On the Load Balancing of Multicast Routing in Multi-Channel Multi-Radio Wireless Mesh Networks with Multiple Gateways

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Summary
Effective multicast routing schemes alleviate potential congestion on nodes and channels, thereby improving network throughput. This paper studies the problem of finding the shortest load-balanced multicast tree with minimum channel utilization in response to a multicast communication request in multi-channel multi-radio wireless mesh networks with multiple gateways. We propose an optimization framework based on mixed integer programming, which minimizes the maximum of the channel utilization in multicast communication. The proposed Load-balanced Multicasting with Multiple Gateways (LMMG) framework benefits from an appropriate node selection in the construction of the multicast tree. LMMG is efficient as it i) constructs the paths between the source and receivers through employment of multiple gateways, thus substantially reducing the interference and usage of resources; ii) simultaneously performs tree construction as well as channel and gateway selection processes. The performance of the proposed scheme is successfully compared to that of an existing method on different simulation scenarios. The results of our simulations demonstrate that balancing channel utilization dramatically enhances the network performance.

Key words:
Wireless mesh network, Multi-radio, multi-channel, Multi-gateway, Multicast routing, Load balancing

1. Introduction

Wireless Mesh Network (WMN) is an emerging and promising network technology that prepares a broadband wireless Internet access for end users. Due to its desirable characteristics such as self-configuration, low installation and maintenance cost, ease of deployment as well as intrinsic path diversity of the multi-hop wireless backbone, wireless mesh networks are considered as one of the best solutions for a wide range of applications [1]. Major components of a wireless mesh network are gateways, mesh routers, and mesh clients. The gateways exchange the data packets between the wireless mesh backbone and the wired Internet backbone. The mesh routers route the data packets through wireless links to deliver them to Internet or the mesh clients as end users [2].

WMN as a broadband internet access suffers from the degradation of throughput due to the underlying interference. Employment of the technology of Multi-Channel Multi-Radio (MCMR) is an effective approach to alleviate this critical problem. In this paradigm, the gateways and mesh routers are equipped with multiple radios adjusted to several available channels. The equipped routers simultaneously allow transmitting or receiving packets through different channels. Even though the limited number of the available channels hinders complete removal of the interference, an efficient channel selection can significantly improve network performance [1], [3].

Maximum network performance cannot be attained unless load balancing is considered. In general, the load balancing problem can be viewed from two perspectives: node load balancing, and channel load balancing [4]. In the former, the congestion on a node makes a long time waiting for data transmission or reception. This clearly diminishes throughput of the entire network. In the latter, which is the focus of this paper, we distribute the load between the channels as to enhance the network performance. This enhance performance makes the network more responsive to the future communication requests.

On the other hand, the demand for group communication to use multimedia services has substantially increased in the last recent years, making the multicast communication a critical research topic in WMN. A multicast routing directs data packets from the source to multiple receivers. Due to the clear inapplicability of unicast-based performing in this scenario, an efficient multicast routing mechanism is essential. Despite the wide range of research devoted to multicasting in WMN, the literature on MCMR is still limited.

In addition, gateways are significantly important in WMN, as they deliver the network traffic to the Internet. Since a single gateway design makes the gateway a bottleneck, multiple gateways are needed to distribute the entire traffic load. Therefore, the gateway selection can directly improve load balancing in the network [2]. In multicasting, in particular, multicast receivers attain the same data through different gateways. Hence, efficient gateways selection is more crucial in multicast communication to enhance network performance [5].

A common way to fulfill a multicast communication is the construction of a multicast tree. This entails the

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specification of the constitutive nodes and the channels for the communication. Depending on their communication load, channels may be unequally utilized, a fact that paves the way for maximum utilization of channels. However, in wireless environments, the channel utilization relative to a node is dependent on the location of the node and its interfering nodes [4][6]. In our scheme, we plan to distribute evenly channel utilization by considering the interference and consumed capacity of the channel for each node in the network.

Our goal is to study the problem of finding the shortest load-balanced multicast tree with minimum channel utilization in response to a multicast communication request in multi-channel multi-radio wireless mesh networks with multiple gateways. To this end, we propose an optimization framework, which we call the Load-balanced Multicasting with Multiple Gateways (LMMG). LMMG features a mixed integer programming formulation and finds the shortest load-balanced multicast tree when the network receives a multicast request. The efficiency and performance of the proposed scheme are successfully compared to an existing method.

