

A maximum-independent-set-based channel allocation algorithm for multi-channel wireless networks

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Abstract: A channel allocation algorithm based on the maximum independent set is proposed to decrease network conflict and improve network performance. First, a channel allocation model is formulated and a series of the maximum independent sets (MISs) are obtained from a contention graph by the proposed approximation algorithm with low complexity. Then, a weighted contention graph is obtained using the number of contention vertices between two MISs as a weighted value. Links are allocated to channels by the weighted contention graph to minimize conflicts between independent sets. Finally, after channel allocation, each node allocates network interface cards (NICs) to links that are allocated channels according to the queue lengths of NICs. Simulations are conducted to evaluate the proposed algorithm. The results show that the proposed algorithm significantly improves the network throughput and decreases the end to end delay.

Key words: wireless networks; multi-channel; channel allocation; maximum independent set

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With the rapid development of wireless technology, the demand for wireless data application has increased significantly. How to improve network throughput is an important problem for wireless network research. Multi-channel technology provides a way to improve network throughput and improves network performance. Currently, most of commercial wireless network interface cards (NICs) work following IEEE wireless network standards, such as IEEE 802.11 standards used for wireless local networks (WLANs), and generally all the nodes operate on the same frequency. Actually, the physical layer protocols of these standards provide multiple channels to use. IEEE 802.11a^[1] provides 12 channels in the 5 GHz band, 8 in the lower part of the band for in-

door use and 4 in the upper part for outdoor use. IEEE 802.11b^[2] has 14 channels available in the 2.4 GHz band and three of them can be used simultaneously without overlapping. IEEE 802.15.4^[3] protocol, designed for low-power wireless personal area networks (WPANs), allows 16 non-overlapping channels in the 2.4 GHz band. Therefore, there are available channels for wireless networks.

These protocols provide the available channels but do not offer the methods to allocate channels for wireless nodes. In recent years, there has been much research on the channel allocation algorithm in the media access control (MAC) layer for multi-channel wireless networks. According to the number of NICs, the multi-channel allocation algorithms can be classified into single-radio multi-channel algorithms^[4-8] and multi-radio multi-channel algorithms^[9-14]. According to the control channel, the multi-channel allocation algorithms can be classified into with^[4-6,9] and without^[7-8,11-14] dedicated control channel algorithms. The single-radio multi-channel algorithms assume that each node has only one NIC which can be switched between different channels, such as the opportunistic multichannel MAC (OMC-MAC)^[5] protocol, the parallel rendezvous multi-channel MAC (McMAC)^[6] protocol, and the slotted seeded channel hopping (SSCH)^[7] protocol. With the OMC-MAC protocol, the time is divided into a channel negotiation phase and data exchange phase. In the channel negotiation phase, all the nodes must work on the same channel to listen and negotiate. In the data exchange phase, nodes switch to the negotiated channel to transmit data. With the SSCH protocol, the dedicated control channel is not needed and frequency hopping is used to allocate channels at every time slot. The multi-radio multi-channel algorithms assume that each node is equipped with more than one NIC, such as the clustered channel assignment scheme (CCAS)^[13]. With CCAS, nodes are clustered intelligently by tackling similar traffic matrices dynamically. Links in a cluster are divided into several sets and each set is assigned to one channel. Generally, the single-radio multi-channel algorithms are less costly in hardware, but may require more complicated protocols to assign channels and usually need full network synchronization which is difficult to achieve for multi-hop wireless networks. Multi-radio multi-channel

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nel algorithms usually use one NIC working on the control channel and others working on data channels, which can solve the problem of network partition easily and provide better performance, but have a higher cost and complexity of hardware. With the improvement in hardware technology and reduction in cost, the multi-radio multi-channel algorithms appeal more to recent research.

In this paper, a multi-channel algorithm based on the maximum independent set (MIS) is presented. This algorithm does not require full network synchronization and can provide quality of service (QoS) for each links. A dedicated control channel is required to solve the hidden terminal problem caused by channel segmentation, but the control channel is not binding to one fixed NIC. By exploiting the details of the network topology and transmitting links, channels are scheduled among several available NICs dynamically to improve network throughput.

