Journal of Korea Multimedia Society Vol. 11, No. 12, DECEMBER 2008(pp. 1697-1705)

Analysis of the Capacity Region for Two-tier Spatial Diversified Wireless Mesh Networks

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ABSTRACT

Several studies made for wireless mesh networks aim to optimize the capacity for wireless networks. Aside from protocol improvements, researches were also done on the physical layer particularly on modulation techniques and antenna efficiency schemes. This paper is concerned with the capacity improvements derived from using spatial diversity with smart adaptive array antennas. The use of spatial diversity, which has been widely proposed for use in cellular networks in order to lessen frequency re-use, can be used in mesh networks both to minimize co-channel interference (CCI) and enable multiple transmissions. This paper aims to study the capacity region and bounds in using smart antennas for single-channel multi-radio systems in relation to the number of spatial diversity or sectors as defined by the beam angle β.

Key words: Wireless Mesh Network, Directional Antenna, Spatial Diversity, Capacity Region

1. INTRODUCTION

A Wireless Mesh Network (WMN) 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. To improve the capacity of wireless networks, simultaneous transmission techniques are being studied by PHY layer engineers. Recently, the use of multiple channels and multiple radios were intensively studied both in industry and academe. Nowadays, focus in bandwidth improvement for wireless mesh networks has been directed at using spatial diversity.

Spatial diversity is a system of antenna arrays combined with adaptive signal processing algorithms that can identify the spatial signal signature such as DoA (direction of arrival) and use it to calculate beam-forming vectors. The resulting directional beam from these vectors can be focused at transmitting or receiving nodes. Directional transmission and reception is achieved by creating antenna geometry to focus radio waves in one direction or utilizing an antenna array that would synthesize directionality through constructive and destructive use of interference. Radiation nulls, which has ideally 0 or negative gain, can also be formed using beam-forming vectors in order to decrease, if not eliminate, co-channel interference. Focused radiation patterns and suppressed interference increases the capacity of a wireless network by minimizing the collision of co-channel transmissions. Increased intelligence in antenna systems with the

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Receipt date : Mar. 12, 2008, Approval date : Aug. 26, 2008

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use of adaptive antenna arrays relies on the use of algorithms for DoA estimation and radiation null steering. Most of these algorithms attempts to maximize Signal to Interference Noise Ratio (SINR) by using correlation matrices of the interfering signal vectors and the desired signal vector.

To effectively exploit the advantages of adaptive antenna arrays, several conditions should be met. First, the node should know where and when to direct its radiation pattern. Similar to the widely studied channel assignment problem in multi-channel environment, this condition is considered as an NP-hard problem. The complexity is also increased when a distributed solution is desired. Second, the node should know where and when to null interference. This is a unique characteristic of adaptive antenna arrays. This allows the node to mitigate the received interference from surrounding nodes. Third, to implement the previous conditions, the node should acquire the node states such as location and antenna directionality from its surrounding nodes. In wireless mesh networks, this can be a challenge since it is desired to acquire node information in a scalable and distributed manner. The gathered node information would then be used to shape the radiation pattern based on desired directions, power control and nulling directions. Fourth, congestion and scheduling mechanisms should be implemented for these scenarios to prevent congestion and coincident transmission. Once the beam and null directions are chosen, line of sight interference can still occur. Also, the problem of MAC capture, where misdirection of beams can lead to the hidden terminals, should also be addressed. Finally, we look at stability. With the dynamic nature of wireless mesh networks, rapid change in node conditions is expected. This abrupt change would result in increasing the possibility of hidden node terminals and delay. It is desired to have some prediction of future behavior of traffic in order to synthesize the radiation pattern for lesser reconfiguration.

It is important to note that though these conditions appear simple and straightforward, these are in fact NP-hard problems similar to channel assignment problems in a multi-channel mesh environment.