The rest of the paper is organized as follows. Section 2 briefly reviews the related works. Section 3 elaborates on the network model and the problem statement. Section 4 presents the optimization model, and Section 5 demonstrates the performance of LMMG under two different scenarios. Finally, summary and conclusions are given.

2. Related Work

The subjects of multicasting and load balancing in wireless mesh networks (WMN) have been studied mostly separately in the literature. In particular, rather less attention has been given to employing multi-channel multi-radio in the network model. In the following, we briefly review multicast tree construction and load balancing in WMN.

Galvez et al. [7] proposed an adaptive online load-balancing protocol for multi-gateway WMNs. Their protocol balances the load between gateways based on the current network conditions. It identifies the congested domains and reroutes flows to other domains. The load of a gateway is measured as the number of flows served by the gateways. If gateways serve a similar number of flows, then the network capacity is shared which provides an improved performance.

Zhao et al. [8] proposed a Gateway-cluster based Load Balancing Multicast algorithm (GLBM) to achieve Quality of Service (QoS) by avoiding uneven traffic load. They used the IFQ (Network Interface Queue) length to examine a certain node’s traffic load. In their scheme, the path with the lowest IFQ aggregation is specified for the multicast tree in order to prevent reusing the heavy load nodes.

Zhao et al. [9] later considered center node load balancing. Their main idea is based on the fact that a node with a heavy traffic makes the neighboring nodes busy too. Therefore, they consider the busy neighborhood rather than the busy node alone in bypassing the traffic.

Pourfakhar and Rahmani [10] presented a neural network model to predict route disjoint or node fault to control congestion. Authors also presented a QoS multicast routing framework for WMNs to solve the problem of load balancing and enhance the QoS in multicast communication among gateways and receivers.

Zeng et al. [11] proposed two multicast algorithms, namely, the Level Channel Assignment (LCA) and Multi-Channel Multicast (MCM) schemes, for the optimization the throughput in MRMC WMNs. LCA algorithm first constructs a multicast tree based on breadth-first search to minimize the hop count distance from the source to the receivers. Then, it uses a dedicated strategy to assign channels to the tree to reduce the interference. In addition, MCM scheme builds the tree to minimize the number of the relaying nodes and the hop count distances between the source and the destinations. It also reduces the interference by exploiting all the available channels.

Liu and Liao [12] considered the joint problem of channel assignment and multicast routing. The goal is to find the minimum cost multicast tree in MRMC WMNs. Here, the cost of a multicast tree is defined as the number of transmissions required to deliver data from source to receivers. An optimal model is presented for solving this problem. They proposed a near optimal algorithm to construct the minimum transmission trees considering their interference.

Asadi Shahmirzadi et al. [13] proposed a cross-layer optimization framework for joint channel assignment and multicast tree construction in MCMR WMNs. The cost function of the problem is the total number of the forwarding nodes and the interference. The proposed model incorporates multiple gateways and partially overlapping channels into the scheme, and offers optimal solution.

Chiu and Yeung [6] proposed a call admission control for multicast in MCMR WMN. To increase the call acceptance rate, load balancing is fulfilled by minimizing the carried load on the overloaded channels and nodes. They proposed an optimal model as well as a heuristic approach to solve the problem.

Avokh and Mirjalily [4] suggested a heuristic algorithm to construct a load-balanced multicast tree in MRMC WMN. In this algorithm, the traffic load on mesh nodes is formulated as a congestion factor related to links. In addition, utilizing wireless broadcast advantage was also devised in the link selection algorithm. These two considerations define a cost function in which the cost of each link is computed to generate minimum cost tree.

As elaborated above, the subjects of multicasting and load balancing in wireless mesh networks have been viewed mostly separately in the literature. Also, major attention has been given to employing single-channel single-radio in the network model. In contrast, we consider the problem of finding the shortest load-balanced multicast tree with minimum channel utilization in response to a multicast communication request in multi-channel multi-radio wireless mesh networks with multiple gateways.

3. Network Model and Problem Statement

In the following, the network model and problem statement are elaborated.

