SAMER: Spectrum Aware Mesh Routing in Cognitive Radio Networks

SHORT PAPER

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***Abstract*—Cognitive radio technology holds great promises in enabling unlicensed operation in licensed bands, to meet the increasing demand for radio spectrum. The new open spectrum operation necessitates novel routing protocols to exploit the available spectrum opportunistically. In this paper we present SAMER, a routing solution for cognitive radio mesh networks. SAMER opportunistically routes traffic across paths with higher spectrum availability and quality via a new routing metric. It balances between long-term route stability and short-term opportunistic performance. SAMER builds a runtime forwarding mesh that is updated periodically and offers a set of candidate routes to the destination. The actual forwarding path opportunistically adapts to the dynamic spectrum conditions and exploits the link with the highest spectrum availability at the time. We evaluate SAMER through simulations, and show that it effectively exploits the available network spectrum and results in higher end-to-end performance.**

***Index Terms*—Cognitive Radio, Spectrum Aware Routing**

I. Introduction

Cognitive radio networks (CORNET) are an emerging multihop, wireless networking technology where nodes are able to change their transmission or reception parameters to communicate efficiently without interfering with licensed users. In a cognitive radio based node, the radio spectrum is dynamically accessed based on instantaneous availability. *Secondary* (unlicensed) users dynamically sense the radio spectrum, and opportunistically utilize currently idle or under-utilized spectrum blocks/slices that are unused by *primary* (licensed) users at the moment. The goal is to increase the overall utilization of the radio spectrum, which is a scarce but under-utilized resource as presented by FCC in [1].

Although the lower layers of CORNETs (PHY, MAC) have been extensively studied ([3], [4], [2], [5]), CORNET routing has been largely unexplored. There are mainly two new issues with routing in CORNETs. First, the concept of "channelization", which serves as the basis for recently proposed routing metrics over wireless mesh networks (e.g. [11], [7], [9]), is no longer valid. The radio spectrum is dynamically sensed and sliced based on current availability and utilization. Therefore, there are no static channels any more in CORNETs and the routing metrics defined over each static channel need to be adapted. Second, to handle the dynamic variation in the added dimension of spectrum, routing over CORNETs has to balance between long-term (say, over 10s of seconds time scales) route stability and short-term (say, from 10s to 100s of milliseconds time scales) opportunistic performance. Most existing routing protocol operations over mesh networks do not handle both issues.

In this paper, we propose SAMER (spectrum aware mesh routing), a new routing solution for CORNETs that addresses both above issues. The design of SAMER seeks to utilize available spectrum blocks by routing data traffic over paths with higher spectrum availability. In SAMER, routes with highest spectrum availability are selected as candidates. Therefore, SAMER computes its long-term routing metric based on spectrum availability and is more or less a "least-used spectrum first" routing protocol. Moreover, it tries to balance between long-term route stability and short-term route performance via building a runtime forwarding route mesh. Once a route mesh that offers a few candidate routes is computed, the runtime forwarding path is determined by instantaneous spectrum availability at a local node. This can lead to short-term opportunistic performance gain. Our simulations show that SAMER can effectively utilize the available spectrum and achieve high end-to-end throughput.

The rest of the paper is organized as follows. Section II describes the overall system model for SAMER, and section III elaborates on new issues of CORNET routing. Section IV presents the design of SAMER. In section V we present our simulation results while section VI concludes the paper.

II. System Model

Our system model considers an underlying distributed cognitive radio architecture where PHY and MAC layer platforms work in concert to provide collaborative spectrum sensing and adaptive management and sharing mechanisms. In our cognitive radio environment, each node individually constructs a spectrum allocation matrix, which captures both the operations of the licensed spectrum users, and the secondary user activities (see [2]). A spectrum block is a slice of the available spectrum determined by the MAC and PHY layers and can be specified as a frequency interval $(f_0, f_0 + \Delta f)$ and a time interval $(t_0, t_0 + \Delta t)$. The bandwidth and the time duration of each spectrum block are tuned according to the perceived contention intensity and the total available spectrum resources.

