links. This could be achieved as long as those transmissions do not degrade the overall quality of the minimum threshold, or so-called Spatial Time Division Multiple Access or STDMA (Nelson & Kleinrock, 1985). STDMA link scheduling algorithms under the SINR-based interference model (Gupta & Kumar, 2000) are considered to be opportunities for improving wireless mesh network performances and have been shown to have a better spatial reuse and throughput performance than the graph-based model (Grönkvist & Hansson, 2001). However, because SINR checking processes must be done iteratively for every active link and for every timeslot, this performance is more computationally complex and is harder to resolve.

In previous work on SINR-based link scheduling algorithm development, a SINR Graph Link Schedule (SGLS) algorithm was proposed (Gore & Karandikar, 2011) and consequently

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provided the best spatial reuse result to date although the computational complexity was high. On the other hand, algorithms with both greedy (Brar et al., 2006) and geometric approaches (Blough et al. 2010; Liu et al., 2012) showed lower complexity when compared with the SGLS algorithm, but continued to result in lower spatial reuse. New modified greedy-based algorithm have been proposed in our previous work (Adriansyah et al.) in order to increase wireless mesh network throughput capacity and length of scheduling.

In this paper, we extend the proposed algorithm by using exploitation of the geometric node location parameters in order to optimize spatial reuse performance. In other words the sum of the link's degree and scheduling weight as a new parameters are exploited to provide higher spatial reuse and a less complex algorithm. Additionally, the sum of the link's degree and scheduling weight are used as a basis of determining link scheduling priorities. The combination of these parameters ordering are assessed as a means to obtain the best performance of the proposed algorithm. The percentage of the overall link that has been scheduled is proposed as a control variable to adjust the schedule weight ordering, whether the order is ascending or descending.

This paper is organized as follows: section 2 describes the multi-hop link scheduling problem formulation and the simulation model. Section 3 describes the proposed algorithm. Section 4 presents the simulation results and analysis, and section 5 presents the algorithm's complexity analysis. Finally, the conclusion and acknowledgments are presented in sections 6 and 7, respectively.

2. PROBLEM FORMULATION AND SIMULATION MODEL

2.1. Multi-hop Link Scheduling Problem Formulation

A wireless mesh or multi-hop network can be modeled as a connectivity graph, expressed mathematically as $\Phi(.) = G(V, E)$, consisting of a number of nodes (or vertices) that are connected by links (edges) which indicate a communication link between the nodes. Set of nodes (vertices) stated as $V = \{v_1, v_2, ..., v_n\}$, where v_j represents the node j in mesh network $\Phi(.)$, so that $v_i, v_j \in E$, and set of links (edge) expressed as $E = \{(i, j), i, j = 1, 2, ..., L, i \neq j\}$ so that $e_{ij} = (i, j) \in E$. N and L are respectively the number of nodes and links in the mesh network.

The capacity of arbitrary wireless networks is limited to interference and can be assessed using one of two models; the protocol (graph-based) model or the physical (SINR-based) interference model (Gupta & Kumar 2000). To better gauge the capacity performance, this study employed the SINR-based interference model rather than the graph-based model. In the SINR based interference model, multiple links can be allocated to a particular timeslot as long as those transmissions do not degrade the communication threshold that is measured in the SINR parameter. For arbitrary link, for example e_{ij} that is influenced by other links e_{kl} that are allocated to the same timeslot, the requirement of the SINR-based interference model is expressed in Equation 1.

$$\frac{\frac{P}{d_{ij}^{\beta}}}{N_o + \sum_{\substack{k \in V \\ k \neq i}} \frac{P}{d_{kj}^{\beta}}} \geq \gamma_c \tag{1}$$

where P is transmission power, d_{ij} is an euclidian distance of link i.e. transmission link from transmitter in node v_i to receiver in node v_j. The β is exponent pathloss, N_0 is noise density in receiver, and γ_c is a communication threshold.

STDMA protocol access determines the transmission that is right for each timeslot. Hence, the output of the link scheduling algorithms is the function of STDMA link scheduling, notated as $S(S_1, S_2, ..., S_C)$, where C is the number of timeslots needed to schedule all of the active links. The STDMA link scheduling problem formulation model is depicted in Figure 1.

