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Impact of Signal Processing Energy and Large Bandwidth on Infrastructureless Wireless Network Routing and Scalability

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Abstract—Throughput scaling and optimal hop distance of *interference-limited* wireless networks have been well characterized in literature. For some emerging wireless networks, throughput may be more limited by battery energy rather than by interference. In characterizing throughput scaling and optimal hop distance of such *power-limited* networks, prior work have invoked a zero signal processing energy assumption, which led to the belief that whispering to the nearest neighbor (WtNN, with the average number of hops per source destination pair increasing with increasing node density) achieves the optimal throughput scaling. We show that this belief must be modified for power-limited networks when signal processing energy is not an insignificant factor. In fact, for a power-limited network with nodes uniformly randomly distributed in a bounded region and in the limit of interference-free operation, taking $\Theta(1)$ (i.e. does not increase or decrease with increasing node density) number of hops is throughput, energy, and delay optimal, achieving $\Theta(1)$ pairwise throughput, energy per bit, and packet delay under uniform traffic, whereas WtNN is strictly suboptimal, achieving a pairwise throughput of $O\left(\sqrt{\frac{\log n}{n}}\right)$, which decreases with increasing node density. In addition, we show that a constant characteristic hop distance of d_{char} simultaneously achieves the pairwise throughput scaling and minimum network energy consumption for random networks.

Index Terms—Wireless networks, ultra-wideband, power-limited, signal processing energy, pairwise throughput, hop distance, routing.

I. INTRODUCTION

RAPIDLY deployable infrastructureless wireless networks have gained much interest in research and development communities in the past decade. Such networks are self-organizing with wireless devices (or nodes) forming a network autonomously and helping one another to route information. Potential applications of infrastructureless wireless networks include large-scale distributed sensing and battlefield communications. Since the envisioned networks may have hundreds, if not thousands, of wireless nodes, network scalability becomes an increasing concern as the number of nodes increases.

In general, network scalability is limited by bandwidth and battery energy at each node. For narrowband systems, inter-

ference from nearby transmissions typically dominate noise; hence these systems are said to operate in the *interference-limited regime*. In this regime, it has been found that for a random network with n nodes distributed in a bounded region according to a uniform distribution, whispering to the nearest neighbor (WtNN, transmitting shorter distances per hop as node density increases) decreases interference and achieves optimal pairwise throughput scaling of $\Theta\left(\frac{1}{\sqrt{n \log n}}\right)$, which decreases with increasing node density¹ [1], [2]. This pairwise throughput scaling can be improved at the expense of increasing hierarchical infrastructure deployment [3], node mobility and delay [4], or complexity for cooperative transmissions [5].

In this paper, we explore the effect of having a large bandwidth on the pairwise throughput of infrastructureless wireless networks operating in the *power-limited regime* and provide insights on the impact of signal processing energy on the optimal hop distance. This is partially motivated by the emerging interests in ultra-wideband (UWB) wireless networks and the fact that many infrastructureless transmissions are low rate. But, more importantly, this study is motivated by the lack of emphasis on signal processing energy consumption (including energy expended by transmitter and receiver electronics, and processors for modulation/demodulation, coding/decoding, and route computation) in network throughput studies. For some wireless networks, especially those with short transmission ranges (fairly typical for UWB systems), signal processing energy can dominate the distance-dependent transmission energy as discussed in [6]. Table I summarizes the transmission and signal processing energy of two low-power wireless systems. Under typical operating scenarios, the signal processing energy is significantly higher than the transmission energy for both systems. As we will show, neglecting signal processing energy can lead erroneously to routing on paths with large numbers of hops, resulting in limited network throughput.

Specifically, we characterize the optimal pairwise throughput scaling and the corresponding hop distance of arbitrary²

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¹The order relationships $O(\cdot)$, $\Omega(\cdot)$, and $\Theta(\cdot)$ that appear in this paper are commonly used in computational complexity theory and represent asymptotic upper bound, lower bound, and tight bound of functions respectively. (i) $f(n) = O(g(n))$ if there is exists a constant c and an integer N such that $f(n) \leq cg(n)$ for $n > N$. (ii) $f(n) = \Omega(g(n))$ if $g(n) = O(f(n))$. (iii) $f(n) = \Theta(g(n))$ if $f(n) = O(g(n))$ and $g(n) = O(f(n))$.

²Users are arbitrarily located in a bounded region

and random³ power-limited wireless networks operating in a bounded region and under the limit of interference-free operation (with sufficiently large bandwidth). The traffic pattern is similar to that of [2] where each node exchanges data with a randomly selected node. The transmissions are limited by an average power constraint at each node. Two types of systems are studied: systems with fixed transmission rate and systems with variable transmission rate. Our key results are:

- 1) For random power-limited networks, optimal pairwise throughput scales well with increasing n , achieving $\Theta(1)$ scaling (i.e. does not decrease or increase with increasing node density) for systems with either fixed or variable transmission rates. This is different from the throughput scaling results obtained under the zero signal processing energy assumption where the pairwise throughput increases with increasing node density [7]. For arbitrary power-limited networks, there exist network topologies and traffic patterns that have very poor throughput scaling behavior, even with infinite bandwidth and variable transmission rate.
- 2) Taking $\Theta(1)$ number of hops (i.e. the number of hops does not increase with increasing node density) achieves the optimal throughput scaling for random power-limited networks operating in bounded regions. In addition, $\Theta(1)$ number of hops is optimal in energy per bit and packet delay scaling, achieving $\Theta(1)$ for both.
- 3) The pairwise throughput of random power-limited networks operating in bounded regions is $O\left(\sqrt{\frac{\log n}{n}}\right)$ under WtNN routing when signal processing energy is non-zero. This routing scheme, while throughput-optimal if signal processing energy is zero, is suboptimal when signal processing energy is non-zero and thus should not be treated as the *de facto* routing strategy for all wireless networks. In fact, there exists a constant characteristic hop distance d_{char} that achieves the optimal throughput scaling and yields the minimum total network energy consumption.

A subset of the results in this paper have been presented in [8] and [9]. We make note of these prior results in this paper and present additional results and insights. This paper is organized as follows: Section II presents the models, definitions, and assumptions used in this paper. Section III derives the pairwise throughput scaling of arbitrary networks for systems with fixed and variable transmission rates. Several throughput achieving scenarios are discussed. Section IV derives the pairwise throughput scaling of random networks and show that WtNN is strictly suboptimal. Section V provides some insights and guidelines on the optimal hopping distance for power-limited networks. Section VI concludes the paper.

