A Weighted Interference Estimation Scheme for Interface Switching Wireless Mesh Networks

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***Abstract*—The co-channel interference problem in wireless mesh networks is extremely serious due to the heavy aggregated traffic loads and limited available channels. It is preferable for mesh routers to dynamically switch channels according to the accurate estimation of co-channel interference level in the neighborhood. Most developed interference estimation schemes, however, do not consider the impact of interface switching. Furthermore, the interference between wireless nodes has been extensively considered as an all-or-nothing event. In this paper, we develop a weighted interference estimation scheme (WIES) for interface switching wireless mesh networks. WIES takes a new version of multi-interface conflict graph to estimate the interference relationships between nodes/links. Besides, WIES uses a weight to estimate the interference level of a node/link on another one. The weight utilizes two empirical functions to denote the impacts of the relative distance between mesh nodes and characteristics of traffic loads in wireless mesh networks. Extensive NS2 simulations show that WIES achieves significant performance improvements, especially when the interference level of the network is high. We also validate that the interference level of networks is affected by the system parameters such as the number of available channels and the ratio between interference range and transmission range.**

KEY WORDS: co-channel interference; conflict graph; dynamic channel assignment; wireless mesh network

1. Introduction

Wireless mesh networks (WMN) [2] have emerged recently as a key technology of the next generation wireless networks. Typically, a WMN is a collection of wireless mesh routers and wireless mobile mesh clients. Wireless mesh routers form the multi-hop WMN backbone without the aid of wired infrastructure. Mesh clients can connect to wireless mesh routers via either wired or wireless connections. In addition, a small number of wireless mesh routers, called gateways, can directly connect to wired networks via wired links. Therefore, mobile users in mesh clients can access the resources that reside on the wired networks through the WMN backbone in a multi-hop fashion. The illustrated architecture of a WMN is shown in Fig. 1, where dash and solid lines indicate wireless and wired links respectively.

As WMNs improve the performance of wireless communications at a low hardware cost, the problem of interference in WMNs, however, is extremely serious due to the heavy traffic loads aggregated from multi-hop mesh clients. Equipping each mesh router with multiple interfaces has been extensively used to decrease the interference level of wireless networks. By fixing interfaces on different channels, mesh routers within each other's interference range can communicate simultaneously with minimal interference. Unfortunately, the number of available channels is quite limited. For example, 802.11b/g and 802.11a only provides 3 and 12 non-overlapped channels respectively [8]. Consequently, not all links within each other's interference range can be assigned different channels. In other words, some links within each other's interference range have to fix on the same channel. And this may sharpen the problem of co-channel interference in multi-interface WMNs.

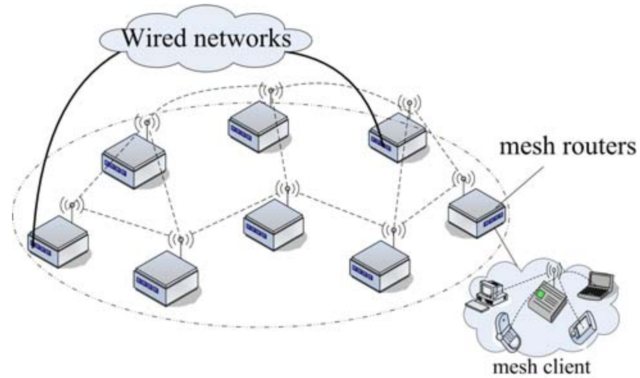

Fig. 1 WMN architecture example

It is preferable for mesh routers to adopt dynamic channel assignment to minimize the co-channel interference in the network when there are limited available channels. It is preferable for a communication link to take the channel that has the least interference level in its neighborhood by interface switching. A proper interference estimation scheme, therefore, is essential for multi-interface WMNs to steer dynamic channel assignment.

However, interface switching induces new challenges in proper estimating the interference level of networks. Mesh routers may adopt different switching modes according to different dynamic channel assignment algorithms/protocols. For example, some proposed protocols [3, 16, 18, 21-23 and 27] require nodes to adjust channels every a relative long period, whereas others [5, 14, 17 and 24] demand channel reassignment (interface switching) whenever they start new communications sessions. Since the interference characteristics of wireless links can be quite different under different interface switching modes, a proper interference estimation scheme should take the impact of interface switching modes into account. In addition, traffic loads [22, 23] and the relative distance [19] between nodes also affect the interference level of network.

Although a lot of effort is being spent on the co-channel interference of wireless networks, current schemes do not consider the impact of frequent interface switching. For example, both the original conflict graph (OCG) [10] and MCG [21] assume that the communication links are either static or changed every a relative long period. Furthermore, most interferecen estimation schemes take the Protocol model [7] to estimate the interference level of one node/link on another one. However, the Protocol model is a rather simple model, which considers the co-channel interference as an all-or-nothing event. Consequently, the Protocol model cannot precisly model the interference level of the network.

