A New Channel Assignment Mechanism for Rural Wireless Mesh Networks

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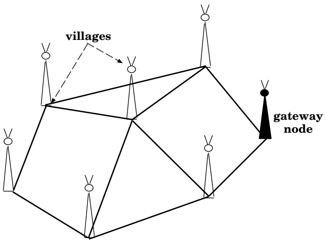

Fig. 1. A rural wireless mesh network.

***Abstract*— In this paper we present a new channel allocation scheme for IEEE 802.11 based mesh networks with point-to-point links, designed for rural areas. Our channel allocation scheme allows continuous full-duplex data transfer on every link in the network. Moreover, we do not require any synchronization across the links as the channel assignment prevents cross link interference. Our approach is simple. We consider any link in the network as made up of two directed edges. To each directed edge at a node, we assign a non-interfering IEEE 802.11 channel so that the set of channels assigned to the outgoing edges is disjoint from channels assigned to the incoming edges. Evaluation of this scheme in a testbed demonstrate throughput gains of between $50-100\%$, and significantly less end-to-end delays, over existing link scheduling/channel allocation protocols (such as 2P [11]) designed for point-to-point mesh networks.**

Formally speaking, this channel allocation scheme is equivalent to an edge-coloring problem, that we call the *Directed Edge Coloring (DEC)* problem. We establish a relationship between this coloring problem and the classical vertex coloring problem, and thus, show that this problem is NP-hard. More precisely, we give an algorithm that, given k vertex coloring of a graph can directed edge color it using $\xi(k)$ colors, where $\xi(k)$ is the smallest integer n such that $\binom{n}{\lfloor n/2 \rfloor} \geq k$.

I. INTRODUCTION

There has been considerable recent interest [1], [3], [4], [6], [8]–[13] in the design of long-distance mesh networks for rural areas, using IEEE 802.11 (WiFi) equipment. Rural areas (especially in developing regions) have populations with low paying capacity. Hence, a major factor in network deployment is the cost of network infrastructure. IEEE 802.11 equipment is highly commoditised and inexpensive (as compared to traditional cellular and wireline networks), and is thus an attractive option for building data networks in rural areas.

(a) (b)

Fig. 2. a) Mix-Rx-Rx interference across links. b) Channel allocation along directed edges to avoid Mix-Rx-Tx interference

A typical rural mesh network, as illustrated in Figure 1, would consist of a cluster of villages connected with each other through point-to-point wireless links. A special node in this mesh (called a *gateway* node) is connected to the wired internet, and other mesh nodes connect to the gateway node (and the rest of the internet) through one or more hops in the mesh. Rural mesh networks are characterized by a *static topology* (a node in this network will be a village) and very *long distance, point-to-point* links between the nodes (about 10-15kms).

The 802.11 MAC was originally designed for (and widely deployed in) short-distance campus area networks with dynamic/mobile nodes. However, as the authors of [11] have demonstrated, by using high-gain directional/sectoral antennas, ensuring line-of-sight, and by appropriately setting certain MAC level timers (such as ACK timeouts), a long distance (> 25 kms.) link with good throughput can be established.

A primary concern in the operation of such a network is interference across the links. As mentioned earlier, nodes in our mesh network will communicate with each other using directional antennas. While directional antennas are designed to transmit and receive in a specific direction, the directionality of this radiation becomes effective only at longer distances from the sender. This is also called the *near field effect.* As a result, there is considerable leaked radiation (side lobes) within a short area from the antenna. Due to this (as shown in Figure 2(a)), at any node, simultaneous transmissions and receptions on the *same channel* are not possible since the transmissions will interfere with the receptions. This is called Mix-Rx-Tx interference.

Another observation (as pointed out in [11]) is that while

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Mix-Rx-Tx interference prevents simultaneous transmission and reception at a node, a node can synchronously transmit (or synchronously receive) on all its adjacent links without any Mix-Rx-Tx interference. This is called SynTx (or SynRx). In a recent work, Raman et al. [11] have proposed the *2P* MAC protocol based on this observation. The protocol operates on graphs by switching each node between two phases: SynRx and SynTx. When a node switches from SynRx to SynTx, its neighbors switch from SynTx to SynRx, and vice versa. The 2P protocol has a desirable property that the link is always active in one direction or the other.