1 Channel Allocation Model

In recent years, the graph theory has been widely applied in the research of wireless networks^[15-17]. In this paper, we use the graph theory to describe the relationship between nodes and links. We consider a multi-channel wireless network with n nodes. Assume that all the nodes use unidirectional antennas with the same transmission power and each node is equipped with m ($m \geq 1$) NICs. We use a graph $G = (V, E)$ to describe the wireless network topology where V represents the set of nodes and E represents the set of links between the nodes.

Based on graph G , a contention graph $C = (V', E')$ is used to describe the contention relationship of multi-channel wireless networks^[16-17]. In a contention graph, each vertex represents a link, and an edge between two vertices denotes contention between the corresponding links. Fig. 1 is the topology of a wireless network. Fig. 2 is the corresponding contention graph.

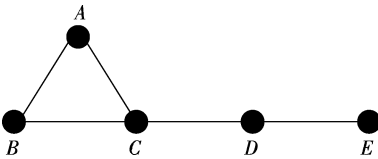


Fig. 1 The topology of a wireless network

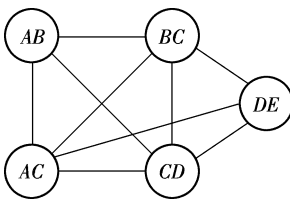


Fig. 2 The contention graph of Fig. 1

Independent set is a subset of vertices in which no two vertices are adjacent. In the contention graph, there is no edge between any two vertices in an independent set. Therefore, the corresponding links can transmit simulta-

neously. That is, for a real network, the links which can transmit simultaneously in the same channel must create an independent set of the contention graph. Links that transmit simultaneously in different channels must compose a series of independent sets. Therefore, the assignment of channels to links can be regarded as the assignment of channels to independent sets. It can be considered that independent sets share channel resource. A maximal independent set is an independent set that is not a subset of any other independent sets. A maximal independent set with maximum cardinality has a maximal number of links transmitting simultaneously.

The proposed algorithm uses the MIS to share channels with more links. Considering the difference of links maintaining network connectivity and the QoS requirement of different traffic types, each link is weighted with a value between 0 and 1. Assuming that for a wireless multi-channel network, there are l links and c channels. Variable $x_{i,j}$ ($1 \leq i \leq l; 1 \leq j \leq c$) is used to describe the status of link i on channel j . If link i works on channel j , $x_{i,j} = 1$; otherwise, $x_{i,j} = 0$. The object of the channel allocation algorithm is to maximize the network throughput. The proposed problem can be formulated as a constrained maximization problem as follows:

$$\max \sum_{i=1}^l \sum_{j=1}^c w_i x_{i,j} \quad (1)$$

s. t.

$$\begin{aligned} x_{i,j} + x_{k,j} &\leq 1 \quad 1 \leq k \leq l \text{ and } k \in I_i \\ \sum_{j=1}^c x_{i,j} &\leq 1 \\ \sum_{j=1}^c \left(\sum_{T(i)=v} x_{i,j} + \sum_{R(i)=v} x_{i,j} \right) &\leq m \quad \forall v \in V \end{aligned}$$

where w_i ($0 \leq w_i \leq 1$) is the weighted value of link i , and I_i is an MIS including link i in the contention graph. The value of w_i can be set according to the importance of link i . $T(i)$ and $R(i)$ are the transmitting node and the receiving node of link i , respectively. The first condition gives the restriction of link contention which can be described by the contention graph. The second condition shows that at any time a link can be active only in one channel. The third condition gives the restriction on the number of NICs. To solve this problem, a heuristic algorithm is proposed.

2 Maximum Independent Set Based Channel Allocation Algorithm

A maximum independent set-based channel allocation (MIS-CA) algorithm is proposed for multi-channel wireless networks. Adopting the MIS-CA algorithm, the first a series of MISs are obtained from the contention graph. Then channels are allocated to MISs based on the weighted contention graph. Finally, an appropriate adjustment

can be made to satisfy the restriction on the number of NICs.