For simplicity of explanation, we refer to the WMNs that adopt dynamic channel assignment as interface switching WMNs. In this paper, we develop a novel co-channel interference scheme, called the weighted interference estimation scheme (WIES) for interface switching WMNs. WIES uses the asymmetric conflict graph (ACG) to estimate the interference relationship between nodes/links. ACG is a new version of multi-interface conflict graph that considers the effects of communication constraints. To the best of our knowledge, it is the first in the literature that considers the influences of frequent interface switching in interference relationship estimation. Besides, WIES takes a weight to denote the interference level of a node/link on another one if they switch to the same channel. The weight considers the impacts of the relative distance between mesh nodes and the characteristics of traffic loads in WMNs.

We compare our proposed scheme with the Protocol model through extensive analysis and NS2 simulations. Results show that our proposed scheme achieves better performance than the compared scheme when the number of channels is very limited. The proposed scheme is roughly equivalent to the Protocol model based scheme only when the number of channels is big enough.

The rest of this paper is organized as follows. In section II, we provide a brief overview of related work. Section III presents essential premises that will be used later in this paper. In section IV, we illustrate details of the proposed interference estimation scheme. Evaluation results and short discussions are provided in section V. In section VI, we give our conclusions.

2. Related Work

Co-channel interference estimation is essential in channel assignment and network capacity bounds analysis. A complete interference estimation scheme consists of two parts: interference relationship estimation strategy and interference level estimation model. The former estimates the set of interference nodes/links for a given nodes/link, whereas the latter estimates the interference level of a link on another one. The problem of co-channel interference estimation has been long studied, and a number of papers [1, 7, 9, 10, 12, 13 and 15-18] have been printed.

Since we consider the interference problem during channel assignment in this paper, we just give a very brief review of dynamic channel assignments here. We also give a brief review of the existing interference relationship estimation strategies and interference level estimation models.

The advantages of interface switching have been extensively acknowledged. A considerable algorithms/protocols [3-5, 14, 16-19 and 21-27] have been proposed to dynamically select channels. According to the number of interface that can adopt interface switching, existing channel assignments can be classified into three types [11, 14], which are the fixed channel allocation (FCA), the dynamic channel allocation (DCA) and the hybrid channel allocation (HCA).

Shacham and King [24] propose and analyze two multi-channel architectures that adopt dynamic channel assignment for the first time. In the first, each node employs a single radio and is assigned a channel on which it listens when it does not transmit. To transmit a packet, the node tunes its radio to the channel of the intended receiver for that transmission only. The second architecture requires each radio to use a single channel for both transmission and reception, but provides some of the nodes with more than one radio each, allowing them to serve as bridges between channels.

Kyasanur and Vaidya [14] proposed another hybrid interface assignment strategy, which classifies the interfaces equipped on each node into two types: receiving interfaces and sending interfaces. Each receiving interface fixes on a unique channel, whereas sending interfaces switch among the "fixed" channels of nodes within their communication range to transmit packets. However, multi-channel protocols that require frequent interface switching are still unavailable to existing user applications. They require new support in the operating system kernel. Chereddi, et al. [5] presented a new channel abstraction module to support frequent interface switching.

Conflict graph [10] is one of the most famous interference relationship estimation strategies. Let *G* be the network topology. Nodes in the original conflict graph (OCG) are established corresponding to links in *G*. There is an edge between two nodes in OCG if and only if the links in *G* denoted by the two nodes in OCG interfere with each other. OCG assume that each node is equipped with one interface. Thereby, OCG cannot correctly model the nodes equipped with multiple interfaces. Ramachandran, et al. [21] extended OCG to multi-interface conflict graph (MCG). Instead of representing edges between the mesh routers as vertices as in OCG, MCG represents edges between the mesh radios as vertices. Nevertheless, the edges in MCG are created in the same way as the original conflict graph is created. That is, there will be an edge between two nodes in MCG if and only if the links in *G* denoted by the two nodes interfere with each other.

There are also a few number of interference level estimation models. Gupta and Kumar [7] presented two extensively used models of interference for wireless networks: the Protocol model and the Physical model. Quite a number of protocols [7, 11, 15 and 21] use the Protocol model to estimate interference between links. The two models are designed for single channel single interface wireless network. We then extend the two models to multi-channel and interface switching environment in next section.

The Protocol model treats the interference between nodes as an all-or-nothing event. However, the interference level is greatly affected by the traffic loads [22, 23] and the relative distance between nodes [19] in fact. Several researchers [10, 16 and 17] then raised the use of a weight to denote the impact of traffic loads. Jain, et al. [10] presented a method to find edge weights for conflict graph with the Physical Model. They regard the weight of a directed edge in the conflict graph as a function of the useful signal strength and noise signal strength received at the receivers. Interference level is modeled by the sum of weights of the edges incident to the vertex in the conflict graph corresponding to a network link. Marina, et al. [16] applied this method to the Protocol Model.

Mishra, et al. [17] presented to use the total number of active clients associated to every AP to indicate its interference level on another AP node within its interference range. They modeled the channel assignment problem of WLANs as a weighted graph coloring problem with a certain objective function. In this weighted variant, each vertex corresponds to a distinct AP. A conflict between two APs is represented by an edge, and each edge has a weight associated with it. The weight of an edge indicates the importance of using different colors (channels) for the corresponding vertices (APs) that are connected by that edge.

3. Premises

We assume that there are limited channels in the network. Each mesh node is equipped with multiple interface, and the number of interfaces equipped on each node is less than that of available channels. We also assume that interfaces can dynamically switch to different channels. A node can communicate with all nodes within its communication range on different channels by interface switching.