Local spectrum availability at a node i depends not only on the interference i perceives from the primary users, but also on the number of requests from the secondary users for the allocation of the available spectrum. Two communicating nodes have first to contend for spectrum access. The contention can take place in a control channel in unlicensed bands. The spectrum block that will be used for the packet transmissions, can be decided by a handshake procedure between the sender and the receiver. The spectrum that the communicating nodes are allowed to utilize depends on the spectrum availability as defined above. The reservation can be announced on the control channel to inform neighboring nodes for the spectrum usage. Because the spectrum block that will be used for packet transmission is decided locally according to: 1) available spectrum, 2) instantaneous contention intensity, and 3) user traffic demand, the routing protocol cannot pre-specify the interfaces that will be used across the path from source to destination node. KNOWS architecture ([2]) implements the functionalities described above.

III. Routing in Cognitive Radio Mesh Networks

The intense spectrum dynamics of cognitive radio systems, make routing a very challenging and yet unexplored problem. In the following sections we discuss the limitations of current routing metrics to utilize the available spectrum in CORNET, we introduce the idea of spectrum aware routing and we argue that PHY, MAC and Network layers must work in concert, to achieve optimal routing. From now on, we define optimal routing in terms of 1) hop count (an optimal path must be close in length to the shortest hop-count path), 2) end-to-end throughput and 3) spectrum utilization (an optimal path must exploit all the available spectrum).

A. Why we need a new routing metric?

There are a lot of metrics that have been proposed so far, both for single channel([6], [10], [11]) and for multi-channel ([7], [8], [9]) wireless multihop networks. Even the metrics designed for multi-channel environments have limitations to be applied in CORNET for the following reasons:

1) Static multi-channel vs Dynamic spectrum environment: Multiradio metrics have been designed to operate in a static multi-channel environment where the available radios in each node are fixed during the network deployment. The multiradio routing approaches address the issues of intra/inter path interference by explicitly defining the sequence of channels to the destination, focusing on encouraging channel diversity. On the other hand in CORNETs, the frequency band that will be used for packets transmission is decided locally according to spectrum conditions, and the routing protocol cannot pre-specify the spectrum blocks that will be used across the path from source to destination. A path in cognitive radio is defined as a sequence of nodes from source to the destination, while two nodes can be considered neighboring when they have at least one spectrum block in common. As a result, intra/inter path interference cannot be handled explicitly by the routing protocol, but have to be addressed by the underlying protocols.

2) The concept of spectrum availability: Routing in cognitive radio networks is a two dimensional problem as it has to address: *1)* Spectrum quality, and *2)* Spectrum availability. Spectrum quality refers to different characteristic of a spectrum block as bandwidth, error rate, path-loss. Spectrum availability between a pair of nodes (i, j) is determined by two factors: 1) the number of spectrum blocks and the aggregate bandwidth across (i, j), 2) how much of this spectrum is not used by other secondary users. The first factor depends on the interference that nodes i, j perceive from the licensed users. The second factor depends on the traffic load routed through (i, j). The metrics that are used in single radio and in multi-radio environments both address the spectrum quality and not the spectrum availability dimension. The popular ETT (Expected Transmission Time) metric ([7]) considers: 1) the number of retransmissions required to send unicast packets across a channel by measuring the loss rate of broadcast packets, and 2) the bandwidth of the channel, but it does not explicitly consider the impact of contention due to traffic from nearby nodes as it is stated in [7].

B. A cross layer approach

Routing solutions in cognitive radio networks that completely ignore either the short-term local spectrum conditions or the global spectrum availability, can lead to sub-optimal routing. In the scenario of figure 1, nodes implement cognitive radio functionality and the link weights reflect both spectrum availability and quality. Source and destination nodes are S and D respectively. Firstly, let's consider that route selection and spectrum management are decoupled and that each node selects its candidate forwarding node using hop count (the best candidate is the forwarding node across the shortest hop-count path). In case that the hop-count is the same for all the candidate forwarding paths, data is forwarded over the link of the smallest weight. In this routing scenario, in the first step of the algorithm the only candidate forwarding node is A, as C is on a longer path towards D. Then S will route its packets across $S-A-B-D$ towards the destination D ignoring the high cost of its links.