II. MODELS, DEFINITIONS, AND ASSUMPTIONS

Consider a fixed infrastructureless wireless network with n wireless nodes operating in a geographically bounded region as illustrated in Fig. 1. Each node can generate new data traffic intended for any other node and help to route pass-through

³Users are independently randomly distributed in a bounded region according to a uniform distribution

TABLE I
ENERGY CONSUMPTION OF TWO LOW-POWER WIRELESS SYSTEMS

Systems	Data rate (Mbps)	Dist (m)	Tx power (mW)	Proc power (mW)	α (nJ/bit)	β (nJ/(bit · m ²))	d_{char} (m)
Wireless sensor [10]	2.5	50	12.5	50	20	0.002	100
UWB [11], [12]	16.7	10	0.8	42	2.5	0.008	18

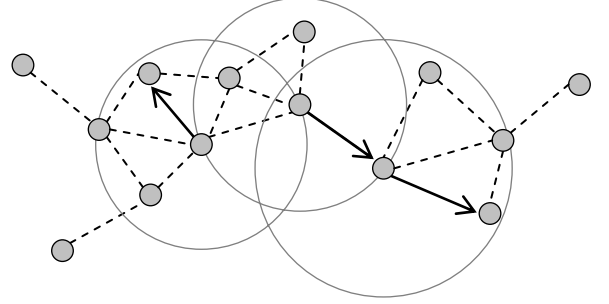


Fig. 1. Infrastructureless wireless network.

traffic for other source-destination (SD) node pairs. The network model in [7] is adopted with three key differences:

- 1) In addition to the distance-dependent *transmit power*, we model *signal processing power* consumption explicitly, which accounts for energy consumed by transmitter and receiver electronics (excluding transmitted power), processor(s), and storage unit(s).
- 2) For analytical tractability under the new energy model, we consider a traffic pattern where each node selects another node for data exchange and both nodes send data to one another at an average rate of λ [bits/sec]. This is termed *uniform and symmetric traffic pattern*. The routing path in either direction is assumed to consist of the same set of intermediate nodes.
- 3) Depending on the transceiver design, the transmission rate is either *fixed* or *variable*. We derive performance results for both types of systems to explore potential gains of the more complex variable-rate modulation systems. In either case, nodes are assumed to employ power control and adjust the radiated power level depending on the distance between the transmitting and receiving nodes.

The primary network performance metric of interest is the *maximum pairwise throughput* (henceforth, pairwise throughput) $\hat{\lambda}$, defined as $\hat{\lambda} = \max \lambda$, subject to a per node average power constraint. For random networks, the pairwise throughput, energy per bit, and packet delay are defined in [1] and will not be repeated here. Since the network performance results are highly sensitive to energy models, we present a detailed discussion of the models and assumptions used in our analysis below.

A. General Node Energy Consumption Model

For many applications, the wireless nodes are required to be untethered, hence the performance of each node - be it sensing, computation, communication, and/or actuation - is limited by the battery unit shared by all electronics in a node. In some cases, the battery unit is connected to energy scavenging devices. The performance of each node is then limited by the rate at which these nodes can charge the battery unit. These power limitations necessitate a much more integrated system design approach to prolonging the operational time of a network. In this paper, we isolate the study to the performance of the wireless communications subsystem and assume that the maximum average power consumption by the subsystem is limited to \hat{P}_{avg} , where a lower \hat{P}_{avg} corresponds to a longer node service lifetime at the expense of poorer network performance.

A typical wireless communications subsystem consists of a power amplifier, transmitter and receiver circuitry, processor(s), and data storage unit(s). The average power expended by the subsystem depends on the average data rate of the transmitted and received signals. Adopting a simple path-loss model, the average data rate R_{ij} a node i can transmit to another node j is upper-bounded as

$$R_{ij} \leq C_{ij} = W \log \left(1 + \frac{\gamma_{ij} P_t^{ij} / d_{ij}^k}{N_0 W + I_{ij}} \right) \quad (1)$$

where C_{ij} is the link throughput, W is the bandwidth, P_t^{ij} and d_{ij} are the average transmitted (radiated) power from i to j and the distance between the nodes respectively, γ_{ij} is the radio frequency (RF) gain factor incorporating antenna gains and RF signal processing losses, k is the path-loss exponent typically in the range of 2 - 6, N_0 is the Gaussian noise spectral density, and $I_{ij} = \sum_{m, m \neq i, j} \gamma_{mj} P_t^m / d_{mj}^k$ is the average received interference power at node j from all other transmitting nodes (P_t^m is the average radiated power by node m).

Define the aggregate average transmitted data rate by node i (new and pass-through traffic) $R_i^t = \sum_{j, j \neq i} R_{ij}$, and the aggregate average received data rate $R_i^r = \sum_{j, j \neq i} R_{ji}$. At the maximum average data rate of $R_{ij} = C_{ij}$, $\forall i, j$, the total average power P_i consumed at node i can be modeled as

$$P_i = \alpha_r R_i^r + \alpha_0 R_i^r + \alpha_1 R_i^t + \alpha_t R_i^t + \eta \sum_{j, j \neq i} P_t^{ij} \quad (2)$$

where α_r , α_0 , α_1 , and α_t are the per bit energy for receiving data, processing and storing received data, storing and processing transmitted data, and transmitting data (excluding the power amplifier) respectively, all measured in [Joules/bit]. The power amplifier draws $\eta \sum_{j, j \neq i} P_t^{ij}$ amount of power, where $\eta \geq 1$ is the inverse of the amplifier power conversion efficiency⁴. Various forms of this first-order power consumption model have been used by researchers in the physical device field [13]–[15].

⁴For a given power amplifier, the power conversion efficiency typically varies with output power. Here we assume that given any output power, there is a power amplifier with power conversion efficiency of η^{-1} .

B. Node Energy Consumption Model in Power-limited Regime

Given (1), the achievable rate region of a network is strongly dependent on the network topology, power allocation, transmission scheduling, and routing schemes. These interdependencies make it difficult to analytically characterize not only the rate region, but also the simpler pairwise throughput under uniform traffic. To derive some understanding of the pairwise throughput in relation to the network size (number of nodes), and more importantly, to derive some useful guidelines on the optimal hop distance, researchers have considered two special operating regimes: *power-limited* and *interference-limited*.

