Distributed Rate Control for High Reliability in Poisson Bipolar Networks

Sanket S. Kalamkar and Martin Haenggi
Department of Electrical Engineering, University of Notre Dame, Notre Dame, IN 46556, USA
E-mail: skalamka@nd.edu, mhaenggi@nd.edu

***Abstract*—Reliable communication is a key requirement in wireless networks. For ad hoc networks, satisfying this requirement is challenging due to the interference caused by uncoordinated concurrent transmissions. In this regard, we provide a simple distributed way for a transmitter to meet the target reliability in an interference-limited network. Specifically, for the Poisson bipolar network with Rayleigh fading, we propose a method for a transmitter to decide on its rate (or, equivalently the signal-to-interference ratio threshold) such that *each link* in the network achieves a certain success probability. Here the *distributed* means that the transmitter only knows the distance from its receiver to the nearest interferer and the fading statistics. Based on this spatial local information, we present a semi-heuristic approach to find the distribution of the signal-to-interference ratio (SIR) threshold corresponding to the total interference power from all interferers. For this purpose, we use the property of the interference that it follows a stable distribution for the standard path loss model. We show that the SIR threshold follows the Weibull distribution.**

***Index Terms*—Stochastic geometry, reliability, interference, Poisson point process, SIR threshold distribution, rate control.**

I. Introduction

Wireless ad hoc networks typically operate in an uncoordinated and decentralized manner. Hence the transmissions over multiple links occur simultaneously, which causes mutual interference and deteriorates the quality of service (QoS). In such framework, the outage probability of a link (or, equivalently, the success probability of a link) is an important QoS metric. It indicates that how reliably a link can transmit in the presence of interference, fading, and path loss. For example, in an interference-limited network, the link success probability effectively captures these three detrimental factors and is defined as the probability that the signal-to-interference ratio (SIR) at the receiver of the link under consideration is above a certain threshold. Usually the locations of interferers are uncertain (*e.g.*, due to mobility) and therefore can be modeled by a random point process.

A. Motivation

In the framwork of modeling node locations by a random point process, a popular approach has been the calculation of the success probability of transmissions over the typical link [1]–[4]. But it is merely an average of individual link success probabilities given a realization of the point process [5]. To gain fine-grained information on the network, it is important to consider individual link success probabilities that may vary greatly across the network for the same mean success probability [6].

To guarantee a reliable transmission over a link, it is necessary to impose a constraint on the link success probability. A link is considered *reliable* if it achieves the target success probability. The goal of this paper is that *each link* should be able to achieve a success probability that is equal to the target reliability $1-\epsilon$. One simple way to do this is to control the rate of transmission, which is directly related to the SIR threshold through the spectral efficiency. Since each link—based on its relative location to interferers—experiences different levels of interference and fading, the SIR threshold for which the link success probability equals $1-\epsilon$ is different for different links. In fact, due to random interferer locations and fading, the SIR threshold at a receiver is a random variable, which we denote by T. Hence we need to find the distribution of T (or, equivalently, the distribution of the rate R) such that each link achieves the target reliability, which we wish to do in a distributed manner. In ad hoc networks, because of its uncoordinated structure, often a transmitter does not have the complete spatial information about the network. On the contrary, obtaining information about other nodes within a certain geometric vicinity is often feasible, which usually includes the knowledge of the location of the nearest interferer. As we shall see, such *spatial local information* allows us to find the distribution of the SIR threshold corresponding to the total interference power in a distributed fashion.

B. Contributions

This paper makes the following contributions:

- For the Poisson bipolar network with Rayleigh fading, we propose a simple and local way for a transmitter to determine its rate (or the SIR threshold) such that a transmission achieves the target reliability of $1-\epsilon$.
- We show that the SIR threshold follows the Weibull distribution and thus has a heavy tail.
- Using simulations we show that the spatial local information which includes the knowledge of the nearest-interferer power can be exploited to obtain the distribution of the SIR threshold corresponding to the total interference power at a receiver.