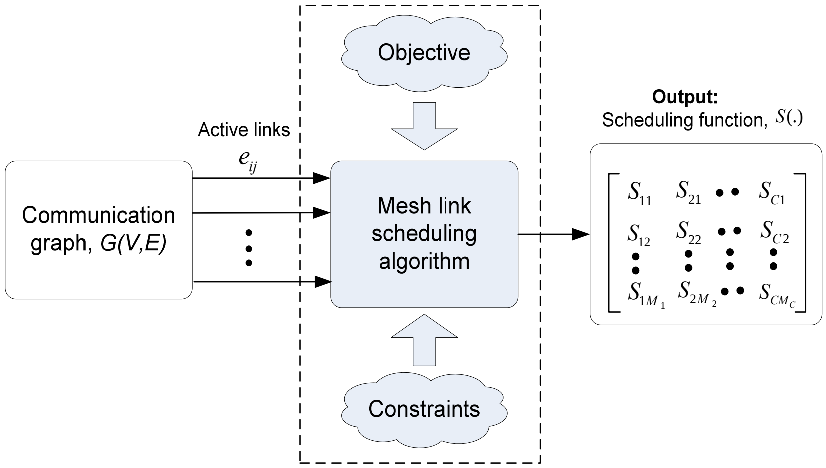


Figure 1 The STDMA link scheduling problem

In wireless mesh network link scheduling optimization problems, an objective function and constraints as Integer Linear Programming (ILP) is formulated in Equation 2.

Objective:

$$\max U\left(r_{ek}\right)$$

Subject to:

$$\text{C1: } \sum_{t=1}^{C} x_{ij}^{t} \geq 1 \qquad \forall e_{ij} \in E$$

$$\text{C2: } \sum_{e_{ij} \in E} x_{ij}^{t} + \sum_{e_{ji} \in E} x_{ji}^{t} \leq 1 \qquad i \in V, j \in V$$

$$\text{C3: } \sum_{v_i \in V^R} x_{ij}^{t} \leq 1 \qquad \forall v_j \in V^R, \forall t$$

$$\text{C4: } \sum_{v_j \in V^R} x_{ij}^{t} \leq 1 \qquad \forall v_i \in V^T, \forall t$$

$$\text{C5: } \frac{\frac{P(v_i)}{d_{ij}^{\beta}} x_{ij}^{t}}{N_0 + \sum_{e_{kj} \in E \setminus \{e_{ij}\}} \frac{P(v_k)}{d_{kj}^{\beta}}} \geq \gamma_c \qquad \forall e_{ij} \in E, \forall t \tag{2}$$

where $U\left(r_{ek}\right)$ is the objective of optimization in mesh link scheduling problem as a function of user data rate, r_{ek}. Constraint C1 guarantees that each active link scheduled at least once along

C timeslots, where x_{ij}^{t} is the binary variable to indicate that link e_{ij} is scheduled to be transmit in timeslot or not, and $x_{ij}^{t} \in \{0,1\}$. Constraint C2 guarantees that each node can not send and receive at the same time. Constraints C3 and C4 guarantee that during a timeslot, a node can transmit to, or receive from, only one node. Constraint C5 expresses the SINR-based interference model evaluation.

2.2. Simulation Model

Simulation was conducted using the Monte-Carlo method of generating a random topology input that is distributed over square-meter areas and then performs the processes of evaluating the mesh topology from communication graphs and scheduling all of the active links of the proposed algorithm. Simulation was repeated 1000 times, each time with different random positions of the nodes using different network topologies. The simulation model is depicted in Figure 2.

