CSMA/CA with Beam Forming Antennas in Multi-hop Packet Radio

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Abstract- Low cost, reliable and easily deployed ad hoc rural-area wireless networks are needed for both civilian and military communications. In order to fulfill the requirement of easy deployment the network needs to be autonomous, self-organising and self-healing. Multi-hop Packet Radio Networks are a suitable solution to fulfill this requirement. In this type of network all nodes use the same frequency for transmission as well as using a store and forward procedure which enables communications between nodes that are out of direct radio range. There are a variety of multiple access protocols applicable to this type of system. Spatial Time Division Multiple Access (STDMA) has been studied and found to be efficient and fair, the draw-back is that it may not offer good peak rates for bursty data traffic. The Carrier Sense Multiple Access/ Collision Avoidance (CSMA/CA) protocol promises high efficiency and the ability to provide high peak data rates. Although CSMA/CA is not new there is very little work one considering the rural-area multi-hop environment. This paper presents the analysis of CSMA/CA in the rural-area multi-hop environment with and without adaptive antennas. An explanation of the system design with adaptive antennas is given as well as simulation results showing the expected performance gain.

I. Introduction

In many practical communications scenarios, simplicity and speed in setting up the network is of primary importance, hence Multihop Ad hoc radio networks are extremely interesting. As defined in [1], "Ad hoc networks are composed solely of stations within mutual communication range of each other that communicate via the wireless medium". One of the principal feature of ad hoc networks are their ability to adapt to the addition or removal of network nodes, a feature which is critical for military and emergency applications.

As the term multihop suggests, the networks being considered convey information through the network using data packets that may be forwarded through a number of nodes between their source and their destination. The two main advantages of "multihopping" are that the range of each terminal is effectively extended to the full range of the network and that less total transmit power is needed in conveying the data. A multihop network can use lower powered and hence cheaper terminals than a directly connected network.

The authors are particularly interested in improving the performance of multihop ad hoc networks in the civilian arena where cost is of paramount importance. The most basic of terminals are expected to use half-duplex transmission, a single frequency for the whole network, an omni-directional antenna and a fixed transmission power. There are opportunities to improve performance while having little impact on cost in the areas of digital signal processing and modem design and more significantly in the area of multiple access control (MAC) layer protocols. Much work has been done in the MAC area however there still remains some work to be done on how various MAC protocols perform within multihop radio networks and rural area networks. [13, Section 1.3]**.** The use of antenna arrays or smart antennas within multihop ad hoc networks will increase cost but promises to significantly increase throughput. Furthermore, if simple antenna systems are used such as switched beam systems, their deployment maybe very attractive. The effective use of smart antennas is integrally linked to the MAC protocol, so combined studies are indicated. This area remains virtually unexamined in the literature.

Spatial Time Division Multiple Access (STDMA) as applied to multihop ad hoc networks has been intensively studied [12][13]. The application of directional antennas to STDMA is relatively uncomplicated and has been found to provide substantial

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gains over the omni-directional case [14]. A promising alternative MAC protocol is Carrier Sense Multiple Access/ Collision Avoidance (CSMA/CA) [1]. This paper focuses on smart antennas in CSMA/CA. Here, the application of smart antennas can also provide significant gains however the system design needs careful consideration.

The type of CSMA/CA protocol considered in this paper was first used by *Apple Localtalk* wire Local Area Networks [3]. Variants of this protocol have been suggested for Multihop packet radio networks [1][3][6][7]. This MAC protocol transfers a data packet in three steps. Firstly a node that has data to transmit sends a short Request to Send (RTS) packet. All nodes hearing the RTS, excepting the target receiver node, defer their transmissions. Secondly, the target node transmits a short Clear to Send (CTS) and all nodes hearing the CTS, excepting the originating node, defer their transmission until after the end of the data packet. Finally the originating node transmits the data, now having a fair degree of confidence that the channel will be free of interference. In addition to these three steps a node inhibits its transmission if it senses another transmitter on the channel, i.e. Carrier Sense (CS). The receiver needs a minimum time to sense the carrier here defines, as a *microslot* period. By setting the *microslot* period to much less than the length of an RTS the probability of collision is reduced. Carrier sensing is also important to avoid conflicts occurring when nodes enter the network.

