Capacity of Large Wireless CDMA Ad Hoc Networks with Retransmission Diversity

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Abstract[1]

In this paper, we consider large wireless CDMA ad hoc networks on which nodes are uniformly distributed in an infinitely large area. The number of nodes per square meter and processing gain trend to infinity with their ratio kept a constant. Nodes access each other through a common CDMA channel without power control. Received power decays with node distance. When a packet is not successfully demodulated at a receiving node, it is retransmitted. A maximum ratio combiner is employed to combine all received data in multiple retransmissions of a packet. Markov chain property is applied to derive stationary distribution of number of retransmissions, stationary link throughput and packet delay. Then the link (one-hop) transport capacity, optimum link distance achieving link transport capacity, node capacity, and node transport capacity are obtained. The network transport capacity obtained per node considering all traffic demand and scheduling is also obtained. Numerical evaluation points out that if multiple retransmissions are necessary for a packet, the one-hop transport capacity is achieved by delivering the packet to a nearest neighbor node, or otherwise by delivering to a farther determinable node. It is also shown that exploitation of retransmission diversity substantially increases the capacity of an ad hoc wireless network and reduces packet delay.

I. Introduction

Capacity estimation at media access control (MAC) layer provides the basis for design of all upper layers in a packet-switched wireless network. Capacity estimation of ad hoc network recently has been paid particularly attention in research. In conventional network study, it is assumed that physical layer is unable to resolve multipackets received at the same time by a node. This assumption is obviously not true, say for CDMA networks, and underestimates network capacity. Early study on stability and capacity of Aloha systems considering multipacket reception capability was performed by Ghez, Verdú, and Schwartz [1]. It is shown that the capacity of an Aloha system with multipacket reception capability is achieved when eventually all nodes have packets to transmit, which is completely defined by its multipacket reception matrix. By means of the multipacket reception matrix, Tong, Zhao, and Mergen [2]-[4] studied capacity and MAC protocols for ad hoc networks capable of multipacket reception. Formulas of capacities for several regular ad hoc networks were obtained. MAC protocols exploiting multipacket reception capability were proposed and demonstrated promising performance improvement. Gupta and Kummar [5] studied the capacity of wireless networks based on two models: the protocol model in which interfering nodes are a certain distance farther away from the receiving node than the desired transmitting node, and the physical model in which signal to interference ratio (SIR) is greater than a threshold for effective transmission. It is indicated that with each link capacity fixed the transport capacity per node vanishes at the rate of at least square root of the number of nodes as the node density increases. Li *et al.* [6] examined effect of IEEE 802.11 MAC and ad hoc forward on the capacity of ad hoc wireless network. They concluded that as the network size grows, the average source-destination distance should remain small to have capacity scaled up with the network size. Xu and Sadaawi pointed out [7] that IEEE 802.11 MAC protocols suffer from hidden node problem when applied in wireless multihop ad hoc networks. Luo and Fan [8] analyzed capacity of CDMA system with selective repeat and Go-back-N protocols. They showed that the capacity should be defined as the maximum throughput as the number of users varies. In the information theory point of view Toumpis and Goldsmith [9] analyzed capacity regions for wireless ad hoc network. It was concluded that the multihop routing, ability for concurrent transmissions, and interference cancellation significantly increase the capacity of ad hoc networks.

Practical communication systems are noise and interference limited. Unless packets are coded at the rate of channel capacity, the packet success probability in one transmission is less than one and then multiple retransmissions of the same packet are necessary. Since channel noise, interference signals, and multipath coefficients are time-variant, packet retransmission provides a diversity gain for demodulation of retransmitted packets and increases packet success probability. Every retransmission of a packet takes up amount of network resources that is transformed into retransmission diversity gain. Hence, retransmission diversity is essentially part of network resources. Partly due to separate layer design strategy, in conventional networks previously received signals with unsuccessful packet demodulation were discarded. When the packet is retransmitted, the packet is demodulated using only the currently received signal, thus wasting network resource embedded in previously received signals. It is shown [10]-[12] that by exploiting retransmission diversity packet success probability and network performance can be substantially improved. Specifically, for a packet of J retransmissions, the retransmission diversity gain is $10\log_{10}J$ dB in SNR for linear multiuser receivers and is square root of J in minimum signal distance for maximum likelihood detector.