2.1 Approximation algorithm for MIS

An approximation algorithm is proposed to obtain a series of MISs. In this algorithm, the vertex cover set is used to obtain the MIS of the contention graph. For a given graph $G = (V, E)$ and a given vertex set, if any edge of E is connected with one vertex in I , then I is the vertex cover set of G . If any proper subset of I is not the vertex cover set, then I is the minimal vertex cover set of G . The minimal vertex set with minimum number of vertices is the minimum vertex cover set. Obviously, I is the vertex cover set if and only if $\bar{I} = V - I$ is the independent set of G . Therefore, searching the MIS can be considered as searching the minimum vertex cover set.

The vertex with maximum degree is first selected for the minimum vertex cover set, because the vertices in the cover set need to concern all edges. Therefore, an approximation algorithm to obtain the maximum independent set is proposed as follows:

- 1) Initialization: Set the initial value of $x_{i,j}$, and set the minimum vertex to cover set $S = \emptyset$.
- 2) Select the vertex with the maximum degree and denote it with v_d . Add v_d to S . If there are several vertices with the maximum degree, select one randomly.
- 3) Delete all the edges connected with v_d in the contention graph. If the set of edges in C is \emptyset , S is the maximum cover set; else, go to step 2).
- 4) Obtain the approximate maximum independent set (AMIS) by finding the complementary set of S .

We take the contention graph in Fig. 2 as an example. The new gray vertex is the maximum degree vertex in the current round. The processes to obtain the MIS are shown in Fig. 3. We can obtain the MIS which is composed of AB and DE .

The complexity of this algorithm is discussed as follows.

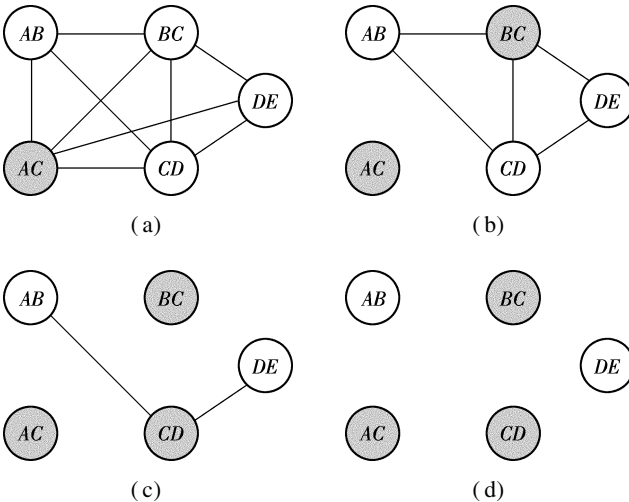


Fig. 3 The processes to obtain the MIS. (a) First round; (b) Second round; (c) Third round; (d) Fourth round

ws. When C is a clique with l vertices, this approximation algorithm needs l round operations, that is the worst situation. According to this situation, the time complexity is $O(|l|^4)$. The depth-first search algorithm in Ref. [18] can also be used to obtain the MIS. Its worst time complexity is $O(3^{l/3})$. Therefore, with the increase in links number, the time complexity of the approximation algorithm decreases. We compare the numbers of vertices in the MIS obtained by these two algorithms. The simulated multi-channel wireless network works in a $400 \text{ m} \times 200 \text{ m}$ square area. The transmission range of each node is 150 m . With different numbers of nodes, the simulation results are shown in Fig. 4.

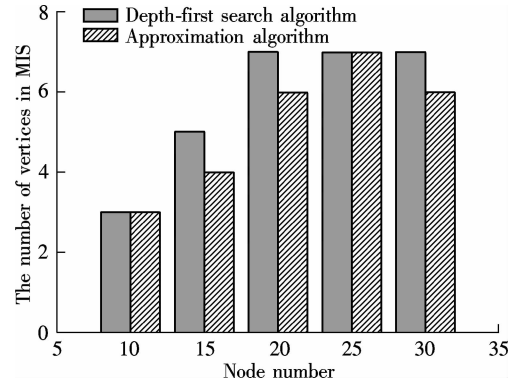


Fig. 4 The number of vertices in MIS with different node numbers

2.2 MIS-CA algorithm

The MIS-CA algorithm is a centralized channel allocation algorithm. This algorithm assumes that the topology of the multi-channel networks can be obtained by a control node. Based on the approximation algorithm for MIS, the links are allocated to different channels to minimize network contention without considering the restriction on the number of NICs. During the transmission process, the node will adjust the assignment if the number of links connected to this node exceeds the number of NICs. The centralized channel allocation algorithm is composed of three steps as follows:

