A load-balancing routing algorithm for multi-channel wireless mesh networks

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Abstract: This paper presents a load-balancing routing (LBR) algorithm for multi-channel wireless mesh networks (WMNs). The objective of this algorithm is to reduce interference and balance network load among links. The LBR algorithm is composed of link allocation algorithm and load-balancing route-selection algorithm. First, the network model is presented. Based on this model, a link allocation algorithm is proposed to allocate all links to channels which aims to minimise interference degree of networks. After links are allocated to channels, a route-selection algorithm is proposed to select a path from source to destination to balance network load. Simulation results demonstrate that the proposed algorithm balances network load and improves the network throughput significantly.

Keywords: multi-channel; load-balancing; routing; link allocation; WMNs; wireless mesh networks.

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1 Introduction

Wireless mesh networks (WMNs) are multi-hop wireless networks with mesh connectivity. A WMN is composed of gateway nodes, mesh routers and mesh clients. Mesh routers form the mesh backbone with low mobility and usually each router is equipped with several wireless interface cards (Akyildiz and Wang, 2005; Pathak and Dutta, 2011). The IEEE 802.11 medium access control (MAC) (IEEE 802.11 Working Group, 2003) protocol is often used in WMNs where routers work with one channel. For single channel, the peak data rate at the MAC layer for IEEE 802.11 a/g (IEEE 802.11 Working Group, 2003) is 54Mbps, and the actual throughput for the application layer is almost half (Raniwala and Chiueh, 2005). Interference from adjacent nodes also decreases the transmission rate. Therefore, the problem of increasing network capacity is important. Since the physical layer protocol of IEEE 802.11 a/b/g (IEEE 802.11 Working Group, 2003) provides multiple orthogonal channels, the wireless interface cards of mesh routers can operate in multiple orthogonal channels simultaneously which can increase the capacity and performance of WMNs.

In multi-channel WMNs, the network load increases with the number of users. Some routers, especially the 'hot' routers, may become the congested node and the links connected with them will become the bottleneck links.

When the congested nodes exist, the probability of long time delay and packets loss increase significantly. However, the routing protocols used for WMNs, such as AODV (Perkins et al., 2003) and HWMP (Kim et al., 2012), do not consider the influence of hot nodes. Once the congested state is formed, it will be maintained until the load reduces or the new paths set up. Therefore, a major challenge in the design of routing protocol in multi-channel WMNs is to balance network load between routers to avoid congestions.

For WMNs, the problem of load-balancing can be divided into gateway load-balancing and router load-balancing (Juan et al., 2012; Tokito et a1., 2009). By current traffic conditions, gateway load-balancing chooses routers associated with gateways and router load-balancing chooses the path for flows. Recently, researchers have proposed load-balancing routing (LBR) for multi-channel WMNs (Narayan, 2013; Le et al., 2009; He et al., 2012; Jung et al., 2009; Wellons and Xue, 2011; Singh and Lobiyal, 2012). A new cross layer routing metric proposed in Narayan (2013) aims at estimating the interference, load and delay of a link efficiently to improve the performance. A LBR protocol for multi-radio mesh network (LBM) (Le et al., 2009) is designed to balance traffic load among channels, in which the route metric of LBM is composed of traffic load and interference. The load-balanced connected dominating set (LBCDS) problem is discussed (He et al., 2012), in which constructing an LBCDS and load-balanced allocating dominatees to dominators are investigated simultaneously. A distributed potential-field-based anycast routing scheme (Jung et al., 2009) can aid in balancing load among gateways and mesh nodes. Wellons and Xue (2011) develops a performance-ratio robust routing formulation for multi-radio, multi-channel networks that exploit traffic demands that fall into a predicted region. Singh and Lobiyal (2012) propose an algorithm by using an adaptive back-off strategy to realise load balance among sensor nodes and achieve fairly uniform cluster head distribution across the network.

The routing protocol proposed in this paper is based on router load-balancing and addresses the issues to minimise the load difference among routers. The network model for multi-channel WMNs with single gateway is presented. Based on this model, the LBR algorithm is proposed, including a link allocation algorithm and load-balancing route-selection algorithm. The link allocation algorithm allocates all links to channels to minimise network interference degree. After that, a load-balancing route-selection algorithm is proposed to decrease the load difference among routers. Using the LBR algorithm, the new flows will select the route with low interference and low load. Therefore, the traffic load is distributed uniformly as much as possible and the performance of network is improved.