Most of the existing work on the pairwise throughput of wireless networks considers narrow-band systems. Rather than using the full rate expression in (1), most of these work adopt a simpler Physical Model [1], [2] in which

$$R_{ij} = \begin{cases} W, & \text{if } \frac{\gamma_{ij} P_t^{ij} / d_{ij}^k}{N_0 W + I_{ij}} \geq \Psi \\ 0, & \text{otherwise} \end{cases} \quad (3)$$

where Ψ is the minimum signal to interference and noise ratio (SINR) threshold for successful transmission. Such a model assumes fixed rate transmissions whenever a node transmits. If $I_{ij} \gg N_0 W$, the transmit power levels have relatively little impact on the link data rate. To see why this is the case, consider a set of transmit powers that satisfy the SINR threshold condition in (3). If the transmit powers are proportionally reduced by a non-zero factor, the SINR threshold condition is still satisfied as long as $I_{ij} \gg N_0 W$ holds. What constrains the data rate is the number of simultaneous transmissions (interference) in the network and the signal processing energy consumed by pass-through traffic. Under this model, [1] shows that $\Theta(1)$ hops (i.e. number of hops does not increase with increasing number of nodes) yields the optimal energy and delay scaling of $\Theta(1)$ but the worst throughput scaling of $\Theta(\frac{1}{n})$. The best throughput scaling of $\Theta(\frac{1}{\sqrt{n \log n}})$ can be achieved by taking short hops at the expense of poor delay and energy scaling of $\Theta(\sqrt{\frac{n}{\log n}})$. Hence, if the network is *both interference and power limited* (in the sense that the available per node energy does not increase with n), then throughput scaling of $\Theta(\frac{1}{n})$ is all we can hope for under uniform traffic.

In contrast to narrow-band systems, power, rather than bandwidth, is more of a premium resource for wide-band systems. We aim to derive the throughput, packet delay, and energy per bit scaling of wireless networks in the power-limited regime. In addition, we aim to dispel the erroneous belief that the throughput of wide-band systems increases without bound with increasing number of nodes and that taking many short hops is the throughput-optimal routing scheme. To these ends, we consider the limit of large bandwidth ($W \rightarrow \infty$) as in [7] (i.e. interference-free operation). In this regime, (1) becomes

$$R_{ij} \leq C_{ij} \xrightarrow{W \rightarrow \infty} \frac{\gamma_{ij} P_t^{ij}}{N_0 d_{ij}^k} \quad (4)$$

Since the bandwidth is assumed to be arbitrarily large, interference and overhearing can be suppressed through proper channelization. At the maximum link data rate of $R_{ij} = C_{ij}$,

$\forall i, j$, the total average power consumed by node i from (2) is

$$P_i = \sum_{\forall j, j \neq i} (\alpha_r + \alpha_0) R_{ji} + \sum_{\forall j, j \neq i} \left(\alpha_1 + \alpha_t + \frac{\eta N_0}{\gamma_{ij}} d_{ij}^k \right) R_{ij} \quad (5)$$

Subsequently, we assume that the RF gain factor is the same at all nodes such that $\gamma = \gamma_{ij}, \forall i, j$.

C. End-to-end Path Energy Consumption

Consider now a single transmission at a data rate of λ , routed through h hops towards a destination node. From (5), the total power consumed by all of the nodes along the routing path in the power-limited regime is

$$P_{path} = \lambda \sum_{m=1}^h (\alpha + \beta d_m^k) \quad (6)$$

where $\alpha = \alpha_r + \alpha_0 + \alpha_1 + \alpha_t$, $\beta = \eta N_0 / \gamma$, and d_m , where $m = 1, \dots, h$, are link distances of adjacent nodes on the path. Some α and β values, and typical transmit and signal processing powers for two energy-efficient wireless systems are shown in Table I. As can be seen, for systems with relatively short transmission distances, signal processing power can dominate transmit power.

As discussed in [8], it is instructive to consider transmit and signal processing energy consumptions from the perspective of fundamental physical limits, regardless of any materials, circuits, or algorithms that make up the system. The fundamental limit for the minimum energy required for a binary switch transition in electronic circuits is $E_c = KT \ln 2$, where K is the Boltzmann's constant and T is the absolute temperature [16]. The fundamental limit for communication (either through an interconnect in a circuit or through a communication channel) is given by the Shannon capacity $W \log_2(1 + P_r / (N_0 W))$. The per bit received energy required is then $E_r = P_r / R \geq (2^{R/W} - 1) N_0 W / R$. At the thermal noise limit, $N_0 = KT$, and in the limit of large bandwidth with $R/W \rightarrow 0$, $E_r = KT \ln 2$. Hence, as electronics improve in efficiency, transmission and signal processing energy are limited by the same fundamental source. By incorporating signal processing energy in the energy model, we allow for maximum flexibility in modeling different technologies and operating scenarios.

III. PAIRWISE THROUGHPUT OF ARBITRARY NETWORKS

In this section, we derive bounds on the pairwise throughput of power-limited networks with n nodes arbitrarily located in a geographically bounded region and for any uniform and symmetric traffic pattern. The main results are summarized below and derived subsequently.

Theorem 1. (i) *The pairwise throughput of an arbitrary power-limited wireless network with fixed transmission rate R under uniform and symmetric traffic is bounded by*

$$\frac{R}{2n-1} \leq \hat{\lambda} \leq \frac{R \rho_{max}}{2\bar{L}} \quad (7)$$

where $\rho_{max} = \left[\frac{1}{\beta} \left(\frac{\hat{P}_{avg}}{R} - \alpha \right) \right]^{1/k}$ is the maximum hop distance, $\bar{L} = \frac{1}{2n} \sum_{i=1}^{2n} L_i$ is the average distance

between SD pairs, and L_i is the distance between SD pair i . If ρ_{max} is too small to form a connected network, then $\hat{\lambda} = 0$.

(ii) *The pairwise throughput of an arbitrary power-limited wireless network with variable transmission rate and under uniform and symmetric traffic is bounded by*

$$\frac{\hat{P}_{avg}}{(2n-1)(\alpha + \beta L_{max}^k)} < \hat{\lambda} \leq \frac{\hat{P}_{avg} d_{char}}{2\alpha \bar{L}} \left(\frac{k-1}{k} \right) \quad (8)$$

where L_{max} is the maximum distance between SD pairs and $d_{char} = \left(\frac{\alpha}{\beta(k-1)} \right)^{1/k}$ is the characteristic hop distance coined by [15].