3.1 Network Model

We consider the static, multi-channel, multi-radio, multi-gateway, wireless mesh network shown in Fig. 1. Let C denote the set of channels, G the set of gateways, and R the set of receivers in the network, with the assumption that receivers not only can receive data, but also can forward the data. Let the communication graph $Gr = (V, E)$ represent this network, where V and E are the set of mesh routers and wireless links, respectively. Mesh routers are equipped with multiple radios, each of which can be tuned to a distinct non-overlapping channel. In addition, wireless links are created when two nodes are located within the transmission range of each other and have a radio tuned to the same channel.

We employ a receiver conflict avoidance interference model [5] in this paper. Under this model, a data transmission from one node to another is successful if there is no other node transmitting data on the same channel within the interference range of the target node.

Here, we assume that i) the channel assignment is given in the network, ii) all radios have a common transmission range, T_r, and a common interference range $I_r(\geq T_r)$, and iii) each mesh router has radios tuned to distinct channels, as to avoid self-interference [14].

3.2 Problem Statement

The goal is to find the shortest load-balanced multicast tree with minimum channel utilization in response to a multicast communication request. Our approach to this problem is to convert it into a min-max problem. Thus, we minimize the longest path in the tree and the maximum

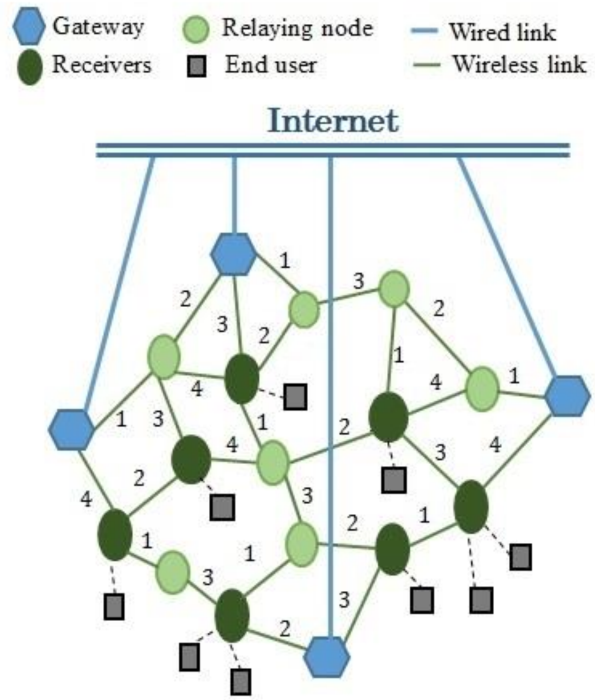

Fig.1 A schematic of a Multi-Channel Multi-Radio Multi-Gateway Wireless Mesh Network (MCMRMG WMN). The number on each link represents the link's channel number.

channel utilization in the network.

The longest path in the tree is defined as

$$h_{max} = \max_{\forall i \in R, g \in G} \{h_v^g\}, \tag{1}$$

where the integer $h_v^g \epsilon [0, N_n]$ quantifies the distance between the node v from the gateway g. Here, N_n is the total number of nodes.

Also, the maximum channel utilization is defined by

$$U_{max} = \max_{\forall v \in V, k \in C} \{U_v^k\}, \tag{2}$$

where U_v^k denotes the usage of the channel k relative to node v. The parameter U_v^k can be written as

$$U_v^k = E_v^k + T_v^k, \quad (v \in V, k \in C), \tag{3}$$

where E_v^k is the occupied bandwidth of channel k relative to node v for the existing links in the network, and T_v^k is that for the tree construction, respectively.

The parameter E_v^k is defined as

$$E_v^k = \sum_{i,j} A_{ij}^k L_{ij}^k, \quad (i \in I_v, j \in V, k \in C), \tag{4}$$

where set I_v contains the node v and those in the interference range of node v. The binary variable A_{ij}^k, when equals one, determines if channel k is assigned to the link (i, j). In addition, the parameter L_{ij}^k denotes the load capacity, which the channel k shares with the link (i, j).

In addition, the parameter T_v^k is defined as

$$T_v^k = \sum_{i,j} l_{ij}^g A_{ij}^k B_m, \quad (i \in I_v, j \in V\ g \in G,\ k \in C), \quad (5)$$

where l_{ij}^g is a binary variable, which, if equals one, indicates that the link (i,j) on multicast tree is connected to the gateway g. Here, B_m is the bandwidth required by the multicast communication.

