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Multiple Constraint Routing Protocol for Frequency Diversity Multi-channel Mesh Networks using Interference-based Channel Allocation

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ABSTRACT

Wireless Mesh Networks aim to attain large connectivity with minimum performance degradation, as network size is increase. As such, scalability is one of the main characteristics of Wireless Mesh Networks that differentiates it from other wireless networks. This characteristic creates the need for bandwidth efficiency strategies to ensure that network performance does not degrade as the size of the network increase. Several researches have been done to realize mesh networks. However, the researches conducted were mostly focused on a per TCP/IP layer basis. Also, the studies on bandwidth efficiency and bandwidth improvement are usually dealt with as separate issues. This paper aims to simultaneously study bandwidth efficiency and improvement. Aside from optimizing the bandwidth given a fixed capacity, the capacity is also increased using results of physical layer studies. In this paper, the capacity is improved by using the concept of non-overlapping channels for wireless communication. A channel allocation scheme is conceptualized to choose the transmission channel that would optimize the network performance parameters with consideration of chosen Quality of Service (QoS) parameters. Network utility maximization is used to optimize the bandwidth after channel selection. Furthermore, a routing scheme is proposed using the results of the network utilization method and the channel allocation scheme to find the optimal path that would maximize the network gain.

Keywords: Multi-Channel, Routing Protocol, Wireless Mesh Network, Channel Allocation

1. INTRODUCTION

Wireless Mesh Networks is a decentralized networking technology that is currently being adapted to connect peer-to-peer clients and large-scale backbone networks. A major consideration in the implementation of wireless mesh networks is scalability. This characteristic creates the need for bandwidth efficiency strategies to ensure that network performance does not degrade as the size of the network increases. In wired mesh networks, this can be handled by adding wired mediums such as fiber optic cables. This is impossible for wireless networks due to the fixed wireless medium. To improve the capacity of wireless networks, simultaneous transmission techniques are being studied by PHY layer engineers. Orthogonal Frequency Multiple Access (OFDM) in 802.11 is one of the high-speed improvements in the PHY layer for WLAN used in mesh networks improving the speed from 11 Mbps to 54 Mbps at most. Software controlled radio transceivers have also started development. These are known as cognitive radios and software defined radios(SDR) where programmability exists in all components of a radio such as programmable radio bands, channel access and modulations. SMART antennas are also

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developed to improve capacity of wireless networks by utilizing multiple transmitter and receiver antennas. These PHY layer researches bring about the possibility of using multiple channels in a single transmission medium. However improvements should be made in traditional TCP/IP layer protocols to take advantage of these PHY layer advantages. Existing researches have studied improvements in TCP/IP protocols with emphasis on either efficiently utilizing the fixed bandwidth or increasing the available bandwidth. In [1], the network parameters are adjusted to meet preset QoS parameters by using numerical methods. However, an optimal point is not guaranteed in a highly dynamic network. Also, the time delay in arriving at a global optimum can be significant in evaluating system performance. In [2], a QoS routing is proposed for a one-to-one pairings network. This type of routing guarantees QoS parameters on a traffic type-destination correspondence basis. This type of QoS parameters processing may not be applicable to general wireless mesh networks. This research aims to consider both the bandwidth efficiency and improvement. We propose a channel allocation scheme to improve the available bandwidth via simultaneous transmission. Simultaneous transmission is achieved by using the concept of non-overlapping channels. Also a network utilization problem is used to efficiently make use of this improved available bandwidth. The network utilization problem aims to maximize network gain while considering a number of QoS parameter constraints. Using the results of the channel allocation scheme and network utilization problem, a routing scheme is proposed that to choose a path that would maximize network gain.

The network model used consists of a number of wireless routers, and wireless clients. The wireless routers are assumed to be stationary while the wireless hosts can either be mobile or stationary. A node is assumed to have one or more transceivers capable of switching channels as dictated by the firmware. Also, the firmware should also

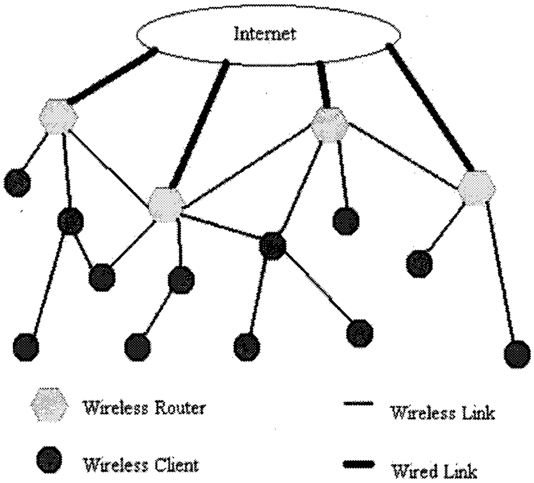

Fig. 1. Wireless Mesh System Architecture.