These results yield the following insights:

1) Systems with fixed transmission rate

- If signal processing energy is zero ($\alpha = 0$), increasing the transmission rate R (correspondingly decreasing ρ_{max}) increases the pairwise throughput upper bound. At a fixed transmission rate R , taking smaller number of long hops can achieve higher throughput in general since it is the amount of pass-through traffic that constrains the pairwise throughput.
- If signal processing energy is non-zero ($\alpha > 0$), there exists a rate $R^* = \frac{\hat{P}_{avg}(k-1)}{k\alpha}$ that maximizes the upper bound (correspondingly $\rho_{max}^* = \left(\frac{\alpha}{\beta(k-1)} \right)^{1/k} = d_{char}$). At a fixed transmission rate R , taking smaller number of long hops achieve higher throughput in general as before.
- Under the worst topology and traffic pattern, pairwise throughput scales with $\Theta(\frac{1}{n})$ due to the existence of bottleneck nodes.

2) Systems with variable transmission rate

- If signal processing energy is zero ($\alpha = 0$), taking larger number of short hops can achieve higher throughput in general since it is the amount of transmit power that constrains the pairwise throughput.
- If signal processing energy is non-zero ($\alpha > 0$), throughput-optimal routing needs to strike a balance between transmit power consumption of taking long hops and signal processing power consumption of taking too many short hops. Taking hop distances of d_{char} minimizes the total network energy consumption but may not achieve the optimal pairwise throughput.
- Under the worst topology and traffic pattern, the pairwise throughput also scales with $\Theta(\frac{1}{n})$. Hence, varying the transmission rate does not improve throughput scalability for some network topologies.

The key observation here is that the rule-of-thumb for routing hop distance depends highly on the type of wireless system and the relative energy consumption between transmission and signal processing. One should not consider WtNN (i.e. taking a large number of short hops) to be the *de facto* throughput-maximizing routing scheme for all wireless networks. We now

proceed to derive Theorem 1.

A. Systems with Fixed Transmission Rate

First, we consider systems with fixed transmission rate. Whenever a node transmits, it transmits at a data rate of R [bits/s] (including new and pass-through traffic). Given a per node average power constraint \hat{P}_{avg} , a transmission is received correctly if the hop distance ρ satisfies

$$\rho \leq \left[\frac{1}{\beta} \left(\frac{\hat{P}_{avg}}{R} - \alpha \right) \right]^{1/k} \equiv \rho_{max} \quad (9)$$

Under uniform and symmetric traffic, there are $2n$ SD pairs exchanging data. The pairwise throughput $\hat{\lambda}$ (under the per node average power constraint) is upper-bounded by the pairwise throughput under a relaxed total average power constraint of $n\hat{P}_{avg}$. Using this relaxed power constraint, an upper bound on $\hat{\lambda}$ can be derived based on simple hop counting arguments similar to the derivation of transport throughput upper bound in [2]. The proof is shown in the Appendix.

Lemma 1. *The pairwise throughput of an arbitrary power-limited wireless network with fixed transmission rate and under uniform and symmetric traffic is upper-bounded by:*

$$\hat{\lambda} \leq \frac{R\rho_{max}}{2\bar{L}} \quad (10)$$

Equality in (10) is trivially achieved if all SD pairs are separated by a distance of ρ_{max} and no node is selected more than once as the destination node. Since \bar{L} is dependent on the network topology and traffic pattern, the pairwise throughput can be arbitrarily high if nodes are located arbitrarily close to one another (ignoring antenna coupling effects).

Now we derive a lower bound on the pairwise throughput $\hat{\lambda}$. Consider the network example shown in Fig. 2. This network has n (odd number) nodes where one node is located at coordinate location $(0, 0)$, $(n-1)/2$ nodes (call these group A) are located at $(-\rho_{max}, 0)$, and $(n-1)/2$ remaining nodes (call these group B) are located at $(\rho_{max}, 0)$. The uniform and symmetric traffic pattern is such that each node in group A exchanges data with a unique node in group B. The node at $(0, 0)$ exchanges data with one of the nodes in either group A or B. Since the distance between nodes in group A and B is greater than ρ_{max} , all transmissions need to be relayed through the node at $(0, 0)$. Hence, the node at $(0, 0)$ needs to sustain a data rate of $(2n-1)\hat{\lambda}$. Since this is constrained by R , the pairwise throughput for this network scenario is $\hat{\lambda} = \frac{R}{2n-1}$, which is of the order $\Theta(\frac{1}{n})$. This scenario is the worst possible for pairwise throughput with the bottleneck node sustaining the maximum amount of pass-through traffic and transmitting at the maximum distance. This gives the lower bound:

Lemma 2. *The pairwise throughput of an arbitrary power-limited wireless network with fixed transmission rate and under uniform and symmetric traffic is lower-bounded by:*

$$\hat{\lambda} \geq \frac{R}{2n-1} \quad (11)$$

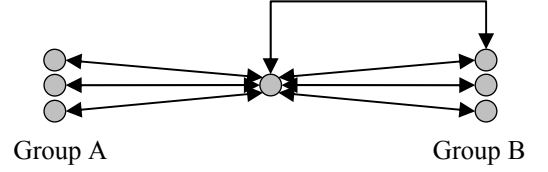


Fig. 2. Network that achieves pairwise throughput lower bound for systems with fixed transmission rate.

B. Systems with Variable Transmission Rate

Now we relax the fixed transmission bit rate constraint. Suppose node i transmits to node j on link (m, n) at a bit rate of Λ_{mn}^{ij} [bits/sec] (including new and pass-through traffic). The problem of throughput maximization under this setting can be expressed as a multicommodity flow problem as in (12) and can be solved by standard multicommodity flow algorithms [17].

$$\hat{\lambda} = \max_{\Lambda_{mn}^{ij}, \forall (m,n), \forall (i,j)} \lambda \quad (12)$$

s.t.

$$\sum_{\forall n} \sum_{\forall (i,j)} \Lambda_{mn}^{ij} (\alpha + \beta d_{mn}^k) \leq \hat{P}_{avg}, \quad \Lambda_{mn}^{ij} \geq 0, \forall m$$

$$\sum_{\forall n} \Lambda_{mn}^{ij} - \sum_{\forall n} \Lambda_{nm}^{ij} = \begin{cases} \lambda, & \text{if } m = i \\ -\lambda, & \text{if } m = j, \quad \forall (i,j), \forall m \\ 0, & \text{otherwise} \end{cases}$$

Instead of solving the above problem for specific networks, we derive upper and lower bounds on the pairwise throughput of arbitrary networks with variable transmission rate.