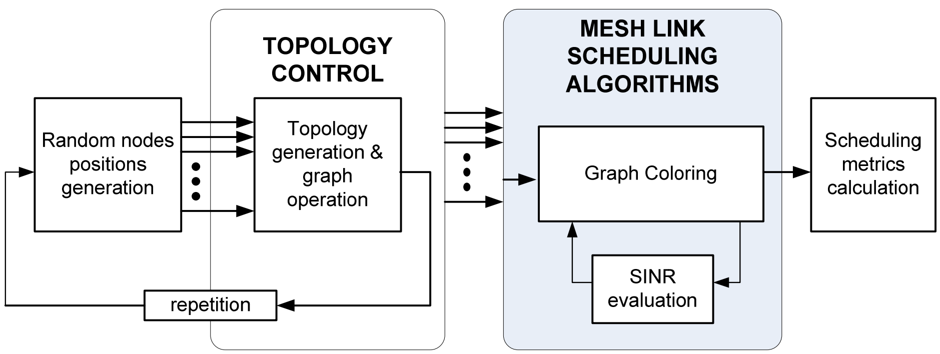


Figure 2 Simulation model

Average spatial reuse is a common parameter for measuring the wireless mesh network performance. This parameter describes the network capacity and efficiency of the multi-hop mesh wireless network. If $I(.)$ is the indicator function, then spatial reuse is defined as the average number of links that have $SINR \geq \gamma_c$ normalized with the number of used timeslots, as follows (Gore & Karandikar, 2011).

$$\sigma = \frac{\sum_{i=1}^{C}\sum_{j=1}^{M_i} I\left(SINR_{r_{ij}} \geq \gamma_c\right)}{C} \tag{3}$$

3. THE GEOMETRIC NODE LOCATION EXPLOITATION APPROACH

In the geometric node location exploitation approach, the location of each node is assumed to be known from the Global Positioning System (GPS) or Ad-hoc Positioning System (APS) (Niculescu & Nath, 2003). Geometrical partition is used to determine the candidate link to be scheduled concurrently for particular timeslots. In Figure 3(a), it can normatively be stated that multiple links can be allocated to the same timeslot if these requirements are satisfied:

- node v_i is in different block partition with node v_k and node v_l
- node v_k is in different block partition with node v_i and node v_j

These normatives also satisfy the constraints in C2, C3, and C4 in Equation (2).

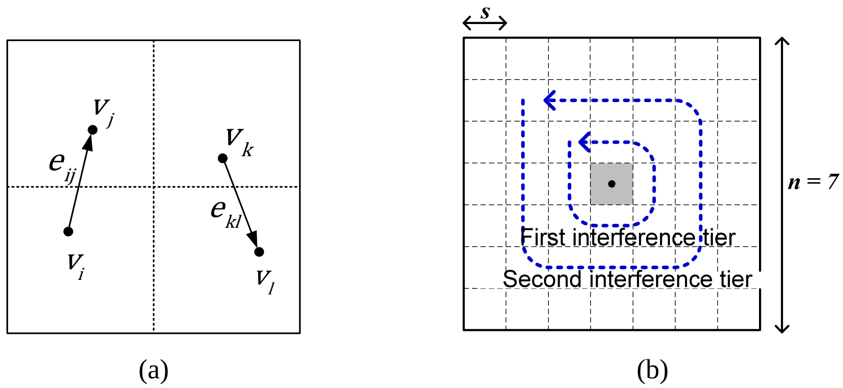


Figure 3 Link: (a) in (2×2) partition size; (b) interference analysis

Interference quantification can be represented by the *interference weight*, w_{ij-kl}, as a function of the considered link distance and transmitter, of other link receiver distances, and of the path loss exponent as follows:

$$w_{ij-kl} = \max\left\{\frac{d_{ij}^{\beta}}{d_{il}^{\beta}}, \frac{d_{kl}^{\beta}}{d_{kj}^{\beta}}\right\} \tag{4}$$

Furthermore, *scheduling weight*, w'_{ij-kl}, is defined as follows :

$$w'_{ij-kl} = 1 - w_{ij-kl} \tag{5}$$

For having SINR guarantee, equation (6) can be derived from Equation (1) below.

$$\frac{\frac{P}{d_{ij}^{\beta}}}{N_o + I_t} \geq \gamma_c \rightarrow I_t \leq \frac{P_i}{\gamma_c d_{ij}^{\beta}} - N \tag{6}$$

For each allocation, the requirement in equation (6) for SINR guarantee should be satisfied.