However, the 2P protocol has several drawbacks. Firstly, the algorithm imposes a constraint that all links at a node remain active in a given direction for the same amount of time. This may result in reduced throughput since the routing protocol running on the network may require the links to be active for different durations for different links. Secondly, when a node is in the Rx phase, data at the node that has to be transmitted needs to be buffered. This can considerably increase the end-to-end delay of sending data across multiple hops. Thirdly, the protocol requires each node to synchronize with its neighbors before it can switch phases through the exchange of tokens. This requires changes in the IEEE 802.11 MAC. Also, it adds to the delay and overhead of the protocol. And, as [12] have found through empirical studies, in case tokens are lost, the protocol wastes time to re-synchronize all the nodes.

In this work we propose a channel allocation scheme for the edges in a point-to-point mesh, that allows all edges at a node to 1) operate independently of each other, with *no synchronization* required 2) do *full-duplex* data transfer at all times, i.e. a node can be simultaneously transmitting and receiving on all its links. Thus our channel allocation ensures significantly higher link bandwidths as compared to 2P (since all links operate in full-duplex mode) and significantly reduced end-to-end delays. Moreover, it achieves this with no changes in the 802.11 MAC and gets rid of any need for nodes to synchronize with each other.

Our approach is simple. We consider any link in the network graph to consist of two directed edges (in opposite directions). As shown in Figure 2(b)), to each directed edge we assign a non-interfering IEEE 802.11 channel[1], in such a manner that at any node, the set of channels on the outgoing directed edges is different from the channels on the incoming edges. Thus, a node can be simultaneously transmitting on a set of channels on its outgoing edges, and receiving on a set of channels on its incoming edges. Since no outgoing and incoming edges share a common channel, there is no risk of Mix-Rx-Tx interference.

Experimental evaluation of this channel allocation scheme in an outdoor test bed demonstrate the feasibility and benefits of this scheme. Our measurements demonstrate that this channel allocation scheme allows link data transfer rates that are twice of what is achieved when using the 2P protocol. Moreover, this channel allocation scheme considerably reduces end-to-end delays in a mesh network as compared to the 2P protocol.

We also propose an algorithm that achieves a channel allocation with the above properties on all nodes of the given graph. Formally, we are given a graph G with bi-directional edges for every link. We are required to allocate a channel to each edge (or equivalently color the edge) such that for each node in the graph, the set of colors assigned to its incoming edges is disjoint from the set of colors assigned to its outgoing edges. We call this the *directed edge coloring* (*DEC*) problem, and the minimum number of colors required the *directed edge coloring number* (*DEC number*) of the graph. If a graph has a directed edge coloring using at most k colors, then the graph is said to be *k-DECable*.

A naive way to directed edge color a bidirectional graph G is as follows. Vertex color the corresponding undirected graph G', say using k colors.[2] Now color every out-going edge of a node in G with the color of that node in G'. As no two adjacent nodes have the same color in G', it is easy to see that for any node in G, no out-going edge has the same color as an incoming edge. Thus, we have obtained a directed edge coloring of G using k colors.

An important contribution of our work is to present a simple directed edge coloring algorithm that substantially improves over this naive algorithm. Given a vertex-coloring of an undirected graph using k colors, we give a directed edge coloring of the corresponding bidirectional graph using n colors, where n is the smallest integer such that $\binom{n}{\lfloor \frac{n}{2} \rfloor} \geq k$. How does this approach compare to the naive algorithm described above? In the extended version of this paper [7], we show that such an n is at most $2 \log k$,[3] which gives an exponential improvement over the naive algorithm. We also show that our algorithm is optimal in the sense that, if the chromatic number of a graph is χ, then its DEC number is n where n is the smallest integer such that $\binom{n}{\lfloor \frac{n}{2} \rfloor} \geq \chi$. We refer the reader to [7] for further details.