Step 1 Based on the topology graph, the control node generates a contention graph C and obtains the series of MISs as follows:

- 1) Set $k = 1$ and the count value $x = 1$.
- 2) Find the MIS of the current C by the approximation algorithm and denote it with M_k .
- 3) Delete all the vertices and the edges concerned with the M_k from C .
- 4) $k = k + 1$, $x = x + 1$. If C is an empty graph, end; otherwise, go to 2).

In this step, the vertices in the contention graph in Fig. 2 will be divided into four MISs, that are $M_1 = \{AB, DE\}$, $M_2 = \{CD\}$, $M_3 = \{AC\}$, and $M_4 = \{BC\}$. The changes of the contention graph are shown in Fig. 5.

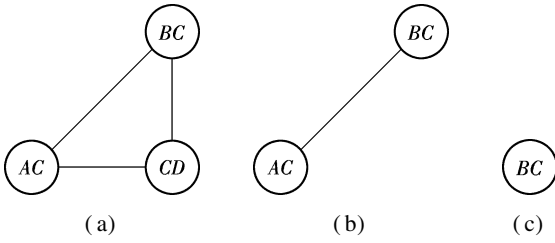


Fig. 5 Changes of contention graph. (a) After the first round; (b) After the second round; (c) After the third round

Step 2 After obtaining the series of MISs, each MIS will be assigned to one channel. Every MIS can be regarded as a vertex. A weighted contention graph composed of vertices of the MISs is introduced to describe the contention relationship of the MISs. If there is a conflict between any two vertices belonging to different MISs, an edge is added between the two vertices. Since the MIS includes the maximum independent vertices in the current contention graph, there must have contention between any MISs. Therefore, the weighted contention graph must be a clique. The weighted value of an edge in the weighted contention graph is the sum of contention vertices between two MISs. The weighted contention graph of Fig. 2 is shown in Fig. 6. Vertices 1, 2, 3, and 4 correspond to $\{AB, DE\}$, $\{CD\}$, $\{AC\}$, and $\{BC\}$, respectively.

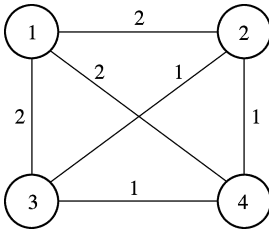


Fig. 6 Weighted contention graph

For vertex j in the weighted contention graph, assume that there are K vertices in the MIS according to the vertex j . The weighted value of vertex j in the weighted contention graph is defined as

$$w'_j = \frac{\sum_{i=1}^K w_i}{k} \quad (2)$$

The assignment of channels to MISs is presented as follows:

- 1) Set the weighted value of each edge.
- 2) Assume that the channel number is c . If $x < c$, the vertices of the weighted contention graph are assigned to different channels and the assignment of channels to MISs is finished.
- 3) Find the edge with the minimum weight value and combine the two vertices connected with this edge into one vertex. The weighted values of edges connected with this new vertex are recalculated. If there are several edges with the minimum weighted value, for each edge, count

the sum of weighted values of the two connected vertices. Then select the edge with the minimum sum of weighted values of vertices.

4) $x = x - 1$, then goto 2).

For example, assuming that the channel number $c = 2$, the process of vertices combination are shown in Fig. 7. After this process, the links $\{AB, DE, BC\}$ can be allocated to channel 1 and the links $\{CD, AC\}$ can be allocated to channel 2. Using this algorithm, all the links in an independent set are allocated to one channel and the contention between links is minimized.