In Figure 3(b), the total number of interferer blocks experienced in the center block is $8k$, where k = 1 if the interference is observed from the first chain, and k = 2 if the interference is observed from the second chain. If the number of partitions is n^2, then the accumulated interference experienced in the center block, I_t, shown in Figure 3(b) above, can be derived as follows:

$$I_t = \underbrace{\left(m_1 \times \frac{P}{s^{\beta}}\right)}_{\text{first tier}} + \underbrace{\left(m_2 \times \frac{P}{(2s)^{\beta}}\right)}_{\text{second tier}} + \ldots = \sum_k m_k \frac{P}{(ks)^{\beta}} = \sum_k m_k \frac{P}{(\Delta_s)^{\beta}} \tag{7}$$

where m_k is the number of interferer from k-tier and s is partition wide. For generality, Equation (7) can be derived as follows:

$$I_t = \sum_{k=1}^{n_t} \frac{P_k}{d_{kj}^{\beta}} \tag{8}$$

Constraint 5 in Equation (2) is satisfied by substituting Equations (6) to (8) yields,

$$\sum_{k=1}^{n_t} \frac{P_k}{d_{kj}^{\beta}} \le \frac{P_i}{\gamma_c d_{ij}^{\beta}} - N \tag{9}$$

Equation (9) defines the requirement for the active links allocation to particular timeslots based on SINR-based interference model.

The degree of vertex (δ) is an important node parameter that can be exploited in link scheduling algorithms. In this paper, the sum of a link's degree (δ_{ij}) is defined, where $\delta_{ij} = \delta_i + \delta_j$. The algorithm prioritizes to schedule links with maximum δ_{ij} that is meant to prioritize dense topology in the evaluated area.

The pseudo code of the proposed algorithm is as follow:

The Proposed Algorithm:

<u>Input:</u>

Sorted link set based on the sum link's degree : $G(V,E) \to E(G) = \{e_1, e_2, ..., e_l\}$

<u>Output:</u>

Transmission schedule $S = \{S_1, S_2, ..., S_t\}$

<u>Steps of algorithm:</u>

1. **Mesh network coverage divided into** n^2 **partition blocks;**
2. **Initialization:** $t = 1$; $E_{uc}(G) = E(G)$
3. $S_t = \{\varnothing\}$
4. **Select one active link from** $E_{uc}(G)$ **based on the sum link's degree of communication link** (δ_{ij})**, i.e.** e_{ij} **; then allocate in** $S_t ; \{S_t\} \leftarrow e_{ij}$ **;**
5. **Create a list of candidate links that can be allocated to slot-*t* concurently with** e_{ij} **, i.e** $\{e_{kl}\}$ **with criteria :**
   - v_k **and** v_l **in different partition with** v_i
   - v_i **and** v_j **in different partition with** v_k
6. **Sort candidate links based on scheduling weight,**

   $$w'_{ij-kl} = 1 - \max\left[\frac{d_{ij}^{\beta}}{d_{il}^{\beta}}, \frac{d_{kl}^{\beta}}{d_{kj}^{\beta}}\right]$$

7. **Select one candidate, e.g.** e_{kl} **to be evaluated. If** $I_t < \frac{P_k}{d_{kl}^{\beta}} - N$ **, allocate** e_{kl} **to** S_t **, then** $S_t = S_t \cup \{e_{kl}\}$
8. **Return for other candidates**
9. ***t*** **=** ***t*** **+1, repeat step 3 to 9 until all links are designated to be scheduled** ; $E_{uc}(G) - S_t$
10. **Compute link scheduling performance**

4. RESULTS AND DISCUSSION

Simulation parameter settings are shown in Table 1. In this paper, we analyze the performance of the average spatial reuse parameter that is proportionally influenced by the network throughput capacity. Simulation was conducted to observe the effect of the sum of link's degree and scheduling weight ordering combination, and to observe the effect of the number of candidate link limitations.

Table 1 Simulation parameter settings

Parameters	Symbol	Value
Bandwidth	W	10 MHz
Transmission power	P	10 mW
Path loss exponent	β	4
Noise power spectral density	N_0	-90 dBm
Communication threshold	γ_c	20 dB
Interference threshold	γ_i	10 dB
Area covered	$R \times R$	886×886 m^2

In first experiment, the effect of the sum link's degree and scheduling weight ordering were examined. This process occurs in steps 4 and 6 in the pseudo-code program. There were four scenarios to exploiting geometrical node location, as follows:

- Scenario 1; Descending degree δ , and descending scheduling weight w'_{ij}
- Scenario 2; Descending degree, δ and ascending scheduling weight w'_{ij}
- Scenario 3; Ascending degree δ, and descending scheduling weight w'_{ij}
- Scenario 4; Ascending degree δ, and ascending scheduling weight w'_{ij}

The simulation results of the effects of the scenarios appear in Figure 4.

