A Sample LaTex Source Code for DNS@Wayne

Xin Che, Xiaohui Liu, Xi Ju, Hongwei Zhang, Wei Wei
Department of Computer Science, Wayne State University, USA
University of Southern California
{chexin,xiaohui,xiju,hongwei,wei}@wayne.edu

Abstract

Interference model is the basis of MAC protocol design in wireless networks, and it directly affects the efficiency and predictability of wireless messaging. To take advantage of the strengths of both the physical and the protocol interference models and to understand the varying relative goodness between physical and protocol interference models observed in the literature, we analyze the impact of network traffic, link length, and wireless signal attenuation on the choice of optimal protocol interference models, and we identify the inherent tradeoff between reliability and throughput in interference model instantiation. Our analysis explains the seemingly inconsistent observations in the literature and sheds light on the open problem of choosing optimal protocol interference models. Based on the analytical results, we propose the physical-ratio-K (PRK) interference model which is suitable for distributed protocol design and has both the high fidelity of physical interference model and the locality of protocol interference model. Via analysis, simulation, and testbed-based measurement, we compare PRK with SINR physical interference model, and we show that PRK based scheduling achieves a network throughput very close to (e.g., at least 95% in many of the scenarios we study) what is enabled by SINR model while ensuring the required packet delivery reliability. These findings shed new light on wireless interference models, and suggest new approaches to MAC protocol design in supporting unpredictable traffic patterns and in addressing application-specific tradeoff between reliability and throughput.

Keywords

Wireless interference model, protocol model, physical model, throughput, reliability, local adaptation, analysis, measurement, simulation

1 Introduction

Due to the broadcast nature of wireless communication, concurrent transmissions in wireless networks may interfere with one another and introduce co-channel interference. Co-channel interference not only reduces the reliability and throughput of wireless networks, it also increases the variability and uncertainty in data communication [23, 27, 26]. As wireless networks are increasingly applied to mission-critical applications such as industrial monitoring and control [4], it becomes critical to address wireless co-channel interference for reliable, predictable wireless data communication.

A basis of interference control is the interference model which determines whether and how a set of concurrent transmissions may interfere with one another. Two commonly used models are the physical interference model and the protocol interference model [8]. In the physical interference model, a set of concurrent transmissions do not interfere with one another if the resulting signal-to-interference-plus-noise-ratio (SINR) at every receiver is no less than a threshold value; in the protocol interference model, a transmission is not interfered by an interferer if the interferer is at least K times the transmitter-receiver distance away from the receiver[1]. For simplicity, we also call the physical interference model the *SINR model* and the protocol interference model the *ratio-K model* in this paper.

The SINR model is based on communication theory, and it can be regarded as an instantiation of the graded-SINR model [13] for satisfying certain minimum link reliability. SINR model is a high fidelity interference model in general, but the interference relations defined by it are non-local and combinatorial since whether one transmission interferes with another may depend on all the other transmissions in the network. Thus it is difficult to use SINR model in distributed protocol design, especially when network traffic pattern is bursty and unpredictable. On the other hand, even though the ratio-K model is an approximate model in principle, it can enable agile protocol adaptation in the presence of dynamic, unpredictable traffic pattern since ratio-K model defines pairwise, non-combinatorial interference relations around the local neighborhood of each transmission. Therefore, one *open question* is whether it is feasible and how to integrate SINR and ratio-K models so that we can take advantage of the high fidelity of SINR model and the locality of ratio-K model at the same time.

The research community have studied the relative goodness of SINR model and ratio-K model, and it has been shown that SINR based scheduling can improve the throughput of ratio-K based scheduling [13, 16]. On the other hand, Chafekar *et al*. [3] found that ratio-K based scheduling can improve the throughput of SINR based scheduling too. Since ratio-K model is only an approximation of SINR model, the latter observation is counter-intuitive and raises the following *open questions*: why can ratio-K based scheduling outper-

[1] Note that we replace the original notation of $(1+\Delta)$ in [8] with K for simplicity of presentation.

form SINR based scheduling in network throughput? How to correctly use physical and protocol interference models in protocol design and evaluation?