The paper is organized as follows. In section II it is introduced the system models and assumptions. Section III introduces the Beam selection policies using Smart Antennas. In section IV it is defined our performance measure. The importance of carrier sense is discussed in section V. Simulation results are presented in section VI and conclusions in section VII.

II. System Models

A. Link quality model

The networks studied in this paper consist of a collection of N nodes spread randomly over a given area. For simplicity, we consider a distance dependent propagation model where the path gain between node i and node j is given by $G_{ij} = d_{ij}^{-\alpha}$. The path gains computed in this way are used to determine the received power P_{ij} at node j resulting from node i's transmission with power P_i,

$$P_{ij} = P_i G_{ij} A_i(\theta_{ij}) A_j(\theta_{ji}) = \frac{P_i A_i(\theta_{ij}) A_j(\theta_{ji})}{d_{ij}^{\alpha}} \quad (1)$$

where d_{ij} is the distance between node i and j, α is the path loss exponent, $A_i(.)$ denotes the (horizontal) antenna patterns of the antenna used by node i, and θ_{ij} denotes the angle to node j as seen from node i.

In the radio environment the probability of a packet arriving error free is dependent on the modulation, coding, multiple access interference and background noise. For the purpose of network modeling we assume that a packet survives if the Signal-to-Interference plus Noise Ratio (SINR) is above a specified threshold γ_0 as defined by .

$$\Gamma_{ij} = \frac{P_i G_{ij} A_i(\theta_{ij}) A_j(\theta_{ji})}{\sum_{\forall (k,l)\neq(i,j)} P_k G_{kj} A_k(\theta_{kj}) A_j(\theta_{jk}) x_{kl} + P_{Noise}} \geq \gamma_0, \quad (2)$$

Γ_{ij} is the SINR for a packet sent from node i to node j and P_{Noise} is the background noise power level at j.

$$x_{kl} = \begin{cases} 1 \ \textit{if} \text{ node } k \text{ transmits to node } l, \\ 0 \ \text{otherwise.} \end{cases}$$

If packets can be successfully transmitted between two nodes while there is no interference from any other node then those two nodes are *connected*. Using this criterion the connectivity diagram for two sample networks is shown in figure 1. The study was confined to *connected networks*, i.e. to those networks for which there exists a path with finite number of hops between every pair of nodes in the network.

B. Antenna Model

In smart antennas, the switched-beam method is one of the simplest approaches that can be used. Here, a linear RF network, called a Fixed Beamforming Network (FBN) [12, page 91], see figure 2, combines M antenna elements to form up to M directional beams.

There are many ways to implement Fixed Beamforming Networks. In order to obtain easily analyzed and general results we adopted the *flat-top* model (3)[12, page 137]. It is assumed that each FBN covers 360 degrees with M sectors selected by the MAC protocol. The horizontal antenna pattern $A_i(\theta,s)$ for each sector s is given by (3),

$$A_i(\theta,s) = \begin{cases} \dfrac{2\pi}{\varphi_h} \ ; \ (\text{s}-1)\varphi_h \leq \theta \leq \text{s}\varphi_h, \\ \dfrac{1}{a_{sl}} \ ; \ \text{Otherwise,} \end{cases} \quad (3)$$