C. Background and Related Works

This work is closely related to the *meta distribution* of the SIR proposed in [5]. The meta distribution is defined as the complementary cumulative distribution function (ccdf) of the conditional link success probability and can be expressed as

$$\eta(\theta, x) \triangleq \mathbb{P}^{!t}(P_s(\theta) \geq x), \quad \theta > 0, x \in [0,1], \tag{1}$$

where $P_s(\theta)$,[1] given the point process Φ, is the conditional link success probability calculated by averaging over the fading and the medium access scheme (if random) of interferers, and $\mathbb{P}^{!t}(\cdot)$ is the reduced Palm probability of the point process, given that a transmitter is present at the prescribed location, and the SIR is calculated at its associated receiver. Hence the conditional link success probability can be expressed as

$$P_s(\theta) \triangleq \mathbb{P}(\mathsf{SIR} > \theta \mid \Phi). \tag{2}$$

For an ergodic point process, the meta distribution can also be interpreted as the fraction of active links that achieve a certain success probability in a realization of the point process. The work in [5] considers the same SIR threshold at all receivers and calculates the distribution of the conditional link success probability (or, equivalently, the link outage probability), *i.e.*, the meta distribution of the SIR. The work in [6] introduces a new notion of capacity, termed the *spatial outage capacity* (SOC), which is the maximum density of concurrently active links that achieve a certain success probability. For the Poisson bipolar network with ALOHA, using the tool of the meta distribution, it is shown that the SOC is achieved when all transmitters are always active, *i.e.*, the transmit probability of a transmitter is 1. This paper takes a dual approach to [5] and [6]: It treats the SIR threshold as a random variable (which depends on the fading, path loss, and interferers' locations) and calculates its distribution such that the conditional link success probability equals the target reliability $1-\epsilon$.

In the framework of random point process, for ad hoc networks, there have been works on the use of some kind of local information to calculate certain performance metrics. For example, the work in [7] calculates the probability of successful transmission for a link in a Poisson bipolar network by approximating the aggregate interference by the interference from the nearest interferer. An adaptive ALOHA scheme based on the local information about neighbors within a certain geometric vicinity is proposed in [8] for the Poisson bipolar network where the nodes have a full-duplex capability. The work in [9] uses five different levels of information about the potential interferer point process to predict the transmission success probability at the typical link. The levels of information vary from zero knowledge to full knowledge of the network, with the knowledge of *nearby* potential interferers as an intermediate case. The works in [7]–[9] consider no reliability constraint and assume a fixed SIR threshold.

II. Network Model

We consider the Poisson bipolar network model where the transmitters form a homogeneous Poisson point process (PPP) $\Phi \subset \mathbb{R}^2$ with intensity λ, and each transmitter is paired with a receiver located at unit distance from the transmitter in a uniformly random direction [4, Def. 5.8]. In a time slot, each transmitter in Φ sends packets to its associated receiver at unit power. The channels in the network are modeled as independent Rayleigh fading, where the channel power gains are i.i.d. exponential random variables with mean 1. The transmission between two nodes is subject to the standard path loss model with the path loss exponent α.

We consider an interference-limited network where the transmission between a transmitter and its associated receiver is successful if the SIR at the receiver exceeds the threshold θ. We add a transmitter at $(1,0)$ to the network model (which does not belong to the PPP) and its associated receiver at the origin. With a slight abuse of terminology, we call this link the *typical link* even before taking the expectation with respect to the PPP. Then the meta distribution is the probability that the typical link achieves a success probability that exceeds the threshold x.

We focus on the scenario where a transmitter has only the spatial local information about its vicinity, which includes the location of its nearest transmitter. This means that the transmitter knows the distance of its receiver to the nearest interferer. In addition, the transmitter has the knowledge of fading statistics (and the path loss exponent). We also assume that each transmitter is always active. This assumption is reasonable in our framework, as it was shown in [6] that, in the high-reliability regime where $\epsilon \to 0$, a transmitter being always active maximizes the density of concurrently active links that achieve a success probability at least $1-\epsilon$.

III. Distribution of the SIR Threshold

In this section we find the distribution of the SIR threshold such that each link achieves a conditional link success probability equal to $1-\epsilon$. In other words, we are interested in finding the distribution of the rate such that each link has a reliability $1-\epsilon$. Calculating the SIR threshold T that results in $P_s = 1-\epsilon$ after averaging over the fading and the interferer locations, the transmitter decides on its rate as $R = \log(1+T)$. The goal here is to find the distribution of T based on the spatial local information only, *i.e.*, based on the knowledge of the location of the nearest interferer and the fading statistics.