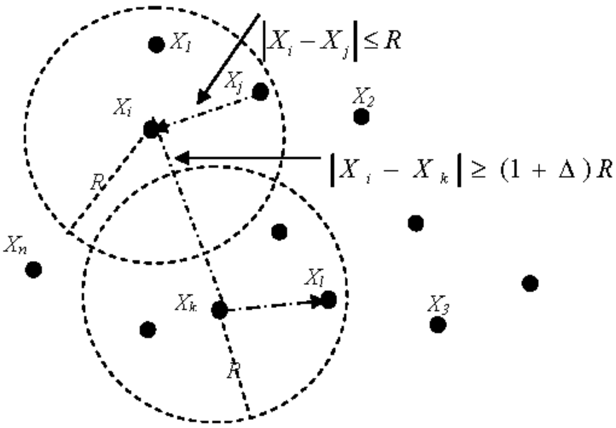
The rest of this paper is organised as follows. In Section 2, we present the network model for WMNs. After that, link allocation algorithm is proposed in Section 3. In Section 4, load-balancing route-selection algorithm is proposed. In Section 5, simulation results are presented and analysed. In Section 6, we summarise the main results of the paper.

2 Network model

We consider a multi-channel WMN with n nodes (routers) and one of them is also acted as gateway. We assume that each node is equipped with m wireless interface cards and uses omnidirectional antennas with the same transmission power. The multi-channel WMN is described with a graph $G = (V, E)$, where V represents the set of nodes and E represents the set of links among nodes. Let X_i denote the location of node i. In Figure 1, according to the protocol model in Gupta and Kumar (2000), a packet from node j to node i can be received successfully when:

- The transmitter and receiver work on the same channel.
- The distance between X_i and X_j does not exceed the effective transmission range R.
- X_i is located outside $(1 + \Delta)R$ of any other transmitters transmitting simultaneously on the same channel. Δ is the guard zone defined by the PHY protocol to avoid excessive interference from any other transmitting node. $(1 + \Delta)R$ is the interference range.

Figure 1 The transmission model for a multi-channel WMN



In Figure 1, if any two nodes are within each other's effective transmission range, we consider there exists a link e $(e = (u, v) \in 1E)$ between two nodes. Assume there are c available channels and $C = \{1, 2, \ldots, c\}$ represents the set of channels. $Q(e)$ represents the set of links interfering with link e. c_0 represents the maximum capacity. $c(e)$ represents the current load of link e. $c(e)$ is subject to:

$$c(e) + \sum_{e' \in Q(e)} c(e') \le c_0. \tag{1}$$

$P(s,d)$ represents the path from source s to destination d. We assume that the desired flow along $P(s,d)$ is $f(s,d)$. The variable $x_e(s,d)$ is used to describe the relationship between link e and path $P(s,d)$. If the path $P(s,d)$ includes link e, the value of $x_e(s,d)$ is 1, else is 0. The total flow of link e is:

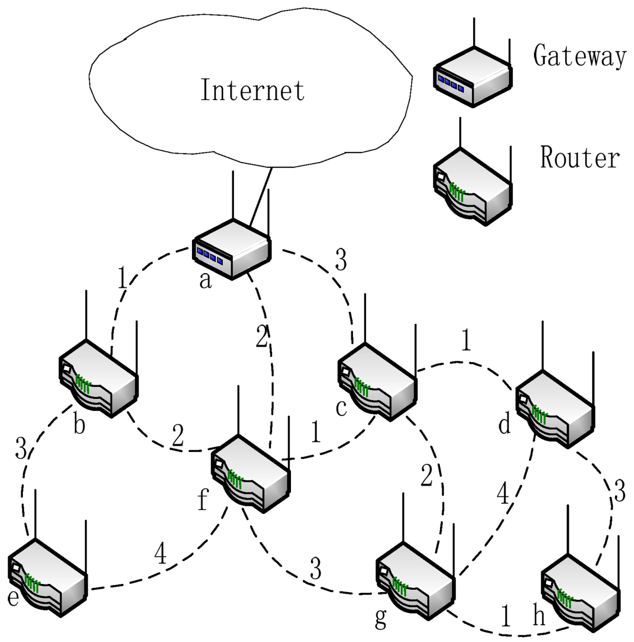
$$f(e) = \sum_{s,d \in V} x_e(s,d) f(s,d) \quad (2)$$

where $f(e) \le c(e)$ For an intermediate node u of path $P(s, d)$, we have:

$$\sum_{v \in V, e=(u,v) \in E} f(e) = \sum_{v \in V, e=(u,v) \in E} f(e) \quad \forall u \ne s, d. \quad (3)$$