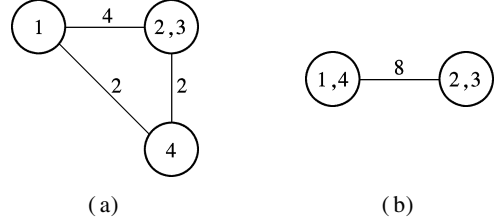


Fig. 7 The process of vertices combination. (a) $x=4$; (b) $x=3$

Step 3 Each node selects an NIC for allocated links. If the number of links to be transmitted is greater than the number of idle NICs, the packets to be transmitted will be stored temporarily in the queue of an NIC. Generally, we choose the NIC with the minimum queue length.

In a real system, the node with the maximum degree is selected as a control node. If there are several nodes with the maximum degree, select one randomly as the control node. Each node sends a location message to the control node periodically. The location message includes the address of this node and addresses of its neighbors. The control node regularly updates the topology of networks and reallocates channels to adapt the change of network topology dynamically. The control messages, such as requests to send (RTS) and clear to send (CTS), are transmitted on a fixed channel. The idle NICs also switch to this channel.

3 Simulation Results

In this section, we evaluate the performance of the MIS-CA algorithm in multi-channel wireless networks. In the simulation, we assume that 10 nodes are placed randomly in a 1 500 m \times 500 m rectangle area to form a multi-channel wireless network. The network topology is fixed during a simulation. The effect of the routing protocol is not considered in these simulations. Packets can be transmitted only one-hop within the transmission range R . If the distance between transmitter and receiver of a packet is within the transmission range R and the receiver is located outside $(1 + \Delta)R$ of any other transmitters transmitting simultaneously over the same channel, the packets can be transmitted successfully. Δ is the guard zone defined by the physical layer protocol. The effective transmission range of each node is 300 m. Every node selects

its neighbor node randomly as destination node and the nodes in the network do not forward the packets. The length of RTS is 44 bytes and CTS is 38 bytes. The length of a data packet is 2 000 bytes. The bursty source model^[19] is used to generate the network load. The value of interval time between successive packet generations in the ON state is changed to generate the needed network load. According to the 802.11b specification, we assume that there are three orthogonal frequency channels available. The data rate of each channel is set to be 11 Mbit/s. The rate of control packets is set to be 1 Mbit/s. The weighted value for each link is set to be 1. Each node is equipped with two NICs. Each NIC is equipped with a transmitter and a receiver.

To evaluate the performance of MIS-CA, metrics used in the simulation are network throughput and the end to end delay. Network throughput is the average transmission rate of packets transmitted successfully from the source to the destination over the entire multi-channel wireless network. The end to end delay is the delay from the time that a packet is generated at the source to the time that it is received by the sink, including the queuing delay at the MAC layer, link layer retransmission delay, and transmission delay. We simulate the wireless networks with the changes of the network load, Δ and the number of channels. We compare MIS-CA with the SSCH and single-radio single-channel (SRSC). SRSC equals the MIS-CA with one channel and one NIC.

When Δ is zero, Fig. 8 and Fig. 9 compare the network throughput and end to end delay with different network loads. From Fig. 8, with the increase in the network load, network throughput also increases. The network throughput with MIS-CA is higher than others. When the network load is 16 Mbit/s, the network throughput with MIS-CA is about 50% higher than that of SRSC and 20% higher than that of SSCH. With SRSC, the end to end delay increases rapidly from the network load of 6 Mbit/s; with MIS-CA, that is from 12 Mbit/s. When the network load is between 6 and 12 Mbit/s, the performance with MIS-CA has significant advantages. With the further increase in network load, the network becomes saturated. From Fig. 9, the end to end delay with MIS-CA increases very fast. The reason is that with the increase in load, the probability of contention on the control channel increases. For MIS-CA, each node has two NICs, which can be considered as doubled numbers of nodes competing on the control channel. When the network works on the saturated status, the contention on the control channel increases significantly and leads to increased end to end delay. For SSCH, the nodes work by the channel hopping schedule and are not competitive for the control channel. Therefore, when the network load is heavy, the delay of SSCH is less than others.