Let's now assume the opposite forwarding approach where routing is handled by the MAC layer and where a node opportunistically forwards data across links with maximum available spectrum and quality (links with low weight). To avoid deviating too much from the shortest hop-count path, the next hop must be in a path which is at most n hops longer from the optimal. In our example (figure 1) we consider $n = 1$. In this case S has two candidate forwarding nodes A, C. The MAC layer is going to forward the packet to C as the $S-C$ link is better. Node C has also two candidate forwarding nodes A, F and is going to pick F for the same reason as before. The final path is going to be $S-C-F-Z-X-E-D$ which is sub-optimal both in number of hops and in spectrum quality and availability.

In cognitive radio routing a cross layer approach must be adopted where spectrum management must work in concert with routing mechanisms.

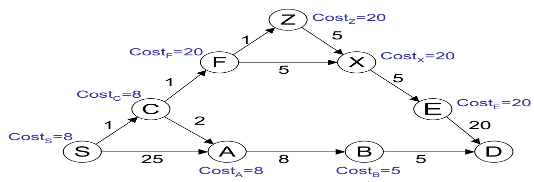


Fig. 1. Cross-layer routing

IV. SAMER Design

In this section we present SAMER, a routing protocol for cognitive radio mesh networks, whose goal is to opportunistically utilize the spectrum in the network, by routing traffic across paths with higher spectrum availability while at the same time it achieves long-term stability by not deviating from the shortest hop-count path.

SAMER builds a forwarding mesh which is adjusted periodically according to the spectrum dynamics, and opportunistically routes packets across this mesh. The mesh is centered around the long-term shortest path (in terms of hop-count), but opportunistically expands or shrinks periodically to exploit spectrum availability. In short, SAMER takes a two-tier routing approach and balances between long-term optimality (in terms of hop count) and shortest opportunistic gain (in terms of higher spectrum availability). SAMER has main two components:

1) Dynamic Candidate Mesh: Every node in the network computes a cost to the destination D (for each destination each node computes a different cost). This cost reflects the spectrum availability of the highest spectrum path whose length is less than H hops. Also every node builds a set of candidate forwarding nodes to D, by including all its neighboring nodes whose cost to D is less than a threshold C . So the mesh is built around the shortest in hop count path and is dynamically adapted to spectrum changes.

2) Opportunistic Forwarding: SAMER opportunistically forwards packets across the links with the highest spectrum availability. Upon a reception of a packet a forwarding node chooses from the links included in the candidate set, the one with the highest spectrum availability. For computing spectrum availability we use PSA metric as defined in section IV-B.

SAMER succeeds in balancing between long-term stability as the paths to the destination do not divert much from the shortest path, and short-term opportunistic utilization of the spectrum. In the following section we present the building blocks of the dynamic candidate mesh.

A. Building a candidate forwarding mesh

SAMER builds a forwarding mesh around the long-term shortest path and adjusts it periodically according to spectrum dynamics. Using this mesh, it greedily forwards data packet across the link with the highest spectrum availability. The forwarding mesh is built by computing for each node i a cost $Cost_i$ which represents the spectrum availability of the highest spectrum path whose length is less than H hops. So it computes all the paths of at most H hops and from these it selects the one with the highest spectrum availability (if there is no such path cost is set to infinity). The appropriate value for H is a difficult decision. By setting a small value for H we may not discover all the paths to the destination or we may not discover the paths with low $Cost_i$. A more flexible cost computation algorithm that can adapt to different application requirements is discussed in [14]. The algorithm increases H until it finds at node i a cost where $Cost_i \leq C_{max}$. C_{max} can be considered the maximum allowable cost to the destination. This is a double objective optimization problem as we would like to minimize H while at the same time maximize the spectrum availability (maximize spectrum availability reflects in minimizing the cost). In [14] we solve this problem using distributed Bellman Ford.

By considering hop-count, we achieve long-term stability, as all the candidate paths towards the destination, are centered around the shortest hop-count path. Except from stability, shorter hop-count paths consume a minimal amount of network resources. By considering spectrum availability, we have a global view of spectrum dynamics. In section III-B we present examples that illustrate that routing based only on local view of spectrum availability can lead to congested links. However we can limit these problems if we have a global view of the spectrum. We realize, that it is very important for each node to have an updated global view of the spectrum availability.