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Meanwhile, these multiuser detectors exploiting retransmission diversity can be implemented without increasing computational complexity. Performance of packet-slotted/unslotted Aloha CDMA network with Poisson arrival over multipath fading channels is analyzed in [13][14] via large system technique. The distribution of number of retransmissions, throughput, average delay in steady state scaled with processing gain are obtained with the MF, decorrelator, and MMSE detectors. It is demonstrated that the retransmission diversity can significantly improve network performance.

In this paper, we study the capacity of large wireless CDMA ad hoc networks with retransmission diversity. We consider that infinitely many nodes are uniformly distributed on an infinitely large plane. The number of nodes on a unit area and processing gain both trend to infinity with their ratio kept a constant. This model is an abstraction of a practical large wireless ad hoc network while providing tractability for analysis. We shall obtain link throughput and packet delay, link transport capacity, optimum link distance, node capacity, node transport capacity, and network transport capacity per node.

II. Network model and packet success probability

A. Network Model

We consider a packet-slotted ad hoc network in which infinitely many nodes are uniformly distributed on an infinitely large plane with A nodes per square meter. Nodes access each other through a common CDMA channel as shown in Fig. 1. All nodes on the network are identical. All nodes have the identical transmission power P_0 and no power control is employed. All nodes have the same computational capability. In any slot, a half number of nodes are transmitting and the other half are receiving. We assume that transmitting nodes are also uniformly distributed. Each node has an infinitely long buffer for arrival packets. Among the packets in each node's buffer, one is the transmitted packet and the others are the waiting packets. If the transmitted packet is not successfully received in a slot, it will be retransmitted but not necessarily in the next slot. If the transmitted packet is successfully received, a previous waiting packet will become a transmitted packet. A new packet arrival in a slot is a waiting packet in the buffer. Denote by $M(t)$ the number of transmissions of the transmitted packet in the buffer. If $M(t) = 0$, there is no transmitted packet and no waiting packet. We assume that the new packet arrival rate is high enough so that each node always has packets in buffer ready to be transmitted.

B. Packet success probability

Consider that a random binary spreading sequence is equiprobably selected for a bit of every transmission in each node. The number of nodes per square meter and the processing gain N trend to infinity and their ratio keeps a constant $\alpha = A/N$ in nodes per square meter per chip (or approximately the number of nodes per square meter per Hz per second). The MF receiver with the maximum ratio combiner [11][12] for optimum combination of signals in multiple retransmissions is applied.

We assume that for a node of distance γ the received power is

$$P(r) = \begin{cases} P_0 / r^{\beta}, & r \geq 1, \\ P_0, & r < 1, \end{cases} \tag{1}$$

with $\beta > 2$ and $r = \gamma/\gamma_0$ is normalized distance. Without loss of generality, here we assume that the received power of a node within the distance γ_0 is fixed as the transmitting power P_0.

Consider a transmitting node that has a normalized distance r to the receiving node and transmits a packet the mth time. For every transmission, the received signal power at MF output is $P(r)$. Consider the interference nodes in the annulus of radius γ and width $\Delta\gamma$. For an inference node k, the interference power is $R_{0k}^2 P_k$ where the transmitting node of interest is indexed with 0 and R_{0k} is the crosscorrelation between the signals of interest and interference. There are approximately $2\pi A\gamma\Delta\gamma/2$ interfering nodes, each of which has approximately interference power $P_k \cong P_0(\gamma_0/\gamma)^{\beta}$ where dividing by 2 is due to the fact that a half number of the nodes are transmitting and the other half are receiving. The total interference power in this annulus is $\sum_{k=1}^{K} R_{0k}^2 P_k \cong \sum_{k=1}^{\pi A\gamma\Delta\gamma} R_{0k}^2 P_0(\gamma_0/\gamma)^{\beta}$. As the number of nodes per unit area and the processing gain trend to infinity, this total interference power converges in probability to $\pi\alpha P_0 \gamma_0^{\beta} \gamma^{-\beta+1} \Delta\gamma$ applying the results in [15]. Similarly, the interference power generated by the transmitting nodes inside the circle of radius $\gamma = \gamma_0$ is $\sum_{k=1}^{K'} R_{0k}^2 P_k \cong \sum_{k=1}^{\pi\gamma_0^2 A/2} R_{0k}^2 P_0$ convergent to $\pi\gamma_0^2 \alpha P_0 / 2$. Then the total interference power converges to

