COMPONENT BASED CHANNEL ASSIGNMENT IN SINGLE RADIO, MULTICHANNEL AD HOC NETWORKS

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COMPONENT BASED CHANNEL ASSIGNMENT IN SINGLE RADIO, MULTICHANNEL AD HOC NETWORKS

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To my mother,

who has always been by side,

during all the ups and downs in my life.

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SUMMARY

In this work, we consider the channel assignment problem in single radio multi-channel mobile ad-hoc networks. Specifically, we investigate the *granularity of channel assignment decisions* that gives the best trade-off in terms of performance and complexity. We present a new granularity for channel assignment that we refer to as *component level channel assignment*. The strategy is relatively simple, and is characterized by several impressive practical advantages. We also show that the theoretical performance of the component based channel assignment strategy does not lag significantly behind the optimal possible performance, and perhaps more importantly we show that when coupled with its several practical advantages, it significantly outperforms other strategies under most network conditions.

CHAPTER I

INTRODUCTION

Multi-channel wireless data networks have garnered increasing attention over the last few years because of the great promise they hold in terms of the achievable spectral efficiencies. In this work, we consider a specific sub-topic of the above general area: *ad-hoc networks* with nodes equipped with a *single radio or interface that can operate on multiple channels.* Within this context, an important problem to solve for attaining any of the perceived benefits of a multi-channel environment is one of *channel assignment*. Simply put, the channel assignment problem asks: *Which of the available channels should a node transmit on at any given point in time?* The problem is not a new one, and has been answered to different extents of efficacy by several related works, with solutions such as SSCH [3], MMAC [12], MCP [9], DCA [14] etc.

In this work, we explore the *granularity of channel assignment decisions* that gives the best trade-off in terms of performance and complexity. By granularity, we refer to the scope of a channel assignment decision in terms of the number of different entities the decision impacts and applies to. Briefly, examples of different granularities include (i) *packet* - channel assignment is performed on a per-packet basis at a given node and the decision does not apply to subsequent packets or other entities; (ii) *link* - channel assignment is performed for a link between two given nodes, and all packets between the two nodes will be transmitted on the same channel for the duration the decision is valid for; and (iii) *flow* - all packets belonging to a flow are sent on the same channel. Approaches such as DCA fall under the category of packet level channel assignment, approaches such as MMAC and SSCH fall under the category of link level channel assignment, and approaches such as MCP fall under flow level channel assignment.

The different channel assignment strategies have different trade-offs in terms of the overall performance they can achieve, and the complexity and hence the practical overheads incurred in realizing them. We explore these trade-offs and in the process arrive at a new granularity for channel assignment that we refer to as *component level channel assignment* that is the least complex of the ones identified above and hence is characterized by several impressive practical advantages including (i) no changes to the off-the-shelf radio hardware or MAC algorithms, (ii) no synchronization requirements, (iii) no channel scheduling overheads, and (iv) no switching between channels to serve data flows. Surprisingly, we also show that the theoretical performance of the component based channel assignment strategy does not lag significantly behind the optimal possible performance even under worst case conditions, and for most practical scenarios does the same as the optimal. Perhaps, most importantly, we show that when coupled with its several practical advantages, it significantly outperforms other strategies under most network conditions.

Briefly, the component based channel assignment strategy involves assigning a single channel to all nodes belonging to a component formed by nodes belonging to mutually intersecting flows. For example, if flow $f1$ intersects with flow $f2$, and flow $f2$ intersects with flow $f3$, then all nodes on the paths traversed by the three flows are assigned to operate on the same channel. We show that such a simple strategy can result in considerable performance gains through both theoretical and quantitative analysis. We also propose centralized and distributed routing layer algorithms that effectively realize the strategy. Thus, the contributions of this work are three-fold:

- We identify a new granularity for channel assignment that is component based and show that the strategy has several theoretical and practical benefits.

- We present centralized and distributed routing algorithms that realize the component based channel assignment strategy effectively.
- We show through a testbed implementation using off-the-shelf hardware, the ease of deployment of the component based strategy.

CHAPTER II

BACKGROUND

In this work, we consider the problem of channel assignment for different flows in the following context:

- *Network Model:* We consider a multi-hop, ad hoc network, where there are multiple channels available in the network.
- *Transceiver Model:* We assume that all nodes in the network are equipped with a *single* half-duplex transceiver.
- *Flow Model:* We consider the case, where flows can either be single hop or multi-hop. Also, a node can potentially serve one or more flows.

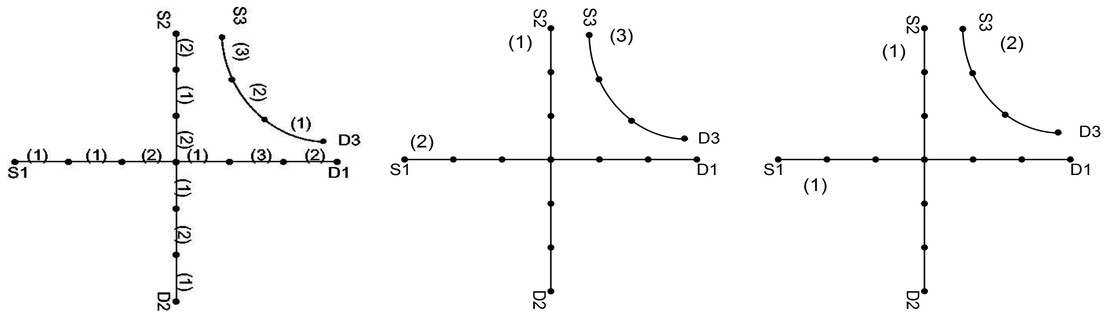
Given the context, channel assignment in a multichannel ad hoc network, can be done in one of the following three ways[1]:

2.1 Link Based Channel Assignment

We refer to a multichannel assignment as *link based assignment, when different links in the flow graph, induced by the different flows in the network, have the capability to choose any of the channels.* In this type of assignment, each link in a flow can potentially operate on a different channel. Figure 3 (i) illustrates the link based channel assignment for a topology with three flows and three channels. In a link based assignment, we observe that different links in the flow can potentially be assigned to

[1]We have identified packet based channel assignment as another type of channel assignment. However, it has been shown in [3, 12], that channel assignment at such a fine granularity may not be feasible in a practical setting because of the various overheads involved.

different channels. Thus, the link based channel assignment leverages the presence of multiple channels to increase the spatial reuse at the granularity of a link.



(i) (ii) (iii)

Figure 1: Topologies to Illustrate (i) Link, (ii) Flow and (iii) Component Based Channel Assignment

2.2 Flow Based Channel Assignment

We refer to the channel assignment as flow based assignment, *when all links in a flow are assigned to a single channel, but different flows have the capability to operate on different channels*. Thus, the channel assignment is performed at the granularity of a *flow*. Figure 3 (ii) illustrates the flow based channel assignment for the the same topology. The two intersecting flows and the third flow can potentially operate on different channels. However, all the links in a particular flow operate on the same channel.

2.3 Component Based Channel Assignment

We refer to the channel assignment as component based, *when all links in a connected component induced by the underlying flow graph operate*[2] *in a single channel. However, different connected components can potentially operate on different channels.* A connected component in a flow graph is defined as the largest subgraph, such that

[2] *The set of active edges carrying flow traffic in the network.*

there exists a path between any node in the subgraph to all other nodes in the subgraph. Figure 3 (iii) illustrates the component based channel assignment for the same topology. The two intersecting flows[3] form a connected component and operate on a single channel, while the third flow is an independent component and can potentially operate on a different channel. All the links in a particular component operate on the particular channel assigned for the flow. Thus, we leverage the presence of multiple channels at the granularity of a component.

Although the component based model is simple, one of the contributions of this work is to show that this model has equal if not better performance over the more complex link and flow based approaches.

[3]Two flows are said to be intersecting, if there is a common node in the set of active nodes for each flow, which serves both flows.

CHAPTER III

MOTIVATION

In this chapter, we compare component based with link and flow based channel assignment by providing intuitive, quantitative, and practical reasons. For the intuitive reasoning, we compare component based with only link based, as it has been established that for a given flow graph, the link based approach provides the optimal performance [2, 7]. However, for quantitative results and practical reasoning, we compare all three approaches.

3.1 Simple Topologies

In this section, we provide intuitive evidence for why a component based channel assignment is efficient. We consider a few practical topologies and perform the slot and channel assignment for component and link based channel assignment.

Topology 1:

Figure 3(i)(a) shows the slot and channel assignment for a single flow using a single channel[1]. We observe that it is possible to come up with a schedule, where links within the same contention region are assigned to different slots. This sequence is repeated across different contention regions. If W is the link capacity, we observe that this slot allocation scheme yields a flow capacity of $\frac{W}{3}$, assuming a two-hop interference region.

Figure 3(i)(b) shows the link based slot and channel assignment, where the per-flow capacity is $\frac{W}{2}$. We observe that irrespective of the number of channels and the slot schedule, the flow capacity is always limited to $\frac{W}{2}$, as each node is equipped

[1]For topologies (i)-(iii), component based assignment reduces to that of a single channel, where only one channel is utilized.