To sum up, in each forwarding step when a node i forwards a packet Pkt towards a destination node D, it performs the following actions: *Action 1*: Node i computes $Cost_n$ for $\forall n \in N$ where N is the set neighboring nodes of i. Node i executes a link state (e.g. OSPF) protocol so it has all the information to compute $Cost_n$ for $\forall n \in N$. *Action 2*: Node i adds to its forwarding candidate set $Candidate_i$ all the nodes n where $Cost_n \leq C$. *Action 3*: Node i forwards Pkt to the highest spectrum availability link (i, n) where $n \in Candidate_i$. Spectrum availability is computed using PSA metric described in the following section.

In this paper we consider that cost C is determined by each node separately and it is independent of the flow. The value of C is a trade-off between long and short term performance. So if C value is high, we focus more on short term path properties. This will be the recommended approach if the spectrum dynamics are very intense while the periodic updates about the spectrum availability is not very frequent which means we have an outdated global view of the spectrum. On the other hand, the value of hop count H determines how much the algorithm expands or shrinks the forwarding mesh.

In the following sections we present PSA, a metric for estimating path spectrum availability and finally we study how SAMER works in the routing scenario presented in section III-B.

B. PSA metric

PSA's goal is to capture 1) *Local spectrum availability*: Spectrum availability at a node i depends on a) the number of available spectrum blocks at i and their aggregated bandwidth and b) on the contention from secondary users. 2) *Spectrum block's quality*: The quality of the spectrum block refers to its bandwidth and loss rate. Loss rate depends both on each frequency band's properties and the interference it perceives from both primary and secondary users.

PSA formulates the throughput between a pair of nodes (i, j) across a spectrum block b as: $Thr_{(i,j),b} = T_{f,b} \times B_{w,b} \times (1 - p_{loss,b})$ where $B_{w,b}$ is the bandwidth and $p_{loss,b}$ the loss probability of the spectrum block b. Loss probability can be estimated by measuring the loss rate of broadcast packets between pairs of neighboring nodes as proposed in [11]. Finally, $T_{f,b}$ is the fraction of time during which the node i is free to transmit and/or receive packets through a spectrum block b, and it can be calculated using MAC layer information. Because the fraction of time $T_{f,b}$ for two neighboring nodes (i, j) can be different as they can perceive different interference signals from licensed users and contention from the secondary users, we consider that $T_{f,b} = min\{T_{f,b,i}, T_{f,b,j}\}$.

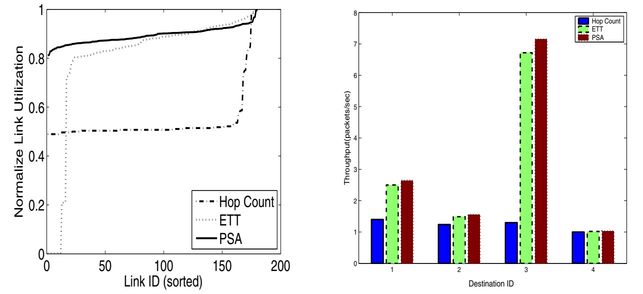
The aggregate throughput between a pair of neighboring nodes (i, j) is given by: $Thr_{(i,j)} = \sum_{b \in B_i \cap B_j} a_b \times \frac{Thr_{(i,j),b}}{maxThr_{(i,j),b}}$ where $maxThr_{(i,j),b}$ is the $Thr_{(i,j),b}$ when $p_{loss,b} = 0$ and $T_{f,b} = 1$ and B_i are the spectrum blocks available at a node i. The weight a_b ($a_b \leq 1$) reflects the different spectrum properties (interference level between neighboring blocks, channel error rate, path-loss). For our experiments we set $a_b = 1$, and we live the study of this parameter as future work.

The *Smoothed Aggregate Throughput* between a pair of neighboring nodes (i, j) is: $SThr_{(i,j)} = \alpha \times SThr_{(i,j)} + (1 - \alpha) \times Thr_{(i,j)}$ and it captures both the current view and the statistical information of spectrum availability. For our simulations we consider $a = 0.4$.

PSA across a path P is: $PSA_P = min\{SThr_{(i,j)}\}_{(i,j) \in P}$. Spectrum Availability for a path P is considered the minimum Smoothed Aggregate Throughput for $(i, j) \in P$ as this link is going to be the bottleneck which affects the whole path.