2. RELATED WORKS

Several researches have been done in studying the capacity region for Wireless Mesh Networks [1-4]. Gupta and Kumar [1] modeled wireless mesh networks and determined the bounds of capacity. Their work has been extended for application in several types of networks [2-4]. In [2], the authors studied the effects of the number of interface and channels in the capacity region of multi-radio multi-channel systems. Using the protocol model proposed in [1], they derived the lower and upper bounds onthe capacity of static multi-channel wireless networks. The authors showed that in an arbitrary network, a loss is incurred when the number of radio interface per node is smaller than the number of channels. However in random networks, a single radio interface is sufficient for utilizing multiple channel transmissions. Our framework aims to formulate a similar formulation using Space Division Multiple Access.

The capacity of hybrid wireless networks is studied in [3]. Hybrid networks in [3] are formed by placing a sparse network of base stations in an ad-hoc network. A trade-off between using a multi-hop adhoc transmission or a base station infrastructure transmission is also studied. Similar to [2], the protocol model [1] is used to model the system.

The capacity region for multi-radio multi-channel wireless mesh networks is studied in [4]. The goal of their research is to develop a network model that characterize the multi-radio and multi-channel features for wireless mesh networks given a limited number of orthogonal channels and available radio interface. They also considered the fundamental problem of feasibility for a given end-to-end demand vector and designed a fast primal-dual algorithm for a fully polynomial time approximation solution to provide an upper bound to the feasibility problem. Similar to [2], we adapt the formulations of this research for single channel space diversity. Reduction of interference in cellular systems are studied in [5] using SFIR(Spatial Filtering for Interference Reduction) where capacity is improved by reducing the frequency reuse factor and rearranging channel assignments in cellular systems. The average C/I(Carrier to Interference) improvement and Outage Probability were used to measure the system performance. The capacity is computed given a beam angle β and side-lobe attenuation D. The use of SFIR can be adapted in adaptive power control, which is one of the future works for this paper. However, this paper is focused on the study for a cellular system. In wireless mesh networks, the capacity gain can be seen as improvements in scheduling.

A problem in the utilization of beam-forming antennas is discussed in [6]. MAC-Layer Capture results in the incapability of the PHY Layer to recognize unnecessary packets. Upon handshake, the beams would then be pointed in the handshake initiator's direction even if a certain node is not the intended receiver. This causes time and energy wastage.

3. SYSTEM ARCHITECTURE

The architecture of wireless mesh networks used in this paper can be simply described as a combination of some features of a cellular network and the Internet. Similar to a cellular network, a base station-like element is present. In Figure 1, these are the gateways. Gateways allow the wireless mesh network access to other networking standards such as the Internet. In this case, the gateways have sockets to allow wired connection to the Internet. Most of the traffic in wireless mesh networks is directed to the gateways, although some exceptions exist in the case of peer-to-peer communications.

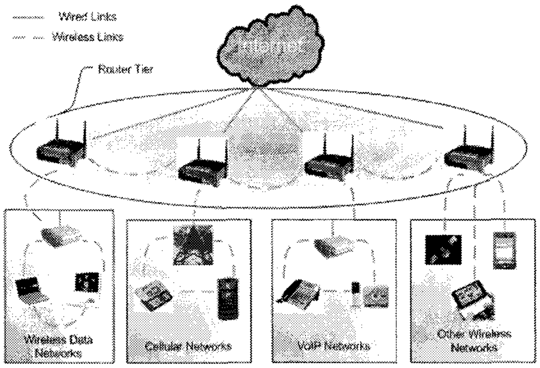

Fig. 1. System Architecture

The difference between wireless mesh networks and cellular networks is the presence of router nodes that relay traffic similar to Internet routers. These routers can be connected in a peer-to-peer manner to improve resilience in connectivity. Each router may or may not have MH(mobile hosts) connected to it. When a mobile host is connected to it, the router forwards the packet to the destination or to other routers that would again forward the message until it reaches the destination. In many cases, this message may need to traverse the Internet, thus it would pass through the gateways.