Contributions of the paper. To address the aforementioned open questions, we analyze, for both grid and random networks, the impact of network traffic load, link length, and wireless signal attenuation on effective instantiation of ratio-K model. We find that, as traffic load increases and wireless signal attenuation decreases, the optimal K for maximizing network throughput and the minimum K for satisfying certain link reliability tends to increase. As link length increases, the minimum K for satisfying certain link reliability also tends to increase, but the optimal K for maximizing network throughput can both increase and decrease. We also find that fixing K to a constant number, as in most existing studies [13, 16, 3], can lead to significant performance loss as network and environmental settings change. For instance, deviation from the optimal K by up to 1 can cause up to 68% throughput loss, and fixing K to 2 may lead to a link reliability less than 80%. These findings suggest that it is important to choose the right K when studying ratio-K models, otherwise the performance evaluation will be biased against ratio-K model.

We also find that there is inherent tradeoff between reliability and throughput when choosing K for the ratio-K model. Maximum network throughput is usually achieved not at the minimum K for ensuring certain link reliability, but at a smaller K. In grid topologies, for instance, $\sqrt{2}$ is the optimal K for maximizing throughput in many scenarios, but, with non-negligible probability, $\sqrt{2}$ is unable to guarantee an 80% link reliability. Moreover, as K increases from the minimum one required for satisfying certain link reliability, network throughput tends to go down, especially when link reliability requirement is high. These findings suggest that one reason why the studies in [13, 16, 3] observe inconsistent relative goodness of SINR and ratio-K based scheduling is because they did not address the reliability-throughput tradeoff and, by choosing a fixed K without considering network and environmental settings, they could not ensure that link reliabilities and thus maximum achievable throughput are the same across different scenarios studied in [13, 16, 3], thus leading to different conclusions. More importantly, our findings suggest that, for cases where link reliability is critical (e.g., for both reliable data delivery and small latency jitter in mission-critical sensing and control), we can use link reliability requirement as the basis of selecting K for the ratio-K model. Since link reliability is a locally measurable metric, link-reliability based selection of K addresses the challenge of how to adapt K according to dynamic, potentially unpredictable network and environmental settings, which has been recognized as an open problem by Shi *et al*. [21] who independently studied protocol interference models in parallel with our work here.

Based on these analytical results, we propose the physical-ratio-K (PRK) interference model. PRK model is the same as ratio-K model except that the parameter K of the PRK model, instead of being constant, adapts to network and environmental conditions as well as application QoS requirements to ensure certain minimum link reliability. Through detailed analysis, we find that, for given requirements on link reliability, scheduling based on PRK model achieves a network throughput very close to (e.g., at least 95% in many of the scenarios we study) what is enabled by SINR model. Moreover, as link reliability requirement increases, the throughput loss in PRK based scheduling further decreases. These findings suggest that PRK model has both the high fidelity (and thus high performance) of SINR model and the locality of ratio-K model. Given that the parameter K of PRK model can be chosen based on local and even passive measurement alone, PRK model also suggests new approaches to MAC protocol design in the presence of unpredictable traffic patterns, for instance, by letting each node locally choose a K for satisfying application-specific link reliability requirement.

The above analytical results give us insights into the behaviors of protocol and physical interference models in a wide range of network and environmental settings. We have verified these results through simulation as well as measurement study in a testbed of 120 TelosB motes.

Organization of the paper. In Section 2, we present the link, radio, and interference models used in this paper. We study the impact of system properties and optimization objectives on the instantiation of ratio-K model in Section **??**, and we examine the optimality of PRK model in Section 3. We corroborate our analytical results through testbed based measurement and simulation in Sections 4 and **??**, and we also examine similar issues for ultra-wideband (UWB) networks in Section **??**. We discuss related work in Section 5 and make concluding remarks in Section 6.

2 Preliminaries

In this section, we present the link, radio, and interference models used in the analysis part of this paper.