Since each node is equipped with multiple interfaces and there are multiple channels available, it is possible that two nodes may establish multiple links that utilize different channels. For simplicity of explanation, we assume that two nodes within the communication range of each other can establish at most one link at a time. Nevertheless, the results achieved in this paper can be easily extended to the scenarios, where two nodes may utilize multiple links at the same time.

The left of this section consists of two parts. In the first part, we give the concept of communication constraint. We then describe the two interference models presented in [15] under multiple interfaces and interface switching environment.

3.1. Definition of Communication Constraint

We define communication constraint as the strategies that decide the interface switching modes of nodes. A communication constraint provides one or several cases. A case defines one link between two nodes within each other's transmission range. Links defined by different cases utilize different channels. Therefore, the number of cases in a communication constraint equals to the number of candidate links two nodes can utilize.

Two nodes may utilize one or multiple communication links according to the definition of communication constraint. Recall that there is only one candidate link can be established at a time no matter how many candidate links they have. These alternative links are dynamically established according to the case that initiates the communications.

We further classify the communication links into two types based on the number of cases included by the communication constraint. If there is only one case in the communication constraint, the corresponding link is called a symmetric link. On the contrary, if the communication constraint consists of multiple cases, all of the candidate links are called asymmetric links. According to the classification, most presented protocols [4, 6, 9, 16-19, 21-23, 26 and 27] utilize symmetric links. Nevertheless, there are also several protocols that utilize asymmetric links [5, 11, 14 and 24]. The co-channel interference of symmetric links has been an active area of research for many years. Interested readers may refer to [7, 9, 10, 12, 13, 15 and 17] for details. We mainly study the co-channel interference characteristics of asymmetric links here.

We use a simple example to illustrate the characteristic of asymmetric links. Suppose that there are C available channels, and nodes A and B are within each other's communication range. Assume that the communication constraint consists of $2c$ ($2c \leq C$) cases. Each case defines a distinct communication link. Hence there are $2c$ asymmetric links between node A and B. We classify the $2c$ links into two sets. Suppose that the two set of links are $\{a_1, a_2 \ldots a_c\}$ and $\{b_1, b_2 \ldots b_c\}$. The $2c$ cases are defined as follows. If A wants to send packets to node B, they can only use channel b_i ($1 \leq i \leq c$). However, if B initiates the communication with A, they can only use channel a_j ($1 \leq j \leq c$).

If c equals to 1, there will be two asymmetric links between two nodes according to the communication constraint. For ease of explanation, we use two opposite links to differentiate the two asymmetric links. Let $\overrightarrow{(A,B)}$ denote the asymmetric link initiated by node A to B, and vice versa. Fig. 2 shows the two asymmetric links between node A and B. In this example, we assume that link $\overrightarrow{(A,B)}$ and $\overrightarrow{(B,A)}$ utilizes channel 1 and 2 respectively. The number besides each link represents the channel used by the corresponding asymmetric link.

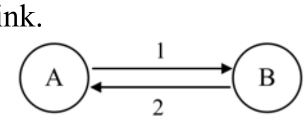

Fig. 2 The candidate asymmetric links between two nodes (In this example, c is set to 1. When c is bigger than 1, we should use other symbols to differentiate the asymmetric links.)

Suppose that a node uses different sets of channels to communicate with different nodes within its communication range. Let n (n>1) be the number of nodes within the transmission range of node A. Node A can totally use $2c*n$ channels by interface switching. Furthermore, the number of channels one node can utilize is decided only by the communication constraint, which is independent of the number of interfaces on nodes.

As two nodes may utilize different asymmetric links on different channels when the communication is initiated by different cases, the set of interference nodes (links) of a node (link) changes dynamically during communication. Consequently, the interferences characteristics of asymmetric links are more complex than that of symmetric links. The interference estimation scheme should consider this characteristic of asymmetric links.

3.2. Two Interference models

Consider a wireless network consists of N nodes, where each node is equipped with m wireless interfaces. Let n_i and n_j $(1\leq i, j\leq N)$ denote the node i and j respectively. Let $d(i,j)$ be the distance between nodes n_i and n_j. Suppose that all nodes have the uniform transmission range R_T and interference range R_I respectively. We denote by $c(i,k)$, the channel on the kth $(1\leq k\leq m)$ interface on node n_i. Suppose that node n_i wants to transmit packets to node n_j at time t. The two interference models presented in [7] are as followings:

Protocol Model: The protocol model treats the interference between nodes as an all-or-nothing event. It associates an interference range for each node, a range up to which a transmitter may interfere with the reception of another receiver. Under this model, the transmission from node n_i to n_j is successful if the following constraint conditions are satisfied:

1. $c(i,k) = c(j,l) \quad (1 \leq \forall k \leq m,\ 1 \leq \forall l \leq m)$;
2. $d(i, j) \leq R_T$;
3. Any other node n_p $(1\leq p\leq N)$ that satisfies the following conditions does not be transmitting.