$$P_{in} = \frac{\pi\gamma_0^2 \alpha P_0}{2} + \pi\alpha P_0 \gamma_0^{\beta} \int_{r_0}^{\infty} \gamma^{-\beta+1} d\gamma = \frac{\beta\mu P_0}{2(\beta-2)} \tag{2}$$

where $\mu = \pi\gamma_0^2\alpha$ is the number of nodes per Hz per second inside the circle of radius γ_0. To have a sense on μ for practical system, consider that nodes are located on cross points of grid with adjacent distance γ_n and then $A = 1/\gamma_n^2$. Define the normalized node distance by $r_n = \gamma_n/\gamma_0$, then $\mu \cong \pi\gamma_0^2 / (N\gamma_n^2) = \pi / (Nr_n^2)$. For $r_0 = 100$ meters, processing gain $N = 50 \sim 100$, and node distance $\gamma_n = 10 \sim 500$ meters, the range of μ is $\mu \cong 1.26\times10^{-3} \sim 6.18$.

As demonstrated in (2), although the whole two dimensional plane is covered by the uniformly distributed nodes and the number of transmitting nodes per unit area treads to infinity with their ratio kept a constant, the effective interference power is finite. In other words, because the received signal power decays in distance with the power of $\beta > 2$, we can allow the number of nodes per unit area to increase to infinity as bandwidth trends to infinity. The signal to interference ratio (SIR) is $P(r)/(P_{in} + \sigma^2)$. When the maximum ratio combiner is applied, the signal to interference ratio after combination of received signals in m transmissions is m times the SIR of one transmission. Hence, we obtain the following theorem.

Theorem 1: For a large wireless CDMA ad hoc network with transmitting nodes uniformly distributed on an infinitely large plane, as the number of transmitting nodes on unit area and processing gain trend to infinity with their ratio kept constant α, the SIR of MF output with optimum combiner for a packet of m retransmissions with transmitting distance r converges to

$$\mathrm{SIR}^{(m)}(r)=\begin{cases}\dfrac{m/r^{\beta}}{\beta\mu/[2(\beta-2)]+1/\mathrm{SNR}_0}, & r\ge 1,\\ \dfrac{m}{\beta\mu/[2(\beta-2)]+1/\mathrm{SNR}_0}, & r<1,\end{cases} \quad (3)$$

where $\mathrm{SNR}_0 = P_0/\sigma^2$ is the signal to noise ratio within the normalized transmitting distance $r = 1$.

Since the interference plus noise is asymptotically Gaussian with zero mean, the bit error rate is $p_e^{(m)}(r) = Q\left(\sqrt{\mathrm{SIR}^{(m)}(r)}\right)$. Since there area always a half number of nodes transmitting, $p_e^{(m)}(r)$ is time-invariant. For a packet of length L in bits without error correction coding, the packet success probability is $p^{(m)}(r) = [1 - p_e^{(m)}(r)]^L$. Clearly, the packet success probability is monotonically increasing with the number of transmissions and decreasing with the distance.

We point out that Theorem 1 is applicable when the number of transmitting nodes is Poisson distributed with the mean number on unit area and processing gain trending to infinity with their ratio kept constant α. Although here the packet success probability is presented for uncoded packets, the matched filter, and Gaussian channel, it is easy to be extended to coded packets, other multiuser receivers, and fading multipath channels by using the results in [10]-[16], as well as blind and group blind scenarios.

III. STATIONARY STATE AND CAPACITY

A. Stationary probability distribution of number of transmissions

The following results are applicable to any receiver, channel, multiple access scheme, error correction coding, etc., provided that the packet success probability is give by $p^{(m)}(r)$ for a packet of its mth retransmission with transmitting distance r.

The number of retransmissions of the transmitted packet $M(t) \in Z^+$ in a buffer with transmitting distance r is a Markov chain. Its state transition probability is

$$\Pr[M(t+1)=m\mid M(t)=j]=\begin{cases}p^{(j)}(r), & m=1,\\ 1-p^{(j)}(r), & m=j+1,\\ 0, & \text{otherwise.}\end{cases} \quad (4)$$

The transition probability matrix is

$$\mathbf{P}(r)=\begin{bmatrix} p^{(1)}(r) & 1-p^{(1)}(r) & 0 & 0 & \cdots & 0 & \cdots\\ p^{(2)}(r) & 0 & 1-p^{(2)}(r) & 0 & \cdots & 0 & \cdots\\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots\\ p^{(j)}(r) & 0 & \cdots & 0 & 1-p^{(j)}(r) & 0 & \cdots\\ \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \end{bmatrix}. \quad (5)$$

Denote by $g_m(r) = \Pr(M = m)$ the stationary probability distribution that the transmitted packet is in its mth transmission. We have the following theorem.

