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Improving Capacity and Flexibility of Wireless Mesh Networks by Interface Switching

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***Abstract*—The capacity and flexibility of wireless mesh networks (WMNs) can be greatly improved by adopting dynamic channel assignment. However, dynamic channel assignment brings new challenges such as switching overheads and dependency problems. We propose a channel assignment protocol, called the hybrid channel assignment protocol (HCAP) for infrastructure WMNs (I-WMN). To find out a reasonable tradeoff between flexibility and switching overheads, HCAP adopts static interface assignment strategy for nodes that have the heaviest loads. For other nodes, it adopts a hybrid strategy. HCAP uses a slot-based coordination policy to implement communications between nodes that adopt hybrid strategy. NS2-based simulations show that HCAP not only improves capacity and scalability of I-WMNs, but also enhances per-flow fairness.**

I. Introduction

Public deployment of Infrastructure wireless mesh networks (I-WMNs) [6] has increased these days due to their advantages such as low cost, high speed, easy installation, etc. One example of I-WMN architecture is shown in Fig. 1. Traffic loads originating from mobile users are loaded to I-WMNs through the mesh routers within their transmission range. Traffic loads are transferred in I-WMNs hop by hop. At last, the traffics are delivered to the wired networks by the mesh routers that connect to wired networks via wired links.

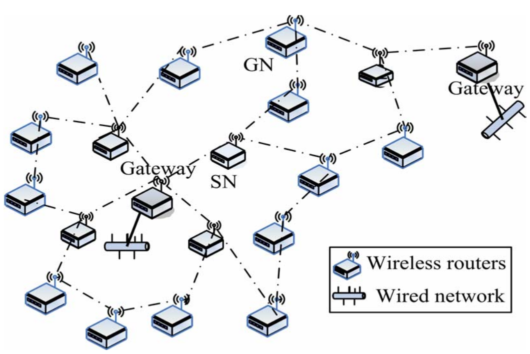

FIG. 1 The I-WMN Architecture

Gateways (GAs): The routers that connect to wired networks via wired links;
SNs: The mesh routers within the transmission range of GAs;
GNs: All of the mesh routers except GAs and SNs.

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Interference in I-WMNs is serious due to their heavy traffic loads aggregated from multiple hops. Increase of interference adversely decreases the performance of I-WMNs. Equipping each node with multiple interfaces may improve the capacity of WMNs. By fixing interfaces on different channels, a node can synchronously communicate with multiple nodes without interference. However, it is difficult to equip each node with the same number of interfaces as available channels due to hardware cost.

Fortunately, most interfaces today are capable of switching over multiple channels. Dynamic channel assignment consists of two parts: the interface assignment strategy and coordination scheme. The former decides the interface switching mode, whereas the latter provides methods to implement communications under given interface assignment strategy. There may be several policies to implement an interface assignment strategy, whereas a coordination policy can only implement one interface assignment strategy. By dynamically channel switching, co-channel interference is minimized, which in turn improves the network capacity. Accordingly, the scalability of WMNs is greatly enhanced.

However, interface switching brings new problems such as switching overheads and dependence problems. One overhead caused by interface switching is switching delay, which is not negligible at present. For example, the switching delay of commodity IEEE 802.11 hardware today is in the range of a few milliseconds [14]. There are two kinds of dependence problems: connection dependence and channel dependence. It is called connection dependence as nodes cannot communicate with each other due to switching to different channels. In addition, changing the channel of a particular link may result in changing allocated channels of many other links in the network. It is called channel dependence.

Existed dynamic channel protocols adopt different strategies to avoid high switching overheads or dependence problems. Some protocols [10, 11, 14, 16] adjust channels every after a relative long period, whereas some protocols [2, 3, 5, 6, 8, 9, 15] change the MAC layer. And some others [3, 12, 13, 16] need additional control interfaces. In this paper, we put forward a channel assignment protocol that combines static and hybrid interface assignment strategies together to find a feasible tradeoff between flexibility and switching overheads. NS2-based simulations show that our proposed protocol not only improves both capacity and scalability of I-WMNs, but also enhances per-flow fairness.

The rest of this paper is organized as follows. Section II gives relevant work. Section III presents essential premises. Section IV describes our proposed protocol. Section V provides evaluation results. Conclusions and future works are given in Section VI.

II. Related Work

Extensively studies have been executed to utilize multiple channels in wireless network during the past decades [1-16]. Quite a number of works need to change MAC protocol [3, 6, 9]. DCA [3] divides the overall bandwidth into one control channel and *n* data channels. It needs two interfaces on each node: one fixes on the control channel, whereas the other dynamically switches among data channels. xRDT [6] uses a busy tone to show the channel reserving information. However, those MAC protocols cannot be applied directly because they are not compatible with commodity hardware. Protocols of [2, 8, 9, 15] seek to use one interface to exploit multiple channels. The protocol proposed in [2] uses slotted channel hoping to allow one interface to visit multiple channels.