Link model. To characterize signal attenuation in wireless networks, we use the log-normal path loss model [18] which is widely adopted in protocol design and analysis. By this model, the power P_r (in dB) of the received signal at a node distance d away from the transmitter is computed as follows:

$$P_r = P_t - PL(d_0) - 10\alpha log_{10}\frac{d}{d_0} + N(0,\sigma^2) \qquad (1)$$

where P_t is the transmission power, $PL(d_0)$ is the power decay at the reference distance d_0, α is the path loss exponent, $N(0,\sigma)$ is a Gaussian random variable with mean 0 and variance σ. In our study, we use different instantiations of α and σ to represent different wireless environments.

Radio model. The reception capability of a radio can be characterized by the bit error rate (BER) and the packet delivery rate (PDR) in decoding signals with specific signal-to-interference-plus-noise-ratios (SINR). Our study mainly focuses on the IEEE 802.15.4 compatible CC2420 radios [1], but we also study UWB radios in Section **??**. To compute the expected PDR for a CC2420 receiver at a specific location, we first derive the PDR-SINR relation for CC2420 radios, then we compute the expected PDR based on the distribution of SINR values at the receiver using the method of [28]. To this end, we derive the PDR-SINR relation for CC2420 (at the 2.4GHz frequency band) as follows.

First, we compute BER as a function of SINR. The relation between BER and SINR depends on the modulation method used. CC2420 uses the O-QPSK modulation method [2], for which the relation between BER and SINR is captured by the following formula [18]:

$$P_e = Q\left(\sqrt{2\gamma\frac{B_N}{R}}\right) \tag{2}$$

where P_e is the BER, γ is the SINR value, B_N is the noise bandwidth, R is the radio chip rate, and $Q(.)$ is the tail distribution function of the standard normal variate. For CC2420, B_N = 2000KHz, and R = 2000 KChips/s. CC2420 radios use a DSSS-like encoding scheme where every 4 bits of data are mapped into a 32 bits chip sequence, which will then be modulated and transmitted. Accordingly, we can compute as follows the PDR at a SINR value based on the corresponding BER:

$$\begin{aligned} \text{PDR} &= (1-P_e)^{8f\times 8} \\ &= \left(1-Q\left(\sqrt{2\gamma\frac{B_N}{R}}\right)\right)^{64f} \end{aligned} \tag{3}$$

where f is the packet length (in units of bytes) including overhead such as packet header.

Interference model. We consider the ratio-K and SINR interference models. In ratio-K model, a concurrent transmitter n_i does not interfere with the transmission from n_s to n_r if and only if the following holds:

$$d(n_i,n_r) \geq K \times d(n_s,n_r) \tag{4}$$

where $d(n_i,n_r)$ is the distance between n_i and n_r, and $d(n_s,n_r)$ is the distance between n_s and n_r. In SINR model, a set of concurrent transmitters S_i does not interfere with the transmission from n_s to n_r if and only if the following holds:

$$\frac{P(n_s,n_r)}{N_0 + \sum_{n_i \in S_i} P(n_i,n_r)} \geq \gamma_0 \tag{5}$$

where N_0 is the background noise power, $P(n_s,n_r)$ is the strength of signals reaching n_r from n_s, $P(n_i,n_r)$ is the strength of signals reaching n_r from n_i, and γ_0 is a SINR threshold chosen to satisfy certain requirement on PDR.

3 Optimality of PRK model

To understand the potential effectiveness of PRK model, we analyze in this section the optimality of PRK based scheduling as compared with SINR based method. To avoid the problem of inconsistent observations on the relative goodness of ratio-K and SINR based scheduling in the literature, we conduct our comparative analysis on the condition that the link reliability in PRK and SINR based scheduling is the same.

3.1 Throughput loss in PRK model

Similar to Section **??**, our analysis here considers infinite sized grid and Poisson random networks with uniform traffic patterns. We will verify the analytical results in Sections 4 and **??** through testbed based measurement and simulation with finite networks and non-uniform traffic pattern.