4. TIER-BASED ANALYSIS OF THE CAPACITY REGION FOR SPATIAL DIVERSIFIED WIRELESS MESH NETWORKS

We build on the model detailed by Gupta and Kumar in [1]. The main difference of our analysis is that we considered a more structured framework of wireless mesh networks as opposed to wireless ad-hoc networks. Also we consider that the beamwidth and antenna gain of each node to be random.

In defining the infrastructure of wireless mesh networks, we segregate the network into two different tiers: a) client tier and b) the router tier. The client tier is composed of mobile hosts, which can either be mobile or stationary. Each mobile host is connected to at most one access point router. On the other hand, the router tier is composed of the access point routers and gateways. These are assumed to be stationary and the locations are predetermined. These are valid assumptions since these routers and gateways are installed by service providers. Unlike wireless ad-hoc networks which can either be arbitrary or random, the distribution model of nodes for wireless mesh networks must follow the structure of the network itself.

4.1 Router Tier Analysis

The router tier can be modeled using arbitrary network type detailed in [1-4,7]. We follow the framework established by [1]. This framework is also the basis for the results in [2-4,7]. Suppose node X_i is transmitting packets to X_j over the m-th sub-channel. Let M denote the set of interfering neighbor transmitters using the same m-th sub-channel. We modify the physical model defined in [1] by making the power dependent on radiation pattern orientations of the transmitter and interfering neighbors: Θ and Φ_M respectively. Figure 2 shows the graphical representations of these directions. In Figure 2, X_h and X_k belong to the set of interfering neighbors M. The notation $P_i(\Theta)$ denotes the power received by X_j from X_i given that X_i is transmitting at angle Θ. In the same way, $P_h(\Phi_h)$ denotes the power received by X_j from X_h given that X_h is transmitting at angle Φ_h.

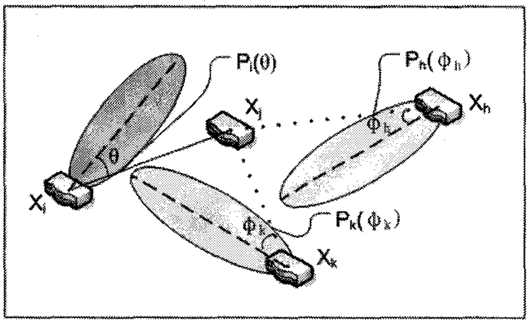

Fig. 2. Power Variation Dependence on Radiation Pattern Orientation

The signal-to-interference-plus-noise ratio requirement at X_j for the physical model can be written as Eq. (1) for a given noise distribution N and the desired signal-to-interference-plus-noise ratio $SINR_{req}$. Here $|X_i - X_j|$ denotes the distance between nodes X_i and X_j. The constant α denotes the free space propagation constant. Thus the $\frac{P_i(\theta)}{|X_i - X_j|^\alpha}$ is the power received by X_j from X_i subject to propagation losses. The denominator of left side of the equation denotes the interference received by X_j.

$$\frac{\dfrac{P_i(\theta)}{|X_i - X_j|^\alpha}}{N + \sum_{k\in M} \dfrac{P_k(\phi_k)}{|X_k - X_j|^\alpha}} \geq \frac{SINR_{req}}{SINR_{req}+1} \qquad (1)$$

Manipulating Eq. (1) yields,

$$|X_i - X_j|^\alpha \leq \frac{SINR_{req}+1}{SINR_{req}} \frac{P_i(\theta)}{N + \sum_{k\in M} \dfrac{P_k(\phi_k)}{|X_k - X_j|^\alpha}}$$

$$|X_i - X_j|^\alpha \leq \frac{SINR_{req}+1}{SINR_{req}} \frac{P_i(\theta)}{N + (\frac{\pi}{4})^{\alpha/2} \sum_{k\in M} P_k(\phi_k)}$$