   $c(p, r)=c(i,k) \quad (1\leq \forall\, r\leq m)$, and

   $d(p, i) \leq R_I$, or $d(p, j) \leq R_I$

Physical Model: The physical model considers a minimum signal-to-interference ratio (SIR) to ensure successful receptions for the receivers. Node n_j first checks whether it has one interface fix on channel $c(i,k)$ at time t. If yes, node n_j will calculate the signal strength received from n_i on channel $c(i,k)$. Let $p_{ij}(c)$ be the signal strength received by node n_j from n_i on channel c, and P_j be the total noise strength at n_i on channel c. Let $SNR_{ij}(c)$ be the ratio between p_{ij} and P_j on channel c. The transmission is successful if the following constraint conditions are satisfied:

1. $c(i,k) = c(j,l) \quad (1 \leq \forall k \leq m,\ 1 \leq \forall l \leq m)$;
2. $SNRij\ (c(i,k)) \geq SNR_{thresh}$

where SNR_{thresh} is a constant, which is defined as the minimum signal-to-interference ratio on a channel that ensures successful receptions.

4. Weighted Interference Estimation Scheme

We present the proposed interference estimation scheme, called the weighed interference estimation scheme (WIES) in this section. WIES bases on the Protocol model, whereas it reflects the influence of frequent interface switching, traffic loads characteristics of WMNs and the relative distance between nodes.

As presented in section 2, OCG and MCG have been extensively used to estimate the interference relationship between symmetric links. However, they cannot correctly formulate the interference relationships between asymmetric links. This is because OCG (MCG) assumes that the links are either static or adjusted every a relative long period. During the period, the links do not change. Thereby, the set of interference nodes (links) is fixed during the period according to OCG (MCG). However, the set of interference nodes (links) of a node (link) changes dynamically during communication since the nodes that utilize asymmetric links may switch to different channels frequently. We then put forward asymmetric conflict graph (ACG), a new version of multi-interface conflict graph, to model the interference relationships between asymmetric links. Besides, we utilize a weight to model the interference level of one node on another node if their interfaces switch to the same channel.

We establish WIES in three steps. In the first step, we introduce the procedures to create the ACG. We then present rules to deciding the weight. At last, we describe how WIES is used in channel assignment.

4.1. The Asymmetric Conflict Graph (ACG)

Suppose that each node is equipped with m interfaces. All nodes have the same communication range R_T and interference range R_I respectively. Let k (k is usually no less than 1) be the ratio between R_I and R_T. We model the original network topology as a graph $G = (Q, E)$. There is an edge in E between nodes u and v in Q if and only if $d(u, v) \leq R_T$, where $d(u, v)$ is the distance between nodes u and v.

ACG is created according to the asymmetric links. We first use a 7-node network to illustrate how to create ACG under the communication constraint described in Fig. 2. We then summarize the procedures of creating ACG under a general communication constraint. The network topology, G is shown in Fig. 3(a).

There are two asymmetric links between two nodes within each other's transmission range according to the example communication constraint. The asymmetric links between nodes are shown in Fig. 3(b), where arrow lines in different types denote the asymmetric links that utilize different channels. We use G' to represent the topology in Fig. 3(b) to distinguish it from the original network topology, G. The corresponding ACG for the sample network is shown in Fig. 3(c).

Assume that there are n nodes within the transmission range of a node. One node can utilize totally $2c$ asymmetric links: c asymmetric links point to the node, whereas the other c asymmetric links start from the node. We then classify these asymmetric links into two types according to their directions. We refer to the asymmetric links pointing to the node as passive links. In contrast, the asymmetric links that start from the node are called positive links. An asymmetric link is the passive link of the node it points to, whereas it is the positive link of the node on the other end of it. For example, $\overrightarrow{(E,A)}$ is the passive link of node A, whereas it is the positive link of node E.

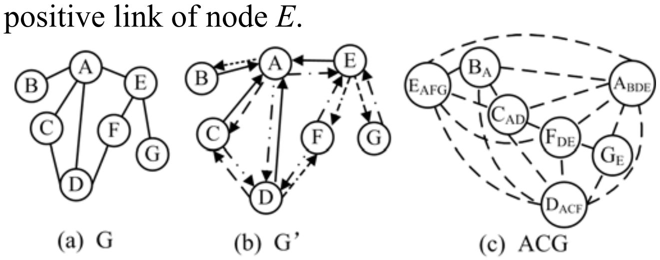

Fig.3 An example of ACG

Theoretically, all asymmetric links of a node should utilize different channels to minimize the interference level on it. However, there are usually not enough available channels in the network. Therefore, some of the $2c$ asymmetric links need to share a channel. For simplicity, we assume that all passive links of a node will utilize the same channel, whereas the positive links utilize different channels. (Similarly, we can also assume that all positive links of a node utilize the same channel, whereas the passive links utilize different channels).

The first step is to create new vertices according to the asymmetric links in G'. We should merge all asymmetric links within each other's interference range that utilize the same channels into a new vertex in ACG. An asymmetric link may be included in two vertexes owing to it belongs to two nodes on both end of it. However, a link cannot utilize multiple channels at one time. Therefore, one asymmetric link cannot be included in two vertexes in ACG. Since all passive links of a node will utilize the same channel, we only merge all passive links of every node into a new vertex in ACG. We named the new vertex in ACG by the nodes ID of all nodes that compose these passive links. The first letter in the name depicts which node these passive links belong to. For example, a vertex named $u_{p_0,p_1,\ldots,p_P}$ in ACG denotes that node u has P passive links, which are $\overrightarrow{(p_i,u)}$ ($0 \leqslant i < P$).

