# Cognitive Greedy-Backhaul Routing Metric Exploiting Cross-layer Design for Wireless Ad Hoc and Mesh Networks

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***Abstract*—We propose a 'cognitive greedy-backhaul' (CGB) routing metric that associates routing with an appropriate channel assignment scheme to determine cognitive backhaul links. Those backhaul links are established in congested areas where higher capacities are required. CGB forces nodes to select those backhaul links which have higher capacities to reduce the relaying burdens that are caused by nodes hopping around in the network. CGB performance is compared with shortest-path (SH) and available capacity-aware routing (AC) metrics and simulation results show that the CGB routing metric can significantly improve end-to-end throughput by using those cognitive backhaul links.**

## I. INTRODUCTION

One of the most important features of wireless ad hoc networks is their decentralized character, with nodes that can function as routers, fulfilling not only their own traffic demands, but also forwarding the packets of others (relaying). This feature helps node transmissions to reach their destination through multi-hop relaying. It also places constraints on ad hoc networks, due to the competition for the limited wireless medium resources between relaying and originated traffic. The relaying burden on intermediate nodes has been considered as one of the main scalability constraints in wireless ad hoc networks [1].

In wireless ad hoc networks, the selection of suitable intermediate nodes for relaying traffic is crucial and will influence the future traffic demands. The traditional wireless ad hoc network routing metric is shortest path by number of hops (SH), which selects routes using the criterion of minimum hop count. This is the simplest routing metric. However, SH tends to cause congestion problems by leading traffic flows to specific locations. Another available capacity-aware routing metric (AC) [2] has been proposed to improve network capacity. By taking interference and capacity into account, AC can move routes from a congested area to one less crowded. However, the relaying burden rises due to an increased number of hops around the network.

Here, we introduce a cross-layer design 'cognitive greedy-backhaul (CGB) algorithm' by combining the routing metric with a channel assignment scheme to create cognitive backhaul links which can reduce the relaying burden and alleviate the bottleneck problem. Backhaul links are created in congested areas with higher capacity. Different from other routing metrics that exploit the spatial-temporal diversity to improve the spatial reuse/capacity of the network, CGB forces routes to go through nodes/links/areas with naturally important geographical locations. The associated links with high traffic demand can obtain more channels/capacity using an appropriate channel assignment scheme. Therefore, CGB can create cognitive backhaul links by exploring network conditions and traffic demand. This requires the routing metrics to exploit environment information sensed by nodes and adapt their weighting factors to indirectly improve the end-to-end performance of the whole network. Therefore it is worth mentioning the related concepts of cognitive radio and cognitive networks. A cognitive radio is a radio that can change its transmitter parameters to communicate efficiently to solve the conflict between the scarcity of frequency spectrum [3]. A cognitive network is a network that can perceive the current network conditions, and then plan, decide and act on those conditions to achieve the end-to-end goals [4]. Thus, we can refer to our routing metrics as cognitive routing [2], which combines the processes associated with cognitive radio and cognitive networks.

This paper is structured as follows. Section 2 outlines routing metric designs and the channel assignment schemes. In section 3, we introduce our network model. In addition, we compare the proposed cognitive greedy backhaul (CGB) routing metric, with shortest path by hops (SH) and available capacity-aware routing (AC) metrics by presenting simulation results in section 4. Finally, the conclusions are drawn in section 5.

## II. ROUTING METRIC DESIGN AND CHANNEL ASSIGNMENT SCHEME

In this section, we introduce our proposed routing metric: cognitive greedy-backhaul (CGB) first and show how CGB can select those backhaul links for relaying. To compare the performance of the proposed metric, we use a popular wireless ad-hoc routing metric, shortest path by hops (SH)/minimum hop count and the available capacity-aware routing metric (AC).