4. LMMG: An Optimization Framework

We cast the problem elaborated in section 3 into an optimization framework. In the following, we propose a solution framework, which we call the Load-balanced Multicasting with Multiple Gateways (LMMG). The objective function and the constraints of this framework are elaborated as follows.

4.1 Objective Function

LMMG minimizes the weighted sum of the maximum channel utilization (given by eq. (1)) and the longest path in the multicast tree (given by eq. (2)). That is,

$$\Omega = h_{max}/N_n + U_{max}/C_a, \quad (6)$$

where N_n is the number of nodes in the network, and C_a is the channel capacity. Note that the parameters C_a and N_n are chosen to effectively combine the contributions of channel utilization and depth of the multicast tree in the definition of the objective function.

4.2 Constraints

It is clear that no channel can be loaded more than its capacity, C_a. Thus, the first constraint in the proposed optimization framework is

$$U_i^k \le C_a, \quad (i \in V,\ k \in C). \quad (7)$$

In addition, the objective function given by (6) assumes that the parameters U_{max} and h_{max} attain maximum values, the fact that constitutes the second set of constraints. That is,

$$U_{max} \ge U_i^k, \quad (i \in V,\ k \in C), \quad (8)$$

$$h_{max} \ge h_i^g, \quad (i \in R,\ g \in G). \quad (9)$$

Further constraints arise due to the construction of the multicast tree. This is common to the problem studied by Asadi Shahmirzadi et al. [13]. Thus, we take advantage of the exiting derivations. Asadi Shahmirzadi et al. [13] presented constraints arising from the usage of gateways, receivers, relaying nodes, and consideration of loop prevention. The constraints for gateways are

$$\sum_{i,g} l_{ip}^g = 0, \quad (i \in V,\ p, g \in G), \quad (10)$$

$$\sum_{i,g} l_{gi}^g \ge 1, \quad (i \in V - G,\ g \in G), \quad (11)$$

$$\sum_{i,g} l_{gi}^g \le r, \quad (i \in V - g \in G), \quad (12)$$

$$\sum_{i,g} l_{gi}^g = \sum_{i,g,p} l_{pi}^g, \quad (i \in V - G,\ p, g \in G). \quad (13)$$

The constraints for receivers are

$$\sum_{i,g} l_{ij}^g = 1, \quad (i \in V, j \in R,\ g \in G), \quad (14)$$

$$\sum_{i,g} l_{ij}^g \ge 0, \quad (i \in R,\ j \in V,\ g \in G). \quad (15)$$

The constraints for relaying nodes are

$$\sum_{i,g} l_{ij}^g \le 1, \quad (i \in V, j \in V - G - R, g \in G), \quad (16)$$

$$\sum_i l_{ij}^g \le \sum_x l_{jx}^g,$$
$$(i \in V,\ j \in V - G - R,\ x \in V - G, g \in G), \quad (17)$$

$$(-1 + \sum_i Z_{ij}) \sum_i l_{ij}^g \ge \sum_x l_{jx}^g,$$
$$(i \in V,\ j \in V - G - R,\ x \in V - G,\ g \in G), \quad (18)$$

$$\sum_g l_{ij}^g \le Z_{ij}, \quad (i,j \in V, g \in G). \quad (19)$$

$$\text{where } Z_{ij} = \begin{cases} 1, & D_{ij} < T_r \\ 0, & else \end{cases}, \quad (i,j \in V). \quad (20)$$

In eq. (20), D_{ij} is the Euclidean distance between the nodes i and j.