As before, the pairwise throughput $\hat{\lambda}$ is upper-bounded by the pairwise throughput under the relaxed total average power constraint. *Under this relaxed constraint, all of the routing paths are decoupled; thus, throughput maximization is equivalent to path power minimization.*

Lemma 3. *The pairwise throughput of an arbitrary power-limited wireless network with variable transmission rate and under uniform and symmetric traffic is upper-bounded by:*

$$\hat{\lambda} \leq \frac{\hat{P}_{avg} d_{char}}{2\alpha\bar{L}} \left(\frac{k-1}{k} \right) \quad (13)$$

The derivation for Lemma 3 can be found in the Appendix. Equality in (13) is achieved if all SD pairs are separated by a distance of d_{char} . Note that upper bounds (10) and (13) are equal if all hop distances are equal to d_{char} . As before, the pairwise throughput can be arbitrarily high if nodes are located arbitrarily close to one another (ignoring antenna coupling effects).

Lemma 4. *The pairwise throughput of a power-limited wireless network with variable transmission rate and under uniform and symmetric traffic is lower-bounded by:*

$$\hat{\lambda} > \frac{\hat{P}_{avg}}{(2n-1)(\alpha + \beta L_{max}^k)} \quad (14)$$

The lower bound is derived by noting that the maximum amount of traffic a node needs to transmit is $\hat{\lambda}(2n-1)$ and the maximum hop distance is L_{max} . There does not exist a

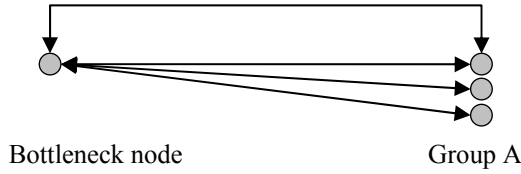


Fig. 3. Network that achieves the scaling order of pairwise throughput lower bound for systems with variable transmission rate.

network topology and traffic pattern that achieves this lower bound; however, it is tight in the order with respect to n . Consider the network topology shown in Fig. 3. This network has n nodes where one node is the bottleneck node, and the rest of the $n - 1$ nodes (call this group A) are located at a distance of L_{max} from the bottleneck node. The uniform and symmetric traffic pattern is such that all message exchanges are between nodes in group A and the bottleneck node. Hence, the bottleneck node needs to transmit at a rate of $n\hat{\lambda}$. This yields $\hat{\lambda} = \frac{\bar{P}_{avg}}{n(\alpha + \beta L_{max}^k)}$, which is of the order of the lower bound $\Theta(\frac{1}{n})$.

IV. PAIRWISE THROUGHPUT OF RANDOM NETWORKS

From Section III, it can be observed that pairwise throughput scaling for some network scenarios is very poor even with infinite bandwidth and variable transmission rate. For many practical networking scenarios, these network topology and traffic patterns may rarely occur. It is of interest, therefore, to study pairwise throughput scaling of random networks and see if it can be improved with a more uniform distribution of nodes and traffic pattern.

Consider a random network with n nodes independently and randomly distributed on a unit torus according to a uniform distribution as shown in Fig. 4. Under uniform and symmetric traffic, each node randomly selects another node and forms a two way communication path with λ [bits/sec] sent in each direction. Define pairwise throughput $\hat{\lambda}$ to be the maximum achievable λ with high probability (where we take with high probability (*whp*) to be probability $\geq 1 - \frac{1}{n}$ as in [18]). We are interested in studying how pairwise throughput scales with increasing number of nodes n . Such study yields insights on the scalability of power-limited networks as well as how optimal hop distance changes with increasing n . The main results are summarized below and derived subsequently.

Theorem 2. (i) *The pairwise throughput of a random power-limited wireless network with fixed or variable transmission rate and under uniform and symmetric traffic is $\Theta(1)$ with high probability (*whp*).*
(ii) *Routing schemes with $\Theta(1)$ hops achieves the pairwise throughput scaling of $\Theta(1)$ and attains the optimal packet delay and energy per bit scaling of $\Theta(1)$ *whp*.*

Theorem 3. *Under WtNN routing, the pairwise throughput of a random power-limited wireless network with fixed or variable transmission rate and under uniform and symmetric traffic is $O\left(\sqrt{\frac{\log n}{n}}\right)$ *whp*.*

These results yield the following insights:

- 1) The pairwise throughput is scalable for power-limited networks with more uniformly distributed node locations and traffic patterns.
- 2) Random power-limited wireless networks are much more scalable in pairwise throughput compared to interference-limited wireless networks. This of course comes at the expense of large bandwidth. In the worst case, bandwidth is divided into non-overlapping frequency slots and each SD pair transmits in a distinct frequency slot. This frequency assignment require the bandwidth to scale on the order of $W = \Theta(n)$.
- 3) For systems with variable transmission rate, if signal processing energy is zero ($\alpha = 0$), taking shorter hops as n increases (WtNN routing) results in increasing pairwise throughput [7]. Our results show that if signal processing energy is non-zero ($\alpha > 0$), then the pairwise throughput *does not* increase indefinitely as n increases. Given large enough n , the pairwise throughput will saturate, attaining an order of $\Theta(1)$. Routing schemes with $\Theta(1)$ number of hops (i.e. the number of hops does not increase with n) attains this order.
- 4) In connection to observation 3, for smaller and smaller α , the point, n_{large} , at which the pairwise throughput begins to saturate becomes larger and larger. As $\alpha \rightarrow 0$, $n_{large} \rightarrow \infty$. For practical systems with limited number of nodes, one may or may not see this saturation effect depending on the relative ratio of signal processing energy coefficient α and transmission energy coefficient β .
- 5) For systems with fixed transmission rate, the amount of pass-through traffic limits the pairwise throughput. Our results show that routing schemes with $\Theta(1)$ number of hops attains $\Theta(1)$ pairwise throughput.

We now proceed to derive Theorems 2 and 3.

A. Systems with Fixed Transmission Rate

For systems with fixed transmission rate, a node transmits at a data rate of R [bits/sec] whenever it transmits. Given the per node average power constraint, the hop distance cannot exceed ρ_{max} . In (10), we have shown that $\hat{\lambda} \leq \frac{R\rho_{max}}{2L}$ for any arbitrary network topology and uniform and symmetric traffic pattern. Recall that \bar{L} is the average distance between SD pairs. For random networks, this is a random quantity. As noted in [19], by the law of large numbers, $\bar{L} = \Theta(1)$ *whp* for the random network scenario under consideration. Hence, $\hat{\lambda} = O(1)$ *whp*.