Thus, if we have 3 available channels (as in IEEE 802.11b and g), then our algorithm can cover (i.e., directed edge color) all graphs that are $\binom{3}{1} = 3$ vertex colorable. These graphs, amongst others, include all bi-partite graphs (and so, all trees). As has been pointed out in [5], it is possible to squeeze out an extra non-interfering channel from IEEE 802.11b and g radios. In this case, we can can cover all graphs that are $\binom{4}{2} = 6$ vertex colorable. This covers a large family of graphs, including all planar graphs, and those with a maximum degree of 5. Needless to say, the class of network graphs that are directed edge colorable with the number of channels available

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[1] IEEE 802.11 allows a radio to be set to one of several non-interfering channels. The IEEE 802.11a version has 12 such non-interfering channels, while 802.11b and 802.11g have 3.

[2] Given a bidirectional graph G, we obtain the corresponding undirected graph G' by replacing each pair of opposite directed edges by a single undirected edge. A *vertex coloring* of a graph assigns a color to each vertex such that no two adjacent vertices have the same color. The smallest number of colors needed to color the graph is called its *chromatic number*. In context of coloring, we use the bidirectional graph and its corresponding undirected graph interchangeably—directed edge coloring refers to the bidirectional graph and vertex coloring refers to the undirected graph.

[3] Unless otherwise mentioned, throughout this paper we use base 2 logarithms.

in IEEE 802.11a (12 non-interfering channels) and in IEEE 802.16 WiMAX networks (that allow a flexible number of non-interfering (sub-)channels) will include most practical network deployments.

II. EXPERIMENTAL VALIDATION OF BI-DIRECTIONAL DATA TRANSFER

In this section, through extensive experiments in an out-door long-distance test bed we demonstrate the feasibility of our channel allocation scheme. As mentioned earlier, a link between any two nodes can be considered as made up of two directed edges in opposite directions. Our goal is to enable full-duplex data transfer on all links incident on a node, simultaneously. In our scheme, any two edges in opposite directions are assigned different non-interfering channels. Our main practical concern is that the cross channel interference across these edges could considerably diminish the bandwidth gains possible in theory, due to full duplex data transfer over the links.

In the remaining part of this section we will describe an out-door, long-distance testbed on which we evaluate the channel allocation scheme. We will describe the equipment and the configuration of the test bed, and then we will present measurement results to demonstrate the feasibility of our channel allocation mechanism.

A. Description of experimental test bed

Our test bed is made up of long distance wireless links that connect 3 Alcatel-Lucent office locations in Bangalore, India. We refer to these locations as ST1, ST3 and GVC, as shown in Figure 3. The distance between the ST1 and ST3 nodes is relatively small - 250 meters, however the distance between ST1 and GVC is 4.7 Kms.

Communication between these links is established using inexpensive off-the-shelf WiFi cards. For our experiments, we used the Prism2 chipset based Senao NL-2511CD plus ext2 PCMCIA cards which support the IEEE 802.11b standard. These cards have an external antenna connector, to which a low-loss RF antenna cable is connected through a pigtail. To make the signals go long-distances, we employ high gain parabolic grid directional antennas, specifically, 24 dBi Andrew make antennas with an 8 degree beam width. Also, we require line of sight to be maintained across the link. Fortunately (considering the dense urban environment of Bangalore), all of the locations are multi-storied buildings. The antenna in ST3 is on top of a five storied-building, in ST1 it is mounted on a 40 feet tall tower on top of a seven storied building, and in GVC on top of a six storied building. The angular separation between the two links is 34 degrees.

The WiFi cards are housed in Linux based PCs and laptops. We use the open source HostAP wireless driver. Using the HostAP driver, we can configure some crucial parameters of the cards. These are a) *Tx rate* or the transmit rate. This is set to 11Mbps, the maximum possible in 802.11b. b) *Tx power*, the transmit power. The minimum SIR value required at the receiver to support 11Mbps data rate (i.e. with a negligible BER value $< 10^{-6}$) is around $10-12$ dB. We set the transmit power values near the minimum required (varies between 0-6dBm across links) so that the SIR value at the receiver is greater than this required value.