There are also several multi-interface channel assignment protocols that need not change current MAC [10-14, 16]. Reference [10] and [11] respectively presented a centralized and distributed channel assignment algorithm for I-WMNs, where every node is equipped with two interfaces. The algorithm sorts and assigns channels to links in the decreasing order of their link loads. A distributed algorithm was proposed in [11]. The algorithm assumes that the routing trees have been established before channel assignment. For each node, its parent node assigns channel to the interface connecting to the parent; it only decides the channel of the other interface. By using this strategy, it alleviates the channel dependence level of the network. To avoid connection dependence and minimizes the switching overheads, most protocols [10, 11, 14, 16] adjust channels after a relatively long period. These protocols need not control channel, whereas they need complex coordination technologies in communications. To ease the channel assignment coordination, the protocols proposed in [12, 13] fix one interface of each node on a "fixed" channel, which is different from any other nodes in its neighborhood; the other interface switches among the "fixed" channels of its neighbors.

III. Premises

We consider an I-WMN that consists of *M* GAs and *N* other nodes (i.e. SNs and GNs), and each node is equipped with two interfaces. In most scenarios, the ratio between *M* and *N* is much less than 1 since there are usually a few GA nodes. We then assume that *M/N* is small enough that any two GA nodes do not interfere with each other even if they are assigned a common channel. For simplicity, we assume that a SN is within the transmission range of only one GA, and a node can only establish one routing path to the GA nodes at a time.

Recall that nodes cannot communication with each other if they fix on different channels due to the characteristic of wireless channels. Therefore, HCAP needs time synchronization to ensure successful communications between nodes that adopt hybrid interface assignment strategy. Nevertheless, synchronization is not the emphasis of HCAP. Hence, we just assume that HCAP adopts one of current synchronization protocols.

We observe that traffic flows in I-WMN are mainly for Internet accesses, which is consistent with the traffic model suggested in [7, 11]. Therefore, we assume that traffic loads in the I-WMNs are all to and from the wired networks. Traffic loads on Gateways are the sum of those on the mesh clients. According to the analysis results of [7], traffic loads on AP nodes are also in Poisson process if traffics arrive to every mesh client in Poisson process. Starting from the GA, loads on the other nodes in the routing path drop dramatically. The farther a node to the GA is, the lighter the aggregated loads on it.

IV. The Proposed Protocol

We illustrate the proposed channel assignment protocol, called the hybrid channel assignment protocol (HCAP) in this section. We first describe its interface assignment strategies, and then briefly describe the coordination policy of HCAP. At last, we give the channel assignment algorithm.

A. The Interface Assignment Strategies

Recall that interface switching may induce additional overheads, whereas static strategy may cause network partition if nodes within each other's transmission range are assigned different channels. HCAP adopts different interface assignment strategies for different nodes to find a reasonable tradeoff between flexibility and switching overheads.

As described in previous, loads on GA nodes are much heavier than those on the other nodes. HCAP adopts static interface assignment strategy for GA nodes to avoid frequent interface switching, and it adopts hybrid strategy for the other nodes (SN and GN nodes thus are also called hybrid nodes) to keep flexible. The interface assignment strategy of hybrid nodes is as follows. One interface of each hybrid node is assigned a channel, which is different from that of nodes within its interference range as possible. The channel is referred to the node's receiving channel (C_{Rec}), and the corresponding interface is referred to its receiving interface (I_{Rec}). Since every node is equipped with two interfaces, only one interface on the node adopts static strategies, and the other interface can switch channels dynamically. We denote by fixed interface (FI) the interface that adopts static strategy is, and refer to the interface that dynamically switch channels as switching interface (SI).

According to the interface assignment strategies, there is no communication link between hybrid nodes on default. If one hybrid node wants to communicate with another hybrid node within its transmission range, the sender first switches to the receiver's C_{Rec} to establish a communication link. We refer to the links between hybrid nodes as dynamic links due to they are dynamically established. In contrast, we refer to the links between GA nodes and SN nodes within their transmission range as static links.