be able to measure the RSSI level received from a neighboring node. In the simulation for this paper, 802.11 nodes are used however usage of different standards is possible as long as interference measure can be provided by the firmware. For 802.11b/g nodes, there are 3 non-overlapping channels that can transmit simultaneously for each time instance while for 802.11a, 12 of such channels can be used. These channels would not interfere with one another thus can be used to transmit data at the same time. Fig. 1 shows the architecture of the system. The Wireless routers are connected to the Internet backbone using wired links. The nodes can be connected in a peer-to-peer manner as shown in the figure.

The remainder of the paper is organized as follows: Section II addresses the related works analyzing current researches done on bandwidth efficiency and improvement for wireless mesh networks. Section III describes the interference-based scheme used for channel allocation. Section IV describes formulation of the network optimization problem including the description of the constraints used. Section V shows the routing scheme proposed combining the channel allocation scheme and the network optimization problem, while handling their interdependencies. Section VI presents the results of simulation of the schemes proposed. Finally, Section VII summarizes the research done as well as future research planned.

2. RELATED WORKS

Several researches have been done in improving network performance of wireless mesh networks. However, most emphasize either on bandwidth efficiency or bandwidth improvement. A few researches have been done combining these two concerns though some limitations have been seen that needs further improvement.

[3] and [4] survey research done regarding wireless mesh networks. [3] discusses issues per TCP/IP layer level. With the improvement in PHY layer, which introduces new technology to further improve the capacity and throughput of wireless mesh transmission, improvements in currently used wireless mesh routing protocols should be done. [4] discusses some techniques used in mesh networks. This paper was done for wired networks however the concept of making the network acyclic is very important for wireless mesh networks. Since mesh clients can connect via peer-to-peer connection similar to wireless adhoc network, avoidance of cycles is helpful to avoid "deadlock" or looping.

The remaining related works for this paper is classified into two areas according to focus: Network Utility Optimization [1,2,5-9], and Channel Allocation [10-13].

2.1 Network Utility Optimization

Using a numerical method based on Mean Field Annealing, [1] proposes a novel routing scheme that uses deterministic equations to relax the system into an optimal state based on delay and capacity constraints given by QoS parameters. This is fit for wireless mesh networks since it can adapt to changes in network parameters such as topology. However, a consequence of using numerical calculations in this protocol is that, at the presence of congestion, a significant amount of convergence time is needed before arriving at globally optimized solution. Also, for frequently changing network parameters, the methodology may not arrive at a global maximum. Also, certain amount of communication overhead is needed to transfer numerical data. Our research aims to lessen the convergence time by using linear optimization in arriving at the optimal routes.

Due to changes in physical layer characteristics, as well as wireless mesh network characteristics, some consequences on per TCP/IP layer performance metrics should be attended to. Also, some traditional metrics would not be applicable for use in wireless mesh networks. In [5], new high-throughput multi-cast metrics are proposed in contrast to traditional uni-cast metrics. In wireless mesh networks, it is common to have multi-cast transmissions specially when using multiple channel transmission to further improve the available bandwidth as well as bandwidth efficiency. However, this paper proposed multi-cast metrics based on a single channel network. A future work of this paper is to conduct similar studies for multi-radio/multi-channel wireless mesh networks. This paper focuses more on the bandwidth efficiency issue with minimum attention to available bandwidth improvement. Since channel variation is included in the focus of our study, we need to add a metric that allows us to observe, as well as improve, the network performance of the network. The channel utilization metric, discussed in the succeeding sections, provides us a logical measure of channel distribution fairness.

[2] proposes a match-making service for wireless mesh network based on content. This is a QoS routing scheme where routing is based on the data content and not specifically on address attached to the messages. This improves the time of arrival for the messages as well as the effective throughput. However, this is based on a matchmaking

service for mesh networks. This implies a traffic type-destination correspondence and can eventually be globally unfair depending on the message sent. This protocol is beneficial for applications where one to one correspondence is possible. However, contention may become a problem for high density networks.