A. The Nearest-Interferer Case

In this subsection, we provide the distribution of the SIR threshold when only the nearest interferer is present. Then in the next subsection, we shall show the use of this case in obtaining the distribution of the SIR threshold corresponding to the total interference power without even having the knowledge of locations of all interferers. Let $\tilde{T}$ denote the random SIR threshold corresponding to the nearest-interferer power.

Theorem 1. *Assuming only the nearest interferer exists, the cdf of the SIR threshold $\tilde{T}$ is given by*

$$F_{\tilde{T}}(\theta) = 1 - \exp\left(-\lambda\pi\left(\frac{(1-\epsilon)\theta}{\epsilon}\right)^{\delta}\right), \quad \theta > 0, \tag{3}$$

[1]Note that θ denotes the deterministic SIR threshold, while T denotes the random SIR threshold.

where $\delta \triangleq 2/\alpha$ and $\delta \in (0,1)$.

Proof: Let $\tilde{x} = \arg\min\{x \in \Phi \colon \|x\|\}$ be the location of the nearest interferer. Setting the target conditional link success probability to $1-\epsilon$, we have

$$1-\epsilon = \mathbb{P}\left(\frac{h}{h_x\|\tilde{x}\|^{-\alpha}} > \theta \mid \Phi\right) \quad (4)$$
$$= \mathbb{E}\left(h > \theta h_x \|\tilde{x}\|^{-\alpha} \mid \Phi\right)$$
$$= \mathbb{E}(e^{-\theta h_x \|\tilde{x}\|^{-\alpha}} \mid \Phi), \quad (5)$$

where h and h_x are independent exponentially distributed channel power gains (with mean 1) on the desired link and on a link to the interferer from the receiver corresponding to the desired link, respectively. Averaging over the fading, it follows that

$$1-\epsilon = \frac{1}{1+\tilde{T}\|\tilde{x}\|^{-\alpha}}. \quad (6)$$

Rewriting in terms of $\tilde{T}$, we have

$$\tilde{T} = \frac{\epsilon\|\tilde{x}\|^{\alpha}}{1-\epsilon}. \quad (7)$$

Then we can write the cdf of $\tilde{T}$ as

$$F_{\tilde{T}}(\theta) = \mathbb{P}\left(\frac{\epsilon\|\tilde{x}\|^{\alpha}}{1-\epsilon} < \theta\right)$$
$$= \mathbb{P}\left(\|\tilde{x}\| < \left(\frac{(1-\epsilon)\theta}{\epsilon}\right)^{1/\alpha}\right)$$
$$\stackrel{\text{(a)}}{=} 1-\exp\left(-\lambda\pi\left(\frac{(1-\epsilon)\theta}{\epsilon}\right)^{\delta}\right), \quad \theta > 0, \quad (8)$$

where (a) follows from the nearest neighbor distribution in a homogeneous PPP [10]. ■

B. The Total-Interference Case

We now provide a semi-heuristic approach to obtain the distribution of the SIR threshold corresponding to the total interference power. We use the fact that the total interference power and the nearest-interferer power are of the same order [11, Chapter 3.4]. In particular, for Poisson bipolar networks with Rayleigh fading and standard power law path loss model, the total interference power follows a stable distribution with the power law tail same as that of the Fréchet distribution, *i.e.*, as $\exp(-y^{-\delta})$. Similarly, the nearest-interferer power, denoted by $\tilde{I}$, follows the Fréchet distribution, *i.e.*, its cdf can be expressed as $F_{\tilde{I}}(y) = \exp(-\lambda\pi y^{-\delta})$ (see [11, (3.31)]). This result implies that

$$C(\alpha)h_x\|\tilde{x}\|^{-\alpha} \stackrel{d}{=} \sum_{x\in\Phi} h_x\|x\|^{-\alpha}, \quad (9)$$

where $C(\alpha) \geq 1$ is a preconstant which depends on the path loss exponent α, and "$\stackrel{d}{=}$" means "equal in distribution." Thus once the preconstant $C(\alpha)$ is found, we can use the information about the location of the nearest interferer to obtain the distribution of the SIR threshold as if we have the information about all interferers' locations.