Finally, the loop prevention constraints are

$$h_g^g = 1, \quad (g \in G), \quad (21)$$

$$\sum_i l_{ij}^g \le h_j^g, \quad (i \in V,\ j \in V - G,\ g \in G), \quad (22)$$

$$N_n \sum_i l_{ij}^g \ge h_j^g, \quad (i \in V,\ j \in V - G,\ g \in G), \quad (23)$$

$$h_j^g - h_i^g \ge -N_n + (N_n + 1) l_{ij}^g, \quad (i,j \in V, g \in G), \quad (24)$$

$$h_j^g - h_i^g \le N_n - (N_n - 1) l_{ij}^g, \quad (i,j \in V, g \in G). \quad (25)$$

5. Simulation Results

The proposed model is implemented in Advanced Integrated Multidimensional Modeling Software (AIMMS version 3.0.1) [15]. We use the built-in CPLEX 12.2 solver and the branch and cut method for mixed integer programming. We conduct two sets of simulations to evaluate the performance of the proposed scheme. In particular, we consider two sets of grid topology sizes in our MCMRMG WMN simulations. One has 16 nodes arranged within a square of 400m ×400m, and the other has 25 nodes arranged within a square of 500m ×500m. Additionally, the number of radios per node is randomly determined and is limited to 3. Finally, three non-overlapping channels are employed in the network, where the transmission and interference ranges of the radios are set to 100m and 200m.

In the following simulations, we employ two metrics, namely, the standard deviation of the channels utilization, and the maximum height of the multicast tree. The less the value of the former, the more the balance of the channel utilization. On the other hand, the smaller the latter, the less the delay in the multicast communication.

Scenario 1: In the first scenario, we study the effect of multicast group size on the algorithm's performance. We consider a network with 16 mesh routers and a varying number of receivers ranging from 2 to 8. In each multicast group, the simulations have been repeated for different permutations of nodes. Multicast tree is built with up to two gateways using two approaches: i) LMMG, and ii) the Shortest Path Tree (SPT), which connects the source to the receivers in the shortest path. The simulations are started with an initially loaded system, with each link loaded randomly up to 10% of the capacity of its channel. In addition, the bandwidth required for the multicast request is set to 5% of the channel capacity.

As illustrated in Fig. 2, LMMG provides a better performance compared to SPT. Recall that the less the channel utilization standard deviation, the better the performance. In particular, improvements are more pronounced when multiple gateways are employed in the multicast tree construction.

In addition, Fig.3 presents the effect of the size of the multicast group on the height of the multicast tree for the two schemes LMMG and SPT. As expected, SPT scheme constructs an optimal multicast tree with minimum height. LMMG not only does obtain the same result, but also returns a load-balanced multicast tree. Also, results follow intuition in that the more the gateways used in the network, the shorter the multicast tree, thus the faster the multicast communication.

Scenario 2: In this scenario, we expand the size of the network to have 25 mesh routers, and the size of the multicast group from 3 to 12 nodes. We configure the network with the same parameters similar to the previous scenario. As illustrated in Figs. 4 and 5, simulations reveal that LMMG retains its enhanced performance compared to SPT.

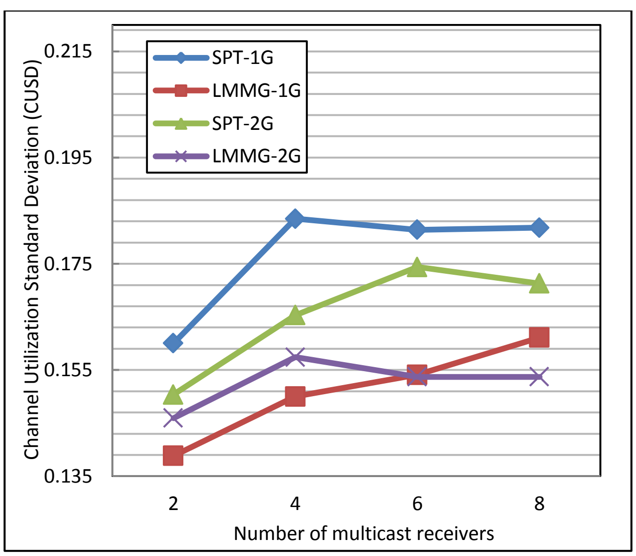

Fig. 2 Comparison of LMMG and SPT schemes on the Channel Utilization Standard Deviation for a 25-node network. Note that the number '1' in SPT-1G stands for the number of gateways. This naturally extends to other cases.