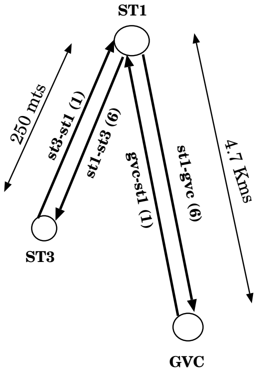

Fig. 3. Depiction of the outdoor testbed (not to scale), and channel assignment on the directed edges.

Next we allocate channels on the links in accordance with our scheme. The outgoing edges on the node ST1, namely *st1-gvc* and *st1-st3* are assigned channel 6, while the incoming edges, *gvc-st1* and *st3-st1* are assigned channel 1. Thus the set of channels on the outgoing edges are different from the incoming edges.

Now, node ST1 has two edges transmitting on the same channel (SynTx) and two edges receiving on the same channel (SynRx). For such simultaneous transmission or reception to be possible (on the same channel) on adjacent links, we need to a) turn off MAC level immediate ACKs, and b) prevent carrier sense based back-off implemented in the hardware. We implement this using the approach suggested in [11] and we refer the reader to that paper for further details.

We use the UDP saturation bandwidth as a measure of the data rate possible on these links. Using the *iperf* [2] tool we sent 1470 byte UDP packets at the rate of $7.5-8$Mbps from the transmitter. This rate is a little more than the peak goodput possible with a 1470 byte payload on an 802.11b link. For one measurement experiment, we transmit continuously for 60 seconds, and then report the data rate measured at the receiver over this period.

B. Measurement results

We carry out three different kind of measurement experiments (i.e. 60 secs burst of UDP traffic, as described above). These are a) M_1: in this experiment a data transfer occurs on only one directed edge and no other edges are active. This measures the achievable bandwidth of each directed edge when operating alone. b) M_2: in this experiment, the two directed edges of a link are active simultaneously, and only one link is active. This measures the throughput on a link when full-duplex data transfer is going on. c) M_3 all directed edges of both the links are active simultaneously. This measures the throughput when full-duplex data transfer is active simultaneously on more than one adjacent link.

	ST1-GVC			*GVC-ST1*			*ST3-ST1*			*ST1-ST3*		
Run	M_1	M_2	M_3	M_1	M_2	M_3	M_1	M_2	M_3	M_1	M_2	M_3
1	6.22	5.56	4.36	6.06	5.94	5.32	7.18	6.67	6.81	7.19	7.19	6.28
2	6.33	4.96	4.30	6.23	6.35	5.86	7.05	6.74	6.88	7.24	7.24	5.61
3	6.35	5.33	4.15	6.35	6.17	5.37	7.19	6.72	6.87	7.24	7.24	5.69
4	6.23	4.98	3.89	6.21	6.17	5.37	7.19	7.19	7.19	6.81	6.95	6.20
5	6.20	5.04	3.83	6.15	6.16	5.46	7.19	7.19	7.18	6.82	6.94	6.16
6	6.36	5.31	3.96	6.29	6.29	6.29	7.16	7.16	7.15	6.90	6.96	6.26
7	5.59	5.64	4.10	6.31	6.30	5.66	7.16	6.65	6.73	7.26	7.18	6.48
8	5.72	5.62	4.10	6.10	6.05	5.63	7.15	6.61	6.67	7.23	7.20	6.16

TABLE I

MEAN (OVER 50 RUNS) UDP SATURATION THROUGHPUT OF M1 (EACH DIRECTIONAL EDGE OPERATING ALONE), M2 (BOTH DIRECTIONS OF ONE LINK OPERATING TOGETHER) AND M3 (ALL EDGES OPERATING TOGETHER) OVER 8 EXPERIMENTAL RUNS

In one experimental run, we carry out M_1, M_2 and M_3 (one after the other, as a group) 50 times, at intervals of 15 mins. We did 8 such experimental runs, spread over several days in March and May, 2007.

Table I lists the results from these experiments. For each directed edge, over each experimental run, we list the mean over 50 runs of M_1, M_2 and M_3.