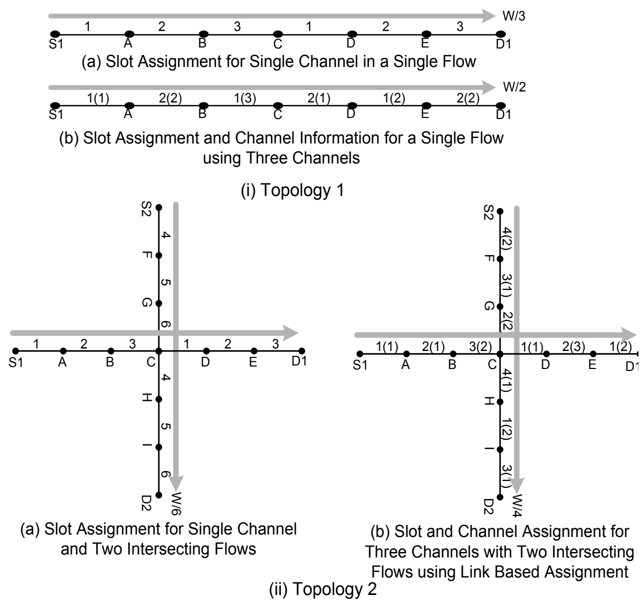


Figure 2: Slot Assignment for Simple Topolgies 1 and 2

with a single, half-duplex radio. Thus, the flow capacity of single and multichannel assignment for a single flow is of the same order. Note that this is valid irrespective of the number of hops in the flow.

Topology 2:

Figure 3(ii) shows the single channel and link based multichannel slot and channel assignment for 2 intersecting flows. Figure 3(ii)(a) shows a single channel slot assignment that will guarantee an aggregate flow capacity of at least $\frac{W}{3}$.

Figure 3(ii)(b) shows a link based slot assignment that yields an aggregate flow capacity of $\frac{W}{2}$. Note that irrespective of the number of channels, the capacity around the bottleneck (intersection) node can at most be $O(W)$. Thus, for intersecting flows, there is no benefit in using multiple channels.

Topology 3:

Figure 3(iii) shows the single and multiple channel assignment for multiple, non-contending bisecting flows. We observe that even for a single channel, the aggregate flow capacity scales with the number of flows as each flow achieves a per-flow capacity

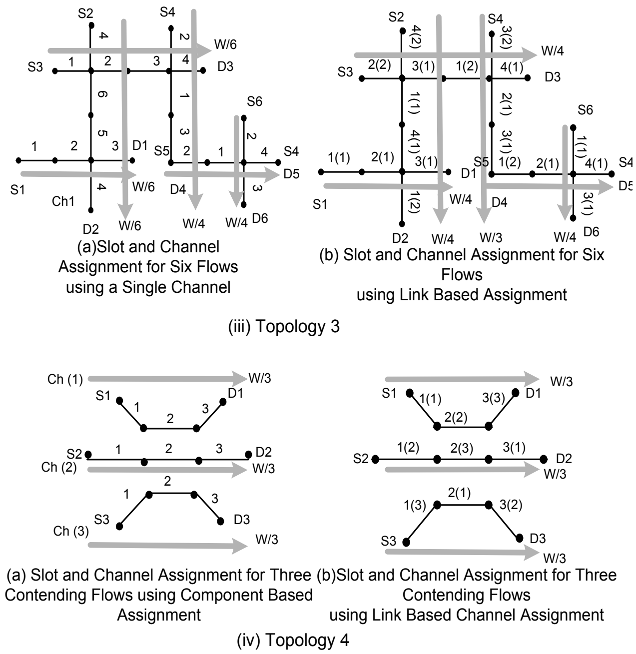


Figure 3: Slot Assignment for Simple Topolgies 3 and 4

of at least $\frac{W}{6}$. In fact, for some flows, the flow capacity is $\frac{W}{4}$. Thus, for the given topology, the aggregate flow capacity for a single channel is $O(F * W)$, where $F = 6$ is the total number of flows in this example.

For a multichannel scenario with single radio, the maximum achievable aggregate flow capacity for F flows is $O(F * W)$. Figure 3(iii)(b) confirms this observation, where the per flow capacity of each flow never exceeds $\frac{W}{3}$.

Topology 4:

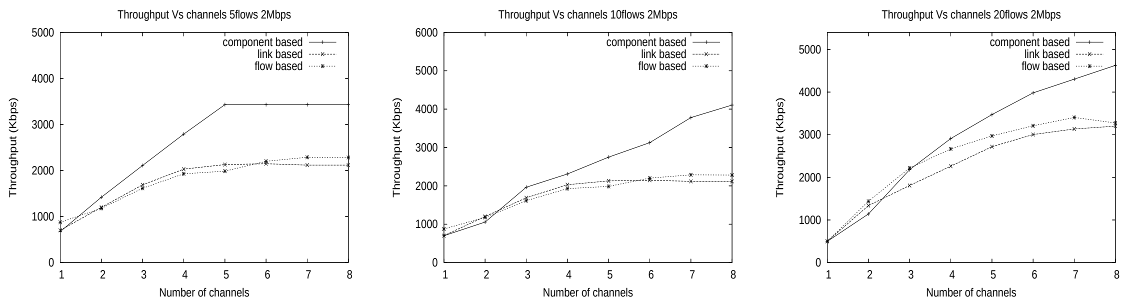
Finally, when F flows contend in a region as shown in Figure 3(iv), the component based channel assignment reduces to a flow based channel assignment. Figure 3(iv)(a) shows the slot and channel assignment for 3 contending[2] but non-intersecting flows. If each component operates on a separate channel as shown in the figure, the per-flow capacity is still $O(W)$. So, for the F flows, where $F = 3$ in Figure 3 (iv)(a), the aggregate flow capacity is $O(F * W)$. This is also the maximum achievable flow

[2]Two flows are said to be contending, if there is at least one node in the set of active nodes for one flow that is within the interference region of the set of active nodes for the second flow.

capacity for a link based channel assignment as shown in Figure 3(iv)(b).

3.2 Quantitative Results

In the previous section, we observed that component based and link based provide similar aggregate capacity for the topologies considered. In this section, we observe the performance of link, flow and component based channel assignment for a random network through simulation results.



(a) Throughput for 5 flows (b) Throughput for 10 flows (c) Throughput for 20 flows

Figure 4: Average Throughput (Kbps) vs. No. of Channels for Varying Number of Flows for Link, Flow and Component Based Channel Allocation

Figure 4 compares the average throughput for component based with flow and link based channel assignment using $NS2$ simulations. We consider a network of size $750m \times 750m$ with 100 nodes randomly deployed with a transmission range of $250m$, channel data rate of $2Mbps$, and vary the number of flows. The other details of the simulation setup and the competing approaches are described in Section 6.1.

Figure 4 (a)-(c) compares the average throughput for all three types of channel assignment for 5, 10 and 20 flows. The total number of channels is varied from $1 \ldots 8$. Figure 4 (a) shows the average throughput for all three approaches for 5 flows. For the component based approach, we observe that there is a linear increase in the average throughput from about 700Kbps for 1 channel to about 3500Kbps for 5 channels. Note that there cannot be any further increase beyond 5 channels as there are only 5 flows. The linear increase in throughput is due to the different components or flows being assigned to different channels when the number of channels is increased. For the flow and link based, the average throughput saturates at about 1800Kbps and 1500Kbps respectively. This is due to several practical constraints such as lack of synchronization and efficient scheduling, and the penalty incurred in switching between channels (switching delay). Figure 4 (b), (c) show the throughput variation with increasing number of channels for 10 and 20 flows. We observe that the difference between component based and link, flow based decreases with increasing number of flows. This is due to the increase in the number of intersecting flows.

3.3 Practical Considerations

Thus far, we have compared the performance of component based with link (and flow) based assignment through simulation results and for simple topologies. Here, we describe some of important practical limitations of link and flow based assignment that are not present in component based channel assignment.

- *Hardware/MAC Changes:* Most of the current realizations of link based approach is performed at the MAC layer [3, 12]. Even for a flow based approach, modification is required at the MAC layer to accommodate fine-grained *switching* at the intersection points [9]. This imposes need to build customized wireless cards to support customized MAC layer functionality. For this reason, standard off-the-shelf wireless cards cannot be used. However, a component based approach is able to achieve almost identical benefits without imposing any requirements for changes in MAC hardware or software.

- *Switching Delay:* Link and flow based approaches require switching, when an intersection node serves two links or flows in different channels[3]. For a typical 802.11 a card, the switching delay is of the order of 80-100 μs [3]. Consider the

[3] The frequency of switching is dependent on the specific protocol and could potentially be at the granularity of a packet [14].

example, where the data packet of size is 1 KB. The packet transmission time is given by $8000/(54 \times 10^6) = 160$ μs. Thus, the switching delay in this example is of the same order as the packet transmission time. Further, the end-to-end delay for each packet transmission in a flow will increase as the switching delay is additive across all nodes that perform switching. It has also been observed that the network capacity degrades as a function of $\frac{S}{S+T}$, where S is the switching delay and T is the transmission time [8]. For the testbed scenario considered in Section 16, where the switching node is equipped with Intel Pro Wireless 2200 802.11b/g card, we observed that the practical switching delays to transmit ICMP control messages are of the order of $900ms$.

- *Synchronization Requirements:* Another important consideration in a link and flow based approaches is the need to perform synchronization at the intersection nodes [3, 12]. When a common node serving two links (or flows), A and B, performs switching from A to B, it requires that: (i) The receiver for that particular link (or flow), B, is also on the same channel, and (ii) The sender of the previously served link (or flow), A, does not transmit packets for the duration of time when the common node is serving B. Constraint (i) is required for efficient operation, while constraint (ii) is required to prevent the previous from triggering unnecessary route failures (stable operation). In link (and flow) based approaches, both these constraints need to be addressed. However, in a component based approach, a connected component is on a single channel and does not suffer from these issues.

- *Scheduling Overhead:* An associated problem to synchronization is the need to perform efficient scheduling for all the links or flows that operate on different channels, and pass through a common node. The common node needs to inform the schedule for neighboring nodes that operate on different channels. The overhead involved in this process makes the link and flow based approaches less desirable. An alternative to avoid synchronization and scheduling in link and flow based approach is to use a control channel for control packet transmissions, and perform data transmissions on the remaining channels [14]. However, this is not desirable in a single radio scenario as it requires frequent switching between data channels and a control channel.