Equation (3) indicates that all flows into the intermediate node u is equal to the flows out of node u. As shown in Figure 2, all intermediate nodes will keep this constraint. In Figure 2, a sample multi-channel WMN with four available channels is illustrated. The links work on different channels and links connected to the same node maybe transmitted simultaneously. For example, the links *ab*, *af* and *ac* connected to the node a work on channel 1, 2, and 3, respectively, and can transmit simultaneously.

Figure 2 The topology of a multi-channel WMN (see online version for colours)



Properly allocating channels to links will reduce interference and increase the number of links transmitting simultaneously, leading to improved transmission efficiency on the paths. The proposed LBR algorithm is composed of a link allocation algorithm and a load-balancing route-selection algorithm. The former is first executed to allocate links to available channels. The latter then selects a path with balanced network load.

3 Link allocation algorithm

We propose a link allocation algorithm to minimise network interference. For a multi-channel WMN with L_0 links, $C_k(e)$ $(1 \le e \le L_0)$ is defined to indicate the distribution of links on the kth channel:

$$C_k(e) = \begin{cases} 1, & \text{if link } e \text{ is allocated to } k\text{th channel}, \\ & 1 \le k \le c, 1 \le e \le L_0 \\ 0, & \text{else} \end{cases}$$

Assume a link is only assigned to one channel, we have:

$$\sum_{k=1}^{c} C_k(e) = 1 \quad \forall e \in E.$$

For two links $e_1 = (u, v)$ and $e_2 = (a, b)$, if $C_k(e_1) = C_k(e_2) = 1$ and any node of one link is within the interference range of another link, it means there exists interference between the two links. Let $Q_k(e)$ represent the set of links interfering with link e on channel k. The interference degree is used to evaluate the interference of a link. The interference degree of link e on channel k is defined as:

$$I(e,k) = \sum_{e' \in Q_k(E)} C_k(e')$$

$x(u, k)$ is defined to describe the status of node associated with channel k:

$$x(u,k) = \begin{cases} 1, & \forall e = (u,v) \in E, \quad C_k(e) = 1 \\ 0, & \text{else} \end{cases}$$

For a node, considering the number of working channels cannot exceed the number of wireless interference cards, we have:

$$\sum_{k=1}^{c} x(u,k) \le m \quad \forall u \in V.$$

To minimise the interference, the goal of the proposed link allocation algorithm is to solve the following problem:

$$\min \sum_{k=1}^{c} I(e,k)$$

$$\text{s.t.} \sum_{k=1}^{c} x(u,k) \le m, \quad \forall e \in E$$

$$\sum_{k=1}^{c} x(u,k) \le m, \quad \forall u \in V.$$

There are some algorithms to solve this linear integer programming problem, such as the branch and bound algorithm (Monticelli et al., 2001; Shafia et al., 2012). However, for large-scale networks, finding the optimal solution is not easy in practice. An alternative method is to use some heuristic methods to find the sub-optimal solution (Wong, 2007). In this paper, we use hierarchical link allocation (HLA) algorithm to solve this problem. For a node u, the number of layers $L(u)$ is equal to the minimum number of hops from this node to the gateway. In Figure 1, node g is located on the first layer. For a link $e = (u, v)$, $L(e) = \min(L(u), L(v))$. Assuming the maximum number of layers is L1, the HLA algorithm is proposed as follows (Algorithm 1):

Algorithm 1 HLA algorithm

1. Initialization. Set $x(u,k)=0,\ \forall u\in V,\ k\in C$. Set $C_k(e)=0$ and $\boldsymbol{Q_k(e)=\Phi}$, $\forall e\in E,\ k\in C$. Set i=0.
2. Allocates links located at the *i*th layer to channels. The number of links at the *i*th layer is denoted by l_i.