To this end, we can express the conditional link success probability as

$$P_{\rm s}(\theta) = 1-\epsilon = \mathbb{P}\left(\frac{h}{\sum_{x\in\Phi} h_x\|x\|^{-\alpha}} > \theta \mid \Phi\right)$$
$$\stackrel{\text{(b)}}{=} \mathbb{P}\left(\frac{h}{C(\alpha)h_x\|\tilde{x}\|^{-\alpha}} > \theta \mid \Phi\right), \quad (10)$$

where (b) follows from (9). Note that the denominator $C(\alpha)h_x\|\tilde{x}\|^{-\alpha}$ in (10) is just a scaled version of $h_x\|\tilde{x}\|^{-\alpha}$ in (4). Hence following the proof of Thm. 1, the cdf of the SIR threshold T corresponding to the total interference power can be given as

$$F_T(\theta) = 1-\exp\left(-\lambda\pi\left(\frac{(1-\epsilon)\theta C(\alpha)}{\epsilon}\right)^{\delta}\right), \quad \theta > 0. \quad (11)$$

Corollary 1. *We have*

$$F_T(\theta) = F_{\tilde{T}}(C(\alpha)\theta), \quad C(\alpha) \geq 1. \quad (12)$$

Proof: Comparing (8) and (11) gives the desired result. ■

Remark: Cor. 1 reveals the surprisingly simple result that the random SIR threshold corresponding to the total interference power is just a scaled version of that corresponding to the nearest-interferer power.

This remark implies that knowing only the location of the nearest interferer and fading statistics, one could obtain the SIR threshold distribution corresponding to the total interference power such that each link achieves the target reliability $1-\epsilon$ and that too without even knowing the locations of all interferers. For $C(\alpha) = 1$, we get the SIR threshold distribution corresponding to the nearest-interferer power. Hence, given only the location of the nearest interferer, if θ is the SIR threshold for which a link is reliable, then by simply dividing θ by a constant $C(\alpha)$ yields the SIR threshold for which a link is reliable when the total interference power is considered.

Using (8), Fig. 1 plots the cdf $F_{\tilde{T}}(C(\alpha)\theta)$ for different values of λ and $C(\alpha)$ such that each link achieves a reliability equal to 0.9. Observe that, for any λ, the curve corresponding to $C(\alpha) = 2$ can be obtained by shifting that corresponding to the nearest-interferer case, *i.e.*, corresponding to $C(\alpha) = 1$, by approximately 3 dB to the left. Also, as expected, the distribution of $\tilde{T}$ is spread more widely at a small value of λ compared to that at a large value of λ. Because at a small λ, the nearest interferer is located at a relatively far distance compared to that at a large λ, which increases the SIR at the receiver. This allows a link to set a higher SIR threshold while maintaining the conditional link success probability at its target value.

Remarks:

- For any λ, the curve of the cdf $F_{\tilde{T}}(C(\alpha)\theta)$ can be obtained by shifting that corresponding to the nearest-interferer case, *i.e.*, that corresponding to $F_{\tilde{T}}(\theta)$, by $10\log_{10} C(\alpha)$ dB to the left.

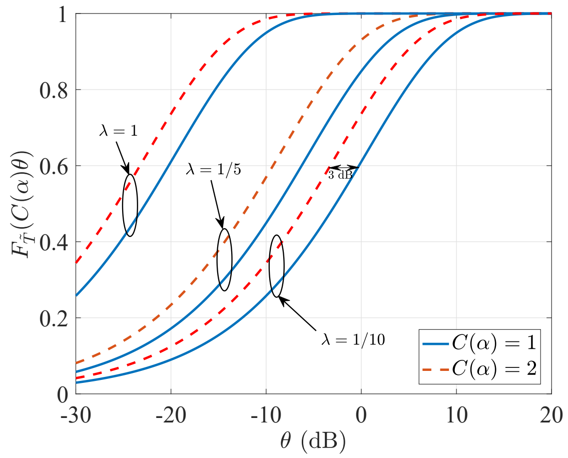


Fig. 1. The cdf $F_{\tilde{T}}(C(\alpha)\theta)$ (given by (8)) with $C(\alpha) = 1$ (the nearest-interferer case) and $C(\alpha) = 2$ such that each link achieves the link success probability of $1 - \epsilon$. $\lambda = 1/10, 1/5, 1$, $\alpha = 4$, and $\epsilon = 0.1$. For any λ, the curve corresponding to $C(\alpha) = 2$ can be obtained by shifting that corresponding to the nearest-interferer case by $10\log_{10} 2 = 3.01$ dB to the left.