CHAPTER IV

THEORETICAL ANALYSIS

The seminal work of Gupta and Kumar [5] derived the capacity of ad hoc wireless networks for a single channel and single interface. The results are applicable to single channel wireless networks, or multichannel wireless networks where every node has a dedicated interface. Kyasanur et.al[8] extended the results of Gupta and Kumar to multichannel wireless networks that do not have a dedicated wireless interface per channel. These works consider the maximum achievable network capacity when there are n nodes in a network, and every node is a source and destination for a few flows. The underlying assumption in the derivation of these bounds is that every node has traffic to send to a neighboring node and that there are $\Omega(n)$ flows. However, we take an orthogonal viewpoint, where the *flow pattern* in a *random* network is given, and the goal is to determine for the *aggregate flow capacity* bounds for different granularities of multichannel assignment, when nodes are equipped with a single interface. This introduces additional constraints in the formulation of the capacity problem: (i) *Directionality of flows:* In this work, there is a directionality associated with the traffic sent by each node. So, the interference model[1] as described in [5, 8] needs to be extended to accommodate *self-contention* and *intelligent scheduling*; (ii) *Intermediate node bottleneck:* Unlike in [8], where only the destination node is a bottleneck in the derivation of capacity bounds for a random network, in our case, any intermediate node in a flow can also be a bottleneck. This occurs when there are several flows contend or intersect at the bottleneck node; (iii) *Spatial Reuse for a flow:* In computing the aggregate flow capacity, if intelligent scheduling is done, it is

[1] We use the protocol model for modeling contention.

Table 1: Notations for Capacity Analysis

Variable	Description
W	Capacity of a single channel
$G(V, E)$	The underlying network graph
V	Set of vertices in the network graph
E	Set of edges in the network graph
F	Total number of flows in the network
$\Lambda(i)$	Aggregate flow capacity of i flows
$G'(P, L)$	The flow graph for the underlying network
P	Set of vertices in the flow graph
L	Set of links in the flow graph
c	Total number of channels
Δ	Maximum number of contending flows in the flow graph
Γ	Maximum number of intersecting flows in the flow graph

possible to schedule transmissions at multiple links in a flow simultaneously so that the per-flow capacity is maximized. While [5, 8] accommodate spatial reuse for the entire network in the derivation of capacity bounds, in our case, the spatial reuse is limited to the flow graph. Thus, our work is complimentary to [5, 8] and derives the *aggregate flow capacity* to a random network where a flow pattern is given.

4.1 Definitions

Table 4.1, shows the list of notations used in analyzing the overall network capacity for the different types of channel assignment.

4.2 Preliminaries

We will now derive a basic set of observations that will be used in the derivation of lower and upper bounds of capacity for the different types of multichannel assignment.

Lemma 0: When there is a single flow in the network, the capacity of single channel assignment and multichannel assignment are the same.

For the single-channel case, it is possible to come up with a schedule, where links

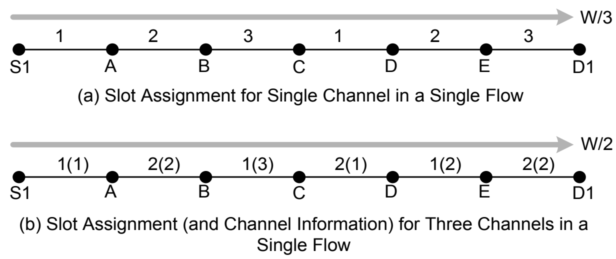


Figure 5: Slot Assignment for a Single Flow

within the same contention region are assigned to different slots, and this sequence is repeated across different contention regions. Figure 5 (a) illustrates such a simple assignment strategy, where the contention region is 3 hops. Thus, the flow capacity achievable using a single channel is $\Theta(W)$, where W is the link capacity.

For multiple channels and single flow, the maximum achievable flow capacity is only W. As in the single channel case, for a half-duplex transceiver at each node, it is always possible to achieve a schedule which will give at least $W/2$ if multiple channels are used. Thus, the flow capacity achievable using multiple channels is also $\Theta(W)$.

Lemma 1: When there are F non-contending and non-intersecting flows in the network, the aggregate flow capacity of a single channel assignment and multichannel assignment are the same.

Consider any two flows in the network, F_i and F_j. Since the flows are non-contending and non-intersecting, no link in F_i contends with a link in F_j. So, even for a single channel scenario, the different flows can be served simultaneously without any capacity degradation. From Lemma 0, the capacity of a single flow is $\Theta(W)$ irrespective of the number of channels. Thus, the overall flow capacity for both single and multichannel assignment is given by $F * \Theta(W)$.

Lemma 2: When F non-contending flows in the flow graph $G'(P, L)$ intersect at a single point, the aggregate flow capacity is the same irrespective of the number of channels assigned to these flows.

Let all F flows to intersect at a common intersection point, p, which we refer to

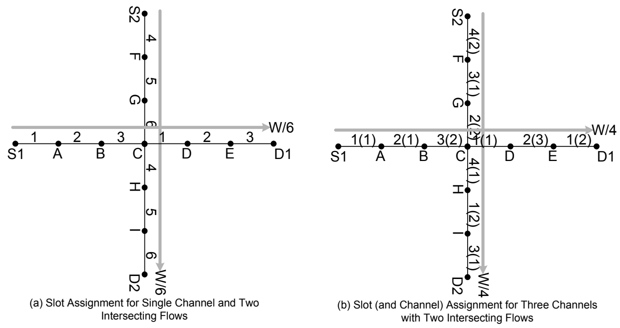


Figure 6: Slot Assignment for Intersecting Flows

as the *bottleneck node*. From the definition of a single radio, half-duplex transceiver, at the bottleneck node, the maximum achievable capacity is $\Theta(W)$ irrespective of the number of channels. If F flows intersect at the bottleneck node, the maximum achievable per flow capacity around the bottleneck node is $\Theta(W)/F$. Thus, the maximum achievable end-to-end per flow capacity of F_i is given by $O(W/F)$, for both single and multichannel case.

The slot assignment problem in a single channel case for the flow graph G'(P,L), when F flows intersect at p, corresponds to the classical *edge coloring* problem. From Vizing's Theorem [1], if $G'(P, L)$ is a simple, loop-free graph with maximum degree F, the graph G' is $O(F)$ edge-colorable. Thus, the minimum achievable per-flow capacity in a single channel scenario is given by $W/O(F)$ for the single channel case. Figure 6 shows the slot assignment for two intersecting flows for single channel and three channel network.

Thus, the end-to-end per flow capacity for single channel case is given by $\Theta(W/F)$. Also, since the per flow capacity of multichannel case is $O(W/F)$ and is at least that of the single channel capacity, the per flow capacity for multichannel case also reduces to $\Theta(W/F)$. Thus, the aggregate flow capacity for both single and multichannel case is given by $\Theta(W)$.

Lemma 3: When F non-intersecting flows in the flow graph $G'(P, L)$ contend in a single contention region, the aggregate flow capacity for a single channel is given by

$O(W)$. The aggregate flow capacity for multichannel network is given by $O(W * c)$.

The proof for single channel network is similar to the intersection case. In a single channel network, the maximum achievable aggregate flow capacity around the contention region is given by $\Theta(C)$. Thus, the per-flow capacity for each flow is $O(W/F)$. Aggregating over all flows, the aggregate flow capacity is $O(W)$[2]. Similarly, for the multichannel scenario, the maximum achievable capacity around the bottleneck contention region is $O(W * c)$. By a similar argument, the aggregate flow capacity is also $O(W * c)$[3].

We now analyze the upper and lower bounds of capacity for link, flow and component based channel assignment. Any given flow graph, $G'(P, L)$, can be classified into the following six categories: (i) Non-intersecting and non-contending flows, (ii) Non-intersecting but contending flows, where the maximum number of contending flows is less than the number of channels ($\Delta \leq c$), (iii) Non-intersecting but contending flows, where the maximum number of contending flows is greater than the number of channels ($\Delta > c$), (iv) Intersecting but non-contending flows, (v) Contending and intersecting flows, where the maximum number of contending flows is less than the number of channels ($\Delta \leq c$), and (vi) Contending and intersecting flows, where the maximum number of contending flows is greater than the number of channels ($\Delta > c$). For ease of analysis, we treat these six cases in isolation and consider the flow graph to exclusively belong to one of these six classifications. The bounds for a generic case, where a flow graph is composed of a few of these classifications can be derived by aggregating the bounds derived for each subgraph. From Lemma 1, for F non-contending and non-intersecting flows, the aggregate flow capacity does not degrade irrespective of the type of channel assignment, and is given by $\Theta(W * F)$. Therefore,

[2]By using an argument similar to Vizing's Theorem for edge coloring, we can further refine the aggregate flow capacity to $\Theta(W)$.

[3]This result can also be further refined to $\Theta(W * c)$ by considering the maximum number of slots required around the bottleneck region.

we analyze the upper and lower bounds for the remaining five classifications in the rest of this section.

4.3 Capacity of Link, Flow and Component Based Multichannel Assignment

We will now study the best case and worst case scenario for the remaining classifications for all three multichannel assignment. Table 2 shows the lower and upper bounds for the different types of channel assignment for all six classifications.