[6] shows a solar battery modeling approach to estimate the current amount of charges that can be provided by a power supply. This model is used as one of the constraints for the network utilization problem as defined by the next sections. In [6], modeling results show that the mathematical model used to represent the battery charging and discharging processes are valid and accurate in comparison with hardware implementation. It is used in this paper to determine the amount of power units available for use by each node.

A scalable ring-based topology is studied in [7] and [8] investigates the capacity, QoS and coverage trade-offs in wireless mesh networks with [8] also focussing on load-balancing of traffic. A frequency planning model is proposed using a ring-based architecture to improve the capacity and coverage of the network. An optimization approach is used to determine the optimal number of rings and the optimal width of each ring. The disadvantage of using this architecture is the existence of a bottleneck near the central gateway/router of the network. All traffic from the cluster would need to access at least one node in the first ring thereby increasing collision occurrence. Also, the effects of power control was not investigated. Our paper eliminates bottlenecks by checking the current channel condition if it meets the preset QoS parameters each time packets traverse a router. Depending on the measured channel condition, the channel condition table and routing table are updated.

A new routing metric is used for wireless mesh networks in [9]. The proposed routing metric is defined as the expected number of transmission before a successful transmission from a node x to node y. Using this metric, the LQSR routing protocol is modified to incorporate their multiple radio framework. The major role of this paper is to obtain an optimal throughput to send data from source to destination. In this paper, channel utilization is not considered as a major factor. Contention within a commonly assigned channel would yield some drop packets and additional delay. In assuming equal utilization, some packet losses are not considered. Our paper considers these loses by adding a channel utilization metric which aims to balance the load of all channel throughout the network. This minimize if not eliminate the packet errors due to contention in widely used channel.

2.2 Channel Allocation

Hyacinth is an implementation of a centralized channel allocation algorithm using WLAN as platform. In [10], the implementation is described in detail with emphasis on the hardware and the messaging protocol. Network performance is compared with a conventional single-channel WLAN implementation. From experiments done, it is shown that network throughput has improved by a factor of 6 to 7. In [11], the details of the channel allocation and selection schemes are described. Papers [10,11] shows that the implementation of multiple channel transmission can improve network parameters by a good factor. However, for a true wireless mesh network, interactions with different standards should also be investigated. Also, the routing algorithms used in Hyacinth are traditional shortest path algorithms where degradation of network performance implies a global rerouting of the network, which could cause delay in message transmissions. Shortest path routing may not be suitable for use in multi-channel wireless networks. This is because traditional computations for path costs may not be enough to sufficiently rate the quality of connection between two nodes.

The DSDV-MC [12] routing scheme improves the conventional DSDV routing protocol to consider available bandwidth improvements by using multiple simultaneous transmissions. It also proposes a channel information gathering scheme with low overhead. Also, a channel reallocation scheme is proposed to reduce unfairness in the network by using a channel distribution index. However, an assumption made is that channel switching overhead is negligible which may not be the case in a dynamic network. Also reference index and time interval variables, used in the channel distribution index computation, are manually set in the simulation as opposed to dynamic variation in the real world scenario.

The Column-based Multi-channel Optimization [13] jointly considered the routing and scheduling layer to propose an adaptive algorithm to maximize network gain. Also, a column-generation based approach is used to generate feasible patterns as needed to construct transmission patterns. However, no further improvement is gained from channel addition when the system time has been dedicated to traffic delivery at bottleneck nodes. Also, a global system time is used.

Our research on channel allocation scheme proposes a sender initiated hybrid channel allocation method. A channel allocation metric is proposed to ensure channel distribution fairness across the network. Based on the channel allocation metric, as well as delay and power, channels are assigned to each node. This channel allocation is fixed as long as the QoS parameters are met. In case of degradation in network parameters, the routers would then initiate the reallocation of channels in its neighborhood. Only routers, which are most probably stationary and directly attached to power, do the channel reallocation processing.

In current researches done, issues were often handled on a per layer basis. Bandwidth efficiency and available bandwidth improvement are treated as separate issues. Upon review of the related literature the following goals are set for this paper:

(1) To simultaneously deal with the issues of bandwidth efficiency and available bandwidth improvement.
(2) To propose an interference-based channel allocation algorithm to improve available bandwidth.
(3) Apply network utility maximization to improve bandwidth efficiency
(4) Based on results of the channel allocation scheme and network utilization problem, propose a modified routing algorithm to maximize network gain.