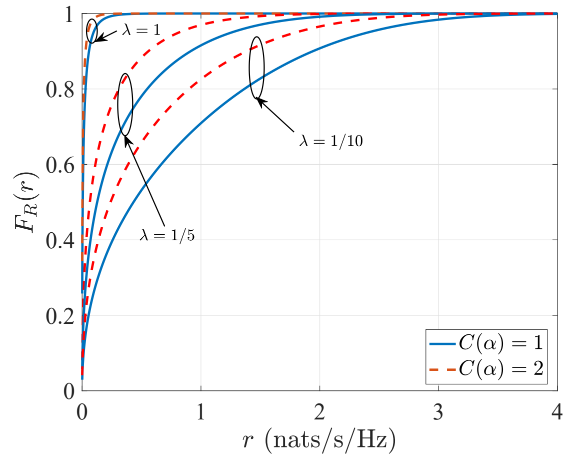


Fig. 2. The cdf of R (given by (15)) for $C(\alpha) = 1$ (the nearest-interferer case) and $C(\alpha) = 2$ such that each link achieves the link success probability of $1 - \epsilon$. $\lambda = 1/10, 1/5, 1$, $\alpha = 4$, and $\epsilon = 0.1$.

- The SIR threshold follows the Weibull distribution, which has the scale parameter $\beta = \frac{\epsilon(\lambda\pi)^{1/\delta}}{(1-\epsilon)C(\alpha)}$ and the shape parameter $\gamma = \delta$. To see this, we rewrite (11) as

$$F_T(\theta) = 1 - \exp\left(-\left(C(\alpha)\frac{(1-\epsilon)\theta}{\epsilon(\lambda\pi)^{-1/\delta}}\right)^{\delta}\right), \quad \theta > 0 \tag{13}$$

and then compare it with the form of the cdf of the Weibull distribution given as $1 - e^{-(\theta/\beta)^{\gamma}}$. Hence the SIR threshold distribution has a heavy tail. Furthermore, the probability density function of T can be expressed as

$$f_T(\theta) = \frac{\gamma}{\beta}\left(\frac{\theta}{\beta}\right)^{\gamma-1} e^{-(\theta/\beta)^{\gamma}}, \quad \theta > 0. \tag{14}$$

- The distribution of T allows us to obtain the distribution of the rate $R = \log(1+T)$ as follows:

$$\begin{aligned} F_R(r) &= \mathbb{P}\left(\log(1+T) < r\right) \\ &= F_T(e^r - 1) \\ &= 1 - \exp\left(-\left(\frac{C(\alpha)(1-\epsilon)(e^r-1)}{\epsilon(\lambda\pi)^{-1/\delta}}\right)^{\delta}\right), \ r > 0. \end{aligned} \tag{15}$$

Fig. 2 shows the distribution of R corresponding to the distribution of $\tilde{T}$ in Fig. 1.

C. Throughput Density

To compare the case of random SIR threshold with that of the fixed SIR threshold, we use the throughput density as a performance metric. It is given as

$$S \triangleq \lambda\mathbb{E}[\log(1+T)P_{\mathrm{s}}(T)], \tag{16}$$

where $P_{\mathrm{s}}(T)$ denotes the link success probability corresponding to the total interference power obtained using the spatial local information. This metric takes into account unreliable links as well. Our second throughput metric includes the meta distribution, *i.e.*, the fraction of reliable links. This metric is called the reliable throughput density and is given as

$$S_{\mathrm{rel}} \triangleq \lambda\mathbb{E}[\log(1+T)\mathbf{1}(P_{\mathrm{s}}(T) > 1-\epsilon)], \tag{17}$$

where $\mathbf{1}(\cdot)$ denotes the indicator function. The reliable throughput density considers only reliable links in the calculation of the throughput.