4.3.1 Contending Flows with $\Delta \leq c$

Lower Bound: The maximum achievable aggregate flow capacity for F flows in any type of channel assignment is given by $O(W * F)$. The worst case occurs when each flow contends with remaining $F - 1$ flows at different places, such that within a contention region only Δ flows contend. However, this will require that the flow graph for this scenario be non-planar when $\Delta < F/2$. Based on this result, we can also show that for a planar flow graph, for a flow and a given Δ, all flows can contend with at most $2 * \Delta$ flows. Figure 7 shows a simple scenario for 6 flows, where $\Delta, c = 4$. As we can observe, this will also require a loop in the flow graph G'(P,L). In the link based, since $\Delta \leq c$, in each of these regions, each contending link in the Δ flows is assigned to a different channel. Thus, the aggregate flow capacity of link based channel assignment when *Delta* flows contend in a region is given by $O(W * \Delta)$. Now, there are at least F/Δ such groups and so, the worst case aggregate flow capacity for link based is given by $O(W * F)$.

The channel assignment for flow and component based are the same in this case as there are no intersecting flows. Consider a simple channel allocation policy, where the F contending flows are split equally among the channels. So, there are at most F/c flows in each channel. Since $c \geq \Delta$, and each flow contends with at most $2 * \Delta$

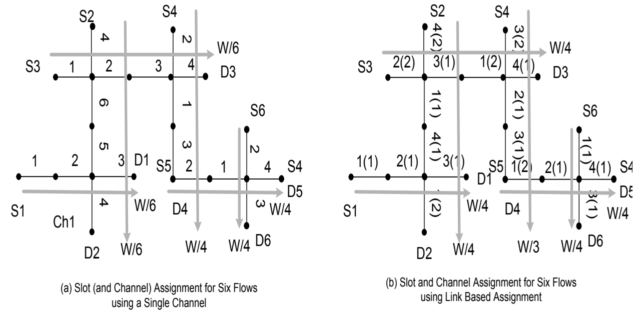


Figure 7: Slot Assignment for Contending Flows

flows in the network, the aggregate flow capacity is given by:

$$\begin{aligned}\Lambda(F) &= F \times O(\frac{W * c}{2 * \Delta}) : c \geq \Delta, \Lambda(F) \leq O(WF) \\ &= O(W * F) \\ &= O(W * F)\end{aligned}$$

So, for both flow and component based channel assignment, the lower bound for aggregate flow capacity under the planar flow graph assumption is given by $O(W*F)$[4].

Upper Bound: The best case occurs when Δ flows contend in a region, and the remaining flows contend with exactly one of these Δ flows in some other region. As before, for the Δ contending flows, the aggregate flow capacity is given by $O(W * \Delta)$. For the remaining $F - \Delta$ flows, the maximum achievable capacity per flow is $O(W)$ for all three types of channel assignment. Thus, the aggregate flow capacity is given by:

$$\begin{aligned}\Lambda(F) &= O(W * \Delta) + O(W) \times (F - \Delta) \\ &= O(W * F)\end{aligned}$$

4.3.2 Contending Flows with $\Delta > c$

Lower Bound: As before, the maximum achievable aggregate flow capacity for F flows is given by $O(W * F)$. The worst case scenario is when Δ flows contend at

[4]For a non-planar graph, each flow can potentially contend with all F flows and hence the lower bound reduces to $O(Wc)$.

several places. In the link based, since $\Delta > c$, the aggregate flow capacity in each of these regions is $O(W * c)$. As before, there are at least F/Δ such groups. Thus, the aggregate flow capacity of link based channel assignment when *Delta* flows contend in a region is given by:

$$\begin{aligned}\Lambda(F) &= O(W * c)\frac{F}{\Delta} \\ &= O(\frac{W * F * c}{\Delta})\end{aligned}$$

As mentioned before, the flow and component based channel assignment are the same in this scenario. For the planar flow graph assumption, each flow can mutually contend with at most $2 * \Delta$ flows. Thus, the aggregate flow capacity for both flow and component based multichannel assignment is given by:

$$\begin{aligned}\Lambda(F) &= F \times O(\frac{W * c}{2 * \Delta}) : \Delta > c, \Lambda(F) \leq O(WF) \\ &= O(\frac{W * F * c}{2 * \Delta}) \\ &= O(\frac{W * F * c}{\Delta})\end{aligned}$$

Upper Bound: The best case occurs when Δ flows contend in a region, and the remaining flows contend with exactly one of these Δ flows in some other region. As before, for the Δ contending flows, the aggregate flow capacity is given by $O(W * \Delta)$. For the remaining $F - \Delta$ flows, the maximum achievable capacity per flow is $O(W)$ for all three types of channel assignment. Thus, the aggregate flow capacity is given by:

$$\begin{aligned}\Lambda(F) &= O(W * \Delta) + O(W) \times (F - \Delta) \\ &= O(W * F)\end{aligned}$$

4.3.3 Intersecting Flows

Lower Bound: From Lemma 1, when Γ flows in the flow graph $G'(P, L)$ intersect at a single point, the per-flow capacity for a intersecting flow is given by $O(\frac{W}{\Gamma})$ irrespective of the type of channel assignment. Under the planar graph assumption, the worst case scenario is when each flow intersects with at most $2 * \Gamma$ flows. Thus, the per-flow capacity is given by $O(\frac{W}{2*\Gamma})$ irrespective of the type of multichannel assignment. Thus, the aggregate flow capacity for all three cases is given by:

$$\begin{aligned} \Lambda(F) &= F * O(\frac{W}{2 * \Gamma}) \\ &= O(\frac{W * F}{\Gamma}) \end{aligned}$$

Upper Bound: The best case scenario is when Γ flows intersect in a single point, and among the remaining $F - \Gamma$ flows at most 1 flow intersects with one of these Γ flows at some other point. From Lemma 1, for each of the Γ flows, the per-flow capacity is given by $O(\frac{W}{\Gamma})$. For the remaining $F - \Gamma$ flows, the maximum achievable *per-flow* capacity, $\lambda(i)$, even for a single channel assignment is given by:

$$\begin{aligned} \lambda(i) &= O(W) - O(\frac{W}{\Gamma}) \\ &= O(W - \frac{W}{\Gamma}) \end{aligned}$$

$$\lambda(i) \approx O(W) \qquad (1)$$

From equation 1, the aggregate flow capacity for all three cases is given by:

$$\begin{aligned} \Lambda(F) &= O(\Gamma * \frac{W}{\Gamma}) + (F - \Gamma) * O(W) \\ &= O(W(1 + F - \Gamma)) \end{aligned}$$

4.3.4 Contending and Intersecting Flows with $\Delta \leq c + \Gamma - 1$

Lower Bound: The worst case is when all Δ and Γ flows contend and intersect at a single point and there are several such points in the network. For link and flow based, consider the case where these Δ flows intersect at some other region in groups of Γ

flows. For link and flow based, the aggregate flow capacity of Δ flows is given by:

$$\begin{aligned} \Lambda(\Delta) &= \frac{\Delta}{\Gamma} * \Gamma * O(\frac{W}{\Gamma}) \\ &= \Delta * O(\frac{W}{\Gamma}) \end{aligned} \tag{2}$$

For the Γ intersecting flows, the aggregate flow-capacity is given by:

$$\Lambda(\Gamma) = \Gamma * O(\frac{W}{\Gamma}) \tag{3}$$

From equations 2 and 3, the aggregate flow capacity of F flows for link and flow based is given by:

$$\begin{aligned} \Lambda(F) &= (\Delta + \Gamma) * O(\frac{W}{\Gamma}) * \frac{F}{\Delta + \Gamma} \\ &= O(\frac{W * F}{\Gamma}) \end{aligned}$$

For component based, consider the case where the Δ contending flows in each region intersect with one of the existing Γ intersecting flows. Since all these flows operate form a single connected component, by definition of component based all these flows will operate on the same channel. Thus, the aggregate flow capacity for component based is given by:

$$\begin{aligned} \Lambda(F) &= (\Delta + \Gamma) * O(\frac{W}{\Delta + \Gamma}) * \frac{F}{\Delta + \Gamma} \\ &= O(\frac{W * F}{\Delta + \Gamma}) \end{aligned}$$

Upper Bound: The best case occurs when Γ flows intersect in a point, and these Γ flows also contend with each other at some other region. Assume a scenario where the Γ intersecting flows are a subset of the Δ flows contending in a region. For the Γ intersecting flows, the aggregate flow capacity is $O(W)$ for all three types of assignment. For the remaining $\Delta - \Gamma$ contending flows, the maximum achievable aggregate capacity is given by:

$$\begin{aligned} \Lambda(\Delta - \Gamma) &= min[(\Delta - \Gamma)O(W), O(cW - W)] : \Delta \leq c + \Gamma - 1 \\ &= (\Delta - \Gamma) * O(W) \end{aligned}$$

For the remaining $F - \Delta$ flows, the maximum achievable capacity per flow is $O(W)$ for all three types of channel assignment as they do not intersect with any of these flows. Thus, the aggregate flow capacity for all three cases is given by:

$$\begin{aligned}\Lambda(F) &= O(W) + O(W) \times (\Delta - \Gamma) + O(W) \times (F - \Delta) \\ &= O(W(1 + F - \Gamma))\end{aligned}$$

4.3.5 Contending and Intersecting Flows with $\Delta > c + \Gamma - 1$

Lower Bound: The worst case scenario is the same as in the previous case, and so the aggregate flow capacity of F flows for link and flow based is given by:

$$\Lambda(F) = O(\frac{W * F}{\Gamma})$$

The worst case for component based is also the same as in the previous case, and the aggregate flow capacity is given by:

$$\Lambda(F) = O(\frac{W * F}{\Delta + \Gamma})$$

Upper Bound: The best case scenario is also the same as in the previous case except for the difference in constraint. Thus, the aggregate flow capacity for all three types of channel allocation is given by:

$$\begin{aligned}\Lambda(F) &= O(W) + O(cW - W) + O(W) \times (F - \Delta) \\ &= O(W(c + F - \Delta))\end{aligned}$$