In [9], we have shown that a particular routing scheme, termed *cell routing*, achieves this scaling *whp*. Under the cell routing scheme, the torus operating region is divided into equal-sized square cells with area $A = \rho \times \rho$, where $\sqrt{\frac{2}{n}} \leq \rho \leq \frac{\rho_{max}}{2\sqrt{2}}$ (i.e. for large enough n such that there is at least one node in each cell *whp* and that nodes in adjacent cells are within one hop distance from one another). Between each SD pair, there are a set of cells that the straight line connecting the SD pair crosses as shown in Fig. 4 (dashed line for cell routing). Under uniform and symmetric traffic, messages exchanged by a SD pair take hops along such cells. The pass-through traffic in each cell is distributed evenly

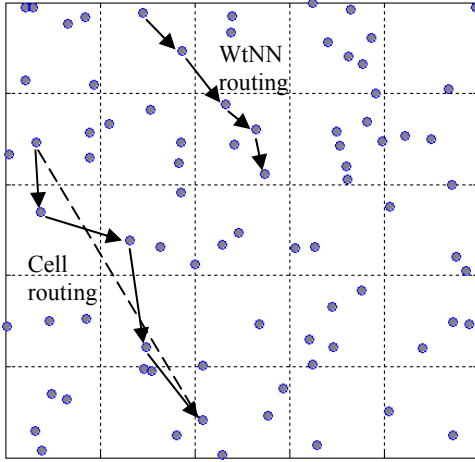


Fig. 4. Random network in a unit torus with two routing schemes.

across the nodes in the cell. This routing scheme has been analyzed in [18] for interference-limited networks. We have extended the results for power-limited networks in [9]. The derivations are shown in the Appendix for completeness.

Note that the pairwise throughput scaling of $\Theta(1)$ is achieved by cell routing as long as the hop distances (equivalently ρ) do not decrease with increasing n . Hence, routing on paths with $\Theta(1)$ number of hops (i.e. the number of hops does not scale increasingly with increasing n) achieves the pairwise throughput scaling as stated in Theorem 2.ii. This yields $\hat{\lambda} = \Theta(1)$ *whp* as stated in Theorem 2.i for systems with fixed transmission rate.

To see the effect of hop distance scaling on the pairwise throughput, we derive an upper bound on the pairwise throughput under WtNN routing. Given a fixed transmission rate R , WtNN routing is defined as the routing scheme that maximizes the pairwise throughput under the zero signal processing energy assumption. Under this routing scheme, the torus is divided into equal sized square cells with area $a(n)$ that scales with n . From Lemma 5.i in the Appendix, WtNN routing dictates that $a(n) = \frac{2 \log n}{n}$ so that each cell has at least one node *whp*. With such a routing scheme, the amount of pass-through traffic per node increases *whp* with increasing n , leading to pairwise throughput scaling of $O\left(\sqrt{\frac{\log n}{n}}\right)$ as stated in Theorem 3 for systems with fixed transmission rate (see derivation in the Appendix).

B. Systems with Variable Transmission Rate

Now we relax the fixed transmission rate constraint. In (13), we have shown that $\hat{\lambda} \leq \frac{\bar{P}_{avg} d_{char}}{2\alpha L} \left(\frac{k-1}{k}\right)$ for any arbitrary network topology and arbitrary uniform and symmetric traffic pattern. Given $\bar{L} = \Theta(1)$ *whp* for the random network scenario under consideration, $\hat{\lambda} = O(1)$ *whp*. In the Appendix, we show that cell routing can achieve this scaling *whp*. Hence $\hat{\lambda} = \Theta(1)$ *whp* as stated in Theorem 2 for systems with variable transmission rate.

For networks that operate in a geographical region with fixed size, the optimal energy per bit and packet delay (defined in [1]) are of the order $\Theta(1)$ since both are proportional to the number of hops. This is achievable by routing schemes with

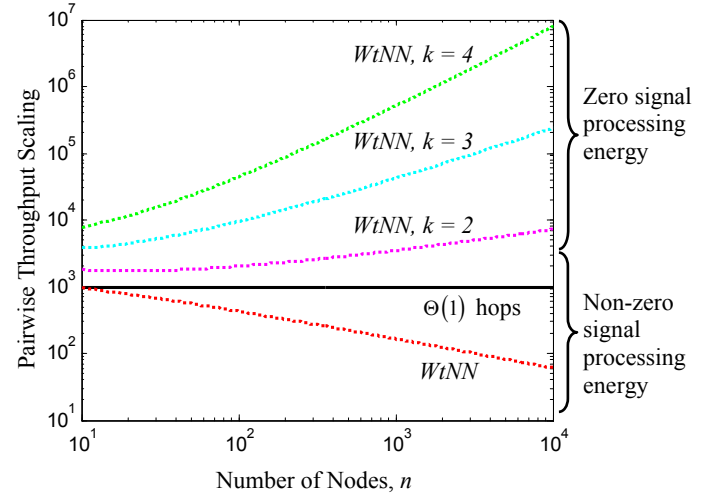


Fig. 5. Pairwise throughput scaling and bounds for variable transmission rate systems under zero and non-zero signal processing energy assumptions (dashed lines = bounds; solid line = exact order).

$\Theta(1)$ hops. In particular, signal processing energy, which is proportional to the number of hops, dominates over transmission energy for large networks.

Now consider the pairwise throughput under WtNN routing. Note that if signal processing energy $\alpha = 0$, then the pairwise throughput is $O\left((\sqrt{n \log n})^{k-1}\right)$ as shown by [7]. With non-zero signal processing energy, however, signal processing energy becomes the throughput-limiting factor as the number of hops gets large under the WtNN routing scheme. In [9], we have shown that the pairwise throughput achievable by WtNN under variable transmission rate is also $O\left(\sqrt{\frac{\log n}{n}}\right)$. The pairwise throughput scaling behavior under WtNN routing is plotted in Fig. 5. From this plot, it is clear that suppressing the signal processing energy has significant impacts on throughput scaling.

V. OPTIMAL HOPPING

From throughput scaling studies, a key engineering insight pertains to rule-of-thumb routing strategies that can attain high throughput in a network or optimize some other performance metric. As shown in [1], for an interference-limited, randomly deployed wireless network operating in a fixed region, $\Theta(1)$ hops attain the best energy per bit and packet delay (equivalently, number of hops) scaling of $\Theta(1)$ at the cost of worst pairwise throughput scaling of $\Theta(\frac{1}{n})$. For interference-limited networks, increasing the number of hops increases the pairwise throughput at the cost of higher packet delay and higher energy per bit.