The above formulation limits the power of the transmitter according to the required SINR. This translates to an upper-bound on the distance between the transmitter and receiver. Note that the resulting equation is only for a single transmitter. Summing over all transmitters, we let define the sum of distances between receivers and transmitters as r^α.

$$r^\alpha = \sum_{i\in M} |X_i - X_j|^\alpha \leq \frac{SINR_{req}+1}{SINR_{req}} \frac{\sum_{i\in M} P_i(\theta_i)}{N + (\frac{\pi}{4})^{\alpha/2} \sum_{k\in M} P_k(\phi_k)}$$

Note that several slots or sub-channels exists in the network. Let h(b) be the total number of hops and λnT be the total number of bits. Summing over all hops and bits and multiplying by a dummy variable 1/H, we formulate Eq. (2) where W is the maximum channel capacity and T is the number of time slots needed to transmit λnT bits.

$$\sum_{b=1}^{\lambda nT}\sum_{h=1}^{h(b)}\frac{r^{\alpha}}{H}\leq\frac{SINR_{req}+1}{SINR_{req}}\frac{\sum_{i\in M}P_i(\theta_i)}{N+(\frac{\pi}{4})^{\alpha/2}\sum_{k\in M}P_k(\phi_k)}\frac{WT}{H} \tag{2}$$

Invoking the convexity of r^{α}, that is,

$$(\sum_{b=1}^{\lambda nT}\sum_{h=1}^{h(b)}\frac{r}{H})^{\alpha}\leq\sum_{b=1}^{\lambda nT}\sum_{h=1}^{h(b)}\frac{r^{\alpha}}{H} \tag{3}$$

Combining Eqs. (2) and (3),

$$\sum_{b=1}^{\lambda nT}\sum_{h=1}^{h(b)}r\leq\left(\frac{SINR_{req}+1}{SINR_{req}}\frac{\sum_{i\in M}P_i(\theta_i)}{N+(\frac{\pi}{4})^{\alpha/2}\sum_{k\in M}P_k(\phi_k)}\frac{WT}{H}\right)^{1/\alpha}H$$

Further simplifications leads to Eq. (4). Let $H:\sum_{b=1}^{\lambda nT}h(b)\leq\frac{WTn}{2}$,

$$\lambda n\overline{L}\leq\left(\frac{SINR_{req}+1}{SINR_{req}}\frac{\sum_{i\in M}P_i(\theta_i)}{N+(\frac{\pi}{4})^{\alpha/2}\sum_{k\in M}P_k(\phi_k)}\right)^{1/\alpha}Wn^{\frac{\alpha-1}{\alpha}} \tag{4}$$

The final equation (4) defines the upper bound transport capacity for the router tier of the wireless mesh network. Upon analysis of the Eq. (4), one can see that the capacity is dependent not only on the number of nodes in the area, but also on the direction at which the antenna of each node is directed.

4.2 Client Tier Analysis

The client nodes of wireless mesh networks are usually mobile. Thus the definition of random networks in [1] can also be used to describe the topology for the client tier in wireless mesh networks. Due to this reason, we consider random network throughput capacity in [1] as the framework for the analysis of the client tier throughput capacity in wireless mesh networks. We follow the general outline of solution in [1] with modifications to formulations to consider adaptive power control and spatial transmission variations. We start by defining Voronoi Tessellation of the surface S^2 of a sphere. Fig. 3 shows a Voronoi Tessellation generated from a set of random points.

Definition 1: Given a set of points $\{a_1, a_2, \cdots a_k\}$ in S^2, a set $V(a_i)$ is a Voronoi cell if it satisfies Eq. (5).

$$V(a_i)=\{x,a_k\in S^2;i,j,k\in\Re;j\neq i:|x-a_i|<|x-a_j|\} \tag{5}$$

Lemma 1: The Generated Voronoi Tessellation V^n for the throughput analysis has the following properties:

1. Every Voronoi cell formed bounds a disk with an area of A_V and radius r(n).
2. Every Voronoi cell is bounded by a disk of radius 2r(n).