Edges between vertexes are established as following. There is an edge between vertexes $u_{p_0,p_1,\ldots,p_P}$ and $v_{q_0,q_1,\ldots,q_n}$ in ACG if links $\overrightarrow{(p_i,u)}$ ($0 \leq i < P$) and $\overrightarrow{(q_j,v)}$ ($0 \leq j < n$) in G' interfere with each other.

We then summarize the general procedures to create the ACG as following. Suppose that the communication constraint consists of S cases. Assume that we know which asymmetric links of a node will utilize the same channel. We first represent each edge of G using S distinct asymmetric links to establish a new topology, G'. We then merge all asymmetric links of a node on the same channel into a new vertex in ACG. The vertex is named in the same way as that is presented in the sample scenario.

An asymmetric link in G' belongs to the two nodes that it connects. However, one asymmetric link should not be included in two vertexes in ACG. We use the following methods to ensure a link be included in only one vertex. The merging decisions are made on a node-by-node basis. In this procedure, nodes are associated with priorities on deciding the merging sequence. The procedure always chooses the node that has the maximum number of co-channel asymmetric links at present. Once a link is included by a vertex, we remove it from G'. The above procedure repeats until there is no link in *G'*. The edges between the vertices in ACG are created in the same way as presented in the sample scenario, and we do not describe them in details here.

4.2. Decision of the Weight

Let $Q_I(i)$ be the set of interference nodes of node *i* ($Q_I(i)$ is gotten from ACG). Let *j* be a node in $Q_I(i)$. The next question is to estimate the interference level of node *j* on node *i* when they switch to the same channel. The interference level of *j* on *i* equals to 1 according to the Protocol model. However, the Protocol model does not reflect the real interference characteristics of communication links. There are two main reasons. For one thing, the interference possibility of node *j* on *i* is greatly influenced by the loads on both *j* and *i*. Secondly, the wireless signal power decreases in an exponential function of distance [19]. Hence, the interference degree of node *j* on *i* decreases dramatically along with the distance between them increasing. We then assign a weight to every node in $Q_I(i)$ to model its interference levels on node *i* when they switch to the same channel. The weight considers the effects of traffic loads and relative distance.

Let $\omega_i(j)$ be the weight assigned to node *j*, which represents the interference level of node *j* on node *i*. The weight $\omega_i(j)$ consists of two parts: $\omega_t(j)$ and $\omega_d(j)$. The weight $\omega_t(j)$ indicates the influences of traffic loads, whereas the weight $\omega_d(j)$ reflects the relative distances between them. The relationship between $\omega_i(j)$, $\omega_t(j)$ and $\omega_d(j)$ is given in (1):

$$\omega_i(j) = \omega_t(j) \times \omega_d(j) \tag{1}$$

Generally speaking, $\omega_t(j)$ and $\omega_d(j)$ are dependent on the specific network settings, which are difficult to predetermine precisely. We thus propose two empirical formulas to decide the value of $\omega_t(j)$ and $\omega_d(j)$ respectively. The simulations presented in latter section prove that our method is feasible.

4.2.1. Decision of the ω_t(j)

It is impractical to get the exact loads on nodes owing to the characteristics of wireless communications. Nevertheless, we know that most of the traffics on a WMN are directed to/from the wired networks via gateway nodes. Therefore, each node should discover at least one path to gateway nodes. Furthermore, gateway nodes provide network access for mobile users in mesh clients. The traffic loads on different nodes of WMNs can be summarized as following. Gateway nodes are assumed to carry heavier traffic. The traffic loads on the other nodes are less than that on gateway nodes. The traffic loads on a node are roughly in an inverse proportion to the distance between it and the nearest gateway.

Let $h(i)$ and $h(j)$ respectively be the hops of the shortest path from node *i* and *j* to the nearest gateway nodes. Based on above observations, we design an empirical function utilizing both $h(i)$ and $h(j)$ to imitate the effects of traffic loads on the interference level. The function is as follows:

$$\omega_t(j) = \begin{cases} \sqrt{h(i)} & (h(i) > 0,\ \ h(j) = 0) \\ \sqrt{h(i)/h(j)} & (h(i) > h(j) > 0) \\ 1 & (Else) \end{cases} \tag{2}$$

As shown in (2), the value of $\omega_t(j)$ is divided into three parts according to the values of $h(i)$ and $h(j)$. If $h(j)$ equals to 0, we say node *j* is a gateway node. Since both $h(i)$ and $h(j)$ are no less than 0, therefore the minimum value of $\omega_t(j)$ is 1.

4.2.2. Decision of the ω_d(j)

The empirical formula to decide the value of $\omega_d(j)$ is the following. Let *k* be the ratio between the interference range (R_I) and transmission range (R_T). Assume that R_I is bigger than R_T. Suppose that *r* is the ratio between $d(i,j)$ and R_T, where $d(i,j)$ is the distance between node *i* and *j*. And $\omega_d(j)$ is estimated using (3):

$$\omega_d(j) = \sqrt{1 - r/(k + \tau)} \tag{3}$$

where τ is a constant. Let δ denote the maximum distance between node *i* and any node in $Q_I(i)$. τ is computed as following.

$$\tau = \delta / R_T - k \tag{4}$$

Since δ is always no less than R_I, δ/R_T is no less than *k*, and accordingly τ is more than or equals to 0. Consequently, we can see that the value of $\omega_d(j)$ is between 0 and 1.