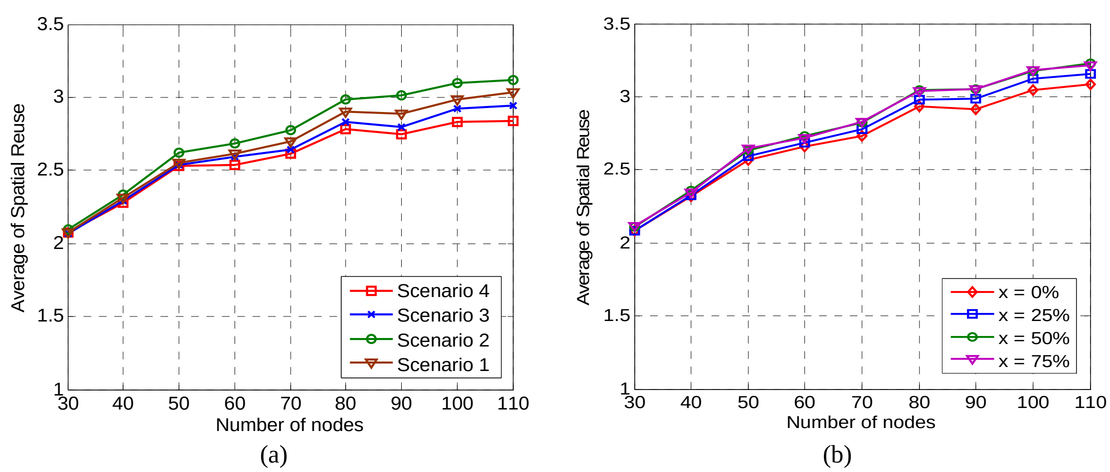
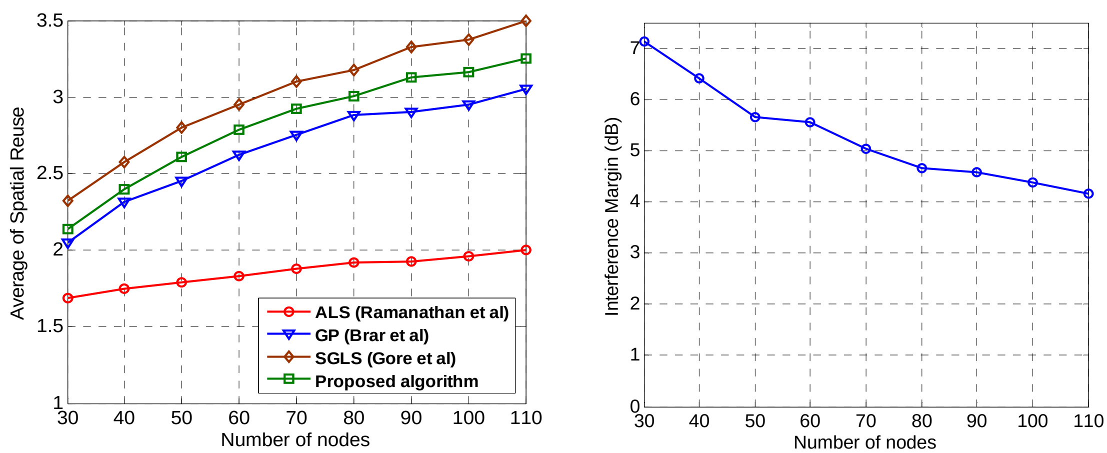


Figure 4 The effect of scheduling weight and degree of nodes combinations to spatial reuse performance

Figure 4(a) shows that scenario 2 provided the best spatial reuse performance and scenario 4 provided the worst performance. In scenario 2, the link with the maximum sum of the links' degree was allocated to a particular timeslot. The candidate links with minimum weight were selected to be allocated to the same timeslot. It can be concluded that scenario 2 prioritized the links in the dense areas to be allocated earlier and prioritized the near links to be allocated to the same timeslot to increase efficiency. The maximum value achieved by scenario 2 in this experiment was 3.117 (110 nodes) and the minimum value of spatial reuse was 2.09 (30 nodes).