Unlike in [1], we consider the range of each transmission and the use of power control in the capacity region analysis. In directional transmission, the range can be increasing by varying the beamwidth (2Θ) of the antenna. To incorporate this characteristic in our analysis, we use the relationship between antenna gain($G_{antenna}$) and effective area of transmission(A_{eff}). This relationship is defined in Eq. (6) where λ is the signal wavelength.

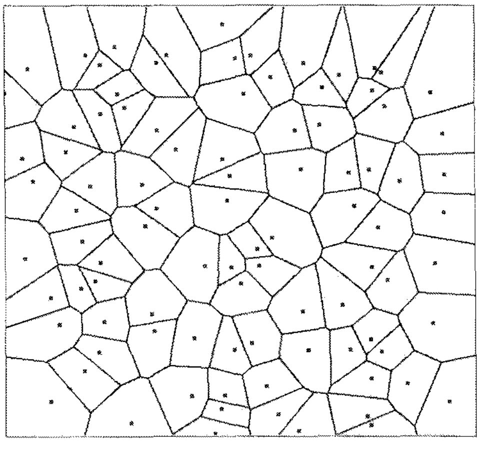

Fig. 3. Voronoi Tesselation

Using this relationship, we modify the range parameter in [1]. The revised range equation is defined in Eq. (7). It is implied in Eq. (7) that the range of transmission increases as the beamwidth is decreased. If the beamwidth chosen is π (omni-directional), then the value T_{range} is equivalent to [1]. Note that G_{π} is the antenna gain for omni-directional transmission.

$$G_{\theta}(n,\theta) = \frac{4\pi A_{eff}(n,\theta)}{\lambda^2} \tag{6}$$

$$T_{range}(n,\theta) = \frac{8G_{\pi}(n,\pi)r(n)}{G_{\theta}(n,\theta)} \tag{7}$$

Definition 2: Two cells are said to be *Likely Interfering Neighbors* if there is a point in one cell which is within the distance $2T_{range}(n, \Theta) + \Delta$.

Lemma 2: For every cell in V^n, the number of interfering neighbors is always less than C_1 where

$$C_1 = \frac{\frac{\phi\theta}{\pi^2}\left(6r(n) + 2T_{range}(n,\theta) + \Delta\right)^2}{r(n)^2} - 1 \tag{8}$$

Proof:

For a given Voronoi cell V, another cell V′ is interfering with it if there are is at least a single point in each cell which are at most $2T_{range}(n, \Theta) + \Delta$. This is dictated by Definition 2. From Lemma 1.2, each cell is bounded by a disk of radius 2r(n). This implies that the interference region for a certain transmitting cell is bounded by a large disk of radius $6r(n) + 2T_{range}(n, \Theta) + \Delta$. This is illustrated by Figure 4.

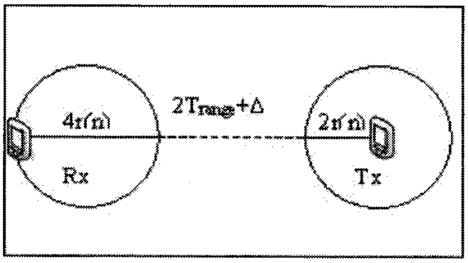

Fig. 4. Simplified Illustration of Interference Region Radius

Since we are concerned with directional communication, only a sector of this disk with radius $6r(n) + 2T_{range}(n, \Theta) + \Delta$ actually contains the interfering neighbors. Since each Voronoi cell has a radius of r(n), Eq. (8) is formulated by dividing the total area of the sector by area of a disk with radius r(n). The decrement of 1 in Eq. (8) excludes the transmitter node from the total number of interfering nodes calculated in the first term of Eq. (8).