IV. Numerical and Simulation Results

In this section, using simulations, we calculate the value of $C(\alpha)$, which allows us to find the distribution of T, (equivalently, the distribution of R) corresponding to the total interference power.

A. Simulation Setup

We consider a square region with the side length 200 centered at the origin. The locations of interferers form a PPP with intensity λ. To find $C(\alpha)$ and evaluate our performance metrics such as the meta distribution and throughput densities, we average over $N = 10,000$ realizations of this PPP of interferers and collect the statistics at the typical receiver located at the origin.

We divide the simulations in three parts:

1) Obtain $C(\alpha)$.
2) Show the distribution of link success probability $P_{\mathrm{s}}(T)$ (the meta distribution) corresponding to the total interference power obtained using the spatial local information.
3) Calculate throughput densities.

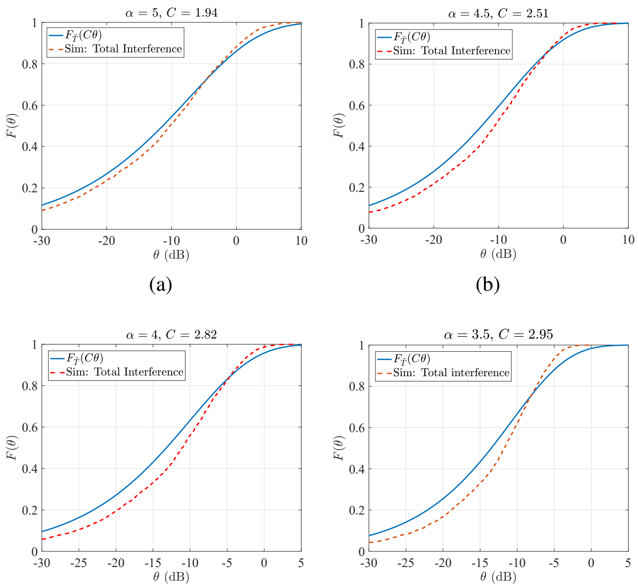
B. Simulation Methodology to Obtain $C(\alpha)$

The steps to obtain $C(\alpha)$ are as follows:

1) For the given values of α, λ, and ϵ, generate a realization and calculate the SIR threshold such that the success probability of the typical link corresponding to the total

TABLE I
VALUES OF C FOR DIFFERENT α

α	C	Average of the ratio $\tilde{\theta}/\theta$
6	1.69	1.51
5.5	1.82	1.59
5	1.94	1.68
4.5	2.51	1.82
4	2.82	2.03
3.5	2.95	2.38



(a) (b) (c) (d)

Fig. 3. The empirical cdfs of the SIR threshold corresponding to the total interference (obtained through simulations) and $F_{\tilde{T}}(C\theta)$ (given by (8)) for different values of α. $\lambda = 1/5$ and $\epsilon = 0.1$.

interference power equals $1-\epsilon$. Obtain SIR thresholds for N realizations. Plot the empirical cdf of the SIR threshold.

2) Plot $F_{\tilde{T}}(C\theta)$ (given by (8)) for different values of C.
3) Compare these two cdfs. The value of C is the one for which $F_{\tilde{T}}(C\theta)$ is as close as possible to the empirical cdf corresponding to the total interference power obtained in Step 1.

Following these steps, Table I lists the values of $C(\alpha)$ and Figs. 3(a)-3(d) plot corresponding cdfs at those values of C. At the receiver associated with the typical link, in a realization, let θ and $\tilde{\theta}$ denote the SIR thresholds corresponding to the total interference power and the nearest-interferer power (obtained through simulations). Table I also gives the average of the ratio $\tilde{\theta}/\theta$ over N realizations. This average value gives a rough estimate about the value of $C(\alpha)$ and hence can be used as a starting estimate of $C(\alpha)$. Observe from Table I that $C(\alpha)$ monotonically decreases with α since the effect of far interferers becomes negligible as α increases, *i.e.*, the SIR threshold distribution in the case of all interferers can be approximated by that in the case of the nearest interferer.