In contrast, we have shown that taking $\Theta(1)$ hops attains the best pairwise throughput, energy per bit, and packet delay scaling of $\Theta(1)$ for power-limited networks. In particular, the $\Theta(1)$ hop distance of d_{char} achieves the $\Theta(1)$ network performance scaling and minimizes the total network energy. For power-limited networks, increasing the number of hops as n increases will result in worse performance for all metrics considered. Table II summarizes pairwise throughput scaling

TABLE II
SUMMARY OF PAIRWISE THROUGHPUT SCALING FOR RANDOM NETWORKS

	Pairwise Throughput	Throughput-optimal Routing
Interference-limited Network:		
	$\Theta\left(\frac{1}{\sqrt{n \log n}}\right)$	WtNN
Power-limited Network:		
Zero signal processing	$O\left((n \log n)^{(k-1)/2}\right)$, $\Omega\left(\frac{n^{(k-1)/2}}{(\log n)^{(k+1)/2}}\right)$	WtNN
Non-zero signal processing	$\Theta(1)$	$\Theta(1)$ hops
	$\Theta\left(\sqrt{\frac{\log n}{n}}\right)$	WtNN

for both random interference-limited and power-limited networks.

It is important to note that all of the scaling results shown in this paper, and in related literatures, characterize network performance relative to increasing node density. Although the pairwise throughput scaling of $\Theta(1)$ can be achieved if the number of hops do not increase with n in a bounded geographical region, the question still remains as to what is the maximum pairwise throughput and the corresponding routing scheme for a given realization of network topology and traffic pattern. Through our discussions, we have seen that transmissions at a hop distance of d_{char} yields the minimum total energy expended by the network. Given a particular topology and traffic pattern though, it may not be possible to find nodes approximately d_{char} away for all SD pairs. Furthermore, routing with hop distance of d_{char} may lead to non-uniform traffic distribution, thus draining nodes batteries at different rates depending on the location of the nodes in the network and, therefore, limit the pairwise throughput.

In practice, hops distances are complicated by flow splitting and edge effects at the boundaries of the operating region. We have simulated n node random networks with variable transmission rate operating in a square region, where $n = [5, 10, 15, 20]$. Solving the multicommodity flow problem in (12), the average hop distance vs. α (holding all other parameters constant) is plotted in Fig. 6. Comparing to d_{char} , which is independent of network density and operating region size, observe that the average hop distances in the simulation increase with α like d_{char} , but is dependent on n . For relatively small α , transmission power dominates signal processing power. Hence, as the number of nodes increases, the average hop distance decreases to reduce the transmission power. For relatively large α , signal processing power dominates. As shown in Fig. 6, the average hop distance approaches a constant for all n (i.e. of the order $\Theta(1)$), which matches our analytical results.

VI. CONCLUSION

In this paper, we studied the impact of signal processing energy and large bandwidth on the pairwise throughput scaling and optimal hop distance of power-limited infrastructureless

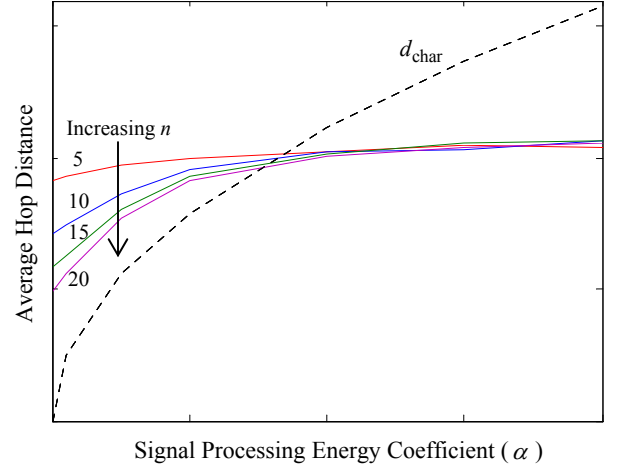


Fig. 6. Throughput-optimal average hop distance vs. signal processing energy coefficient.

wireless networks. While these quantities are well characterized and understood for interference-limited networks, this is the first paper, to our knowledge, that presents analytical results for arbitrary and random power-limited networks for both systems with fixed and variable transmission rates and based on more realistic energy models.

Our results show that, first, having a large bandwidth that scales with the number of nodes improves the throughput scalability significantly compared to interference-limited networks if the network topology and traffic pattern are sufficiently uniform. Otherwise, throughput scalability can be very poor even if the bandwidth is infinite. While having variable transmission rate improves pairwise throughput over systems with fixed transmission rate, the order of pairwise throughput scaling is not improved.

Second, for wireless network throughput studies, ignoring the distance independent signal processing energy can lead to erroneous throughput scaling behaviors and suboptimal routing strategies. As we have shown, for power-limited wireless networks, the best pairwise throughput scaling is $\Theta(1)$, achievable with routing schemes that has $\Theta(1)$ number of hops. This shows that the pairwise throughput cannot increase indefinitely with increasing number of nodes as previously believed under the zero signal processing energy assumption. Furthermore, the routing strategy recommended under the zero signal processing energy assumption is strictly suboptimal when signal processing energy is considered, achieving a pairwise throughput scaling of $O\left(\sqrt{\frac{\log n}{n}}\right)$. As a rough guideline, routing hop distance on the order of $d_{char} = \left(\frac{\alpha}{\beta(k-1)}\right)^{1/k}$ can achieve high pairwise throughput if traffic can be sufficiently balanced across different nodes.

It should be noted that all of the results presented in this paper are applicable for networks with a large number of nodes and a sufficiently large bandwidth. If the signal processing energy coefficient α is relatively small, increasing n does increase the pairwise throughput for small n . It is only for sufficiently large n that the pairwise throughput saturates to $\Theta(1)$. In addition, in practice, bandwidth cannot scale indefinitely with increasing n , hence eventually interference does

limit the pairwise throughput for dense networks. Additional shortcomings of this and similar studies include the simplistic path-loss model and uniformity of traffic pattern and network topology. In practice, presence of obstacles and scatterers limits interference exposure but places additional energy burdens on the transceivers. Furthermore, traffic pattern for large-scale networks may be more locally clustered than uniform. The nodes in a network are also likely to be heterogeneous which may lend itself to a more hierarchical network architecture. These effects may change the throughput scaling of large-scale networks. Hence, while the family of scaling studies elucidates certain network behaviors for large-scale networks and hold true under the set of stated assumptions, one cannot be too fixated on interpreting such results to be global solutions under all network scenarios.