Continuing with the analysis framework in [1], we get the lower bound for the throughput as seen in Eq. (9). Note that unlike in [1] and [7], the number of interfering neighbors is a linearly varying with order $O((H(n,\Theta) + H(n,\Theta)\Delta)^2)$, where $H(n,\Delta)$ is proportional to $G_{\pi}(n,\pi)/G_{\Theta}(n,\Theta)$ and W is the maximum channel capacity.

$$\lambda(n) = \frac{\pi^2}{\phi\theta} \frac{cW}{\left(H(n,\theta) + H(n,\theta)\Delta\right)^2 (\sqrt{n \log n})} \tag{9}$$

4.2 Total Upper bound Capacity

In the process of structuring the wireless mesh network, we tier the whole network such that there is independence in each analysis. Maximum Total Upper bound capacity therefore would be the minimum between the capacity of the client and router tiers defined in Eqs. (4) and (9).

$$C_{UB} = \min\left\{\begin{array}{l} \left(\frac{SINR_{req}+1}{SINR_{req}} \frac{\sum_{i \in M} P_i(\theta_i)}{N + (\frac{\pi}{4})^{\alpha/2} \sum_{k \in M} P_k(\phi_k)}\right)^{1/\alpha} \frac{Wn^{\frac{\alpha-1}{\alpha}}}{\bar{L}} \\ \frac{\pi^2}{\phi\theta} \frac{cW}{\left(H(n,\theta) + H(n,\theta)\Delta\right)(\sqrt{n \log n}} \end{array}\right. \tag{10}$$

5. SIMULATION RESULTS

In this section, we modeled and analyzed the network using directional antennas. We also did analysis assuming the use of power control at the router tier. In one set of numerical results, we model the resulting antenna patterns for several antenna designs. We can utilize these antenna pattern models in the actual simulation of the network on the transmitter side. These patterns are plotted according to the antenna type while varying the wavelength sand the antenna element separation.

In addition to transmitter power plots, a successful communication requires the user to direct its radiation pattern to the transmitter's radiation pattern. This is a difficult task since the receiver must be able to predict the direction of arrival of the transmission. With multiple transmissions that can possibly arrive at the receiver, the receiving node must be able to predict where to direct its antenna. To determine this, we use direction of arrival estimation algorithms to predict where to point the antenna array. Several algorithms exist that are used in hardware implementations. We implemented the Multiple Signal Classification (MUSIC) in Matlab to predict the direction of arrival of radio waves. MUSIC estimates the frequency components (phase and amplitude) using an eigenspace method [8]. Figure 5 shows the result of the implementation done in Matlab. This simulations was done with $\text{SINR}_{req}=10$, expected signal arrival at 45° and 60° using a 4-element antenna array as the medium at 2Ghz . In Figure 5, it shows that at the phase angle of 40-60 degrees, the magnitude of the signal peaks. Therefore, it can predict the angle of arrival to be within the range of 40-60 degrees. Simulation was done using the scenario illustrated in Figure 2. Table 1 shows the simulation parameters for the numerical analysis and simulation.

Table 1. Simulation Parameters for Numerical Analysis

SINR_{req}	0.5
Signal Arrival	45° and 60°
Propagation Constant(α)	1.5
Frequency	2Ghz
Channel Capacity (W)	100Mbps
Noise	Additive Gaussian White Noise
Array Elements	4

We plot the relationship of the capacity with the number of array elements in the antenna array (Fig. 6). The number of array elements represents the directivity, a measure of the beamwidth of transmission. The more elements we incorporate in our array, the narrower our antenna pattern gets. Let nt represents the number of array elements at the transmitter while nr represents the number of elements in the receiver. These nt and nr values represents the number of directions that the antenna can be directed at.