C. SAMER in an example routing scenario

In routing scenario presented in section III-B (figure 1), we showed that routing approaches that decouple Network and MAC layer can lead to sub-optimal routing in cognitive radio mesh networks. Let's consider that in the topology of figure 1, the mesh nodes execute SAMER routing protocol where H is equal to the diameter of the network. In the example topology except from the link weights, we present also the cost $Cost_i$ for each node i and we also consider for every node $C = 8$. In the first round, the algorithm has two candidate forwarding nodes C, A, and because link $S - C$ is better, it will forward the packet to C. In the second round, C has only one candidate, node A as $Cost_F > 8$. So the final path to the destination D, will be $S - C - A - B - D$ which is one hop longer than the shortest path and it has the highest spectrum availability.



(a) Link Utilization (b) TCP Throughput

Fig. 2. Link utilization and throughput performance of 3 routing metrics

V. Evaluation

In this section we evaluate the effectiveness of SAMER to 1) distribute data traffic across paths with under-utilized spectrum, and 2) improve end-to-end throughput.

A. Simulation setup

We perform our simulations using Qualnet [12]. We randomly deploy 52 static equivalent (with the same radio capabilities) nodes in a $1500m \times 1500m$ terrain. The available frequency band has aggregated bandwidth 10Mbps and can be divided by the cognitive radios in 5 spectrum blocks of 2Mbps each. A node i can have from 0 to 5 spectrum blocks b available at a time t. A spectrum block b is considered available if it is not allocated from a neighboring node or a primary user. Two neighboring nodes can exchange data if they have at least one common block available. Each time t a spectrum block at a node i is allocated by a primary user with probability P (we set $P = 0.1$).

The SAMER is simulated as described in IV. We use OSPF [13] to advertise link state information periodically, while we use the pre-computation approach where costs are pre-computed to all destinations periodically. Finally we set $C^{id}_{max} = C^{id}_{Aver}$ from a node i to a destination node d where $C^{id}_{Aver} = max\{Cost^{id}\}/2$. Intuitively we pick this value to balance between short and long term performance. The study of how C_{max} affects SAMER's performance is a part of future work.

In the following section we compare the performance of SAMER using PSA, ETT metric on each spectrum block with the shortest path (in terms of hop-count) distributed Bellman Ford algorithm. To evaluate the effectiveness of these approaches, we create intense TCP traffic that is destined to four nodes located at the edge of the mesh topology. The following results are the average of multiple simulations.

B. Link utilization and Throughput gain

We first evaluate the effectiveness of each metric to utilize the available spectrum. In table I, we present the Minimum, Maximum, Mean, and Standard Deviation of normalized link utilization, while in figure 4a we illustrate the normalized utilization for every link in the network.

Metrics	Min.	Max.	Mean	StdDev
Hop count	0.489	1.0	0.537	0.102
ETT	0.001	1.0	0.807	0.243
PSA	0.811	1.0	0.893	0.032

TABLE I
MIN., MAX., MEAN AND STANDARD DEVIATION OF NORMALIZED LINK UTILIZATION OF THE 3 DIFFERENT ROUTING METRICS

From table I we observe that the standard deviation of the link utilization for PSA metric is an order of magnitude smaller than hop count and ETT metric; the difference between minimum and maximum link utilization of PSA is much smaller than the other two metrics. This result shows that PSA can effectively utilize the spectrum. One interesting observation is that the ETT performs worse than the others metrics in balancing traffic load across different paths. The reason is that ETT favors high quality paths and it does not explicitly consider the impact of contention due to traffic from nearby nodes as stated in [7].

Figure 4a shows a detail view of the link utilization for each link. The sharp curves for ETT and hop-count metric reveal that many links are either over-utilized or under-utilized. On the other hand, the PSA metric results in a relatively flat distribution, which means load is balanced across the network.

Throughput for PSA, ETT and Hop-count in log scale is presented in figure 4b. In general, PSA and ETT metrics perform better than hop count. This is because the hop-count approach considers neither spectrum availability nor spectrum quality. Hop-count metric does not consider the spectrum dynamics which are resulted from the interference of the primary users and which lead to changes in bandwidth availability. This results in low end-to-end throughput. On the other hand, both PSA and ETT metrics consider the path quality and choose high bandwidth paths. PSA metrics is slightly better (about 0.5% to 6.4%) than the ETT metric as it also explicitly considers spectrum availability in terms of traffic load, so it avoids congested links.