In the next experiments, we differed the candidate links sort order based on the percentage of the overall link that was scheduled in steps 6 and 7. If the links that had been scheduled did not exceed x%, then the subsequent scheduling was started from the lowest weight. Conversely, if the links that had been scheduled exceeded x%, the scheduling was started from the highest weight. This process was intended to improve the efficiency of scheduling when the network was still in a dense condition and the majority of the link had not yet been scheduled. Therefore, scheduling starting from the highest weight indicated that scheduling was initiated from nearby links. Simulation results shown in Figure 4(b) shows that the setting of x = 50% provides the best performance, but a slight discrepancy occurs with a result of x = 75%. The maximum value of the average spatial reuse is 3.213 and the minimum value is 2.115.

The comparison references used were the basic Greedy Physical (GP) (Brar et al., 2006), the Arborical Link Schedule algorithm (ALS) (Ramanathan & Lloyd, 1993) which is based on graph-based interference model, and the SINR Graph Link Schedule (SGLS) which is based on SINR-based interference model (Gore & Karandikar, 2011). The number of nodes varied from 30 to 110. In general, for nodes lower than 30 in number, mesh topology has not been established. The simulation results of performance compared to that of mesh link scheduling algorithms are presented in Figure 5.



(a) (b)

Figure 5 The performance comparison of mesh link scheduling algorithms

Figure 5(a) depicts the comparison of the proposed algorithm with the others. The proposed algorithm performed better than both the GP algorithm (Brar et al., 2006) and the ALS algorithm but performed below the spatial reuse algorithm (Gore & Karandikar, 2011). Based on our simulation results, the average spatial reuse performance of the proposed algorithm was 5.05% better than the GP algorithm and 7.14% worse than the SGLS algorithm performance. The proposed algorithm guarantees that the actual SINR for all scheduled links will be above the communication threshold, γ_c. The average difference between the actual SINR from the communication threshold, also called the interference margin, is depicted in Figure 5(b). From these figures, it can be concluded that there is an opportunity to increase the mesh network capacity.

5. COMPUTATIONAL TIME COMPLEXITY

Due to time constraint, the analysis of the proposed algorithm time complexity was determined by using asymptotic time complexity analysis. In the input process, the partition evaluation was performed for each transmitting node in the active links in order to create the node's geometrical parameter and the candidate links that could be transmitted concurrently with the evaluated link, so that this processes requires $O(e)$ operations. The set of active links is sorted based on the sum link's degree requires $O(e \log e)$ operations. The calculation of the interlink co-schedule-ability weight takes $O(e^2)$ operations. So that, the input generator requires $O(e + e \log e + e^2) \sqcup O(e^2)$.

In the proposed algorithm, the first step is to select a link with a largest sum of link's degree to allocate to the first timeslot and read its candidate links. Furthermore, sorting the candidate links and select one link with highest (or lowest) scheduling weight to be SINR evaluated requires $O(|e_c| \log |e_c|)$ time, where $|e_c| < |e|$ and in the worst case $|e_c| = e$. SINR checking for m_i candidate links requires $O(m_i)$ complexity where m_i is the number of links that is allocated to the same timeslot and . This process is repeated until all links have been allocated. The total time complexity of the proposed algorithm is $O(e(|e_c| \log |e_c| + m_i))$. Furthermore, in the worst case the total computational complexity is approximated to $O(e(e \log e + m_i)) \cong O(e^2 \log e)$.

The comparison of the computational time complexity with other algorithms is shown in Table 2.

Table 2 Computational time complexity comparison

Interference model	Algorithm	Computational time complexity
SINR-based	SINR graph link schedule (SGLS) algorithm	$O(e^3)$
SINR-based	Greedy Physical (GP) algorithm	$O(ve^2)$
Graph-based	Arborical Link Schedule (ALS) algorithm	$O(ev \log v + v\theta\rho^2)$
SINR-based	Proposed algorithm	$O(e^2 \log e)$

For the table above, e is the number of active links, v is the number of nodes, θ is the thickness of graph, and ρ is the maximum node degree.

6. CONCLUSION

The research shows that geometrical node location parameters, such as the sum of a link's degree and distance, derived through interference and scheduling weight parameters, can be exploited to improve the spatial reuse in a SINR-based STDMA wireless mesh network. This improvement proportionally increases the network throughput. The simulation results show that the proposed approximation algorithm can increase the spatial reuse performance with similar complexity with the conventional greedy physical algorithm.

7. ACKNOWLEDGEMENT

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