Theorem 2: If there is an integer $n \ge 1$ such that $p^{(m)}(r) > 0$ for $\forall m \ge n$, then the Markov chain defined by (5) has a unique stationary state with probability distribution

$$g_m(r)=\frac{\prod_{j=1}^{m-1}\left(1-p^{(j)}(r)\right)}{1+\sum_{i=2}^{\infty}\prod_{j=1}^{i-1}\left(1-p^{(j)}(r)\right)} \quad (6)$$

where the numerator is one for $m = 1$.

The stationary probability distribution $\mathbf{g}(r) = [g_1(r), g_2(r), \ldots]$ must solve $\mathbf{g}(r) = \mathbf{g}(r)\mathbf{P}(r)$. From (5), we have

$$g_m(r)=g_{m-1}(r)\left(1-p^{(m-1)}(r)\right)=g_1(r)\prod_{j=1}^{m-1}\left(1-p^{(j)}(r)\right) \quad (7)$$

for $m \ge 2$. Since

$$\sum_{m=1}^{\infty} g_m(r)=g_1(r)\left(1+\sum_{m=2}^{\infty}\prod_{j=1}^{m-1}\left(1-p^{(j)}(r)\right)\right)=1,$$

we obtain (6). For the stationary probability distribution to satisfy the first column of $\mathbf{P}(r)$, we must have

$$\sum_{m=1}^{\infty} p^{(m)}(r)\prod_{j=1}^{m-1}\left(1-p^{(j)}(r)\right)=1 \quad (8)$$

which is verified as follows

$$\begin{aligned}\sum_{m=1}^{\infty} p^{(m)}(r)\prod_{j=1}^{m-1}\left(1-p^{(j)}(r)\right)&=\sum_{m=1}^{\infty}[1-(1-p^{(m)}(r))]\prod_{j=1}^{m-1}\left(1-p^{(j)}(r)\right)\\ &=\sum_{m=1}^{\infty}\left[\prod_{j=1}^{m-1}\left(1-p^{(j)}(r)\right)-\prod_{j=1}^{m}\left(1-p^{(j)}(r)\right)\right]=1-\prod_{j=1}^{\infty}\left(1-p^{(j)}(r)\right)\\ &=1. \end{aligned} \quad (9)$$

where the last equality holds due to the condition in Theorem 2. In fact, the left hand of (8) is the probability that a packet is successfully received in infinitely many retransmissions.

For any practical receiver, we have $p^{(m)}(r) \ge 1/2^L$. Hence, the unique stationary distribution always exists.

B. Stationary link throughput

The stationary link throughput with transmitting distance r in packets per slot is

$$S(r)=\sum_{m=1}^{\infty} p^{(m)}(r)g_m(r)=g_1(r) \quad (10)$$

where the last equality follows from (8). Since $M = 1$ if a previous transmission is successful, g_1 is the average probability that a packet is successfully transmitted. Note that the number of transmissions for a particular packet has a probability distribution $p^{(m)}(r)\prod_{j=1}^{m-1}\left(1-p^{(j)}(r)\right)$, that is, m–1 unsuccessful transmissions followed by a success. The link delay (average number of retransmissions per packet) is

$$\begin{aligned}D(r)&=\sum_{m=1}^{\infty} mp^{(m)}(r)\prod_{j=1}^{m-1}\left(1-p^{(j)}(r)\right)\\ &=\sum_{m=1}^{\infty} m\left[1-(1-p^{(m)}(r))\right]\prod_{j=1}^{m-1}\left(1-p^{(j)}(r)\right)\\ &=\sum_{m=1}^{\infty} m\left[\prod_{j=1}^{m-1}\left(1-p^{(j)}(r)\right)-\prod_{j=1}^{m}\left(1-p^{(j)}(r)\right)\right]\\ &=\sum_{m=1}^{\infty}\prod_{j=1}^{m-1}\left(1-p^{(j)}(r)\right)-\lim_{m\to\infty} m\prod_{j=1}^{m}\left(1-p^{(j)}(r)\right)\\ &=\frac{1}{g_1(r)}. \end{aligned} \quad (11)$$

where the last equality is due to condition in Theorem 2.