   for *e*=1 to l_i
   for $1\leqslant k\leqslant c$
   $I(e,k)=\sum_{e'\in Q_k(e)} C_k(e')$
   End
   $I(e,k^*)=\min\{I(e,k)\},\ 1\le k\le c$
   $C_{k*}(e)=1$
   If $\sum_{k=1}^{c} x(u,k)\ge m$
   $C_{k^*}(e)=0\ ,x(u,k^*)=x(v,k^*)=0,\ \ \forall e=(u,v)\in E$
   $I(e,k^*)=\min_{1\le k\le c} \sum_{e'\in Q_k(e),x(u,k)=1} C_k(e')$
   $C_{k^*}(e)=1$
   End if
   End
3. i=i+1
   if $(i\le L_1)$ goto 1
   else end

Considering generally the nodes close to the gateway have more load, the HLA algorithm begins to allocate links from the lower layer. For a link, if there exist several channels with minimal interference degree, the algorithm selects one randomly.

4 Load-balancing route-selection algorithm

In this section we present the load-balancing route-selection algorithm for multi-channel multi-hop WMNs. After all links are allocated to channels, the goal is to find a path from source to destination with network load-balancing. First, we formulate this problem as a linear programming (LP) problem. Then, a heuristic algorithm to find a feasible route is presented which distributes the flows uniformly among the links.

To balance the flows of links, we try to reduce the load difference among links. The difference between the maximum and the minimum load of links is:

$$f=\max_{e\in E} f(e)-\min_{e\in E} f(e). \tag{4}$$

To avoid the extra delay due to excessive hops, we limit the number of hops of a path. Let *h* be the number of hops in *P*(*s*,*d*) and $h_m(s,d)$ be the path from s to d with minimum hops, we set a limitation:

$$h\le \beta h_m(s,d)\quad (\beta\ge 1) \tag{5}$$

where $\beta\ge 1$ is hop coefficient. When $\beta=1$, the selected path is the path with minimum hops.

To balance the load of links, the object of the LBR algorithm is to minimise *f*. This problem can be formulated as:

$$\begin{aligned}
&\min\ \ f\\
&\text{s.t.}\ \ f=\max_{e\in E} f(e)-\min_{e\in E} f(e)\\
&f(e)=\sum_{s,d\in V} x_e(s,d)f(s,d)\\
&\sum_{v\in V,e=(u,v)\in E} f(e)=\sum_{v\in V,e=(v,u)\in E} f(e),\quad \forall u\ne s,d\\
&f(e)\le c(e)\\
&c(e)+\sum_{e'\in Q(e)} c(e')\le c_0\\
&h\le \beta h_m(s,d)
\end{aligned}$$

We propose a heuristic algorithm to solve this problem. For a multi-channel WMN with L_0 links, *f*(*s*,*d*) represents the flows from source s to destination *d*. $f_i(s,d)$ represents the *i*th flows from *s* to *d*. For a link e in *P*(*s*,*d*), *CD*(*e*) is the channel repetition number. If the link of next hop works on the same channel, *CD*(*e*) is 1, else is 0. The channel repetition number of *P*(*s*,*d*) is:

$$CD_{P(s,d)}=\sum_{e\in P(s,d)} CD(e)$$

The set $F=\{f(e),\ 1\le e\le L_0\}$ is used to denote the load of each link. Assuming there are L_2 flows, the load-balancing route-selection algorithm is proposed as follows (Algorithm 2):