4.3.6 Competitive Ratio for Component Based to Link Based

Thus far, we have analyzed the upper and lower bounds for link and component based. While these are important bounds to study the absolute performance of each of these channel assignment strategies, it is also equally important to identify the worst case competitive ratio with respect to optimal. In this section, we derive the ratio of link based to component based for different types. Figure 3 summarizes the competitive

Table 2: Bounds for Link and Component Based Channel Assignment

Type	Condition	Link LB	Link UB	Comp LB	Comp UB
NC	N/A	$O(WF)$	$O(WF)$	$O(WF)$	$O(WF)$
C	$\Delta \leq c$	$O(WF)$	$O(WF)$	$O(WF)$	$O(WF)$
C	$\Delta > c$	$O(\frac{WFc}{\Delta})$	$O(W(c+F-\Delta))$	$O(\frac{WFc}{\Delta})$	$O(W(c+F-\Delta))$
I (NC)	N/A	$O(\frac{WF}{\Gamma})$	$O(W(1+F-\Gamma))$	$O(\frac{WF}{\Gamma})$	$O(W(1+F-\Gamma))$
I and C	$\Delta \leq c+\Gamma-1$	$O(\frac{WF}{\Gamma})$	$O(W(1+F-\Gamma))$	$O(\frac{WF}{\Delta+\Gamma})$	$O(W(1+F-\Gamma))$
I and C	$\Delta > c+\Gamma-1$	$O(\frac{WF}{\Gamma})$	$O(W(c+F-\Delta))$	$O(\frac{WF}{\Delta+\Gamma})$	$O(W(c+F-\Delta))$

ratio of link to component based for all scenarios. From Lemmas 0-3, we notice that the competitive ratio of link to component based is $O(1)$[5].

For intersecting and contending flows, the worst case scenario for component to link based is when $\Gamma = 2$ and $F-1$ non-intersecting but contending flows intersect with a single flow. In this case, for component based channel assignment, all the flows will operate on a single channel. The aggregate flow capacity of component based is given by:

$$\begin{aligned} \Lambda(F) &= (F-1) * O(\frac{W}{\Delta}) + O(W - \frac{W}{\Delta}) : \Delta \leq c \\ &= (F-2) * O(\frac{W}{\Delta}) + O(W) \\ &= O(\frac{W * F}{\Delta}) \end{aligned} \quad (4)$$

For the link based, the $F-1$ contending flows can operate on different channels, and so the aggregate flow capacity for the same scenario is given by:

$$\begin{aligned} \Lambda(F) &= (F-1) * O(\frac{W * c}{\Delta}) + O(W) : \Delta \leq c \\ &= (F-1) * O(W) + O(W) \\ &= O(W * F) \end{aligned} \quad (5)$$

From equations 4, 8, the competitive ratio for link based to component based given by $O(\Delta)$.

[5]For planar flow graphs. For non-planar graphs with only contending flows, the competitive ratio is given by $O(\frac{F}{c})$.

Table 3: Worst Case Competitive Ratio of Component Based with respect to Link Based Assignment

Type	Condition	Link/Component
NC	N/A	$O(1)$
C	N/A	$O(1)$[a]
I (NC)	N/A	$O(1)$
I and C	$\Delta \leq c, \Gamma = 2$	$O(\Delta)$
I and C	$\Delta > c, \Gamma = 2$	$O(c)$

[a]For planar flow graphs. For non-planar graphs, the competitive ratio is given by $O(\frac{F}{c})$.

When $\Delta > c$, the worst case scenario is the same and the aggregate flow capacity of component based remains the same. However, the aggregate flow capacity of link based reduces to:

$$\begin{aligned} \Lambda(F) &= (F-1) * O(\frac{W * c}{\Delta}) + O(W) : \Delta \leq c \\ &= (F-1) * O(\frac{W * c}{\Delta}) \\ &= O(\frac{W * F * c}{\Delta}) \end{aligned}$$

Thus, the worst case competitive ratio in this case reduces to $O(c)$.

4.4 Insights

- For (i) purely non-contending flows, and (ii) purely intersecting flows, flow, link and component based all have the same aggregate flow capacity.

- For a combination of intersecting and contending flows, the flow capacity of flow based and link based is dictated by the number of intersecting flows and the fraction of contending flows with respect to the number of channels at each node within the flow. The performance of component based degrades to that of single channel if the F flows form a single connected component. However, the competitive ratio of component to link based is at most $O(min[\Delta, c])$.

- For the contention case, the aggregate flow capacity of flow and component based channel assignment converges to the aggregate flow capacity of link based channel assignment, when each flow contends with $O(\Delta)$ other flows. This happens when:

    1. All flows contend at a single bottleneck region.

    2. If the underlying network graph is planar.

CHAPTER V

REALIZING THE COMPONENT BASED CHANNEL ASSIGNMENT STRATEGY

We have motivated the need for a component based channel assignment in chapter 3. In this chapter, we present centralized and distributed approaches for realizing a component based channel assignment strategy.

5.1 Centralized Approach

(i) Overview:

In the previous chapter, we analyzed that the worst scenario in comparison with link and flow based approaches occurs when there are both intersecting and contending flows. The key objective of the centralized approach is to minimize the occurrence of this scenario. In this regard, we propose a greedy centralized approach for path selection and channel assignment for a component based channel assignment strategy. The goal of the path selection phase is to select paths that have *minimal intersecting* paths, given source-destination pairs. From the analytical results in Section 4, we observe that channel assignment only addresses flow capacity degradation due to contention in the network, and not the case when there are intersections. Once the component set has been determined, channel selection is performed for the different components. This procedure *minimizes the contention* between different components in the underlying flow graph (generated after the path selection phase). In this fashion, the centralized approach identifies the component set efficiently, and performs efficient channel assignment on the component set. We now describe the details of the approach with the pseudo-code described in Figure 8.

Variables:
i: Node id, c:Number of channels,
f:Flow id, F_j: Flow set at j_{th} iteration,
cid: Channel id, NU:Number of unassigned flows,
$C(cid)$: Channel Contention Cost in channel cid,
NS(f):Node set for flow f, w(i):Node Weight,
ch(l):Channel assigned to component l,
δ :Node weight increment,
NUC:Number of unassigned components,
UCS:Unassigned Comp. Set,
ACS:Assigned Comp. Set,
PC(l,m):Pairwise contention cost between components l and m,
TC(l):Total contention cost for component l

Route(f)
INPUT: k pair shortest path tree for all unassigned (S,D) pairs
OUTPUT: NS(f)
For f = 1 to NU
    For each one of the k shortest paths for flow
    Compute path cost in the path
    Return(path(minimum(k path costs)))
    For each node $i \notin F_j$ on flow f
        w(i) = w(i) + δ
Return(NS(f))

Assign Channel(f)
INPUT: UCS
OUTPUT: ch(1) ...ch(NUC)
    Do
        For each component m in ACS (with channel x)
            PC(l,m) = sum(CF_x(l),CF_x(m))
            TC(l) = TC(l) + PC(l,m)
        l=maximum(TC(l))
        ch(l)=minimum(C(cid))
        Update ACS, UCS; Update C(id)
    While $UCS \neq NULL$

Execution Sequence
For each unassigned flow f
    Route (f)
For each unassigned component l
    Assign channel (l)

Figure 8: Centralized Component Based Channel Assignment Approach

(ii) Path Selection:

The path selection approach is performed in a greedy fashion, where given source-destination pairs, the path with minimum number of intersections with already computed paths is determined. This is accomplished by the following procedure. For each source destination pair, k shortest paths are determined using a shortest path algorithm. The cost of a path is determined as the sum of the node weights w(i) for all nodes i in the path. *The path with the minimum aggregate weight is chosen as the path for this flow.* Once the path has been established, the weights of all the nodes that constitute this path and do not belong to already formed paths, is incremented by a value δ. This is performed to dissuade future flows from choosing nodes that constitute this flow. The overall goal is to minimize the number of intersection points (nodes), and so the path where a single node that serves many flows, would be preferred over several nodes that serve exactly 2 flows. For this reason, we only increment the weights of nodes that do not belong to an existing path by δ. A high value of δ causes longer paths to be preferred over intersecting paths[1]. This procedure is repeated for all source destination pairs. In Figure 8, lines 10-16 describe the path selection procedure.

(iii) Channel Assignment:

Once the path selection procedure has been accomplished, the component set for the underlying flow graph is known. The channel selection procedure is performed in a greedy fashion, where a component minimizes the contention with previously formed components. Let Assigned Component Set(ACS) refer to the set of components that have already been assigned channels and Unassigned Component Set (UCS) refer to the set of unassigned components. The total contention for a component l is obtained as the sum of it's pairwise contention with all assigned components. We also define a channel contention metric to determine the contention level for each channel. Here, pairwise contention between components can be defined as the sum of all contending nodes between two components. The channel contention metric for a channel, l can be defined by the number of nodes already assigned to that channel with which the intended component contends (if it were to operate on that channel). The greedy algorithm works by selecting the component in UCS with the maximum total component contention metric is chosen and assigned to the channel with least contention metric. This procedure chooses the component with maximum contention with other components in the assigned component set, and assigns it to the channel with least contention. In Figure 8, lines 20-27 show the channel assignment procedure.

(iv) Component Set Update:

Once a channel has been assigned to a component, the channel contention metric

[1]We determine this value of δ empirically to be 3.

corresponding to the newly assigned component is updated. Also, the assigned component set and the unassigned component set need to be updated. This procedure is repeated for all components in the unassigned component set, UCS. In Figure 8, line 26 shows the modification of channel cost, ACS and UCS.

5.2 Distributed Approach

In this section, we present a distributed realization of the greedy component based centralized approach. In the centralized approach, we perform path selection and identify the different components in the flow graph before efficient channel assignment is performed for different components. In a distributed realization, it is not possible for a node to know the complete list of components before channel selection is performed. Hence, in our distributed approach channel and route selection are performed in an integrated fashion.