Finally, we simulate the network in Qualnet to determine the effects of neighbor interference in the router tier. In this simulation, in Fig. 7, we compare the transport capacity between omni-directional transmission, our directional capacity estimation

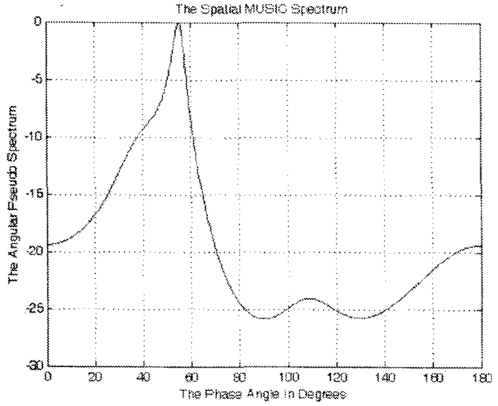

Fig. 5. MUSIC Implemention Result

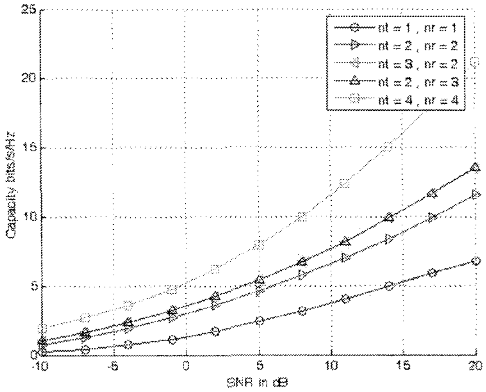

Fig. 6. Capacity vs SNR in varying antenna elements at the transmitter and receiver

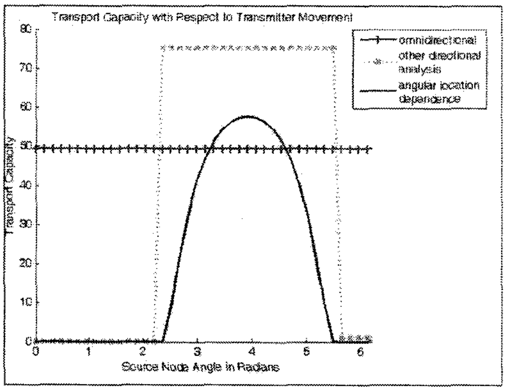

Fig. 7. Transport Capacity with respect to Transmitter Movement

results and the results in [5,7]. Using the same scenario as in Figure 2, the transmitter is made to move with respect to the receiver. The resulting transport capacity is higher for directional antennas than in omni-directional transmission when the beams are pointed directly at each other. Also, other directional analysis provides an over-estimation of the transport capacity. References [5,7] considers a binary estimation where in if the antenna patterns are overlapping, the receive maximum power. This explains the over-estimation of the transport capacity.

6. CONCLUSION

In this paper we discussed the conditions needed for successful transmission using direction antennas in wireless mesh networks. We extended the work of Gupta and Kumar [1] to wireless mesh networks by dividing the overall infrastructure of wireless mesh networks into two tiers: a) router tier and b) client tier. The analysis of the router tier was done using the arbitrary network analysis with the use of adaptive power control. Antenna pattern simulations were done to represent transmitter radiation pattern. Direction of arrival algorithm MUSIC was implemented to represent and form the receiver radiation pattern. For future works, we intend to work on removing the assumption of no power control for mobile hosts in the client tier. This would involve the reformulation of the Voronoi Tessellation in [1]. Additional simulation results are in progress.

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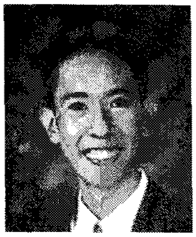

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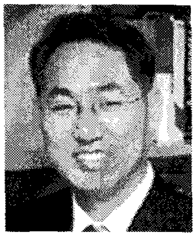

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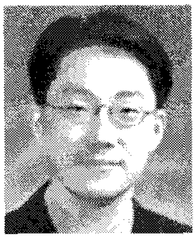

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