$$s = 1,2,...,M.$$

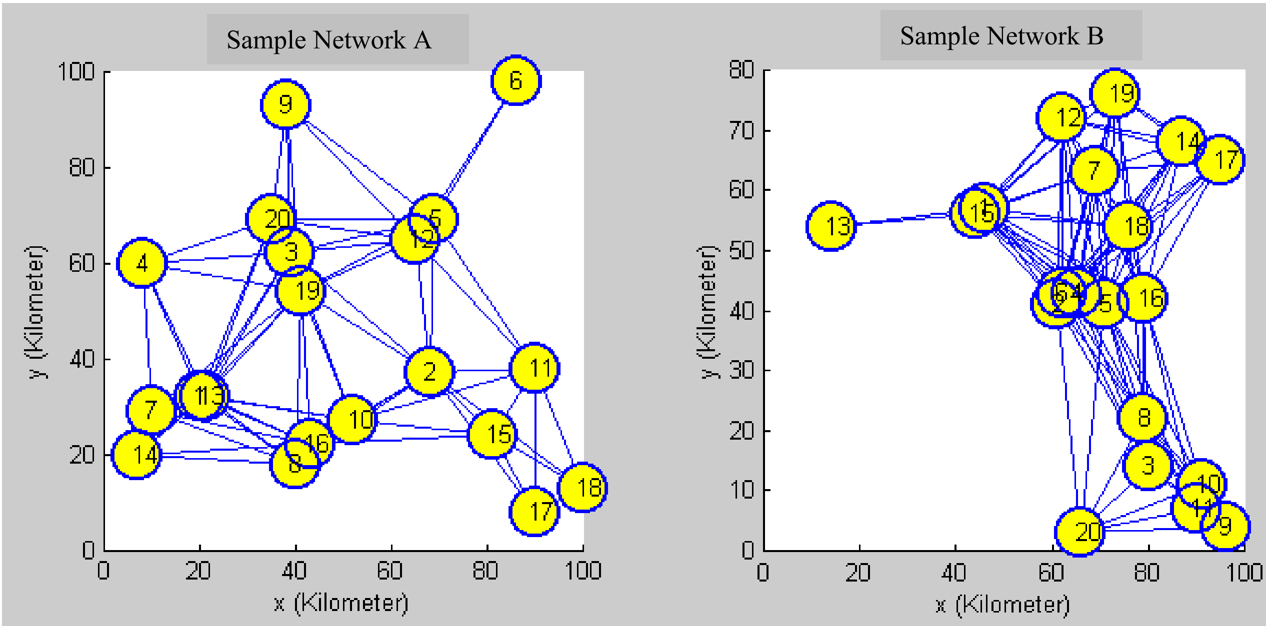

Fig. 1. Typical networks realization (Network A and B) with N=20 random generated nodes in 100x100 Km^2. Lines indicate possible bi-directional communication links with distance less than 40 Km. The average number of hops to reach any other nodes is 1.8 and 1.5 for network A and B respectively.

where φ_h is the horizontal antenna beamwidth (BW) and a_{sl} is the side lobe attenuation.

C. Traffic model

We assume that packets are of constant length and arrive according to a Poisson process with total external traffic load of λ packets per packet duration. Furthermore, it is assumed that the traffic load is evenly distributed (4).

$$\lambda_i = \lambda/N \quad i \in \{1, 2, \ldots N\}. \quad (4)$$

λ_i is the external traffic load on node *i*.

The initial Source (S) and final Destination (D) of a packet is denoted by an *(S,D)* pair. Due to the store-and-forward mechanism, packets between *(S, D)* pairs may travel through intermediate nodes. Therefore, the traffic load λ_{ij} going through a link *(i,j)* is the result of external and internal traffic [12, page 25] (5).

$$\lambda_{ij} = \sum_{\substack{\forall (S,D) \text{ routed} \\ \text{through link } (i,j)}} \frac{\lambda}{N(N-1)} = \frac{\lambda}{N(N-1)} T_{ij}, \quad (5)$$

where

$$T_{ij} = \sum (S,D) \text{ routed through link } (i,j).$$

T_{ij} is called the *relative traffic load* for link *(i,j)*. In this study the Minimum Hop Algorithm has been used to determine the *(S,D)* routes, for simplicity. The routing affects network capacity and the Multiple Access Interference (MAI), however it is not the subject been considered here.