### *A.* ROUTING METRIC DESIGN

#### *1)* COGNITIVE GREEDY-BACKHAUL ROUTING

Earlier, we discussed one of the main constraints of wireless ad hoc networks, which is the relaying burden. Relaying burdens are created when more hops are used to try and avoid crowded links. Cognitive greedy-backhaul routing (CGB) aims to build backhaul links due to traffic demands and forces local traffic to go through those links instead of moving around them. By forwarding traffic through those higher

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capacity backhaul links, the relaying burdens and bottlenecks can be minimized.

There are three main steps to show how CGB works. Initially, CGB starts to function as shortest path by hops (SH). Based on the learning process of CGB, heavily used nodes/links can be distinguished. Then, backhaul links are established to fulfill the high traffic demand around the crowded nodes/links by using an appropriate channel assignment scheme. Finally, CGB reduces the weight value of backhaul links to reinforce local nodes to forward their traffic through those backhaul links with higher capacity. Some routing metric designs have been proposed to overcome the bottleneck problem by diverting around crowded areas such as a hotspot mitigation protocol (HMP) [5]. Those ideas of diverting around congested areas or bottleneck nodes/links create an increased relaying burden because of the longer distance/hops they require. This can also potentially create more bottlenecks and congested areas. CGB forwards nodes with a high utilization channel level (number of channels occupied). Here the link weight of CGB is defined as:

$$w_{ij} = \left\{ \begin{array}{l} \frac{1}{U_j}, U_j < |P| \\ \frac{1}{|P|}, U_j \geq |P| \end{array} \right. , \forall i, j \in V \quad \textbf{(1)}$$

Where $U_j$ is the utilization channel level, which is the number of channels that have been assigned to node *j*. *P* and |*P*| are the set that contains the channels, and the number of channels that can be used in the network, respectively. CGB prefers to pick nodes/links which have more occupied channels. This means the higher the utilization of a node/link, the more likely it is that CGB will select it for future traffic flows, thus cognitive backhaul links are established. If all of the channels have been assigned to node *j*, the weight of node *j* stays at a minimum value, which is *1/*|*P*|.

CGB builds cognitive backhaul links by exploring the traffic conditions and important geographic location of nodes; it can occupy more channels, delivering higher capacity where a high level of traffic is required. Therefore the bottleneck problem is reduced by using a backhaul which can obtain more capacity if needed. In addition, traffic flows become concentrated on those backhaul links; interference is thus limited to regions nearby those links rather than the whole network.

### *2)* SHORTEST PATH BY HOPS (SH)

We introduce traditional shortest path routing here as a reference with which to compare the novel routing metric design. To find the shortest path route in terms of hop count, the route weight through a link can be defined as:

$$w_{ij} = 1, \forall i, j \in V \quad \textbf{(2)}$$

Where $w_{ij}$ denotes the weight associated with transmitting on the link from node *i* to node *j*. *V* is the set of nodes. This routing scheme is often known as the 'hop count', and is the most commonly used routing metric in existing routing protocols.

### *3)* AVAILABLE CAPACITY-AWARE ROUTING

In heterogeneous networks, nodes have different transmission rates, transmit powers and antenna gains. Traditional ad hoc routing metrics, like shortest path, cannot take these different link capacities into account. Higher capacity links might remain unused and lower capacity links might end up being crowded. As a result, it is crucial for an ad hoc network to relay more traffic through the higher capacity links to improve load balancing avoid creating bottlenecks.

We have highlighted that the constraint of an ad hoc network is the scalability. It is desirable to the divert traffic from a lower capacity node to those which are more capable to relay. The available capacity-aware routing algorithm is based on the maximization of the accumulated impact available capacity has on multi-hop communication. Capacity is determined by active traffic interactions (intra-flow and inter-flow interference), available capacity-aware routing (AC) can divert the upcoming traffic to an uncongested area in order to make the whole network more scalable. The link weight is defined by [2]:

$$w_{ij} = \frac{1}{C_{a\_j}}, \forall i, j \in V \quad \textbf{(3)}$$

Where $C_{a\_j}$ is the available capacity of node j which has been introduced in section III.