The approach presented in this section enables route computation, maintenance and termination in a reactive and distributed manner. The approach does not require synchronization between nodes once a route has been established. At a high-level, the receiver performs channel selection in an informed fashion based on the contention and channel usage for the different paths between source and destination. We now describe the basic operations in the distributed approach.

During the flow initiation phase between a source and destination, the source transmits a RREQ message on all *active* channels. The list of active channels is determined by passive channel monitoring of the neighboring nodes using a particular channel. Each intermediate node determines whether it already belongs to a certain component and if so piggybacks the active channel, the number of nodes in the component and the component contention level in each channel, along with the route request message. This information is propagated by each node during the propagation of RREQ message. Destination determines the best path and channel for a flow based on the contention level in the component for each intermediate node (if it already belongs to one), and the penalty incurred in switching components. We describe the details of this phase later in this section. Destination nodes inform the intermediate nodes in the selected path with the channel chosen for the component. Intermediate nodes that already belong to a previous component updates its component information, and performs a component level update on all other nodes. The intermediate nodes in the component also perform passive monitoring to determine the contention level in each channel. This information is used to update the component contention level in each channel, once they have been assigned to a component. We now elaborate on the different phases of the approach using the pseudo-code shown in Figure 10.

(i) Pre-preparation Process:

Each node performs a pre-preparation procedure in order to aid in the determination of the component based routing and channel assignment. As part of the process it keeps track of two pieces of information: (i) the number of active channels in the neighborhood, and (ii) the total number of other components on each channel that are in the vicinity of its component. While the number of components locally in the vicinity of the node can be monitored locally, the total number is accumulated through reports from all nodes in its component. Component IDs are used to prevent double-counting of the number of contending components[2].

(ii) Route Request Broadcast:

During the flow initiation procedure, a source node that has data to send, broadcasts route request packets (RREQ) on all *the active channels* in its neighborhood. This procedure prevents unnecessary transmission on all available channels if there

[2]We use the destination ID of the oldest active flow in the component as the component ID.

are no active neighbors in a particular channel. When the route request is transmitted by the source, it piggybacks the source and destination node identifier with the packet. Apart from this information, the source also specifies the current operational channel (set to *default* if the source does not belong to an existing component), and the number of components in each channel in its neighborhood.

(iii) Route Request Update:

When an intermediate node receives the route request, it piggybacks the following n-tuple $(x, ch, nc, (cf(1)...cf(k)))$. Here x is the commit flag, which is set to 1 when a node is committed to a channel and 0 otherwise. The current operating channel, ch, of node, i, is the operating channel of the component if it already belong to a component. In this case, the number of nodes in the component, nc, is also piggybacked. Otherwise, it is set to the default operating channel. Also, the component contention level in each channel for that particular node, $cf(1)\dots cf(k)$, is piggybacked by each node. If a node does not belong to any component, this reduces to the local contention level on each channel.

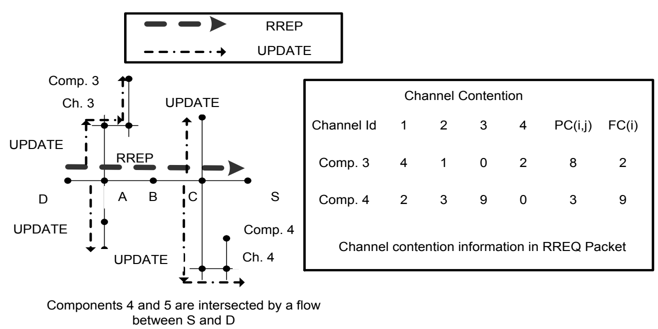


Figure 9: Component Channel Selection and Update Process

(iv) Channel Selection:

The destination waits for at a time corresponding to T_{RREQ} seconds or receipt of k $RREQ$, whichever occurs earlier, before selecting a path and channel for a particular route[3]. The destination chooses the path according to the following order of rules:

- If paths consisting entirely of uncommitted nodes are available, such a path with the minimum ambient congestion at any given channel is selected, and the path assigned to that channel.

- Otherwise, if paths consisting of some committed nodes, but with all on the same channel, are available, such a path with the minimum ambient congestion for the committed channel is selected, and the path assigned to that channel.

- Otherwise, if only paths consisting of committed nodes, with nodes committed to different channels are available, the path with the minimum number of such channels is selected. Figure 9 illustrates this scenario, where there there is a path in which two nodes are already committed to different channels. Now, the destination needs to choose one of the channels and have all the other nodes in the other component switch their channels to that channel. The destination performs this operation by appropriately considering an overall penalty function associated with each of the components under consideration to switch. For instance, if the different components are say C1 and C2 operating on channels ch1 and ch2, the relative penalties based on the channel contention $C1(cf(ch1) - cf(ch2))$ and $C2(cf(ch2) - cf(ch1))$, referred to as FC_1 and FC_2, are considered. The total number of nodes in each of the components is also taken account as a cost function, PC_1 and PC_2. The overall penalty function for each component is computed as $FC_i + PC_j$, and the component with the smaller penalty function is made to switch. Figure 9 illustrates the component selection procedure for nodes belonging to two different components.

(v) Route Reply Propagation:

[3]In the simulation results, k is set to 3, and T_{RREQ} is set to 5 seconds.

Once, the path and channel selection procedure has been performed by the destination, the route reply packet is transmitted on the chosen channel (see Figure 9). In addition, a unique component identifier is chosen for the new flow, and all pre-existing components as outlined earlier. The component identifier (with the maximum total penalty) corresponding to which the channel selection was performed, can be used as the new component identifier for all other components in the return path. In addition to that, the destination node also sends the total number of nodes in the newly formed component. This information can be computed from the original *RREQ* packet that was received. The destination node transmits the route reply on the channel information piggybacked on the original *RREQ*. Each intermediate node also performs the same operation.

(vi) Component Update:

As the route reply propagates, the intermediate nodes identify the chosen channel from the packet and updates this information for further transmissions. Further it also performs a component broadcast, where it informs all nodes in the component with the updated information. The component broadcast is a directed broadcast sent by nodes in a previously assigned component, where nodes receive a packet only if they belong to that component. Thus, the overhead of the broadcast mechanism is only limited to the number of nodes in the component. The route reply messages are sent upstream towards the source, and each intermediate node along the path performs a similar procedure. Note that nodes use the old (active) channel to propagate new component information so that nodes that still use the old channel, can update their information and also change channels if necessary.

(vii) Route Maintenance:

Whenever an intermediate node is unable to forward packets to a downstream node (towards the destination), it results in a route error. This triggers a route error message, which is propagated in to the source. The source initiates a new route discovery process as mentioned earlier in this section. Note that such a simple RERR scheme is possible only because of the fact that all nodes in the path are guaranteed to be on the same channel.

(viii) Flow Termination:

Flow termination is accomplished by the maintenance of *soft state*. When a node does not receive any packets from the upstream node in a flow for a threshold period of time T_{flow}, the flow is declared to be terminated. The nodes update their channel, commitment status and the contention values, and return to the default channel if they serve no other flows.

Variables:
i: Node id, s_i:Source id,
d_i:Destination id, c:Number of channels,
ch:Current channel of node i,
x :Commitment Indicator,
$cf(c)$: Number of contending flows on channel
k around node i,
nc:Number of nodes in the component
to which node i belongs,
$CF_1(i) \ldots CF_c(i)$:Number of contending flows in each channel for Component i
$PKT-TYPE$:Packet Type,
$RREQ$:Route Request Packet,
$RREP$:Route Reply Packet,
$RREQ(r)$:Route Request of path r
$UPDATE$:Update Packet,
cc:channel id in the $RREP$ packet,
$active(i)$:List of active channels on node i
cid: Channel id, $comid$:component id,
$PC(i,j)$:Cost between component i and component j,
$TC(i)$:Total cost for component i,

Transmit** $RREQ$**(i)
Transmit on all active channels $RREQ$ packet with a 4 tuple,
(x,ch,nc,$cf(1)$...$cf(c)$) ,

Receive** $RREP$**(i)
If(ch != cc) ,
 $ch = cc$,
 Transmit update(i),
If ($x == 0$) $x = 1$
Update with (cid,$comid$,nc)

Transmit update(i)
Transmit update packet with 3-tuple (cid,$comid$,nc)

Receive update(i)
$ch = cc$
Transmit update(i)

Decision process(i)
For each $RREQ(r)$
For each component i in the RREQ packet with channel id x
For each component j in the RREQ packet with channel id y
PC(i,j) = difference(CF_x(i),CF_y(j))
TC(i) = TC(i) + PC(i,j)
$cc(r)$= channel(maximum(TC(i))), $TC(r)$ = maximum(TC(i))
If $RREQ(r) = k$ or timer expired
 cc=channel(maximum($TC(r)$)
Transmit $RREP$(i)

Execution Sequence
If $PKT-TYPE == RREQ$
If $d_i == i$
 Decision process(i)
Else
 Transmit $RREQ$(i)
If $PKT-TYPE == RREP$
 If($s_i == i$)
  Transmit data
 Else
  Receive $RREP$(i)
If $PKT-TYPE == Update$
 Receive update(i)
If $PKT-TYPE == Data$
 Forward Data on channel ch
Do
 Monitor channels and save active channels
 Update component information
  If (flow inactive == True)
   Reset state
   Send update message
While (!(epoch end))