To evaluate the impacts of the parameters on the network

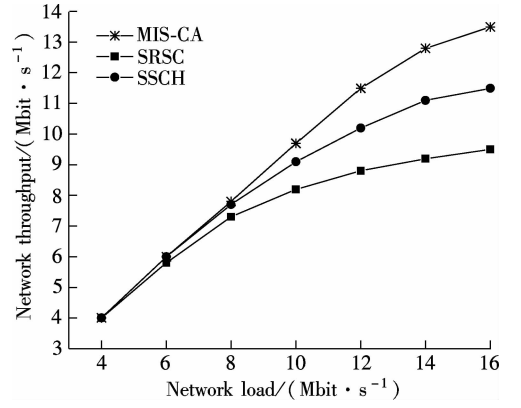


Fig. 8 Network throughput with different network loads

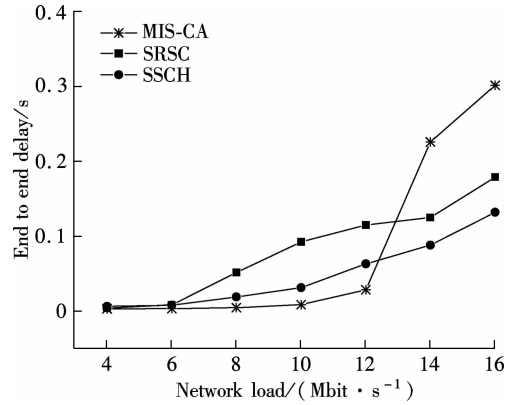


Fig. 9 End to end delay with different network loads

performance, we run simulations with different Δ values, where Δ is set according to the size of interference area. Network conflicts increase with the increase of Δ . Using the MIS-CA algorithm and the SSCH algorithm, the added conflicts can be dispersed into multiple channels. But for SRSC, all the added conflicts are in one channel, which lead to degraded performance. From Figs. 10 and 11, we can see that generally the impact of change on multi-channels with the MIS-CA algorithm is less than that on others. For SRSC, the network throughput decreases rapidly and the end to end delay increases signifi-

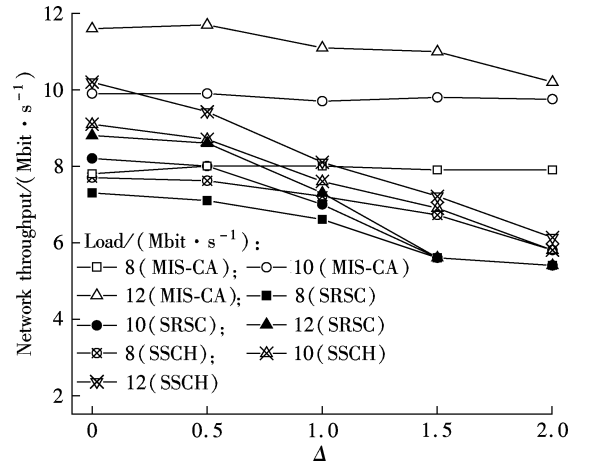


Fig. 10 Network throughput with different Δ values

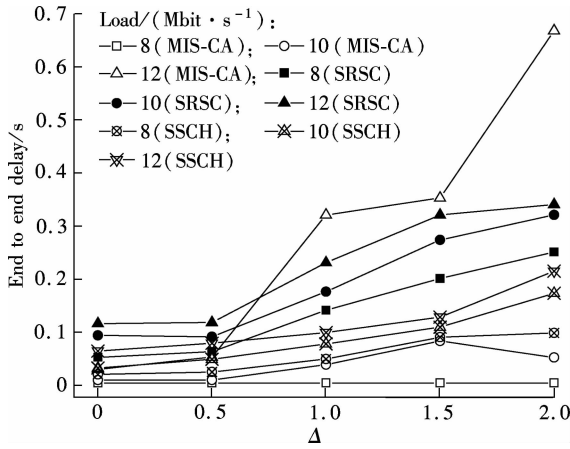


Fig. 11 End to end delay with different Δ values

cantly with the increased interference. For SSCH, although there are multiple channels that can be used, and only one NIC can be used. Therefore, compared with the MIS-CA, the change of Δ has more impact on the performance of SSCH. For MIS-CA, when the network is not saturated, there are little changes in the performance of the MIS-CA algorithm. When the network is saturated, the network load also decreases clearly and the end to end delay increases significantly.