## *B.* CHANNEL ASSIGNMENT SCHEME

To illustrate the benefits of using the cognitive greedy-backhaul algorithm, the network needs to operate in a multi-channel environment. Therefore we introduce the two channel assignment schemes here.

The cognitive greedy-backhaul routing metric has the ability to force traffic flows to form concentrated backhaul links. In order to reduce the bottleneck problem, we need to consider the cross-layer design and assign more channels (capacity) to the backhaul links as needed. Due to the focus on routing metric design in this paper, we therefore introduce two relatively basic channel assignment schemes for the benefit of illustrating our routing metric designs. To simplify the channel assignment scheme in this paper, the same channel is assigned to an entire end-to-end traffic flow. In other words, assuming an appropriate channel assignment scheme is used and there are sufficient channels, we only need to consider the intra-flow rather than inter-flow interference and resource sharing. In the case where there are insufficient channels for this to occur, capacities are equally divided by intra-flow and inter-flow interference. The point of illustrating these two channel assignment schemes is to show the cognitive greedy-backhaul routing metric can cope better with a better channel assignment scheme than a poor one.

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### *1)* RANDOM SCHEME

A random channel assignment scheme assigns channels from a spectrum pool randomly to a new traffic flow without considering spatial reuse and fairness. We assign a random channel $x_i \in \{1,2,3,..,p\}$ to each new end-to-end traffic flow, where $p$ is the number of channels available in the network.

### *2)* QUASI-FAIR SCEHME

The quasi-fair channel assignment scheme assigns channels from a spectrum pool corresponding to current channel utilization in the network. The least utilized value ($u_p$) channels are selected for new traffic flows that arrive in the network rather than using the channels that have already been allocated to the existing traffic flows. Each source node sends HELLO packets that include the channel it occupies periodically on all channels. Nodes receive the HELLO packets from source nodes and can determine the utilized value of each channel and make a decision of which channel is assigned in the link layer. For example, if there are 3 channels ($x_i \in \{1,2,3\}$) available and 5 concurrent traffic flows in the network. If channels 1, 2 and 3 are assigned to traffic flows twice ($u_1 = 2$), twice ($u_2 = 2$) and once ($u_3 = 1$) respectively, then channel 3 will be allocated to the 6th concurrent traffic flow. This is because $u_3$ is the lowest utilized value compared with other channels. The quasi-fair scheme is more ‘cognitive’ than the random scheme due to the fairness it embeds into the network, which it achieves by considering the current network conditions.

## III. NETWORK MODEL

In this section, we introduce our network model which includes the main performance factors: end-to-end throughput and available capacity. Finally, our simulation results are shown.

### *A.* CAPACITY AND THROUGHPUT

Link capacity is influenced by a number of factors, such as: power level of the transmitter, distance between the nodes, the medium where it operates, the spectrum that is available for the transmission, the noise floor, intra-flow and inter-flow interference. We use a multi-channel model to examine how well the greedy routing metric can cope in a realistic network scenario. The available capacity ($C_a$) is determined by the summation of the remaining capacity ($C_r$) on each channel. We assume nodes have the same transmit power, therefore the remaining capacity ($C_r$) of channel $k$ for the objective node $j$ is only defined by the intra-flow and inter-flow interference on channel $k$ within the interference range of node $j$ and maximum channel capacity ($C_{k\_max}$) as:

$$C_{r,j\_k} = \frac{C_{k\_\max}}{CL_{j\_k}+1}, \forall j \in V, \forall k \in P \quad \textbf{(4)}$$

Where $V$ and $P$ are the set of nodes and channels in the network respectively. $C_{k\_max}$ is the maximum capacity that can be achieved by channel $k$, which is 20 Mbit/s in this paper for all channels. $CL_{j\_k}$ is the congestion level of node $j$ on channel $k$.