We observe that for three of the directed edges, *gvc-st1, st3-st1, st1-st3* the impact of cross channel interference across the links on the achieved throughput is limited. The reduction in the throughput from M_1 (when the edge is operating alone) to M_3 (when all edges are operating simultaneously) is in most cases less than $10-15\%$ (and around 20% in a couple of cases). However, for one edge *st1-gvc* the reduction in throughput from M_1 to M_3 is around $30-35\%$[4]. Also, the total throughput of any link (summed over both edges) ranges from $9.5-13.5$Mbps. This is nearly $50-100\%$ more than the throughput achieved by the 2P protocol on a single link (as reported in [11]).

In our experimental testbed, we have also empirically measured the 2-hop end-to-end delay (the sum of queueing and propagation delays) between GVC and ST3 (via ST1). We have found this delay to be much smaller than the expected worst case delay if the network had implemented the 2P protocol. For more details we refer the reader to [7].

The above numbers are encouraging and demonstrate not only the feasibility of our channel allocation scheme but also bring out the significant gains that are possible compared to existing approaches. Next, we look into algorithms to achieve the above channel allocation over links in any given graph.

III. PROBLEM FORMULATION

In this section, we formulate the problem of assigning channels to links in the mesh network on which our proposed bi-directional protocol will operate. Since each physical link shall be used for information transmission in both directions using different channels, we model the network links as bi-directional edges in the network graph. The problem of assigning channels can now be interpreted as a directed edge coloring problem where each channel corresponds to a color. Clearly, to avoid Mix-Rx-Tx at any node, no overlap is allowed between the set of channels being assigned to the incoming links at any node with the set of channels being assigned to the outgoing links. We would like to minimize the number of channels used for communication in the network under this constraint. We frame this channel allocation problem in terms of edge coloring, and call it the *minimum directed edge coloring problem* (or DEC, in short). The problem is defined as follows.

Minimum Directed Edge Coloring Problem. *Let* $G_d = (V, E_d)$ *be a bi-directional graph, i.e.* $(u,v) \in E_d$ *if and only if* $(v,u) \in E_d$*. Further, assume that* $\Psi = \{1, 2, \ldots, \gamma\}$ *represents the set of available colors. A directed edge coloring of* G_d *is a function* $col : E_d \rightarrow \Psi$ *such that the following constraint is satisfied: for any vertex* v*, the set of colors assigned to its incoming links,* $In(v) = \{col(u,v) : (u,v) \in E_d\}$ *is disjoint from the set of colors assigned to its outgoing links,* $Out(v) = \{col(v,u) : (v,u) \in E_d\}$*. In other words,* $In(v) \cap Out(v) = \emptyset, \forall v \in V$*. The minimum directed edge coloring problem seeks to output a directed edge coloring of the input bi-directional graph* G_d *such that the number of colors used,* γ *is minimized.*

The minimum value of γ for which a directed edge coloring exists for a bi-directional graph G_d is called its *directed edge chromatic number* (or, DEC number, in short). If a graph has a directed edge coloring using k colors, then it is said to be *k-DECable*.

For ease of presentation we introduce the following definitions. Given an undirected graph $G = (V, E)$, the *corresponding bi-directional graph* $G_d = (V_d, E_d)$ is the directed graph such that, $V_d = V$, and for every undirected edge $(u,v) \in E$ ($u, v \in V$), there are two directed edges (u,v) and (v,u) in E_d. For the bi-directional graph G_d we say that G is the corresponding undirected graph.

IV. A SIMPLE DIRECTED EDGE COLORING ALGORITHM

Let $G_d = (V, E_d)$ be the input bidirectional graph and $G = (V, E)$ be the corresponding undirected graph. We use a vertex coloring algorithm as a black-box sub-routine in our algorithm. Suppose this vertex coloring algorithm returns a

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[4] We are looking into the reasons why this link under performs. Our conjectures are: 1) We are unable to completely eliminate CSMA induced back-off during synchronous transmissions on node ST1 2) High level of external RF pollution on the ST1-GVC link.