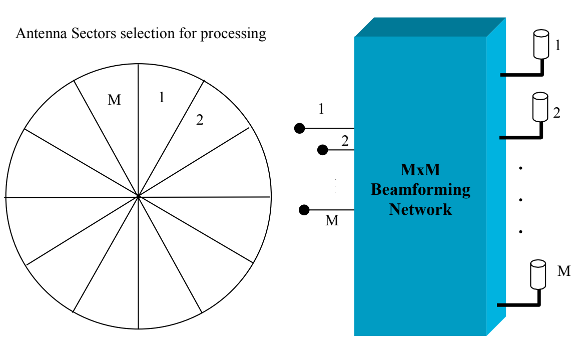

Fig.2. Switch-beam method used as our antenna model.

III. Beam Selection Policies

For each transmission from *i* to *j* over link *(i,j)*, node *i* and node *j* must select the appropriated antenna sector. Three cases have been studied

1. **Omnidirectional Antennas:** All nodes within the network use omnidirectional antennas for communications for the whole time. This is the reference case.

2. **Beam Selection Policy I (Omni-RTS):** During the transmission of an RTS both nodes use omnidirectional antennas while during CTS and DATA transmissions both nodes use directional beams. See figure 3.a.

3. **Beam Selection Policy II (Di-RTS):** This policy is the same as policy I except that the RTS is transmitted using a directional beam. See figure 3.b.

A superficial examination of these policies reveals that policy I reduces the number of hidden terminals while policy II reduces the number of exposed terminals. Therefore a closer investigation was required.

IV. Performance Measure

Two parameters have been used to evaluate performance, the *throughput* and the *average end–to-end packet delay*. We define the maximum throughput as the maximum external traffic load that produces a finite average packet delay. Our second performance measure, the expected *end-to-end packet delay*, is defined as the time between the arrival of a packet at the buffer of the Source node and its successful reception at the destination node. The *end-to-end packet delay* allows us to evaluate quality of service (user point of view) under low, moderate, and high traffic. Computer simulations have been used since multihop networks are difficult to analyze mathematically.

V. Carrier Sensing Threshold Influence on Performance

CSMA/CA is a distributed scheme whereby interference is avoided using only the CTS, RTS signals and Carrier Sensing. This results in two well known problems, the *hidden* terminal and the *exposed* terminal problems. Figure 4 illustrates a packet transmission from Node A to Node B. The maximum range of Carrier Sensing d_{CS} is greater than the range of error free reception d_{RTS}. Note that node C can not sense the RTS yet may be close enough to Node B to interfere with RTS's reception. Node C is said to be the *hidden* terminal. Carrier Sensing is important in reducing the *hidden* terminal problem [5]. Alternatively Node D can sense the RTS and DATA but may be able to transmit without interfering with the DATA packet's reception. Node D is said to be *exposed*. The range of the RTS and CTS is set by the modulation and coding while the range of carrier sensing is determined by the carrier sensing time constant and threshold.

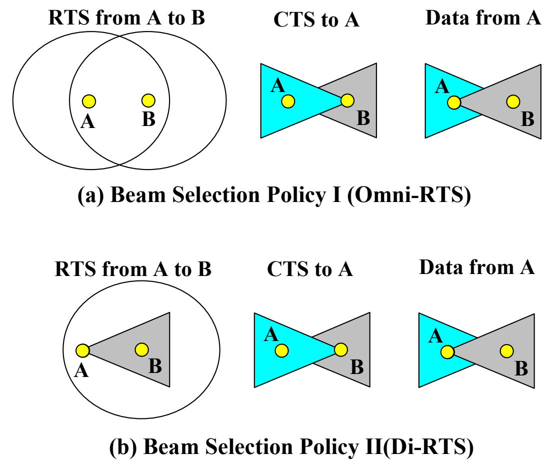

Fig.3. Beam Selection Polices used by node A to communicate with node B. Circles indicates the use of omnidirectional antennas and triangles directional antennas.