3. INTERFERENCE-BASED CHANNEL ALLOCATION SCHEME

3.1 Channel Allocation Scheme

To provide a distributed manner of channel allocation as well as routing, two groups of channels are provided: control channel group and data channel group. The control channel allows exchange of routing and channel allocation information such as channel requests, routing requests and addressing information. Node Broadcast packets and multi-cast packets are also transmitted using the control channels. To minimize congestion in the control channel, a set of non-overlapping channels would be assigned for use, i.e. for 802.11b/g three channels can be used as control channels while twelve channels are used in 802.11a nodes. The remaining channels available would be used for transmitting data packets. The network architecture has dynamic topology due to possible existence of mobile clients. As a result, no channel is specifically assigned per node and channel allocation would be on a per-demand basis.

Channel allocation would be based on the interference of neighboring nodes. This means that the node should transmit at the frequency with least interference. In the case of 802.11, some channels are non-overlapping, thus no interference occurs when these non-overlapping channels transmit simultaneously. To make an ideal transmission, the neighbors of the transmitter must be transmitting using a channel that is non-overlapping with the transmitter's channel of transmission. In the same way, the receiver's neighbor should not receive any transmission using overlapping channels of the transmitter's channel.

Definition 1.

Two channels A and B (where center frequency of A is higher than B) are non-overlapping if CenterA + Bandwidth = CenterB − Bandwidth where CenterA and CenterB are the center frequencies of channels A and B respectively.

When a node x needs to transmit data to node y, x first checks its neighbors on which channel they are transmitting at. Checking the received signal strength (RSSI) in each channel of transmission would accomplish this task. The transmission channels of its neighbors are noted by the transmitting node x. Node x then sends a transmission request using an available control channel group. The set of channels used by the neighbors of x, C_{NBx}, is included in the transmission request message. The receiver, upon receiving the request, checks which of the channels, that are non-overlapping with the channels in C_{NBx}, are available. Take note that not all channels that can be heard by the receiver necessarily transmit information to the receiver. A possibility is that another node is transmitting information to a neighbor of the receiver. A channel that is being used by the receiver y to receive information from another node cannot be considered as an available channel. The receiver would then choose the channel based on these available channels. The channel selection would be based on the Shannon-Hartley capacity equation (1). C_i is the maximum capacity that can be transmitted in channel i and B is the bandwidth per channel.

$$C_i = B\log(1+\gamma_i) \tag{1}$$

$$\gamma_i = \frac{RSSI_x}{\sum_m RSSI_{m\neq x} + Noise} \tag{2}$$

If a channel w, which is non-overlapping with the any of C_{NBx}, then $RSSI_{m\neq x}$ is 0. This channel would be a priority channel since minimal interference is achieved when transmitting using this channel. Channel w can now be sent to the transmitter in the reply message indicating that this channel is available for transmission. If no such channel is found, that is available channels are overlapping channels, receiver y would consider the "unused" overlapping channels and find which channel would give the maximum capacity.

Definition 2.

A channel is said to be "unused" if the receiver is not using it to receive information from another transmitting node.

$$\begin{aligned} &\max C_i = B\log(1+\gamma_i) \\ &s.t. \\ &\gamma_i = \frac{RSSI_x}{\sum_m RSSI_{m\neq x} + Noise} \end{aligned} \tag{3}$$

Eq. (3) describes the problem of choosing the channel to maximize the capacity. Maximizing the capacity also equates to minimizing the Signal to Interference Noise Ratio (γ_i). With a minimum γ_i, this implies that the algorithm has found a non-overlapping channel with the channel used by the node. A non-overlapping channel yields a γ_i that approaches to 0.

3.2 Channel Utilization Metric

If multiple non-overlapping channels are found or if a number of channels have the same computed maximum channel capacity, a node needs to decide which channel would be advantageous to the whole network. This involves the knowledge of channel utilization in the whole network. This is important especially when the network has a large number of nodes. There would be instances when some part of the network would have available channels while on some part overlapping channels are already utilized. This is a case of network channel distribution imbalance. We can get the utilization equation given in (4). Q_i is the number of neighbor nodes of x which uses channel i. $\sum_i Q_{kNBx}$ is the total number of neighbor nodes of x hat are currently transmitting. Ideal channel utilization is when all CU_i are equal. To add the channel utilization to the channel allocation problem, we can reformulate equation (3) to include equation (4). We can then arrive at (5) which consider both the channel utilization metric and SINR as constraints to choosing the best channel for transmission. The expression in (5) implies that we choose the channel with the highest SINR(γ_i) while evenly utilizing the available channels.