Figure 10: Distributed Component Based Channel Assignment Approach

CHAPTER VI

PERFORMANCE EVALUATION

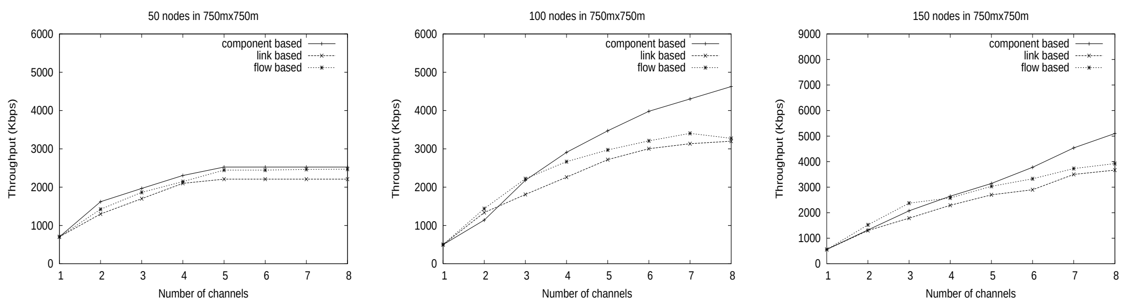
6.1 Performance Evaluation

6.1.1 Simulation Environment

We use $NS2$ for all our simulations. Unless otherwise specified the simulations are carried out for a $750m \times 750m$ grid with 100 nodes placed randomly. We vary the number of orthogonal channels available from 1 to 8. We use 3 different transmission rates namely 2, 10 and 54 Mbps to reflect realistic 802.11 a/b/g datarates. By default we use a 2Mbps channel. We use constant bit rate traffic over UDP and try to maximize the utilization of the channels (ie we increase the traffic rate of each flow till we reach saturation in each scenario). All simulation results are shown over averaging 10 seeds of the topology generated using the random waypoint topology generator provided in $NS2$. We use a constant switching delay of $100\mu s$. Our focus is on multi-hop scenarios rather than a single hop network. We use DSR as the base routing protocol and modify it for certain cases. We simulate the distributed component based approach described in Section 5.2, and approximations of the flow based (MCRP [9]), and link based (MMAC [12]) approaches. Since MMAC does not support broadcast inherently, we use pre-computed routes for simulating the link based scheme. We use aggregate end-to-end throughput and average end-to-end delay to compare the three approaches.

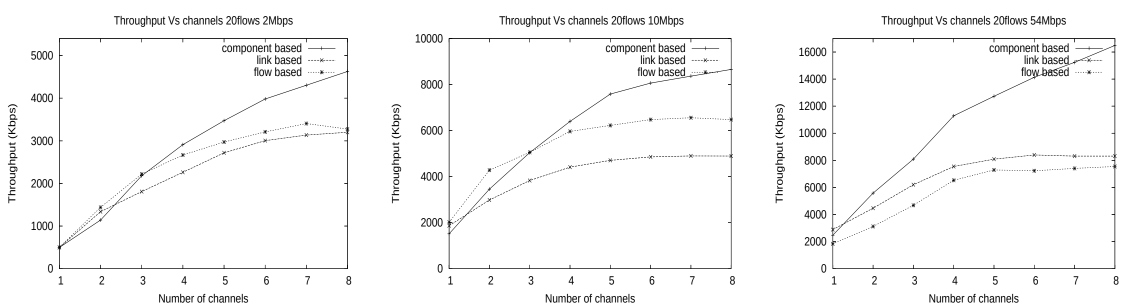
6.1.2 Effect of Density of the Network

First, we study the effect of node density (Figure 11). We vary the number of nodes in a $750m \times 750m$ grid from 50 to 150. From the figure, it can be observed that the relative performance improvement of the component based approach is significant for intermediate node densities. In a sparse network there is not much improvement with increasing number of channels due to the presence of cut vertices at which many flows intersect. For sparse networks the improvement in the component based is comparable to the flow based and link based approaches.The link based approach has a slightly lesser throughput because of the $20ms$ ATIM window overhead [12]. Also for very dense network there is a high probability that we have independent routes.Hence, for very high and very low node densities all three approaches yield similar results.



(a) 50 nodes (b) 100 nodes (c) 150 nodes

Figure 11: Effect of Density of the Network

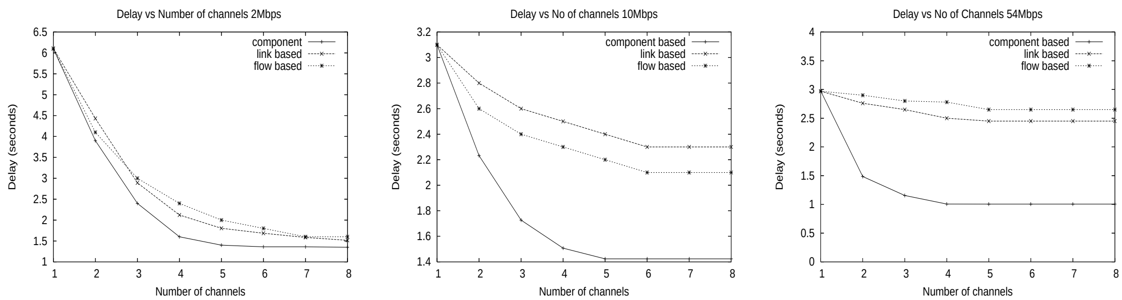


(a) 2Mbps (b) 10Mbps (c) 54Mbps

Figure 12: Effect of Channel Rate

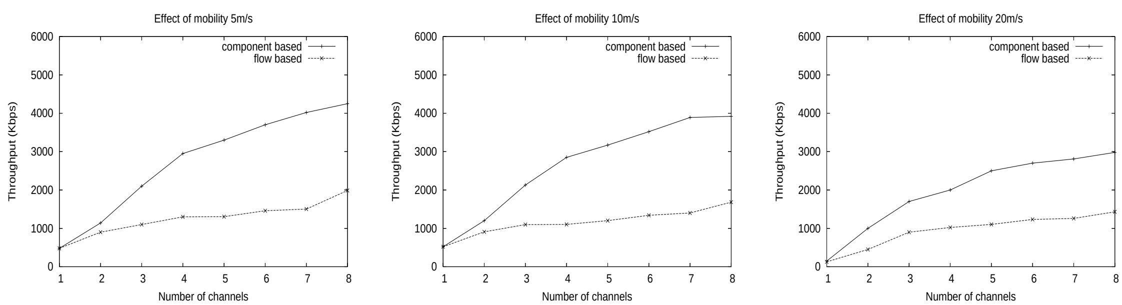
6.1.3 Effect of Channel Rates

Now we look at the effect of the channel rate on the throughput (Figure 12). We simulate for 2Mbps, 10Mbps and 54Mbps cases to reflect realistic 802.11 data rates .It can be observed that the relative performance improvement of the component based approach increases with increasing channel data rates. For the flow based and link based schemes, the effective throughput inherent in the above mentioned approaches.Since the switching nodes (nodes that keep switching between flows) accumulate packets meant for the flow that is inactive, but when they switch to a different channel for the new flow they will not be able to transmit these packets and this will lead to a significant number of packet drops for the flow on the new channel. This problem also lead to a large end-to-end delay (Figure 13). We find that as the rate increases the end-to-end delay for flow based and link based approaches is significantly higher than the component based approach, due to switching delay and lack of synchronization at the intersection nodes.



(a) 2Mbps (b) 10Mbps (c) 54Mbps

Figure 13: Average End-to-End Delay



(a) Max speed 5m/s (b) Max speed 10m/s (c) Max speed 20m/s

Figure 14: Effect of Mobility

6.1.4 Effect of Mobility

We now look at the effect of node mobility on the throughput characteristics (Figure 14). For component based approach, in the event of route failures due to mobility, a procedure similar to the route maintenance phase described in Section 5.2 is performed. We do not present mobility results for link based as handling route failures becomes non trivial in the case of MMAC, where there is lack of broadcast support. For flow based, an approach similar to component based is adopted at the granularity of a flow. First, we observe that the throughput is reduced with increasing node speeds for both the flow based and component based schemes. This is because of more route failures and a subsequent waste of time for new route computations. Further, the results show that even in the presence of node mobility, the component based approach yields a higher aggregate throughput when compared to the flow based approach.

6.1.5 Effect of Number of Flows

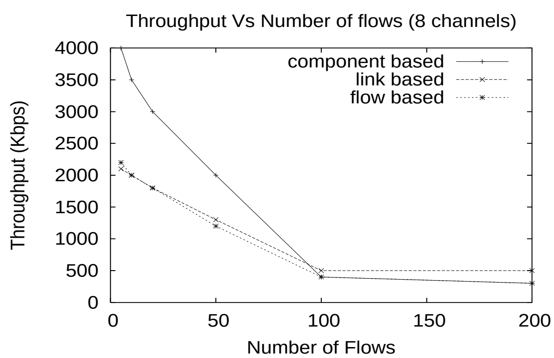


Figure 15: Impact of Number of Flows

In Chapter 3, we had discussed the impact of small number of flows for different channel rates. Here, we now consider the impact of varying number of flows (with emphasis on large number of flows) on all three strategies for a 2Mbps channel rate. Figure 15 shows the variation of the aggregate throughput in an 8-channel network with large number of flows. In all the cases the aggregate rate of all the flows is kept constant, *viz.*, 20 flows at $400kbps$ (aggregate of $8Mbps$), 50 flows at $160kbps$ each, and so on. We observe that as the number of flows increases, the aggregate throughput for all three approaches decreases. The general nature of this decreasing trend in aggregate throughput is primarily because of the distributed inefficiencies of the CSMA/CA approach [13]. For small number of flows the component based approach performs better than the link and flow based approaches because of the reasons identified in Chapter 3. However, when the number of flows is larger than 100, the component based approach yields only one component, and effectively utilizes only a single channel. In this case, the link and flow based approaches perform slightly better than component based because they use the available multiple channels. Hence, the number of transmissions on any particular channel in a contention region is reduced, and so, the utilization is likely to be higher than component based when using any contention based MAC. However, the absolute channel utilization is quite low for these scenarios, where there are large number of flows. For instance, with 100 flows the aggregate throughput observed for the link based approach is $500kbps$ while the total capacity available is $16Mbps$ ($8 * 2Mbps/channel$), which translates to a very poor channel utilization of only 3.125%. Since it is not desirable to operate the network at such low utilizations, the perceived benefit in using link and flow based approaches over component based is less significant.