The next question is to choose the I_{Rec} for hybrid nodes. In other words, which interface should a C_{Rec} be assigned to? The C_{Rec} can be assigned to the FI of GN node. However, the C_{Rec} should not be assigned to the FI of a SN node. This is because the FI of every SN node should fix on one channel of the GA within its transmission range. According to the interface assignment, none interface on GA nodes can switch interfaces dynamically. Therefore, every SN node should fix its FI on one channel of the GA within its transmission range to communicate with the GA. Recall that the aggregated loads on GA nodes are the heaviest of all the nodes. The assigned channels of GAs should be shared among the fewest nodes to minimize the interference level on them. Based on above observations, we then assign the C_{Rec} of each SN node to its SI. However, this strategy induces connection dependency without control. We will illustrate the problem and our resolutions in next part.

The sketch of HCAP is shown in Fig. 2(b), where a rectangle denotes one interface. The number in an interface represents its assigned channel. Lines without arrows represent the static links between the GA node and SN nodes within its transmission range, whereas arrow lines represent the dynamic links between hybrid nodes. A dynamic link always starts from the SI of a sender and points to the I_{rec} of the receiver. For example, link $\overrightarrow{CD}$ denotes that node C and D is the sender and the receiver respectively. The number besides a link represents its channel.

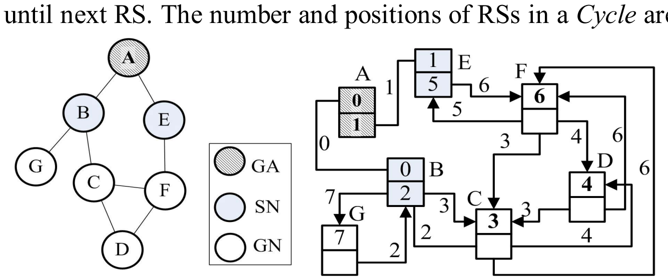
B. Coordination Policy of HCAP

We first illustrate the connection dependency problem existed in HCAP using the example shown in Fig. 2, and then give our solution to implement HCAP.

Suppose that node B is transmitting packets to node G on link $\overrightarrow{BG}$ at present. If node C wants to send some packets to B, it should use link $\overrightarrow{CB}$ by switching its SI to channel 2. However, the transmission cannot be immediately executed due to the I_{rec} of B is fixing on channel 7. This is the connection dependency problem according to the definition described in section I. Since the FI of a GN node always fix on its C_{Rec}, there is no connection problem when GN node is the receiver.

We divide the time of hybrid nodes into slots, whereas several slots compose one Cycle. The SI of a hybrid node can only fix on one channel during a slot, whereas it may switch to different channels in different slots of a Cycle.

To eliminate connection dependence, we designate several slots in every Cycle for the SI of every SN node to fix on its C_{Rec}. Hybrid nodes can only send packets to SN node during these slots. We denote these slots by Receiving Slots (RS) to differentiate with other slots. If hybrid nodes receive packets that are sent to SN nodes during other slots, they buffer them until next RS. The number and positions of RSs in a *Cycle* are



(a) Network topology (b) Sketch of HCAP

FIG. 2 A simple example of HCAP

determined by the settings of each specific network.

Another difficulty in implementing HCAP is to transmit broadcast packets between hybrid nodes. This is because the FIs of hybrid nodes are assigned different channels, whereas their SIs switch to different channels dynamically. We take several slots from the left slots of every Cycle as Broadcast Slots (BS), during which the SI of all hybrid nodes switch to a predefined channel to only transfer broadcast packets. If every hybrid node has multiple SIs, each SI should switch to a different broadcast channel. To ensure that a hybrid node may communicates with all nodes within its communication range during a BS, it should has at least one common broadcast channel with every hybrid node within its transmission range. The broadcast strategy does not need additional broadcast interface. In addition, the channel used in every broadcast slot can also be used to transfer data in other slots.

C. Channel Assignment Algorithm

The channel assignment algorithm operates in three phases. In the first phase, the algorithm assigns channels to both interfaces of GA nodes. In the second phase, the algorithm assigns channels to the FI of SN nodes. At last, the algorithm assigns C_{Rec} to hybrid nodes.

We do not describe the algorithm for the first phase since it is very simple in this paper. This is because we assume that any two GA nodes do not interfere with each other, the algorithm does not need to estimate the interference level of the network, and it just need to randomly select channels for GAs. However, it is most likely that the number of channels is fewer than that of nodes within the interference range of other nodes due to limited available channels. Therefore, the algorithm should estimate the interference level of the network on selecting channels for nodes. The interference model used in this paper is as follows. If node i is transmitting packets to node j within its transmission range on channel c. The communication is successful only if no node in the set of interference nodes of j is transmitting on channel c at the same time. The set of interference nodes for nodes that adopt hybrid strategy is computed using the ACG presented in [4], whereas the set of interference nodes for a node that adopts static strategy is computed using the MCG [16].