4.3. Estimate interference Level using WIES

The aim of channel assignment is to maximize the overall network throughput or the sum of packets it can transport between the wireless mesh routers and gateway nodes within a unit time. Channel assignment algorithms use the interference level of a channel on one node/link as the channel selection criteria to achieve this goal. In this part, we describe the method to combine WIES with the channel selection criterion.

We define the interference level of a channel on one node/link as the sum of weights of the node's interference nodes that are assigned the same channel. Let θ be the set of system available channels, and $Intf_i(c)$ be the interference level of a channel c on node i. $Intf_i(c)$ is estimated as following on considering the weight $\omega_i(j)$:

$$Intf_i(c) = \sum_{j \in Q_I(i)} \mu_j(c) \times \omega_i(j) \quad (5)$$

where $\mu_j(c)$ is an binary variable, which default value is 0. If one channel of node j is c, $\mu_j(c)$ is set to 1. The meaning of $Q_I(i)$ is the same as in previous.

Suppose that C_i is the channel assigned to node i. C_i should satisfy the following constraint:

$$Intf_i(C_i) = Min_{r \in \theta} Intf_i(r) \quad (6)$$

The constraint shown in (6) is the channel selection criterion that is used to choose channels for nodes in the channel assignment.

5. Performance Evaluation

In this section, we compare the performances of WIES with a Protocol model based scheme through the combination of graph-based analyses and NS2 [20] simulations. We refer to the compared scheme as the simple interference estimation scheme (SIES) to differentiate with WIES.

We apply WIES and SIES in a simple multi-interface WMN channel assignment algorithm. The algorithm can be summarized as following. Assume that every node has already discovered a path to the wired network. Suppose that each node is equipped with two interfaces. Except for the gateway nodes, one interface of any node is used to communicate with its parent node, and the other one is used to communicate with its children nodes. Gateway nodes choose channels for both of their interfaces. All the other nodes are only responsible for assigning channels to the interfaces that communicate with their children nodes. The channel assignment algorithm used here is similar to the algorithm in [22]. However, instead of the traffic dependent selection criterion in [22], we respectively use WIES and SIES as the channel selection criterion in simulations.

The followings are the default simulation settings for both graph based simulations and NS2 based simulations. We generate a 36 two-interfaces nodes wireless network topology. Each node is equipped with two interfaces. The 36 nodes distribute in a 6×6 square grid network. Three nodes that distribute uniformly across the network are chosen to be the gateway nodes. Suppose that all nodes respectively have the same communication range R_T and interference range R_I. The distance between two neighbor nodes equals to R_T.

5.1. Graph Based Evaluations

Let $Q_I(i)$ be the set of interference nodes decided by ACG. Noticed that only those that switch to the same channel as node i at the same time will interfere the communications of the node/link after channel assignment. We refer to these nodes as the co-channel nodes of i. We evaluate the maximum co-channel nodes and the maximum interference level of the network respectively in this part.

Let k be the ratio between R_I and R_T. The maximum co-channel nodes of WIES and SIES are shown in Fig. 4. The maximum number of co-channel nodes equals to its maximum interference level according to the definition of SIES. Therefore, Fig. 4 also shows the interference level of SIES, whereas the corresponding interference level of WIES is shown Fig. 5.

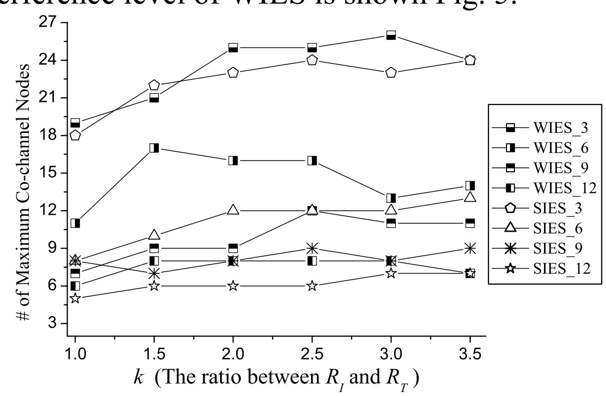

Fig. 4 Comparison of maximum co-channel nodes (i.e. the maximum interference level of SIES)

As shown in Fig. 4, the maximum co-channel nodes for WIES are roughly higher than that of SIES. This indicates that WIES does not think the channel that has the minimum number of co-channel nodes is the channel that has the minimum co-channel interference level.