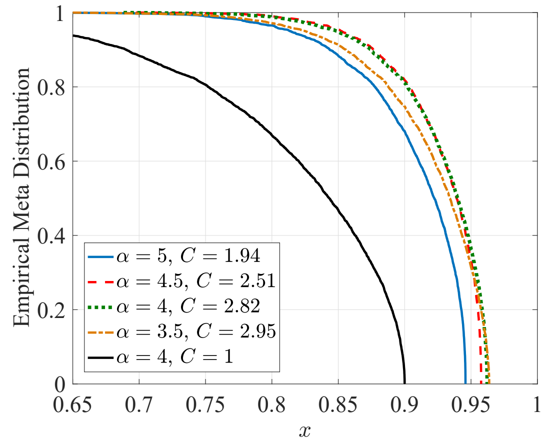


Fig. 4. The empirical meta distribution of the SIR corresponding to the total interference power, calculated using the spatial local information. $\lambda = 1/5$ and $\epsilon = 0.1$.

C. Distribution of the Link Success Probabilities Obtained using the Spatial Local Information

We now show how the link success probabilities $P_s(T)$ corresponding to the total interference power obtained using the spatial local information are distributed across the network. For this purpose, we plot the empirical meta distribution. In a realization, the link success probability is calculated by comparing the SIR value corresponding to the total interference power to the SIR threshold value that follow the cdf $F_{\tilde{T}}(C\theta)$. The empirical ccdf of $P_s(T)$ gives the empirical meta distribution. As Fig. 4 shows, for $\alpha = 4$, almost 80% of the links achieve a success probability greater that 0.9 when the SIR threshold corresponding to the total interference power is set using the spatial local information. Hence the knowledge of the location of the nearest interferer is sufficient to allow a high fraction of links to achieve the target reliability.

In Fig. 4, note that for the case of $\alpha = 4$ with $C = 1$ (the case corresponding to the nearest interferer), there are no links that achieve a success probability larger than $1-\epsilon$, *i.e.*, 0.9, because the case of $C = 1$ underestimates the interference and the support of P_s is $[0, 1-\epsilon)$. The reliability equal to $1-\epsilon$ would only be achieved if only the nearest interferer existed. To ensure that most links have success probabilities at least $1-\epsilon$, $C > 1$ is needed.

D. Throughput Density

Fig. 5 compares the throughput densities (given by (16)) for different fixed SIR thresholds (denoted by θ) with that obtained using the spatial local information, *i.e.*, for the random SIR threshold. For this metric, the proposed distributed way is better than the fixed threshold setting for small and large values of fixed SIR thresholds. Fig. 5 also visualizes the trade-off between the link success probability and the link spectral efficiency. The throughput metric in (16), however, does take into account unreliable links, *i.e.*, the links which do not meet the target reliability of $1-\epsilon$. Hence in an effort to make

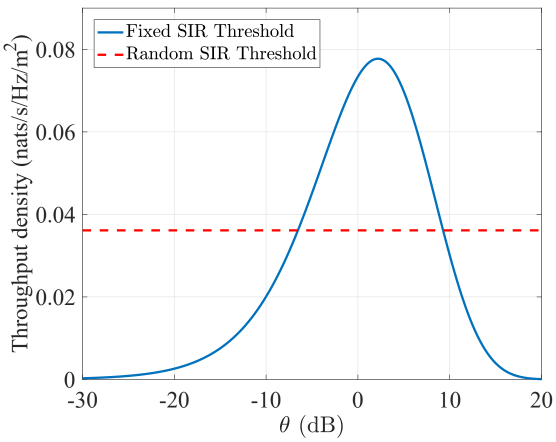


Fig. 5. Throughput densities, given by (16), for the random SIR threshold (dashed red curve) and the fixed SIR threshold (solid blue curve) settings. $\lambda = 1/5$, $\epsilon = 0.1$, $\alpha = 4$, and $C = 2.82$.