Let Φ and ψ be the set of all kinds of wireless mesh routers and the set of SN nodes respectively. Pseudocode for the second phase is presented in Algorithm 1, where R_I is the interference range. For a node, η denotes the number of its interference nodes that have been assigned channels.

Algorithm1. Assign Channels to the FI of SN Nodes

while (ψ is not null) {
  for (each node $i \in \psi$) **Compute** η for i;
  let $\Psi' = \{\gamma \mid \gamma \in \psi$, and γ has the maximum $\eta\}$;
  for (each node $\alpha \in \psi'$) {
    let $Q_I(\alpha)=\{\delta \mid \delta \in \Phi$, and $d(\delta,\alpha) \le R_I\}$;
    let β= the GA that is within the transmission range of α;
    Compute interference of each channel that is assigned to β;
    Select the channel that has the minimum interference;
    Broadcast the channel assignment to all nodes in $Q_I(\alpha)$;
    Delete node α from ψ' and ψ respectively;
  }
}

Pseudocode for the third phase is presented in Algorithm 2, where ψ denotes the set of both SNs and GNs. C and θ is the set of candidate channels of node a and the set of available channels in the network respectively.

Algorithm2. Assign Receiving Channels to Hybrid Nodes

```
while (ψ is not null) {
    for (each node i∈ ψ)   Compute η for node i;
    Let Ψ' = {γ | γ∈ ψ, and γ has the maximum η};
    for (each node α∈ ψ' ) {
        Let Q_I(α)= {δ |δ∈ Φ, and d(δ,α)≤R_I};
        Let C=θ;
        If (α is a SN node)  {
            Let β= the GA within the transmission range of α;
            Delete all channels that are assigned to β from C;
        }
        For (each channel c ∈ C)
            Compute the interference level of channel c;
        Select the channel that has the minimum interference;
        Broadcast the channel assignment to all nodes in Q_I(α);
        Delete node α from both ψ' and ψ;
    }
}
```

As shown in both algorithm 1 and 2, the algorithm always assigns channel to the node that has the biggest η. If multiple nodes have the biggest η, they are assigned channels in a random order. This sorting gives higher priority for nodes that have more restrictions.

V. Performance Evaluation

In this section, we compare the proposed protocol with two multi-interface channel assignment protocols [10, 13]. For ease of explanation, we refer to the two reference protocols as HYBRID and STATIC respectively.

We execute most simulations in a 36-node I-WMN, where each node is equipped with two half-duplex interfaces. The 36 nodes randomly distribute in a 6×6 square grid network, four nodes are designated as GA nodes and connected to the wired network. The distance between two neighboring nodes equals to transmission range. The ratio between interference range and transmission range is set to 2. The default number of system available physical channels is 12, and the data rate of every channel is set to 11Mbps. The data rate of every traffic flow is set to 8Mbps. The simulation period is between 24-58 seconds. We utilize the DSR protocol for route selection.

A. Throughput Comparison

We first measured the throughputs by varying the number of traffic flows. These traffic flows are loaded to the network orderly, and all of them will last till the end of simulation. The results are shown in Fig. 3.

We can see that the network saturates when the number of traffic flows is about 20. Before the network saturating, the throughput of all protocols increases monotonically along with the number of flows increases. In this example, the throughputs of HCAP achieve more than 30% and 50% in excess of the HYBRID and STATIC under the given number of traffic flows.

B. Adaptation to Flows Change

We then compare their abilities of adapting to traffic flow changes. In this case, total 32 flows are loaded to the network in

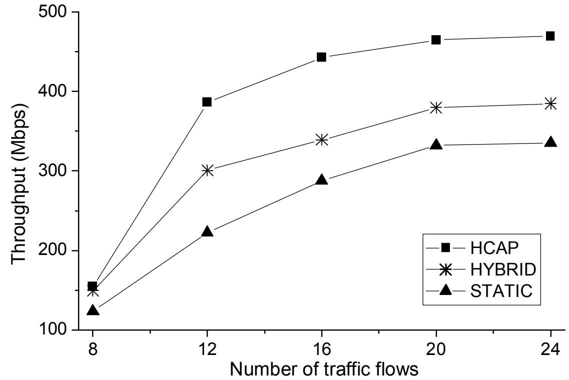


FIG. 3 Throughput Comparison

3 groups. The first group of flows, including 11 flows, was loaded to the networks between 1 and 2 seconds. The second group of 11 flows joined the network at time 7-9 seconds, and the rest 10 flows were loaded to the network during 15-17 seconds. Each traffic flow lasts about 8-15 seconds. Fig. 4 gives the throughputs at the end of every second.