As a particular instance, when retransmission diversity is not employed, all retransmissions are treated as a new transmission. Then $p^{(m)}(r) = p^{(1)}(r)$, $m \ge 1$. The stationary probability distribution becomes $\breve{g}_m(r) = [1-p^{(1)}(r)]^{m-1}\ p^{(1)}(r)$, $m \ge 1$. The link throughput is $\breve{S}(r) = p^{(1)}(r)$ and the link delay is $\breve{D}(r) = 1/p^{(1)}(r)$.

C. Link transport capacity

The link transport throughput with normalized node distance *r* is $T(r) = rS(r)$ packet-meters per slot where the meter is in the sense of normalized distance. The link transport capacity is defined as the maximum link transport throughput for all distances

$$T = \max_{r>0}\{rS(r)\}\ . \tag{12}$$

Accordingly, the optimum transport distance achieving the link transport capacity is $r_{opt} = \arg\max_{r>0}\{rS(r)\}$. Since the link throughput is monotonically decreasing with distance, the link transport throughput $T(r)$ is convex down. Hence, the optimum link transport distance uniquely exists.

D. Network transport capacity per node

In the following discussion of network capacity, we do not give extra credit when a packet has multiple destinations. Consider a packet that has a demanded source-destination distance *r*. Suppose the packet is delivered to destination in $h(r)$ hops each with distance r_i, $i = 1, \ldots, h(r)$. To achieve the maximum total transport throughput, all the relaying nodes must be on the line between the source and destination, that is, $r = r_1 + r_2 + \ldots + r_h$, because the link throughput is decreasing with link distance. Then the maximum transport throughput for delivering this packet with a scheduling on $h(r)$ and r_i as

$$T_n(r) = \max_{h(r),r_i} \frac{r}{\sum_{j=1}^{h(r)} 1/S(r_j)}\ . \tag{13}$$

Denote by $R(r)$ the probability density function of source-destination distance *r* of packets for each node. The network transport capacity in packet-meters per slot per node is defined as

$$T_n = E[T_n(r)/2] = \frac{1}{2}\int_0^\infty R(r) \max_{h(r),r_i} \frac{r}{\sum_{j=1}^{h(r)} 1/S(r_j)} dr\ . \tag{14}$$

Proposition 1: Suppose that each node has a throughput of $\lambda(r)$ packets per slot with source-destination distance *r*. If a half number of nodes transmit with the other half receiving and transmitting and receiving nodes are in pairs in any slot, then the transport throughput in packet-meters per slot obtained by each node is upper bounded by

$$E[r\lambda(r)] \le T_n \tag{15}$$

for all MAC protocols and traffic patterns.

Consider a large number of slots *t* and a total number of *n* nodes. The total transport throughput of the network is $\lambda nt\bar{r}$. Since only a half number of nodes transmit, the total transport capacity is ntT_n assuming the optimum scheduling in (13). Irrelative to MAC protocols and traffic patterns, the total transport throughput can not be greater than the total transport capacity. Hence, we obtain (15). Note that the network transport capacity T_n obtained per node is achieved if delivery of packets is scheduled such that (i) in any particular slot, transmitting nodes are uniformly distributed, (ii) all nodes transmit packets on the same hop of their own optimum schedule defined by (13), and (iii) in each slot the buffer of each node is long enough to make (ii) achievable.

E. Node capacity and node transport capacity

Finally, we discuss the node capacity and node transport capacity in the case that all transmitting nodes transmit packet to one receiving node. In an annulus of distance γ and width $d\gamma$, there are $2\pi A\gamma d\gamma/2$ nodes. The total stationary throughput of a node in packets per slot is $S = \pi A\int_0^\infty \gamma S(r)d\gamma = \pi\gamma_0^2 A\int_0^\infty rS(r)dr$. Then the node capacity (spectral efficiency) in bits per Hz per second is

$$C = \lim_{N\to\infty} \frac{SL}{NL} = \mu\int_0^\infty rS(r)dr\ . \tag{16}$$

C is also the network capacity per node for a fully connected network in which all packets are delivered with one hop. *C* takes into account all nodes no matter how far a node is. However, when node distance is large, the packet success probability is low and so the delay may be intolerably large. In this case, a non-fully connected network must be considered.