The congestion level of node $j$ on channel $k$ is defined as [2]:

$$CL_{j\_k} = \sum_{i\_j=0}^{NI_j} R_{i\_j}, \forall j \in V \quad \textbf{(5)}$$

Where $NI_j$ is the number of nodes within the interference range of node $j$, $R_{i\_j}$ is the number of routes going through node $i\_j$, which is one of the interferers of node $j$, using channel $k$. $R_{0\_j}$ indicates the number of routes going through the object node itself. For example, we can see from figure 1 that the congestion level of objective node ($N_0$) by using channel 3 is 6 active links which includes all intra-flow and inter-flow interference. This indicates that each activated link which uses the same channel shares the same amount of bandwidth to fulfill their transmission.

The available capacity of node $j$ is defined as:

$$C_{a\_j} = \sum_{r\_j=1}^{|P|} C_{r\_j}, \forall j \in V \quad \textbf{(6)}$$

Where $|P|$ is the number of channels that can be used for the network, $C_{r\_j}$ is the remaining capacity of node $j$ by using channel $r\_j$ which is one of channels in the network. In figure 1, there are three channels in the network. The remaining capacities of the node $N_0$ for channel 1, 2 and 3 are 5 Mbps, 4 Mbps and 2.5 Mbps respectively. Thus the remaining capacity of node ($N_0$) is 11.5 Mbps. This implies that the route has to share the bandwidth not only with routes going through the node of interest, but also with the routes going through the interferers of the objective node.

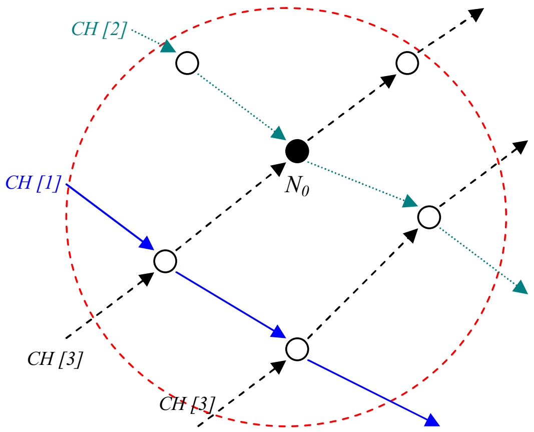

Figure 1 Example of traffic flows through the network

The throughput of node $j$ is defined as:

$$S_j = \eta \sum_{ch\_k=1}^{NC} \frac{C_{ch\_k,\max}}{CL_{ch\_k}+1}, \forall j \in V \quad \textbf{(7)}$$

Where $\eta$ is a MAC efficiency factor; $NC$ is the number of channels that have been utilised by node $j$; $C_{ch\_k,max}$ is the

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maximum capacity of channel *ch_k* and $CL_{ch\_k}$ is the congestion level of node j on channel *ch_k*.

End-to-end bottleneck throughput is our main way to evaluate performance of the combined routing metrics and channel assignment schemes. It is constrained by the minimum throughput value along the path, i.e. it occurs when the upstream node of the bottleneck node injects more packets into the link than the bottleneck node can forward. End-to-end delay increases as packets get stuck at the bottleneck and the throughput reduces as these packets are eventually blocked by the congested node.

### *B.* NETWORK MODEL

In this paper, we focus our modelling on a wireless mesh network (WMN) where the mobility of nodes and energy are less of a concern. The aforementioned routing metrics will be examined in a randomly located node environment. There are 99 source nodes and 1 quasi-random sink node which is located randomly in the middle of the network constrained by a circle located on the network centre. The key parameters are shown in Table 1. This is a fully connected scenario. We assume routes do not change during their life-time once they are established. This is convenient for nodes to sense the states of the network and to reduce the route oscillation problem [6] .