The *hidden* terminal and *exposed* terminal problems are difficult to thoroughly analyze, however RTS collisions are considered to be critical[8]. An example showing the relationship between carrier sense threshold and RTS collision between two given nodes is presented in this section.

In absence of multiple access interference, the range for error free reception of the RTS is given by,

$$d_{RTS} = \sqrt[\alpha]{\frac{P_A}{\gamma_0 P_{Noise}}},$$

where $P_{Noise} = kT_0 BF_{sys}$, $k=1.38x10^{-23}$ J/K is the Boltzmans constant, $T_0 = 290\ K$, F_{sys} is the receiver Noise Factor and B is the receiver equivalent noise bandwidth. The RTS reception area can be computed by $A_{RTS} = \pi d_{RTS}^2$.

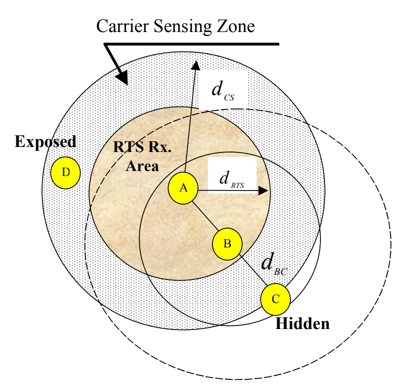

Fig.4. Carrier Sensing and RTS reception zones. If A transmit a RTS, B may decode it correctly, D may detect the channel busy but no C.

In similar way, the carrier detection distance can be computed

$$d_{CS} = \sqrt[\alpha]{\frac{P_A}{\gamma_{CS} P_{Noise}}} = \sqrt[\alpha]{\frac{P_A}{P_{Th}}},$$

P_{Th} is the carrier detection power level and γ_{CS} is the signal to noise ratio for carrier sensing, $1 < \gamma_{CS} \le \gamma_0$.

Assume a hidden Node C lies just out of carrier sensing range as shown in figure 5 ($d_{AC} = d_{CS}$). The received SIR Γ_{AB} (ignoring background noise) is

$$\Gamma_{AB} = \frac{P_{AB}}{P_{CB}} = \left(\frac{d_{BC}}{d_{AB}}\right)^{\alpha} \ge \gamma_0,$$

where

$$d_{BC}^2 = d_{AB}^2 + d_{CS}^2 - 2 d_{AB} d_{CS} \cos\theta$$

Hence, the distance for which A's RTS survives is d_{AB}=d_{cap}. Then

$$\left(\frac{d_{CS}}{d_{cap}}\right)^2 - 2\cos\theta\left(\frac{d_{CS}}{d_{cap}}\right) + 1 \ge \gamma_0^{2/\alpha},$$

Hence, the capture range can be approximated by

$$d_{cap} \approx min\left(d_{RTS}, \frac{d_{CS}}{\cos\theta + \sqrt{\left(\gamma_0^{2/\alpha} - 1\right) + \cos^2\theta}}\right) \quad (6).$$

Some examples of the resulting relative capture area using (6) are draw in figure 6 using the parameters of table I with carrier sensing thresholds of 3dB, 6dB, 9dB and 10 dB (No CD zone) above the noise floor. It can be seen from the figure that the correct detection area of the RTS is shrink to 75.6% , 57.9%, 40.8%, 34.9%

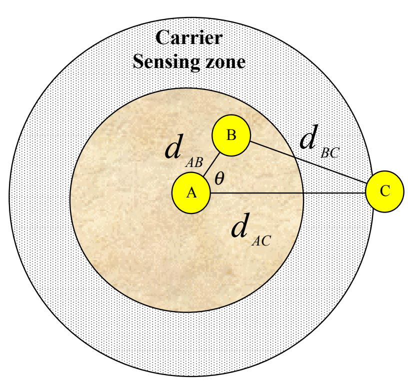

Fig.5. Node C being out of the Carrier Sensing zone may start transmitting while Node A transmits an RTS to Node B.