$$CU_i = \frac{Q_{iNBx}}{\sum_i Q_{kNBx}} \quad (4)$$

$$\max C_i = B\log(1+\gamma_i) - (CU_i)$$
$$s.t.$$
$$\gamma_i = \frac{RSSI_x}{\sum_m RSSI_{m \neq x} + Noise}$$
$$CU_i = \frac{Q_{iNBx}}{\sum_{\substack{for \\ all \\ i}} Q_{kNBx}} \quad (5)$$

4. NETWORK UTILIZATION PROBLEM

4.1 Network Utility Constraints

After the assignment of the channel to be used, another optimization problem is needed to choose the optimal path that the packet will traverse using the assigned channel. In wireless mesh network, delay, power and link transmission rate are considered important factor due to the topology and complex nature of wireless mesh networks.

4.1.1 Link Transmission Rate Constraint

Wireless transmission is usually unconstrained when it comes to link capacity. The only constraint results from the Shannon Hartley Theorem, which defines the maximum allowable transmission rate for minimum packet loss. In this paper, simulations would be done in scenarios where the capacity is a given constraint (constant) and another possible scenario is when the link capacity is a function of the SINR (Signal to Interference Noise Ratio). Eq. (6) defines the constraint for the transmission rate.

$$0 \leq x_{sl} \leq c_l \quad (6)$$

The variable x_{sl} defines the transmission data rate from node s to node l. The variable c_l defines the upper bound to the transmission rate from node s to node l. This can be defined as a constant for simplicity or assigned according to the Shannon-Hartley Theorem as a function of SINR. Suppose we have a power vector P $(P_1, P_2, \cdots Pi, \cdots P_N)$, a gain matrix G, where G_{ik} defines the transmission gain from node i to node k, and a noise power vector N $(N_1, N_2, \cdots N_i, \cdots N_N)$, the equation for the SINR is defined as Eq. (7). The power vector P defines the measured power transmission from neighboring nodes. This can be quantified as the measured RSSI.

Given Eq. (7) we can find the maximum capacity for a link given by Eq. (8) where C_{MAX} the maximum capacity that can be provided for link l. In one scenario of this paper, this value of c_l is considered as the maximum transmission rate for minimum packet loss.

$$SINR_l = \frac{P_i G_{ii}}{\sum_{i \neq k} P_k G_{ik} + N_i} \quad (7)$$

$$c_l = C_{MAX} \log_2(1 + SINR_i) \quad (8)$$

4.1.2 Delay Constraint

Delay parameter for QoS is related to both the memory size and the transmission data rate. As we increase the transmission data rate, we have a high probability of increasing the queue. We assume that the effect of delay due to packets being dropped from the queue is more significant than the reduction in delay caused by the increase of transmission rate. The delay parameter is given by Eq. (9) indicating that the delay experience is inversely proportional to the service rate and the queue parameter.

$$D_l(x_{sl}) = \frac{1}{\mu(1-\rho)} \quad (9)$$

$$\rho = \frac{x_{sl}}{x_{lout}} \quad (10)$$

where

x_{sl} = the transmission rate at link l
x_{lout} = the outgoing transmission rate at node l
ρ = queue parameter
ì = service rate

The delay parameter can be expressed as Eq. (11) where D_{MAX} is defined as the QoS parameter for the delay.

$$0 \le D_l(x_{sl}) \le D_{MAX} \quad (11)$$

4.1.3 Power Constraints

Power is one of the most important parameter for wireless mesh networks. Ideally, wireless mesh networks are designed to be unattended and must have long lifetime to reduce deployment cost. Suppose that the power consumed is given to be proportional to the transmission data rate, we can also get the measure for the power parameter using Eq. (12) where ó is the proportionality constant. The QoS parameter for power is expressed as Eq. (13) where P_{Min} the QoS requirement. Details of the model used in for these equations can be seen in [6]. The model used for power is a solar recharging power supply. Comparisons of the simulation results with hardware implementation measurements can also be seen in [6].

$$P_l = P(n) - \sigma x_{sl} \quad (12)$$

$$P_{\min} \le P_l(x_{sl}) \le P_{MAX} \quad (13)$$

4.2 Utility Function

The utility function U_l should be defined such that the transmission data rate is maximized while minimizing the delay and power parameter within the limits of a set of QoS requirements. The utility function should also be strictly concave to make sure that a maximum exists for the optimization problem. The utility function used is defined by Eq. (14) where D_l and P_l given by Eq. (9) and (13) respectively. The logarithmic function ensures that addition of the parameters would still yield a concave function for convex problem analysis.