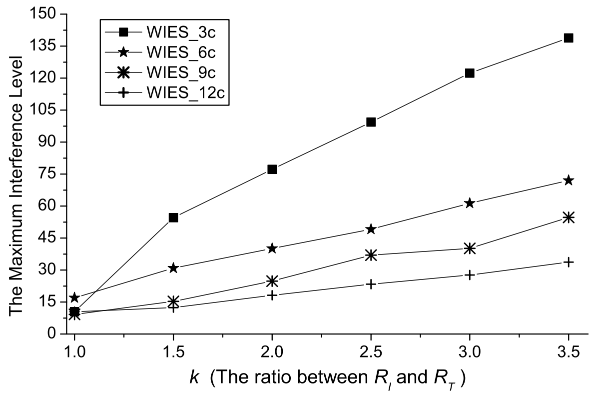

Fig. 5 The maximum interference level of WIES

We can observe that both the number of channels and k affect the interference level of the network. The maximum interference level increases roughly in a direct proportion function of k, whereas it decreases dramatically along with increasing the number of available channels.

Results also show that the number of channels affects the force of k on deciding the maximum interference level. As shown in Fig. 5, the slope of the interference level is reduced when we increase the number of channels. In other words, the more the number of channels, the lighter the impact of k on the interference level of the network is. For example, the maximum interference level for 3 channels increases about 4 times when k increases from 1 to 3.5, whereas the corresponding maximum interference level for 12 channels increases only about 0.3 times. The force of available channels on deciding the maximum interference level is also affected by the value of k. If k equals to 1, the impact of channels on the maximum interference level is very limited. Otherwise, the force of available channels is relative independent of k. For example, the maximum interference level of the network for 3 channels is proximately five times of that for 12 channels when k is more than 1.

5.2. NS2 Based Evaluations

The following are the default settings for NS2 simulations. We conduct the simulations in an 802.11a network, where the bandwidth of each channel is 54Mbps. The communication range, R_T is set to 150m. The ratio between interference range and communication range is set to 2. During the simulation period, the network randomly generates several independent multi-hop CBR traffic flows. We utilize the Dynamic Source Routing (DSR) protocol for route selection.

We mainly vary three network parameters, which are the number of flows, the data rate of each flow and the number of available channels, to evaluate the performances of WIES and SIES. For simplicity of analysis, we change one parameter at a time. All the other parameters keep constant when we change the value of a parameter. Although we have done a lot of simulations, we only present a set of typical results due to the limitation of space. Without declaration, the three parameters in the presented simulations are 8Mbps, 21 and 4, respectively.

The main evaluation metrics used in NS2 simulations are the aggregated throughput and per-flow performance. Aggregated throughput is defined as the sum of packets successfully received at the destination of each flow during the simulation time period.

The per-flow performance is represented by the average data delay of each flow. Suppose that the destination node of a flow receives the first data packet from the flow at time t_1. It has totally received m packets from the same flow by the time t_2. The average packet delay of the flow, T_d, is computed as following.

$$T_d = (t_2 - t_1)/(m-1) \tag{7}$$

5.2.1. Throughput Performance

We first compare the network throughputs of WIES and SIES on varying the number of offered traffic flows. There are only three flows in the network at the very beginning of simulations. We add one to three new flows to the current set of traffic loads every time till the network is overloaded. Fig. 6 presents the results.

Results in Fig. 6 show that WIES achieves much higher peak throughput than SIES. Compared to SIES, WIES improves the peak throughput by 21%. In addition, WIES achieves steadier performance than SIES. The throughput of WIES increases monotonically, whereas the throughput of SIES fluctuates before the peak point.

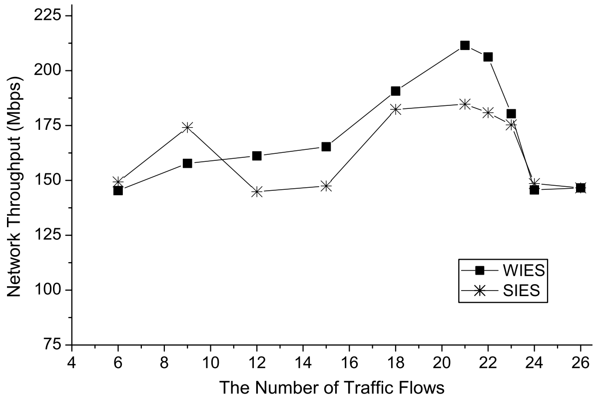

Fig. 6 Network throughput on varying the number of flows

The throughputs of both schemes decrease after the peak point because the network is overloaded. WIES decreases a little faster than SIES before they achieve equivalent throughputs. After that, the throughputs of WIES and SIES keep constant and equivalent.

We then evaluate the impact of data rate on the network throughputs. Fig. 7 gives the results.

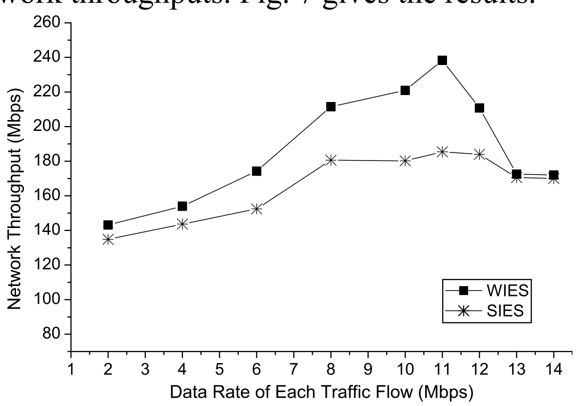

Fig. 7 Network throughput on varying data rate of flows

We can observe that the impact of data rate on throughput is similar to that of the number of flows, except that the throughputs of both WIES and SIES increase monotonically along with increasing the data rate before the network is saturated. WIES achieves higher throughput than SIES at the peak point. In this example, WIES shows an improvement of more than 30% over SIES.