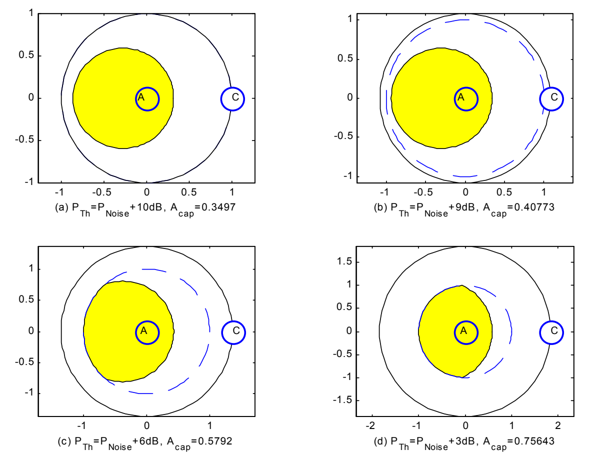

Fig.6. Reception area of A's RTS when a hidden terminal C is located at the carrier detection boundary for different values of CS threshold. RTS reception in absence of MAI is indicated by a dotted line.

for 3dB, 6dB, 9dB and 10dB carrier sensing threshold respectively. If nodes are uniform distributed over this area this correspond to the probability of successfully reception of the RTS.

VI. Simulation Results

Discrete step simulations were performed using the system models described in section II. The simulation parameters are summarized in table I. The impact of different carrier sense thresholds with omnidirectional antennas in network A are shown in Figure 7. Using the minimum carrier sense threshold of 3dB yields best performance. Similar results were founds for network B.

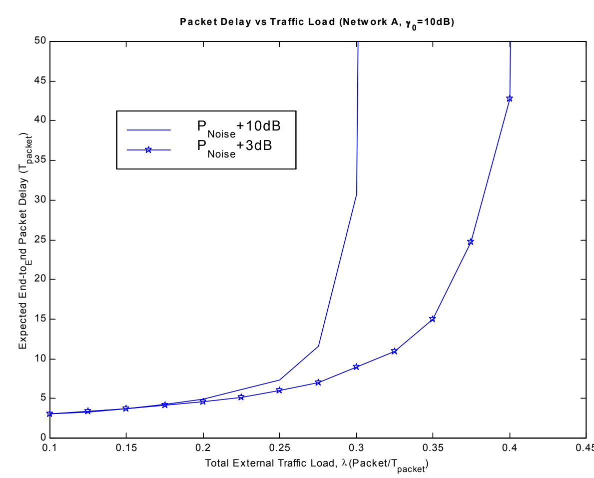

Fig.7. Performance of Network A with omnidirectional antennas and carrier detection threshold of 3dB and 10 dB above the Noise Floor.

TABLE I
Simulation Parameters used for Performance Evaluation

Parameter	Value
Packet Size (PS)	500 Bytes
RTS size	25 Bytes (5% P S)
CTS size	25 Bytes
Data Rate	100 Kbps
Buffer Length (FIFO)	100 packets
Clock Step (microslot)	5Bytes (1% PS)
Number of Nodes (N)	20
Packet Transmitted per Node	2000
External Packet Arrival	Poisson Distributed
Packet Destination	Uniform Distributed
Routing Method	Minimum Hop Algorithm (MHA)
Maximum Radio Range	40 km
Minimum SINR	$\gamma_0 = 10$ dB
Receiver Noise Figure	15 dB
Equivalent Receiver Noise Bandwidth (B)	100 kHz
Carrier Sensing Threshold above the Noise Floor	+3 dB minimum +10dB maximum

Performance Evaluation with Smart Antennas

Next, the performance using the beam selection policies described in section III was determined. A CS threshold of 3dB was used since it performed best in the omni-directional case. The results for sample network A and B are shown in figures 8 and 9 respectively. Furthermore, table II summarizes the throughput improvement with respect to the omnidirectional case.