$$U_l = w_1 \log(x_{sl}) - w_2 \log(D_l) - w_3 \log(P_l) \quad (14)$$

From Eq. (14), it can be observed that to maximize the utility function we need to maximize the transmission data rate x_{sl}, which has trade-offs on delay. The variable w_1, w_2 and w_3 are constants which can be used to add a priority service in choosing which QoS parameter would have more significant effect on the transmission of data. The utility function is strictly concave since a logarithm function is strictly concave. Also the utility function follows the concavity criterion described by Eq. (15) where $f(x)$ and $f(y)$ are instances of our utility function U_l.

$$f\left(\frac{x+y}{2}\right) \ge \frac{f(x)+f(y)}{2} \quad (15)$$

4.3 Optimization Problem

The preceding sections handled the problem of choosing the optimal channel to use by taking into consideration SINR and the channel utilization metric. After making the optimal channel choice, the algorithm must also choose the optimal path that the packet should follow. A second optimization problem arises and this would involve the using the link transmission and delay constraints.

From the formulations given, we can express the problem of utility by using optimization. The aim of the problem is to maximize the transmission rate while minimizing the delay. Using this optimization problem, we also aim to minimize the cost of transmission of data through link l. This minimized cost would then be used to determine the path from source to the gateway node that would yield the lowest cost to the system. Cost is defined as the aggregation of delay and transmission rate characteristics for a given link. The optimization problem can be expressed as in Eq. (16).

From looking at the problem, it is observed that the main goal is to find the optimal x_{sl} such the utility function U_l would be maximized which also implies maximizing the transmission data rate x_{sl} while minimizing the delay and power.

$$\mathbf{P}: \max U_l(x_{sl}, D_l(x_{sl}), P_l(x_{sl})) \tag{16}$$
$$\text{Subject to}$$
$$0 \le x_{sl} \le c_l$$
$$0 \le D_l(x_{sl}) \le D_{MAX}$$
$$P_{Min} \le P_l(x_{sl}) \le P_{MAX}$$

To simplify the problem, we can express the utility as a function of x_{sl}. This is possible because D_l is also a function of x_{sl}. The utility function can then be expressed as Eq. (17).

$$\bar{U}_{sl}(x_{sl}) = w_1 \log(x_{sl}) - w_2 \log(\frac{x_{lout}}{\mu(x_{lout} - x_{sl})}) - w_3 \log(P_l) \tag{17}$$

The utility function is simple because it is only dependent on one variable, x_{sl}. The constraint set can also be expressed as functions of one variable x_{sl}. We can express the constraint as the following set of equations in Eq. (18).

$$0 \le x_{sl} \le c_l \tag{18}$$
$$0 \le x_{sl} \le \frac{(\mu D_{MAX} - 1)x_{lout}}{\mu D_{MAX}} = K_1$$
$$P_{\min} \le x_{sl} \le \frac{P(n)}{\sigma} = K_2$$

It can be seen that these equations are sets of limits for x_{sl}. Since these equations limit only one variable, it can be proved that these constraints can be combined into a single constraint. The simplified form of the optimization problem defined in Eq. (14) is shown in Eq. (20). Equation (20) implies that we find the maximum value of the concave utility function such that the link data rate x_{sl} is not more than a max value defined by the min of the upper limits defined in (18). This implies that our optimization problem would depend on only the data rate value for each link.

$$Q: \max \bar{U}_{sl}(x_{sl}), \tag{19}$$
$$\text{Subject to}$$
$$0 \le x_{sl} \le \min(c_l, K_1, K_2)$$

V. Multiple Constraint Routing Protocol for Frequency Diversity Multi-channel Mesh Networks using Interference-based Channel Allocation

In Section III, we described our channel allocation scheme using interference measurements. In addition Section IV, we gave details on how we arrived at a network utilization problem that maximizes link data rate in the system with constraints on power and delay. In this section, we combine the two schemes to find the optimal path that data packets would traverse to achieve optimal data rates.