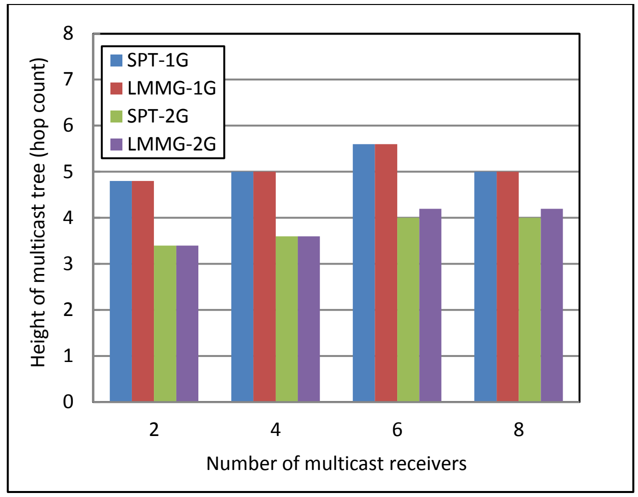

Fig. 3 Comparison of LMMG and SPT schemes on the height of the multicast tree for a 16-node network

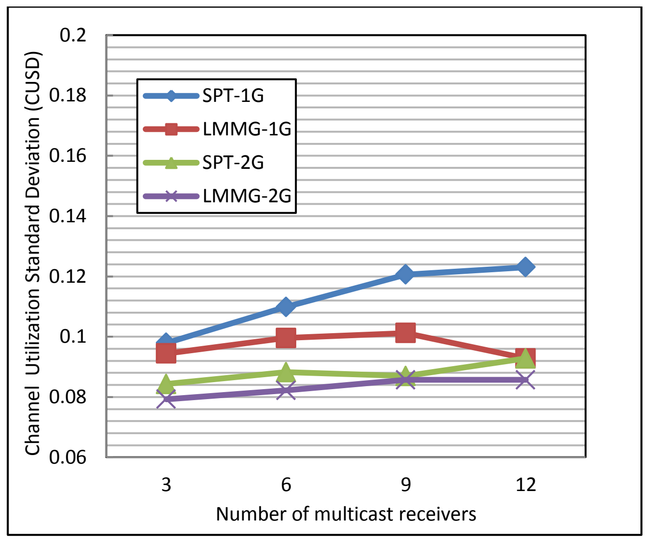

Fig.4 Comparison of LMMG and SPT schemes on the Channel Utilization Standard Deviation for a 25-node network

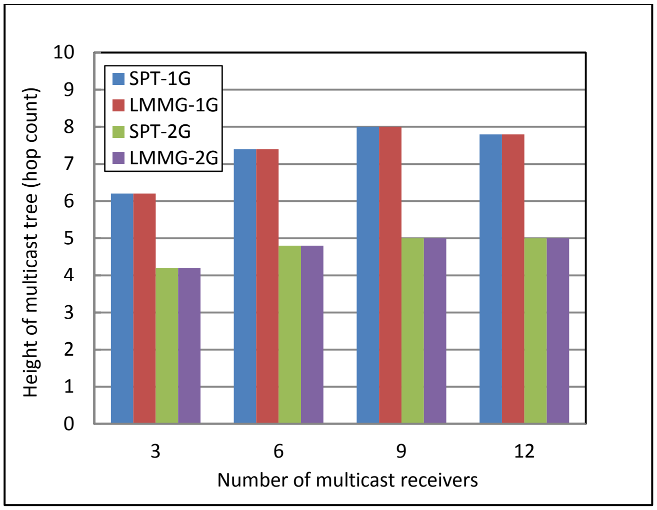

Fig.5 Comparison of LMMG and SPT schemes on the height of the multicast tree for a 25-node network

6. Conclusion

We studied the problem of finding the shortest load-balanced multicast tree with minimum channel utilization in response to a multicast communication request in multi-channel multi-radio wireless mesh networks with multiple gateways. We proposed an optimization framework based on mixed integer programming, which minimizes the maximum of the channel utilization in multicast communication. Our framework benefits from an appropriate node selection in the construction of the multicast tree. The framework is efficient as it i) constructs the paths between the source and receivers through employment of multiple gateways, thus substantially reducing the interference and usage of resources; ii) simultaneously performs tree construction as well as channel and gateway selection processes. We demonstrated the superior performance of the proposed scheme compared to an existing method on different simulation scenarios. The results of our simulations demonstrated that balancing channel utilization dramatically enhances the network performance. Also, the results confirm that the performance of LMMG is retained as the network size is increased.

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