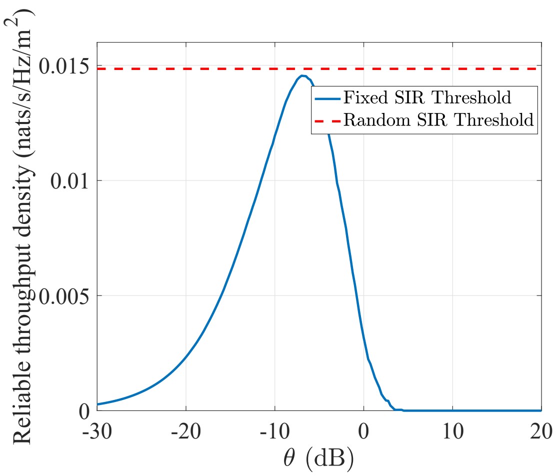


Fig. 6. Reliable throughput densities (which includes the meta distribution), given by (17), for the random SIR threshold (dashed red curve) and the fixed SIR threshold (solid blue curve) settings. $\lambda = 1/5$, $\epsilon = 0.1$, $\alpha = 4$, and $C = 2.82$.

all links the same in terms of the reliability, our distributed approach has to bear a cost in terms of the throughput compared to the fixed SIR threshold case for a range of the values of fixed SIR thresholds (*e.g.,* for $\theta \in [0.2239, 8.414]$ in Fig. 5).

Fig. 6 plots the reliable throughput density (given by (17)), which shows that the local adaptive choice of SIR threshold outperforms the case of fixed SIR threshold for the complete range of fixed SIR thresholds. This is because our distributed method allows a transmitter to set its SIR threshold adaptively such that its link achieves a high reliability, making a large fraction of links in the network reliable.

V. Conclusions

This paper has provided a simple distributed approach that allows a transmitter—when it knows only the distance of its receiver from the nearest interferer—to set its rate such that each link in the network achieves a certain success probability. We observe that the SIR threshold follows the Weibull distribution. We can obtain the distribution of the SIR threshold corresponding to the total interference power (due to all interferers in the network) by simply scaling the SIR threshold corresponding to the nearest-interferer power by a factor. We found this factor using simulations, where we showed that the spatial local information is sufficient to allow a high fraction of links to achieve the target reliability.

Acknowledgment

We thank Stephen Hanly for bringing this problem to our attention. We also gratefully acknowledge the partial support of the U.S. National Science Foundation through grant CCF 1525904.

References

[1] M. Zorzi and S. Pupolin, "Optimum transmission ranges in multihop packet radio networks in the presence of fading," *IEEE Transactions on Communications*, vol. 43, pp. 2201–2205, July 1995.

[2] F. Baccelli, B. Błaszczyszyn, and P. Mühlethaler, "An ALOHA protocol for multihop mobile wireless networks," *IEEE Transactions on Information Theory*, vol. 52, pp. 421–436, February 2006.

[3] M. Haenggi, J. G. Andrews, F. Baccelli, O. Dousse, and M. Franceschetti, "Stochastic geometry and random graphs for the analysis and design of wireless networks," *IEEE Journal on Selected Areas in Communications*, vol. 27, pp. 1029–1046, September 2009.

[4] M. Haenggi, *Stochastic Geometry for Wireless Networks*. Cambridge, U.K.: Cambridge Univ. Press, 2012.

[5] M. Haenggi, "The meta distribution of the SIR in Poisson bipolar and cellular networks," *IEEE Transactions on Wireless Communications*, vol. 15, pp. 2577–2589, April 2016.

[6] S. S. Kalamkar and M. Haenggi, "Spatial outage capacity of Poisson bipolar networks," in *Proc. IEEE International Conference on Communications (ICC'17)*, (Paris, France), May 2017.

[7] F. Baccelli and C. Singh, "Adaptive spatial ALOHA, fairness and stochastic geometry," in *Proc. International Symposium and Workshops on Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks (WiOpt'13)*, (Tsukuba Science City, Japan), pp. 7–14, May 2013.

[8] Z. Tong and M. Haenggi, "A throughput-optimum adaptive ALOHA MAC scheme for full-duplex wireless networks," in *Proc. IEEE Global Communications Conference (GLOBECOM'15)*, (San Diego, CA, USA), pp. 1–6, December 2015.

[9] S. Weber, "The value of observations in predicting transmission success in wireless networks under slotted ALOHA," in *Proc. International Symposium and Workshops on Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks (WiOpt'17)*, (Paris, France), May 2017.

[10] M. Haenggi, "On distances in uniformly random networks," *IEEE Transactions on Information Theory*, vol. 51, pp. 3584–3586, October 2005.

[11] M. Haenggi and R. K. Ganti, "Interference in large wireless networks," *Foundations and Trends in Networking*, vol. 3, no. 2, pp. 127–248, 2009.