Unlike in traditional wireless networks, routing is done by choosing the optimal channel and choosing an optimal route in the chosen channel. All nodes have the capability to choose the optimal channel. However, a significant amount of delay may be experienced due to the control messages that need to be sent between the source and destination nodes. The more practical approach is process channel selection only at router nodes. The reason for this is the assumption that router nodes would have more processing capabilities to monitor neighboring node status. Also, in mesh networks, the router nodes usually do not have power limitations, i.e. usually not battery powered.

The data channels and the control channels are separated to ensure that the control packet do not affect the transmission of data. The control channel is used to broadcast routing information to the neighboring nodes. This is done using a single set of non-overlapping channels for the control channel set. The control packets contain the source address, destination address, QoS parameters and the cost of the link used.

Fig. 2 shows the step-by-step procedure for the algorithm. In this algorithm, only the routers process the channel assignment algorithm. The nodes update their routing tables as packets arrive. Initially, the sender checks the channel condition and decides on which channel to use to communicate to its neighbor. Based on the present channel conditions for all available channels, it would update the channel condition and routing table. If the chosen next node is already part of the set of nodes that the packet has traversed, it would choose the next best node to avoid the possibility of looping in the routed path (step 5 to 7). When a router is traversed, the channel condition is again determined. This implies that only the sender and the traversed router update the channel condition table. The channel allocation scheme is only implanted at the sender node and routers. The delay can be considered minimal since the nodes updates using the current value of RSSI that they are receiving. Also since the control channel is separate, waiting time for queries is reduced. Take note also that the optimal path is not necessarily the shortest path to the destination. This happens when the shortest possible path to the destination is congested with traffic. The delay constraint from the network utility problem prevents the accumulation of excessive delay. This minimizes bottlenecks in the network since packets can take alternative paths when the shortest path is not available. The routing algorithm proposed is dependent on the network link condition, similar to existing QoS routing protocols. The update of the routing table and channel condition table makes use of equations (5) and (19) to calculate and predict changes in network parameters.

Initialization
Initialize routing table
Initialize channel condition table
Begin
Repeat until successor = destination

1 Check Channel condition at the source and decide which channel to use.
2 Update channel condition table
3 Using a chosen channel, calculate the link cost.
4 Update Routing table according to the gathered data.
5 **If** successor is already part of the set of nodes that the packet has traversed,
6 Choose another successor.
7 **Goto** 4.
8 Forward data to successor node.
9 **If** successor node is router,
10 **Goto** 1
11 **Else,**
12 **Goto** 3

Fig. 2. Routing Algorithm.

6. SIMULATION RESULTS

In the simulation, we assume usage of 802.11g compliant clients and routers. There are 11 available channels and for each channel there are 2 non-overlapping channels. In the simulation, we assume 500 transmission requests where the transmitter initiates the channel allocation scheme. Using equation (4) we can get the channel utilization for each channel.

Using Lagrangian dual method for solving optimization problems, we can simplify further the optimization problem presented in Eq. (19). The Lagrangian function is defined for Eq. (19) by Eq.

(20), which leads to the dual problem solution.

$$L(x_l, \lambda) = \bar{U}(x_l) + \lambda(K - x_l) \qquad (20)$$

Numerical analysis was done using Matlab. For simplicity and to show tradeoff characteristics, it is assumed that the parameters all have equal weights, i.e. $w_1=w_2=w_3$. However, note that the values of these weight does not in anyway affect the general performance of the proposed protocol. These weights are added to provide service providers customization in providing QoS service. For example, if higher data rate is more important for a certain business are, then the service provide can choose w_1 such that $w_1<w_2$ and $w_1<w_3$. Of course in doung this, delay and power improvements would be sacrificed. The value of these weight indicate the priorities for QoS handling. Fig. 3 illustrates the scenario used in simulation of the proposed protocol using 40 nodes. Each node is capable to connect two channels simultaneously. Fig. 4 shows that adding the channel utilization metric channel characteristic is given more attention thus allowing equal priority for all channels in the bandwidth. It also shows that the utilization is good enough since the range of difference between the channel utilization for each channel ranges from 0.02-0.04. This means that the channels are efficiently used. The utilization of channels becomes more efficient

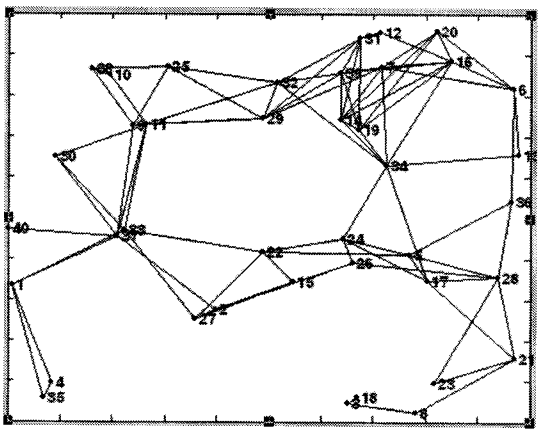

Fig. 3. Simulation Scenario.