Finally, we observe that for the destination node 4, and the three metrics seem to achieve almost the same throughput performance. After examining the routes of the TCP packets, the shortest path (in terms of hop-count) is not so congested as node 4 is at the edge of the network and it is not greatly affected by the cross traffic.

Our preliminary simulation results show that, PSA can more effectively utilize the available spectrum than the other two metrics. This eventually leads to higher end-to-end performance. Additional simulation results are presented in [14].

VI. CONCLUSION

CORNETs raise a new challenge as the wireless resource is no longer a 2-D factor in time and space, but is now a 3-D factor across frequency, time and space. Therefore, protocol design has to explicitly handle the implications brought out by the added dimension of radio spectrum, in order to fully realize the potential of cognitive radio nodes.

In this paper, we propose SAMER, arguably the first routing protocol in the literature that addresses two new routing issues in a CORNET: dynamic spectrum availability without the conventional concept of "channelization" in traditional mesh networks, and tradeoffs between long-term route stability and short-term opportunistic routing performance. To address both issues, SAMER renovates both the routing metric and the routing protocol operations. The routing metric of SAMER explicitly considers both route quality based and high spectrum availability. The ultimate goal is to provide optimal spectrum aware routing in the long term. To increase short-term routing performance, SAMER selects a fine-time-scale (say, 10s to 100s of milliseconds), opportunistic forwarding path out of a mesh of candidate routes computed based on coarse-time-scale (say, 10s of seconds) spectrum availability. This way, SAMER flexibly balances between long-term stable routing and short-term opportunistic forwarding. It serves as another concrete example of applying cross-layer design over a CORNET.

Our preliminary simulation evaluations have shown SAMER as a viable routing solution that can provide better performance in CORNET. Ongoing work seeks to provide more thorough evaluations via comprehensive simulations and further refine the design of SAMER.

REFERENCES

[1] FCC *Unlicensed operation in the tv broadcast bands, notice of proposed rulemaking*, ET Docket No. 04-186, May, 2004.
[2] Y. Yuan, P. Bahl, R. Chandra, P. Chou, I. Farrel, T. Moscibroda, S. Narlanka, and Y. Wu, *KNOWS: Cognitive Networking Over White Spaces*, in IEEE DySpan 2007.
[3] IEEE 802.22 WRAN WG, *www.ieee802.org/22/*
[4] M. Buddhikot, P. Kolodzy, S. Miller, K. Ryan, J. Evans *DIMSUMNet: New Directions in Wireless Networking Using Coordinated Dynamic Spectrum Access.* In WOWMOM 2005
[5] V. Brik, E. Rozner, S. Banerjee, and P. Bahl, *DSAP: A Protocol for Coordinated Spectrum Access*, in IEEE Dyspan 2005
[6] A. Adya, P. Bahl, J. Padhye, A. Wolman and L. Zhou *A Multi-Radio Unification Protocol for IEEE 802.11 Wireless Networks* In BROADNETS '04: Proceedings of the First International Conference on Broadband Networks (BROADNETS 2004).
[7] R. Draves, J. Padhye and B. Zill, *Routing in multi-radio, multi-hop wireless mesh networks*, In MobiCom '04: Proceedings of the 10th annual international conference on Mobile computing and networking, 2004.
[8] Y. Yang, J. Wang, and R. Kravets, *Interference-aware load balancing for multihop wireless networks*, UIUC Technical report, 2005.
[9] A. Adya, P. Bahl, J. Padhye, A. Wolman, and L. Zhou, *A multi-radio unification protocol for ieee 802.11 wireless networks*. In BROADNETS '04: Proceedings of the First International Conference on Broadband Networks (BROADNETS '04).
[10] S. Keshav, *A Control - Theoretic Approach to Flow Control*, In Proceedings of the conference on Communications architecture and protocols pages 3-15, 1993.
[11] D. Couto, D. Aguayo, J. Bicket and R. Morris, *A High-Throughput Path Metric for Multi-Hop Wireless Routing* In MOBICOM 2003.
[12] Scalable Network Technologies, *QualNet Simulator*
[13] J. Moy, *OSPF Version 2*, RFC 2328. Apr 1998.
[14] Ioannis Pefkianakis, Starsky. H.Y. Wong, and Songwu Lu, *Spectrum Aware Routing in Cognitive Radio Mesh Networks* Technical Report, UCLA CS Department, TR 080024, August 2008