Results show that HCAP and STATIC has the best and the worst ability of adapting to flow change respectively. For all of the three protocols, the network throughputs in each second incline to keep steady around a certain value, whereas their network throughputs in each second decrease dramatically when traffic flows change. However, their drop degrees are different. HCAP always has the lowest drop degree, which denotes that HCAP performs the best in dynamic environment.

C. Throughputs vs. Flow Fairness

Since the number of wireless channels is very limited, some flows may be always blocked due to the limitation of bandwidth of channels. We divide the total simulation period into 5 sub-phases. We compare the throughput with successfully transmitted flows till the end of each sub-phase. Fig. 5 gives the results.

We can observe that the throughput of STATIC is similar to that of HCAP, whereas the successfully transmitted flows of STATIC is less than half of that of HCAP. The successfully transmitted flows of both HCAP and HYBRID are similar. However, the throughputs of HYBRID are much less than that of HCAP. The results show that HCAP adapts better than STATIC to flows change, whereas it always achieves higher throughput than HYBRID.

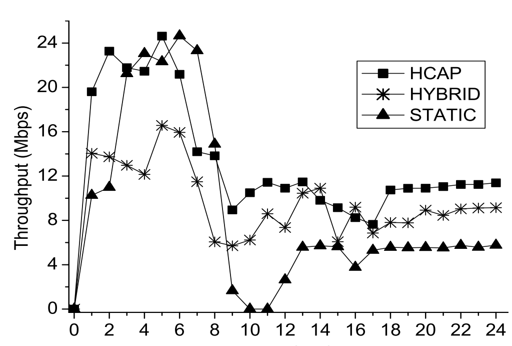


FIG. 4 Adaptation to flow changes

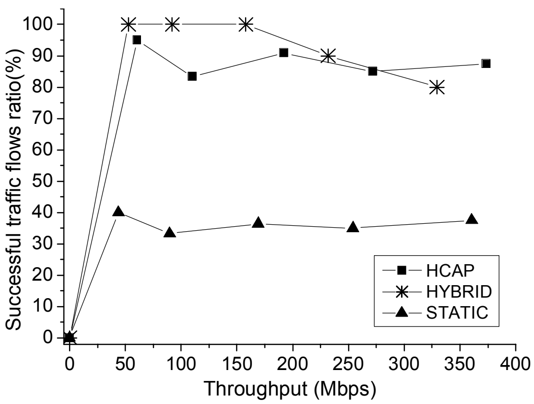


FIG. 5 Throughputs vs. traffic fairness

D. *Impact of Varying Broadcast Slot*

In previous simulations, we have assumed that all slots in each cycle should have the same size. In this part, we varied the period of broadcast slot to evaluate its effect on network throughputs. In these cases, all the other slots are set to 5ms, and the period of broadcast slot increases from 1ms to 10ms. The throughputs results of HCAP under different broadcast slot period are presented in Fig. 6.

The results show that broadcast slot period should be shorter than that of the other slots in order to achieve the highest throughputs. In this case, the throughput arrives at the peak point when the broadcast slot is about 2ms, which is about half of the other slots.

VI. CONCLUSIONS AND FUTURE WORKS

We proposed a hybrid channel assignment protocol to improve the capacity and flexibility of WMNs. The proposed protocol jointly solves the interface assignment, communication coordination and dependency problems. Our protocol does not depend on prior information on the traffic loads, whereas it can adapt automatically to the changes in the network. Extensive simulations show that the proposed protocol improves the network capacity and flexibility. It also achieves better per-flow fairness, whereas it keeps both interface switching overheads and coordination complexity under tolerable range. The protocol can be implemented easily using current hardware. Nevertheless, we do not discuss the complexity and the overheads of the proposed algorithms due to the limitation of space. As future work, we will provide analyses results and describe how to the algorithm in details.

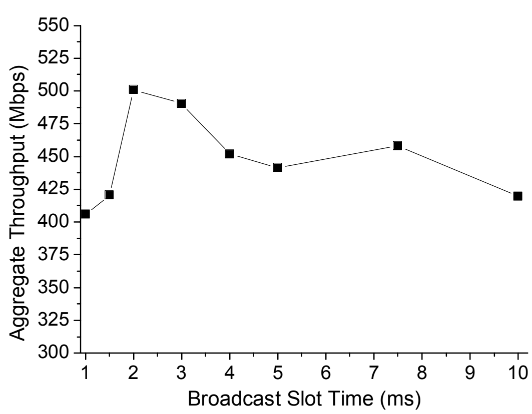


FIG. 6 Impact of broadcast slot

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