Algorithm 2 Load-balancing route selection algorithm

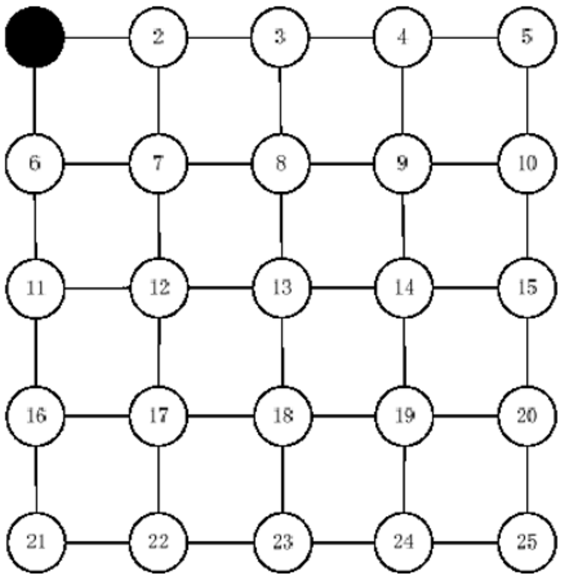
1. Initialization. Set the set $\boldsymbol{F=\Phi}$ and i=1.
2. For the *i*th flow, we get the path with minimum hop from graph *G* and denotes with $h_{mi}(s,d)$.
3. By the constraint, we obtain all satisfying paths for the *i*th flow. We assume there are *q* satisfying paths and represent with set $P_i=\{P_j(s,d),\ 1\le j\le q\}$.
4. Select the path with minimum *f*. If there exit several paths with minimum *f*, select the path with minimum *CD*. Then, update ***F*** by the selected path.
5. *i*=*i*+1. If $i=L_2$, the process is end; else goto step 2.

To implement this algorithm practically, we assume that all channels are available before link allocation. And the nodes will send the local topology information to the gateway periodically. The gateway updates the topology of the whole network and sends the updated topology to nodes periodically. Change of the channel structure will lead to the changes of link allocation and route selection. The LBR algorithm can be combined with routing protocols for WMNs, such as AODV and HWMP.

5 Simulation results

In this section, we evaluate the performance of the LBR algorithm in multi-channel WMNs and compare it with the minimum hop routing. In the simulation model, we assume that 25 routers are placed in a 1000×1000 m^2 square area to form a multi-channel wireless network, as shown in Figure 3. The black node is the gateway. The topology is assumed to be static. Each router is equipped with two wireless interface cards. The effective transmission range and interference range are both 250 m. The maximum capacity of transmission is 2 Mbps. Each node is equipped with two network interface cards (NICs). Three orthogonal frequency channels are available. We set the hop coefficient β to 1.2. In the simulated network, there are five flows with the same traffic. For each flow, the source and destination are selected randomly. The source node generates traffic following a Poisson process with average rate λ. Traffic load is varied by adjusting λ.

Figure 3 Simulation topology



The performance metrics used in the simulations are network throughput and load-balancing index *p*. Network throughput is the total of successful packets (in bps) delivered from the source to destination over the entire multi-channel WMN. The load-balancing index is used to evaluate the balance of networks and is defined as:

$$LB = \sum_{e \in P} \left| \frac{f(e) - \bar{f}}{N\bar{f}} \right|$$

where P is the set of links including all flows. N is the number of links in P. f is the average load of links in P. A smaller LB value leads to better load balance of network.

Figure 4 shows the load-balancing index with varying network load. Compared with minimum hop routing, the load-balancing index of the LBR algorithm is better. When network load is low, the network is not congested. The load-balancing indexes are low. The load differences among links with flows are small. Following the increasing of network load, the network becomes congested. The LBR algorithm can select a path to balance load so the generation of hot nodes is avoided and congestion is decreased. When the network load is 5 Mbps, Figure 4 shows that the load-balancing index obtained from the LBR algorithm is half of the minimum hop routing algorithm.

Figure 5 compares the network throughput between LBR and minimum hop routing with varying network load. The minimum hop routing does not consider the congestion of nodes. When network load increases, it may cause nodes to become bottlenecks and cause packets loss. The network throughput does not increase significantly with increase in network. Reversely, compared with network load of 3 Mbps, the network throughput has some decline when network load is greater. The LBR algorithm decreases the congested node and allocates links to channels with minimum interference, which leads to higher utilisation of network resources. Therefore, as shown in Figure 4, network throughput of LBR increases significantly with the increase of network load.