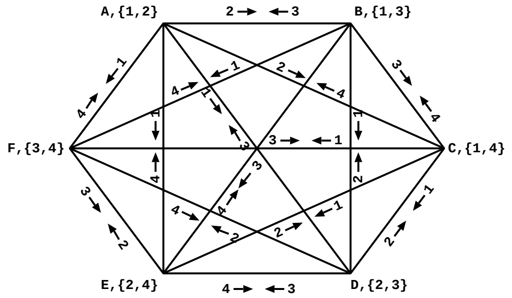

Fig. 4. 4-directed edge coloring a complete graph on six nodes.

vertex coloring of G using k colors. We define a function $\xi : Z^+ \rightarrow Z^+$ (where Z^+ is the set of positive integers). $\xi(i)$ is the smallest integer n such that $\binom{n}{\lfloor \frac{n}{2} \rfloor} \geq i$. We now give an algorithm to directed edge color G_d using $\xi(k)$ colors.

We group the nodes into k disjoint node-sets according to their vertex color. To each node-set, we assign a distinct subset of $\{i : i \leq \xi(k), i \in Z^+\}$ of size $\lfloor \frac{\xi(k)}{2} \rfloor$, which we call its edge-color-set. (Since the edge-color-sets are of the same size but distinct, no edge-color-set is completely contained in another.) Definition of $\xi(k)$ ensures that there are enough edge-color-sets for all k node-sets. Now consider an arbitrary (directed) edge $e \in E_d$. From the definition of vertex coloring, we know that the endpoints of e are in different node-sets. Suppose e is an edge from node-set X to node-set Y. We color edge e using any color in the edge-color-set of X that is not in the edge-color-set of Y. There is always such a color, because no edge-color-set is completely contained in another, and each node-set is assigned a distinct edge-color-set. Clearly, this scheme ensures that no outgoing edge of a node has the same color as an incoming edge.

Figure 4 shows a possible directed edge coloring of a complete graph on six nodes obtained using our algorithm. Vertex coloring the graph needs $k = 6$ colors, say $A, \ldots, F$ (where each node-set contains a single node). Thus, for our DEC algorithm, we need $\xi(6) = 4$ edge colors. We assign a two-element subset of $\{1, 2, 3, 4\}$ to each node. Consider the (directed) edge from the node with vertex color A (and edge-color-set $\{1, 2\}$), to node with vertex color B (and edge-color-set $\{1, 3\}$). Following our algorithm, this edge is colored 2 (a color that is in the edge-color-set of A but not of B), and the reverse edge is colored 3. Other edges are colored similarly.

Theorem 1: Given a vertex coloring of an undirected graph using k colors, there is a polynomial-time algorithm for directed edge coloring the corresponding bidirectional graph using $\xi(k)$ colors.

In the extended version of this work [7], we have established a relationship between the chromatic number of an undirected graph and the DEC number of its corresponding bi-directional graph, and, thus, showed that this problem is NP-hard. The following theorem, which we prove in [7], captures this relationship.

Theorem 2: If the chromatic number of an undirected graph is χ then the DEC number of the corresponding bi-directional graph is $\xi(\chi)$.

Moreover in [7], we also compute an upper bound on the value of $\xi(\chi)$.

Theorem 3: $\xi(\chi) \leq 2\lceil \log \chi \rceil$.

V. DISCUSSION AND CONCLUSIONS

In this paper we have described a simple channel allocation scheme that allows point-to-point links in a rural mesh network to operate in full-duplex mode at all times and completely independent of each other. We have evaluated this scheme in an out-door testbed, demonstrated its feasibility and quantified its significant gains over existing channel allocation/link scheduling schemes.

We also wish to explore the case when we do not have enough channels to cover the entire graph. In this context, we would like to examine the routing problem as a maximum concurrent flow problem.

We have observed that in some cases our attempts to switch off CSMA are not completely successful. Hence, in these cases, simultaneously operational transmitters back off, since they can hear each other's transmissions. We would like to explore means to cleanly turn off CSMA in WiFi cards for long-distance networks.

It should be noted that while this work has been geared towards rural WiFi based meshes, this channel allocation scheme (and the algorithms) can easily be applied in the context of WiMAX meshes (with applications in cellular backhaul and rural connectivity).

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