All traffic originates at source nodes. Each source node generates 5 route connections and those connections follow an exponential start and stop distribution. The routing metrics are examined on a time event basis. An event occurs when an end-to-end flow is established or deactivated in the network.

| **Key parameters** | **Value** |
|---|---|
| Network size | 40 × 40 $m^2$ |
| Number of nodes | 100 |
| Number of source nodes | 99 |
| Number of sink node | 1 |
| Node's transmission range | 7 m |
| Node's interference range | 14 m |
| Maximum channel capacity | 20Mbps |
| Mean duration of each connection per source node | 0.2 seconds |
| Interarrival distribution range per source node | 0.25 to 6 arrivals/second |

Table 1. Parameter values used in the example scenario

## IV. SIMULATION RESULTS

In this section, we examine the effectiveness of the different routing mechanisms proposed. We assume a perfect MAC which has an efficiency factor of 1 in the equation (7). Figure 2 shows the cumulative distribution function of the average maximum number of channels per flow at an offered traffic of 20 Erlangs using different routing metrics and channel assignment scheme. There are 10 channels available in the network. Here, 1 Erlang refers to one end-to-end traffic flow operating continuously in the network. From figure 2, shortest path by hops ($SH_{QF}$) and available capacity-aware routing ($AC_{QF}$) of using quasi-fair channel assignment scheme both have 45% of total traffic through maximum number of 9 channels per flow. This amount of traffic is gathered to congested links due to their important locations. Comparing with $SH_{QF}$ and $AC_{QF}$, we can see that there are about 72% of total flows which have maximum number of channels greater than 9 on an end-to-end basis by using cognitive greedy-backhaul routing metric associated with quasi-fair channel assignment scheme ($CGB_{QF}$). This additional 27% of total traffic flows are encouraged to go through cognitive backhaul links by using $CGB_{QF}$. In section 2, we showed that link weight of CGB is determined by the number of channels assigned to it. The more channels allocated to a link, the lower the weight associated with it. The advantage of using CGB is to encourage local traffic to go through nearby backhaul links in a more concentrated rather than a distributed manner, which can reduce total interference and relaying burdens caused by the increased number of hops through the network.

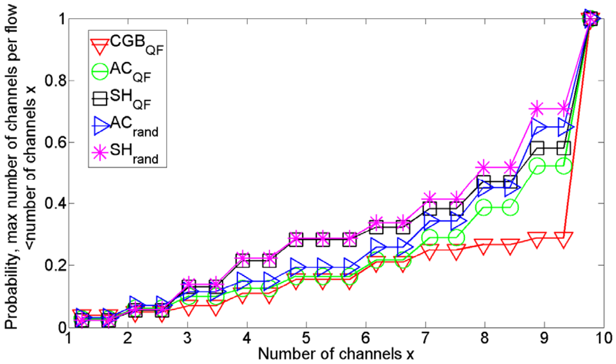

Figure 2 Mean end-to-end bottleneck throughput versus snapshot

Figures 3 and 4 illustrate the end-to-end bottleneck throughput versus different offered traffic levels and number of channels respectively. In figure 3, there are 3 channels available in the network and we can see that the channel assignment scheme plays a significant role for the end-to-end bottleneck throughput at a low level of offered traffic. Due to the intra-flow, inter-flow interference and the limited number of channels available in the network, it is reasonable that bottleneck throughput value keeps low. In figure 3 where offered traffic is quite low, the cognitive greedy backhaul (CGB), available capacity-aware (AC) and shortest path by hops routing metrics have similar end-to-end throughput using the same channel assignment scheme. This is because channel capacities are adequate to accomplish the traffic demand without causing too many bottleneck links. The disadvantage of using the random channel assignment scheme by routing metrics AC and SH (referred to $AC_{rand}$ and $SH_{rand}$ respectively) is that it does not have any knowledge of current network conditions. The same channel can be assigned to routes within a close distance which results interference to each other. End-to-end bottleneck throughput cannot show the great advantage of using different routing metrics due to the limited resources, which is the number of channels available in the network at the higher level of offered traffic. However, $CGB_{QF}$ improves

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the end-to-end bottleneck throughput by around 25% compared with $SH_{rand}$ at offered traffic of 4 Erlangs. Although the MAC layer design is the main factor to improve the network performance (e.g. throughput), it encourages the use of better routing metrics associated with MAC design to maximize network performance.