Suppose that only the nodes within a normalized distance r_d are accepted to have an effective link. Then the node capacity is

$$C_d = \mu\int_0^{r_d} rS(r)dr\ . \tag{17}$$

In an annulus of distance γ and width $d\gamma$, the transport capacity of a node in packet-meters per slot is $\tilde{T}_n = \pi A\int_0^\infty \gamma T(r)d\gamma = \pi\gamma_0^2 A\int_0^\infty rT(r)dr = \pi\gamma_0^2 A\int_0^\infty r^2 S(r)dr$. Then the node transport capacity is

$$C_{Tn} = \lim_{N\to\infty} \frac{\tilde{T}_n L}{NL} = \mu\int_0^\infty r^2 S(r)dr \tag{18}$$

bit-meters per Hz second. Here node capacities are irrelative to MAC protocols and traffic patterns.

F. Numerical evaluation

As shown by numerical evaluation in Figs. 2-4, when $\mu < 0.045$, the probability of retransmission is small and then the link transport capacity is approximately the same with and without retransmission gain. The optimum transport distance achieving transport capacity is greater than one. However, as $\mu > 0.045$ increases, the link transport capacity is much higher and packet delay is much lower with exploitation of retransmission diversity than without. In this case, the optimum transport distance is always equal to one, $r_{opt} = 1$. That is, in practical system the packet on each hop should be delivered to the nearest node if there is no node within distance $r = 1$, or to the farthest node among those within distance $r = 1$.

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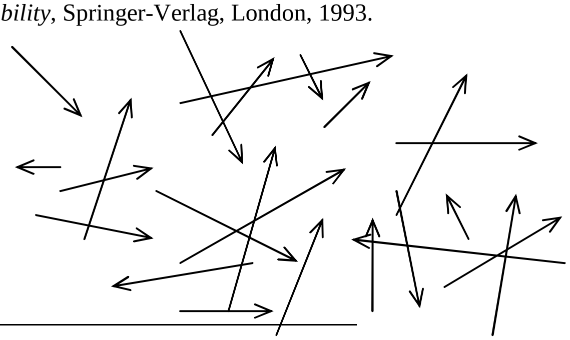

Fig. 1. Packet transmissions in an ad hoc network.

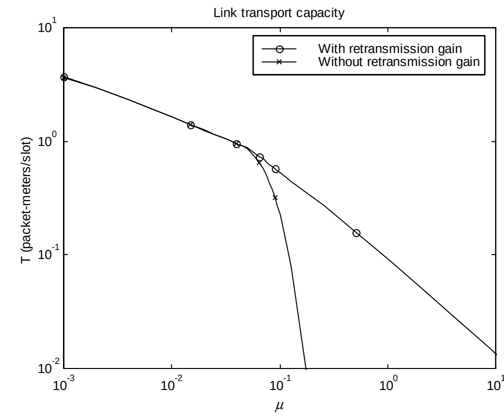

Fig. 2. Link transport capacity. SNR_0 = 30 dB, β = 2.5, L = 64 bits.

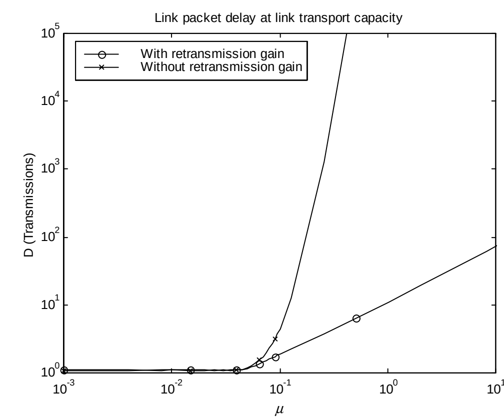

Fig. 3. Link packet delay achieving the link transport capacity. Same conditions as in Fig. 2.

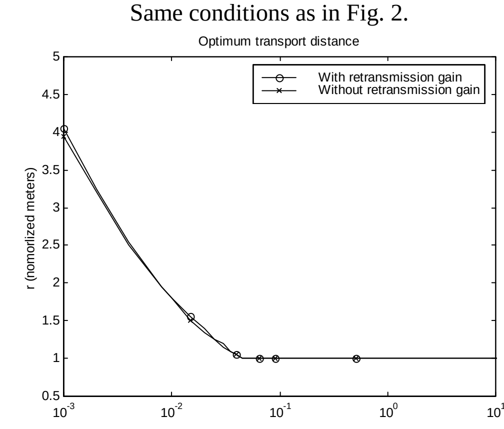

Fig. 4. Optimum link distance achieving the link transport capacity. Same conditions as in Fig. 2.

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