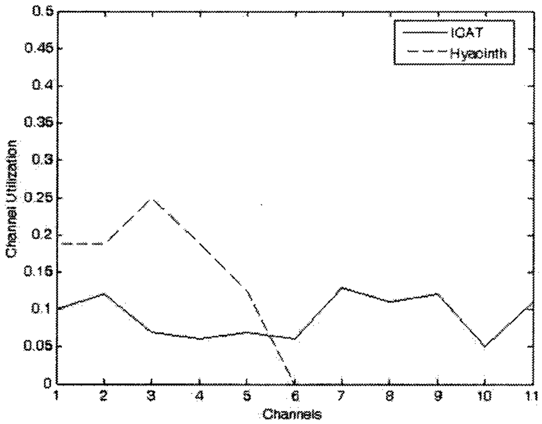

Fig. 4. Chann]el Utilization.

as the size of the network increase. Since the higher channels are more prone to degradation, increase in number of nodes would tend to decrease channel quality resulting in bulk of the links choosing lower frequency channels. With the channel utilization metric, the distribution of channels is balanced out among the links.

Fig. 5 shows the variation of the Link Data Rate after application of the algorithm with respect to the listed values of the service rate. Fig. 6 shows the measure of the power dependence in relation to data rate for a given queue service rate. These two figures show that as the link data rate increase, the queue service rate and power dependence also increase. This implies the tradeoff characteristics for power dependence and queue service rate. Queue service rate improvements can directly imply improvements on the delay and queue length parameters described in section IV. We can adjust the network parameters based on the preset QoS parameters defined by weights w_1, w_2 and w_3. Note that in Fig. 5 and 6, these weights are assumed to be equal.

The optimization problem includes power as a part of its constraints. In this simulation, we assume a photo-voltaic cell powered system as described in our previous work [6]. Simulation of this work shows the accuracyof the power model used in representing solar charging of battery systems.

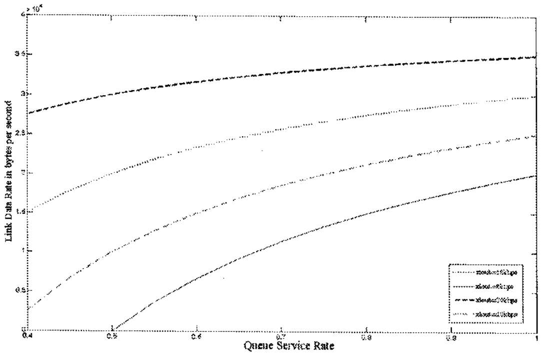

Fig. 5. Queue Service Rate vs. Link Data Rate.

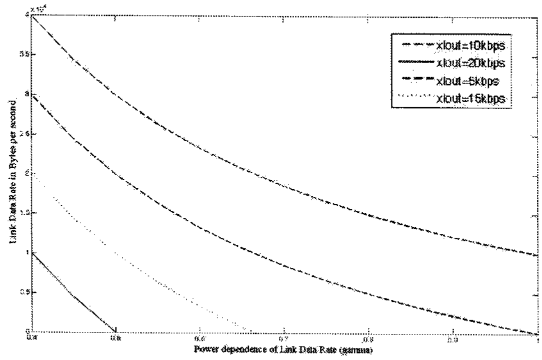

Fig. 6. Power Dependence vs Data Rate.

7. CONCLUSION

This paper proposes a multi-transmission QoS route discovery with emphasis on delay and link data rate. A new channel assignment metric is proposed which takes into consideration the traffic load balance between different channels. In the route discovery, the optimal channel is chosen first by the source. The nodes along the path would check the optimal path by calculating the link cost while traversing the path. Separate data channels and control channels were used to control the delay and traffic load for channels especially during the updating process. A future work to be done in this research is the study of directional SMART antennas and other spatial diversity techniques to further increase the capacity of wireless mesh networks.

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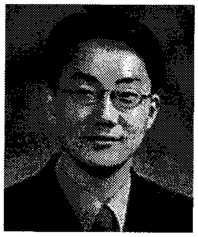

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