From figure 8 it can be seen that the use of a narrower beam always reduces the average packet delay. This effect is insignificant for low traffic loads. Th results show that the Di-RTS policy outperforms the Omni-RTS policy in all cases. It is suspected that RTS interference with DATA reception is the significant factor. Directional RTS transmission generates less interference.

From table II it can be seen that a higher improvement is achieved for network A with the application of directional antennas. This is a reasonable result of the contrasting topologies as seen in figure 1.

TABLE II
Throughput Improvement Respect to the Omnidirectional Case

Network A			
Antenna Beamwidth (BW)	**90 deg**	**60 deg**	**30 deg**
Beam Selection Policy I (Omni-RTS)	9.3%	26.3%	62.5%
Beam Selection Policy II (Directional RTS)	37.6%	72.1%	94.2%
Network B			
Antenna Beamwidth (BW)	**90 deg**	**60 deg**	**30 deg**
Beam Selection Policy I (Omni-RTS)	11.5%	21.6%	58.7%
Beam Selection Policy II (Directional RTS)	26.2%	47.7%	85.1%

VII. Conclusions

In this paper we have analyzed the performance of Carrier Sense Multiple Access/Collision Avoidance protocol with RTS/CTS control handshaking using omnidirectional and smart antennas. We found that when omnidirectional antennas are used, selection of low carrier detection threshold substantially increases throughput. This suggests that without carrier detection the hidden terminal problem dominates over the exposed terminal problem.

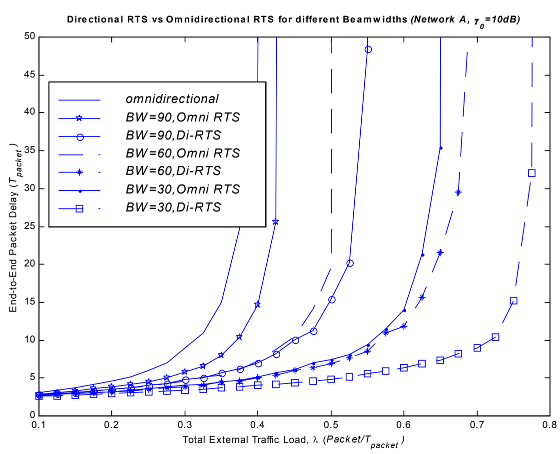

Fig. 8. Performance of Network A with omnidirectional and smart antennas. Note that transmission of Directional - RTS is the best beam selection policy.

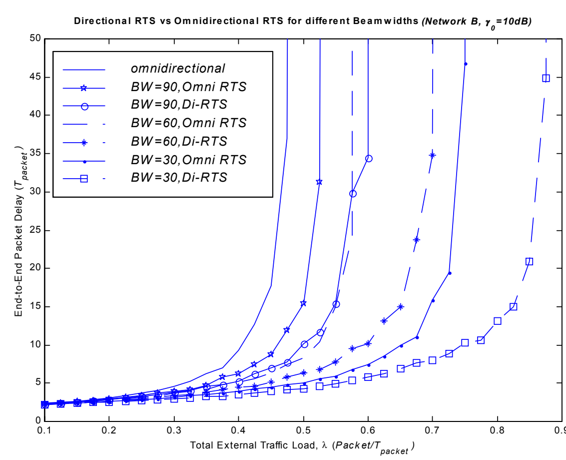

Fig.9. Performance of Network B with omnidirectional and smart antennas.

We studied two beam selection policies using Fixed Beamforming Networks. The beam selection is done by the MAC sub-layer. We found that the best strategy, providing roughly twice the improvement, initiates its transmission with a directional beam. Up to 72% throughput improvement was achieved by utilizing 60 degrees beamwidth antennas.

The application of Fixed Beamforming Networks is practical for fixed nodes as the required off-the-shelf components are affordable. An interesting topic for future research is the mixed scenario whereby fix nodes using smart antennas communicates with nomadic nodes.

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