The throughputs of both schemes also decrease after the peak point. Their throughputs keep decreasing until they achieve equivalent throughput. In this example, the data rate of each traffic flow is about 13 Mbps when the throughput of WIES roughly equals to that of SIES.

5.2.2. Impacts of the Available Channels

According to the results presented in Fig. 5, the interference level of the network decreases dramatically along with increasing available channels. We then evaluate the throughput of WIES and SIES on varying the number of available channels. The results are shown in Fig. 8.

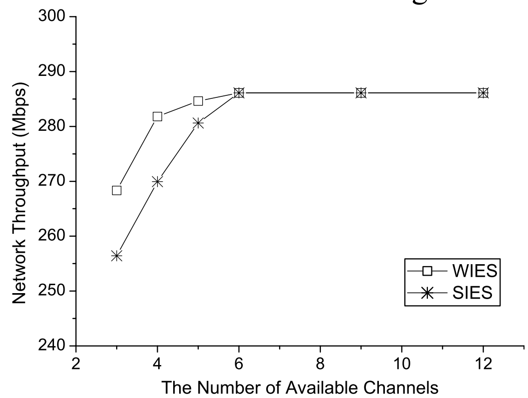

Fig. 8 Network throughput on varying the number of channels

Results in Fig. 8 indicate that WIES achieves higher throughput than SIES when the interference level of the network is high. In other words, WIES achieves higher throughput than SIES when the number of available channels is small. The smaller the number of available channel is, the higher the difference between their throughputs is. For example, WIES improves the throughput about 5% over SIES when the number of channels is 3, whereas both schemes achieve roughly the same throughput when the number of channels is about 6.

5.2.3. Traffic-flow Performance

At last, we compare the traffic-flow performance of WIES and SIES. For simplicity, we consider a WMN that consists of only 9 traffic flows, which is numbered from *a* to *i*. The number of channels here is set to 3. Fig. 9 presents the average data delay of the nine flows, which are sorted in the same sequence they were loaded to the network.

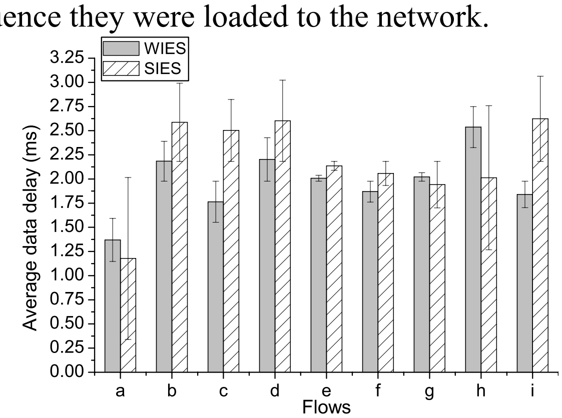

Fig. 9 Average packet delays of each flow
(Flows are sorted by the time they were loaded to the network)

As shown in Fig. 9, the average data delays of most traffic flows in WIES are less than that in SIES (six of nine flows in WIES have less average data delays than that of SIES). For quantitative comparison, we further compute the mean squared deviation of average data delay for the nine flows. The mean squared deviation of average data delay for WIES and SIES is 0.095031ms and 0.194543ms respectively. In other words, the discrete degree of average data delay for WIES is less than half of SIES. Consequently, the traffic flows in WIES have fairer transmission priority than those in SIES. That is, the traffic flows in WIES have fairer transmission priority than those in SIES. This also provides some reason why WIES achieves better performance than SIES.

5.3. Discussions

Above simulations show that our proposed scheme achieves higher or equal throughput, and better per-flow performance compared with the protocol model based scheme. The reason is probably due to the more curate reduced interference and collisions, which in turn leads to lesser channel access delays in the MAC layer and consequently less queuing delays. The simulations also show that the interference level of a WMN is affected greatly by the network parameters such as the number of channels and the ratio between interference range and communication range.

It should be noted that our simulations are executed in a relative simple and small network environment. During above simulations, we do not consider the impacts of other factors such as the overheads caused by interface switching. This is because interface switching induces additional delay, which should not be neglected today. Therefore, interface switching can also affect the aggregated throughput and average packets delay of flows. However, it is difficult to distinguish the effects of interface switching from the interference estimation schemes. Hence, we assume that both schemes do not switch channels during the simulation time period. We will consider the impact of interface switching in future researches.

6. Conclusions

In this paper, we have studied the problem of interference estimation in interface switching WMNs. We have presented a traffic independent interference estimation scheme. The proposed scheme uses a novel strategy to estimate the interference relationship between asymmetric links, whereas it takes a weight to denote the interference level of a node/link on another one. Our presented scheme considers the effects of frequent interface switching, characteristics of traffic loads on mesh nodes and the relative distance between nodes. Extensive simulations prove that the proposed scheme achieves much better performance than the original protocol model when the interference level of the network is high. Furthermore, our presented scheme is practicable and can be easily applied to current conflict graph based interference schemes.

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