Figure 4 Load balancing index with different network load

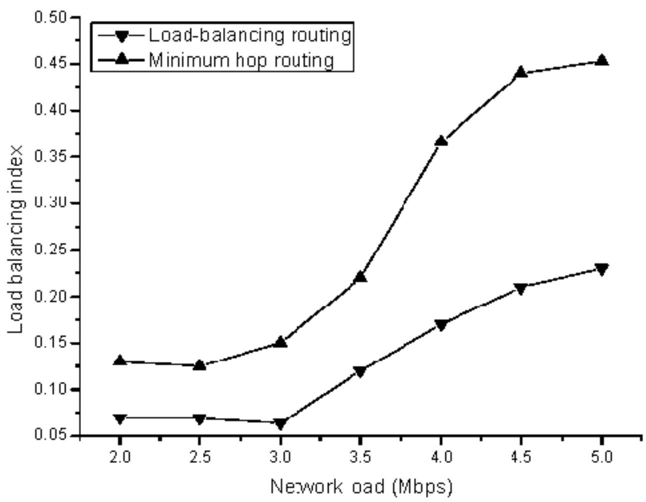


Figure 5 Network throughput with different network load

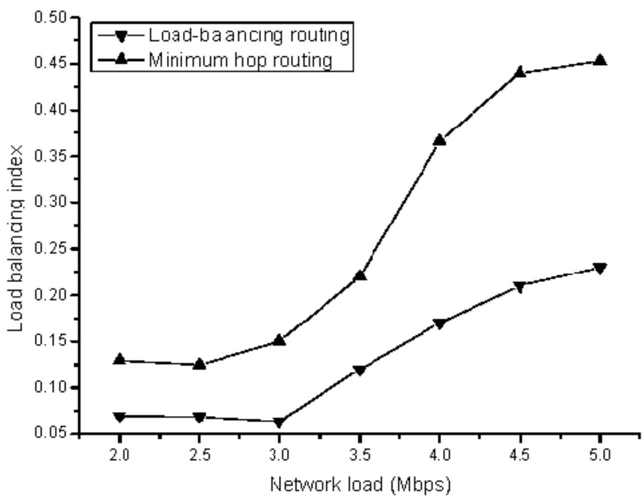
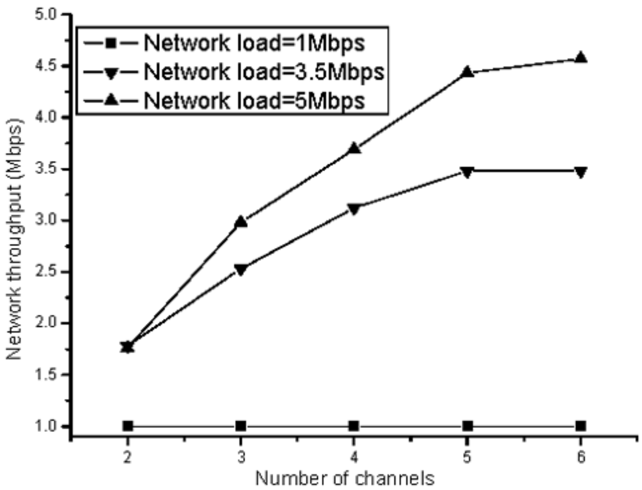


Figure 6 shows the network throughput varying with the number of channels when network load is 1Mbps, 3.5 Mbps and 5 Mbps, respectively. When the number of channels is low, there are fewer links that can be transmitting simultaneously. When network load is low, such as 1 Mbps, the packets do not need many resources to transmit. Therefore, the network throughput almost equals to the network load and the increase of channels has less influence on network throughput. Following the increase of network load, there are more packets to be transmitted and need more resources to transmit. Increasing the channels leads to increasing the links being transmitted simultaneously and decreases the congested links. Therefore, the network throughput increases with the number of channels when network load is high.

Figure 6 Network throughput with different number of channels



6 Conclusion

This paper has presented an LBR algorithm for multi-channel WMNs, composed of link allocation algorithm and load-balancing route-selection algorithm. Based on the transmission model, a heuristic link allocation algorithm is presented to allocate links to channels. The objective of this link allocation algorithm is to minimise interference among links. After all links are allocated to subnets, the load-balancing route-selection algorithm is presented to select a path considering network load-balancing. To solve this problem, a near-optimal heuristic algorithm is designed. The proposed routing algorithm balances the load among links and decreases interference among links. Therefore, it can provide higher network throughput for multi-channel WMNs. Simulation results show that compared with the minimum hop routing algorithm, the LBR algorithm provides better load-balancing index and higher network throughput. When network load is high, the LBR algorithm also increases network throughput significantly with the increase of channels.

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