Finally, the impacts of the number of channels on the MIS-CA are shown in Figs. 12 and 13. When the number of channels changes from 2 to 3, the network throughput and end to end delay improve significantly. When the number of channels continues to increase, the improvement in performance becomes less significant. This is related to the number of NICs and the design of the protocol. In our simulations, the number of NICs is 2, which means that only up to two channels can transmit data packets simultaneously. For the MIS-CA algorithm, all the nodes exchange the control messages on one channel, and the saturation of the control channel leads to the saturation of the network.

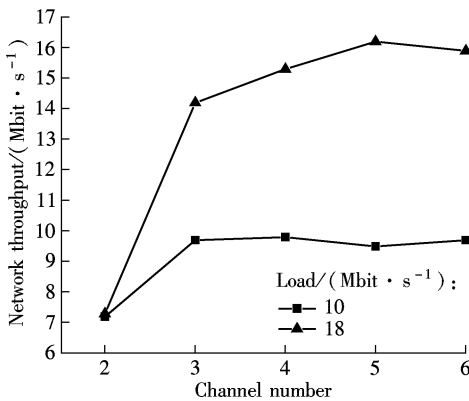


Fig. 12 Network throughput with different numbers of channels

4 Conclusion

This paper proposes a channel allocation algorithm based

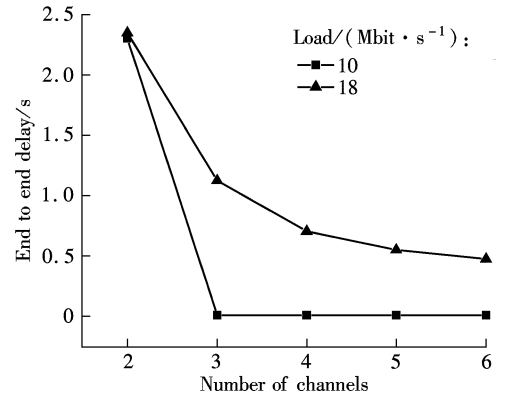


Fig. 13 End to end delay with different numbers of channels

on MIS for multi-channel networks. First, the MIS-CA algorithm finds the series of MISs from the contention graph. All the links in an MIS are without contention. An approximation algorithm is presented, which can find the series of MISs with low time complexity. Then, the MIS-CA algorithm allocates links to each channel to minimize network contention. The links on an MIS will be assigned to the same channel. The weighted contention graph is used to assign MISs to channels to deduce the contention between MISs. Finally, each node allocates NICs to transmission links by the queue length of NICs. Simulation results show that the MIS-CA algorithm generally utilizes the resource of multi-channels effectively and can provide better network throughput and end to end delay. When the multi-channel network is saturated, the end to end delay increases rapidly. The impacts of parameters, including Δ and the channel number, are evaluated. Simulation results show that by using the MIS-CA algorithm, the performance of the multi-channel network is robust to the change of Δ . When the channel number exceeds a certain value, the performance reaches a stable state.

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基于最大独立集的多信道无线网络信道分配方法

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摘要:提出了一种基于最大独立集的信道分配方法,以减少网络冲突提高网络性能.首先,建立信道分配模型,并通过所提出的低复杂度近似算法求取冲突图中的最大独立集序列;然后,以独立集间的冲突顶点数作为加权值,获得加权冲突图,通过加权冲突图,以最小化独立集间冲突为目标将链路分配至各信道;最后,每个节点根据本节点网卡中队列长度为已分配信道的链路分配网卡.仿真结果表明,该方法有效地提高了网络吞吐量,降低了端到端延时.

关键词:无线网络;多信道;信道分配;最大独立集

中图分类号:TP393