Lemma 1

Proof: Given a time period T , there is a total of $2\lambda Tn$ bits generated under uniform and symmetric traffic. Consider bit, b , where $1 \leq b \leq 2\lambda Tn$, which moves from the source to the destination in $h(b)$ hops, where the h^{th} hop traverses a distance of r_b^h . The total distance traversed by all of the bits satisfies

$$\sum_{b=1}^{2\lambda Tn} \sum_{h=1}^{h(b)} r_b^h \geq 2\lambda Tn \bar{L} \quad (15)$$

Since the length of each hop is limited by the maximum transmission range, from (9), each hop distance is bounded as $0 < r_b^h \leq \rho_{max}$. Hence

$$\sum_{b=1}^{2\lambda Tn} \sum_{h=1}^{h(b)} r_b^h \leq \sum_{b=1}^{2\lambda Tn} \sum_{h=1}^{h(b)} \rho_{max} = \rho_{max} \sum_{b=1}^{2\lambda Tn} h(b) \quad (16)$$

The total number of hops taken by all of the bits is denoted by H , where $H = \sum_{b=1}^{2\lambda Tn} h(b)$. This is equivalent to the total number of bits (new and pass-through traffic) transported by the network. Since each node has a rate constraint R , H cannot exceed nTR . Combining this with (15) and (16), we obtain $2\lambda Tn \bar{L} \leq nT \rho_{max} R$. ■

Lemma 3

Proof: Given a time period T , there is a total of $2\lambda Tn$ bits generated under uniform and symmetric traffic. The total amount of energy consumed by the network is $E_{total} = \sum_{b=1}^{2\lambda Tn} \sum_{h=1}^{h(b)} \left(\alpha + \beta \left(r_b^h \right)^k \right)$, which is constrained by $E_{total} \leq n \hat{P}_{avg} T$ under the relaxed total average power constraint. For each SD pair i , the total path energy consumed for transmitting λT bits is lower bounded by $E_{i,min} = \lambda T n_i^* \left(\alpha + \beta \left(\frac{L_i}{n_i^*} \right)^k \right)$ as shown in [9], where $n_i^* = L_i \left(\frac{\beta}{\alpha} (k-1) \right)^{1/k}$. Summed over all SD pairs, $E_{total} \geq \sum_i E_{i,min} = \lambda T \left(\frac{\beta}{\alpha} (k-1) \right)^{1/k} \alpha \left(\frac{k}{k-1} \right) \sum_{i=1..2n} L_i$. Hence, $\hat{\lambda} \leq \frac{\hat{P}_{avg} d_{char}}{\alpha} \frac{k-1}{k} \frac{1}{\frac{1}{n} \sum_{i=1..2n} L_i}$, which yield the result. ■

The following Lemma is useful in deriving the pairwise throughput scaling under cell routing.

Lemma 5. Consider a random network with n nodes independently and randomly distributed on a unit torus according to

a uniform distribution. The torus is divided into square cells of area $a(n)$

- (i) If the cell size $a(n) \geq \frac{2 \log n}{n}$, then each cell has at least one node whp [18].
- (ii) If $a(n) = A$, then each cell has at least $\frac{nA}{2}$ nodes whp.
- (iii) If $a(n) = \frac{2 \log n}{n}$, then each cell has at most $6 \log n$ nodes whp.
- (iv) The number of SD lines passing through any cell is $O\left(n\sqrt{a(n)}\right)$, whp [18].

Proof: Let X be the number of nodes in a cell, and $\mu = E[X] = na(n)$. By the Chernoff bound

$$Pr[X < (1 - \delta)\mu] < e^{-\mu\delta^2/2} \quad \text{where } \delta \in (0, 1] \quad (17)$$

$$Pr[X > (1 + \delta)\mu] < e^{-\mu\delta^2/4} \quad \text{where } \delta < 2e - 1 \quad (18)$$

To prove Lemma 5.ii, let $\delta = 1/2$. By (17), $Pr[X < \frac{nA}{2}] < e^{-\frac{nA}{8}} < \left(\frac{8}{An}\right)^2$, for any $A \in (0, 1]$. Applying the union bound, we obtain:

$$Pr\left[\min \# \text{ nodes in any cell} = \frac{nA}{2}\right] \geq 1 - \frac{(8/A)^2}{n} \quad (19)$$

To prove Lemma 5.iii, let $\delta = \sqrt{\frac{8 \log n}{na(n)}}$. Then by (18), $Pr[X > 6 \log n] < \frac{1}{n^2}$. Applying the union bound, we obtain:

$$Pr[\max \# \text{ nodes in any cell} = 6 \log n] \geq 1 - \frac{1}{n} \quad (20)$$

Now we show that cell routing achieves the optimal pairwise throughput scaling.

Lemma 6. Under cell routing, the pairwise throughput for a random power-limited network under uniform and symmetric traffic is $\Theta(1)$ whp for systems with fixed or variable transmission rates.

Proof: Under cell routing, each cell has a fixed cell size, $A = \rho \times \rho$. From Lemma 5.ii, we can see that as long as $\rho \geq \sqrt{\frac{2}{n}}$, each cell has at least one node whp. Given large enough n , this condition, as well as the condition $\rho \leq \frac{\rho_{max}}{2\sqrt{(2)}}$, can both be satisfied. Combining Lemmas 5.ii and 5.iv, we can see that each node needs to transmit at most $O\left(\frac{n\sqrt{A}}{nA/2}\right) = O(1)$ amount of data whp.

For systems with fixed transmission rate, given the fixed transmission rate constraint R per node and the fact that the pairwise throughput is $\hat{\lambda} = O(1)$ whp, the achievable pairwise throughput under cell routing is $\Theta(1)$ whp.

For systems with variable transmission rate, since hop distances are upper-bounded by a constant and the amount of pass-through traffic at each node is $O(1)$ whp, the amount of power each node expends is also $O(1)$ whp. Given a per node average power constraint \hat{P}_{avg} and the fact that the pairwise throughput is $\hat{\lambda} = O(1)$ whp, the achievable pairwise throughput under cell routing is $\Theta(1)$ whp. ■

Theorem 3 for systems with fixed transmission rate

Proof: Recall that each node randomly selects another node and sends messages at a rate of λ [bits/sec] in each direction. Let L_i be the distance between SD pair i and h_i be the number of hops taken by a bit for SD pair i .

Then $h_i \geq \frac{L_i}{\sqrt{2a(n)}}$. Let $H = \sum_{i=1}^n h_i$. Given the maximum network transmission rate of nR , $nR \geq 2\lambda E[H] \geq \frac{2\lambda}{\sqrt{2a(n)}} \sum_{i=1}^n E[L_i] = \frac{2\lambda n E[L_1]}{\sqrt{2a(n)}}$. The last equality is a result of random destination node selection and symmetric network topology. Since $E[L_1]$ is a constant and $a(n) = \frac{2 \log n}{n}$, we obtain $\lambda = O\left(\sqrt{\frac{\log n}{n}}\right)$. ■

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