6.2 Testbed Implementation

6.2.1 Setup

The testbed consists of 8 IBM and DELL laptops. For both scenarios shown in Figure 16, the source and destination nodes are equipped with Lucent Orinoco 802.11b WiFi cards. Three of these laptops have Fedora Core Linux OS, and the remaining five run on Windows XP. We consider two testbed scenarios as shown in Figure 16. For single hop flows, the source and destination nodes are configured to the same $SSID$. For multi-hop flows, we configure two of the Linux laptops as forwarders by enabling IP_V4 forwarding. *The forwarding nodes are equipped with Intel Pro Wireless 2200*

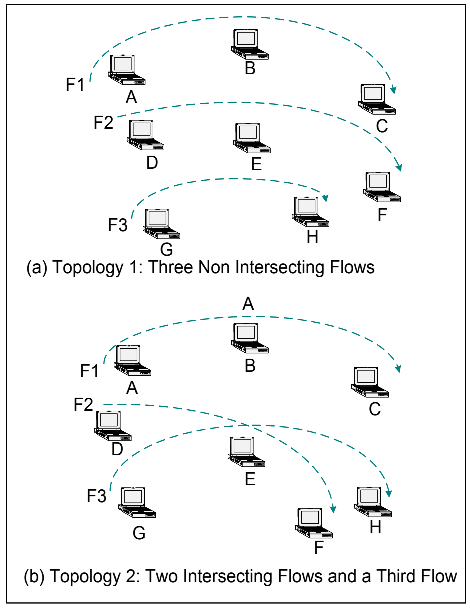
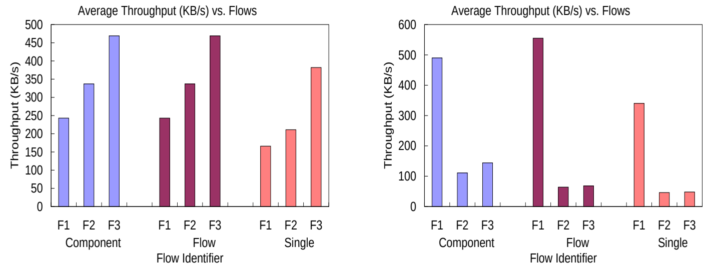


Figure 16: Testbed Scenarios for Comparison of Component Based, Flow Based and Single Channel

802.11 b/g cards. The routing tables of the source and destination nodes of each flow are configured to allow for host-specific routing. As in the single hop case, the source, destination and the forwarder are all in the same $SSID$. The source nodes for all the flows act as ftp servers and the destination node establishes a ftp connection with the server using winsock utility.

Figure 16 (a) illustrates a topology, where there are three non-intersecting flows, two of which are 2-hop flows. The third flow is a one-hop flow. In this scenario, in the single channel case, all the flows operate on the same channel. Here, both flow and component based approaches yield the same channel assignment, and each flow is set to a different channel. Figure 16 (b) illustrates a topology, where there are two intersecting flows, and a third non-intersecting flow.

To implement a flow based approach, we perform periodic switching at the forwarder between the two channels assigned for each flow at intervals of 10s. This time



(a) Topology 1 (b) Topology 2

Figure 17: Average Throughput for Component, Flow and Single Channel for the Two Testbed Scenarios

is dependent on the practical switching delay from one channel to another. To determine this switching delay, infinite number of ping messages were transmitted from one of end nodes (D,E,F,G,H) to the forwarder node, E at a constant rate of 10ms. The switching interval was increased from 100ms until the first ICMP message was received. We observed this time to be around 900ms. This 900ms is the practical switching delay, which includes hardware switching, and software updates required to receive ICMP messages. However, for the FTP connection to remain stable, the switching delay had to be much larger, and was determined to be 10 sec.

To implement a component based approach, we identify the different connected components in the network and assign different channels to them. For single channel assignment, all the flows operate on the same channel, while for flow based, each flow is assigned to a different channel and *periodic* switching is performed at intersection nodes. For both topologies, we observe the average throughput for each flow for downloading a 500 MB file. The results are averaged over 5 runs.

6.2.2 Results

Figure 17 (a) shows the average throughput in KB/s of three flows using component, flow and single channel assignment for topology 17 (a). In this scenario, component and flow based assignment yield the same channel assignment and hence the performance of these two approaches are the same. So, for this topology, we compare the component based throughput with a single channel throughput. The aggregate throughput of all three flows using a component (and flow) based approach is 1049 KB/s, and that of a single channel is 758 KB/s. The improvement in using multiple channels is only 1.4 as opposed to an ideal case of 3. This result corroborates an earlier observation in [4], where they have observed that the different sub-channels in 802.11b overlap to a certain degree. Aside from this observation, the different channels that were used in this scenario also had different background load conditions that varied with time. Also, we had selected the best channel (with the least background load) for the single channel scenario. For both component based and single channel, the average throughput for a single hop flow is about 1.8x that of two hop flows. This degradation in throughput for multi-hop flows is due to self contention.

Figure 17 (b) shows the average throughput in KB/s of three flows for topology 16 (b). Here, component and flow based assignment yield different channel assignments. Here, flows $F2$ and $F3$ are assigned to the same channel in component based, while they are on different channels in flow based. $F1$ is on a separate channel in both scenarios. The aggregate throughput for component based is 745KB/s, while that of flow and single channel are 685KB/s and 431KB/s respectively. The improvement of component based over flow based and single channel are 1.1x and 1.7x respectively. However, for flows $F2$ and $F3$, the component based assignment is 1.95x and 2.6x that of flow and single channel assignment.

CHAPTER VII

RELATED WORK

We divide the related work into three different categories based on the network layer at which channel assignment strategies have to implemented and theoretical work on capcity of wireless networks.

7.1 Multichannel Routing and Channel Assignment Approaches

In [11], a routing architecture for multichannel packet radio networks is proposed for both single interface and multiple interfaces. Although the work provides heuristics to perform routing, the details of the protocol are not discussed. The broadcast storm problem is identified but no solution has been presented. In [9], a flow based routing and channel assignment approach has been proposed for a single interface. The authors merely identify flow based and node based assignment as two possible approaches to channel assignment. They do not analyze the achievable flow capacity using a flow based assignment. On the other hand, we present theoretical analysis of capacity improvements with channel assignment at different granularity. Moreover, no rationale is presented for the use of a flow based assignment. Also, the approach is based on a simple heuristic and the practical performance of the approach has not been studied. In our approach, we have proposed centralized and distributed approaches based on the analytical results. We quantify the performance of the component based approach in a practical environment using a testbed implementation.

7.2 Multichannel Link and MAC Approaches

[3, 12] are medium access control solutions for a multichannel, single interface network. SSCH [3] is a link layer protocol for frequency hopping systems, where every node switches channels periodically following a pre-determined pattern. MMAC [12] uses a contention window based approach for channel agreement, and the data transmissions are scheduled in a periodic time-slotted manner. The above approaches are flow-unaware and cannot perform channel assignment at a granularity greater than a link. As mentioned in Chapter 3, synchronization, scheduling and switching delay are practical limitations of these approaches. Our solution performs channel assignment on a component basis, and do not have these practical limitations.

7.3 Capacity Related Work

There have been several approaches to determine the capacity of wireless networks [5, 6, 7, 8]. In [5], the transport capacity of wireless networks under the arbitrary and random network model has been derived. The results are applicable to single channel wireless networks, or multichannel wireless networks where every channel has a dedicated interface. [8] extends the results of [5], for multichannel wireless networks with varying number of interfaces. The assumptions in this work are similar to those in [5]. On the other hand, our analytical results compute the aggregate flow capacity for a given flow graph in random networks. Thus, the capacity results presented in this work are complimentary to these works. While [2, 6] consider the problem of optimal channel assignment, scheduling and routing using a linear programming technique, their analysis is for a link based channel assignment. [7] extends the analysis of [6] for multiple interfaces.

CHAPTER VIII

FUTURE WORK AND CONCLUSION

8.1 Future Work

We performed theoretical analysis of the component based approach. We identified the lower and upper bounds of the component and link based approaches. We identified that the lower bound of component based approach suffers when there are intersections and contentions in the network. We also identified specific scenarios where the component based approach performs poor. But we have not identified the probability that such a scenario occurs. We want to build up on the existing theory to identify the probability for a random topology that component based approach performs poorer compared to other techniques. Further we assumed that all nodes have only one radio. But with advances in VLSI technology and mass manufacture of the 802.11 radios, they are becoming cheaper by the day. Thus having multiple radios at a single node should be feasible. The component based approach should still be applicable in such a scenario. We plan to investigate the effect of multiple radios. We looked only at the channel assignment strategy, but did not consider end-to-end transport characteristics. We plan to look at transport charecteristics in multi-channel environments.

8.2 Conclusion

In conclusion we have considered the channel assignment problem in single radio multi-channel mobile ad-hoc networks. Specifically, we have investigated the *granularity of channel assignment decisions* that gives the best trade-off in terms of performance and complexity. We have identified a new granularity for channel assignment that we refer to as *component level channel assignment* that is simple and has impressive practical benefits. The theoretical performance of the component based channel assignment strategy does not lag significantly behind the optimal performance, and perhaps more importantly when coupled with its several practical advantages, it significantly outperforms other strategies under most network conditions. This work resulted in a publication in Mobicom 2006 [10]

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