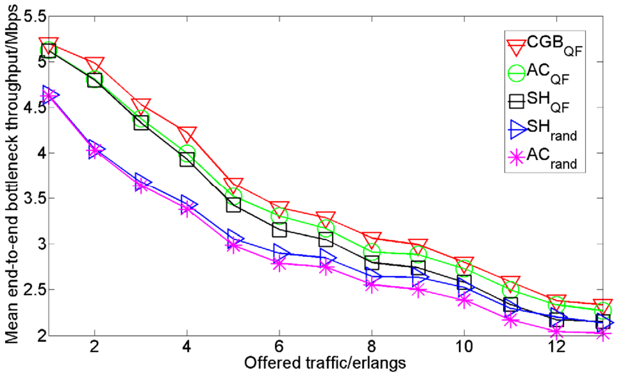

Figure 3 Mean end-to-end bottleneck throughput versus offered traffic

Figure 4 shows the dramatic difference between the different channel assignment schemes as a function of the number of channels. $AC_{QF}$ selects routes to maximise the total end-to-end capacity value. This can increase relaying burden by hopping around to find the high capacity links/nodes. Due to the lack of cognition of the network environment, $SH_{QF}$ selects routes depending on their location and can potentially create bottlenecks. $CGB_{QF}$ reduces the relaying burden by routing traffic flows through common cognitive backhaul links and as traffic is forced to flow through those backhaul links, ensuring that interference is limited to the backhaul areas. The rest of the nodes in the network can therefore fulfill future traffic demands by minimising interference around them.

Although this paper has focused on the network layer rather than the MAC layer design, due to the cross-layer design concept of the cognitive greedy-backhaul routing metric, CGB benefits from an appropriate channel assignment scheme. The main concept of CGB is to occupy more channels for the links which have the potential to become bottlenecks due to their geographical importance in order to create backhaul links. In figure 4, we can see that CGB has a trend to perform better at end-to-end bottleneck throughput compared with others as the number of channels is increased. The end-to-end bottleneck throughput increases by about 30% by using $CGB_{QF}$ compared with $SH_{rand}$. This is because backhaul links are more likely to be generated by obtaining available channels in the network, since as the number of available channels increases, the capacity of the backhaul links is enhanced.

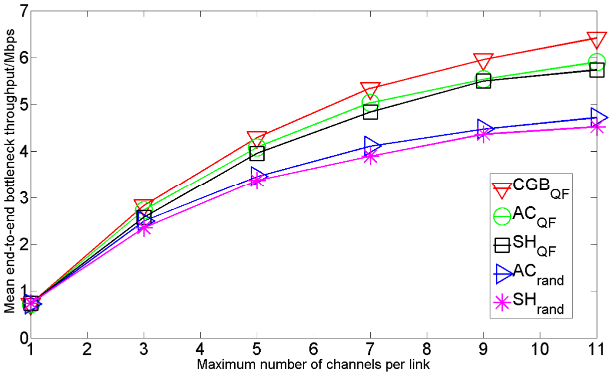

Figure 4 Mean end-to-end bottleneck throughput versus maximum number of channels per link

## V. CONCLUSIONS

We proposed a cognitive greedy-backhaul routing metric which is associated with a channel assignment scheme to build backhaul links with higher capacity and enhance local nodes to forward their traffic through those links. Our simulation results show the benefit of using a cognitive greedy-backhaul routing (CGB) metric associated with quasi-fair channel assignment. End-to-end bottleneck throughput can be improved by up to 30% by compared with shortest path (SH) with a random channel assignment scheme. This cross-layer routing metric design collaborates with the channel assignment scheme which can sense the current network conditions and create cognitive backhaul links. This approach reduces the network relaying burden and interference.

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