To satisfy certain link reliability requirement and thus certain packet-delivery-rate (PDR) for data and acknowledgment (ACK) reception along a link L, we need to make sure that the SINR at the receiver R and the transmitter T is above certain threshold γ_0 and γ_0' respectively. For a given received signal strength P_r and background noise N_0 at R, this requirement translates into a requirement on controlling the maximum tolerable interference I_t at R to be $\frac{P_r}{\gamma_0} - N_0$. Similarly, we can derive the maximum tolerable interference I_t' at T. To control interference, we need to silence the transmission of some nodes in the network, and to maximize network throughput, we need to minimize the number of silenced transmitters. Then,

PROPOSITION 1. *To minimize the number of nodes silenced for ensuring certain minimum SINR at the receiver R (or the transmitter T), we should first silence nodes s-closer to R (or T) rather than those s-farther away, whether or not we use PRK or SINR model.*

PROOF. PRK model silences the nodes within an exclusion region around the receiver (or the transmitter), so the proposition holds for PRK model. For SINR model, we prove the proposition by contradiction. Suppose the receiver R has two potential interferers A and B nearby. The s-distances from A and B to receiver R are d_A and d_B respectively, with $d_A < d_B$. If not silenced, the interference that node A generates is greater than that generated by B. To ensure that the total interference incurred to R does not exceed the threshold I_t, therefore, the number of nodes that have to be silenced when B but not A is silenced is no less than the number of nodes that have to be silenced when A but not B is silenced. Thus, if we silence B instead of A, the number of silenced nodes may not be minimized, which contradicts the objective of minimizing the number of silenced nodes. The same argument applies to the transmitter T. Thus the proposition holds for the SINR based scheduling. □

Therefore, the set $\mathcal{S}$ of nodes silenced by the data reception at receiver R are the $|\mathcal{S}|$ number of nodes s-closest to R, where $|\mathcal{S}|$ denotes the number of elements in set $\mathcal{S}$. We denote the set of nodes silenced by R in SINR and PRK based scheduling as $\mathcal{S}_{sinr}$ and $\mathcal{S}_{prk}$ respectively. For a tolerable interference I_t at R, we let I_{sinr} and I_{prk} be the interference incurred at R in SINR and PRK based scheduling respectively. Similarly, for correct ACK reception at the transmitter T in SINR and PRK based scheduling, we denote the set of silenced nodes as $\mathcal{S}'_{sinr}$ and $\mathcal{S}'_{prk}$ respectively, and, for a tolerable interference I_t' at T, we let I'_{sinr} and I'_{prk} be the actual interference incurred at T respectively. We also define $\mathbb{S}_{sinr} = \mathcal{S}_{sinr} \cup \mathcal{S}'_{sinr}$ and $\mathbb{S}_{prk} = \mathcal{S}_{prk} \cup \mathcal{S}'_{prk}$ to represent the set of silenced nodes around link L in SINR and PRK based scheduling respectively. Then,

PROPOSITION 2. *Given the tolerable interference I_t and I_t' at the receiver R and the transmitter T respectively, $\mathcal{S}_{sinr} \subseteq \mathcal{S}_{prk}$, $\mathcal{S}'_{sinr} \subseteq \mathcal{S}'_{prk}$, $\mathbb{S}_{sinr} \subseteq \mathbb{S}_{prk}$, $I_{prk} \leq I_{sinr} \leq I_t$, and $I'_{prk} \leq I'_{sinr} \leq I'_t$.*

PROOF. Let the longest s-distance from a node in $\mathcal{S}_{sinr}$ to R be d_{sinr}. By the definition of PRK and SINR models and Proposition 1, all the nodes in $\mathcal{S}_{sinr}$ and $\mathcal{S}_{prk}$ are within d_{sinr} s-distance away from the receiver R. The difference between PRK model and SINR model is that, by the definition of PRK model (see Inequality **??**), all the nodes that are d_{sinr} s-distance away from R have to be silenced in PRK model as long as at least one of them has to be silenced; whereas in

SINR model, we only need to silence the minimum number of nodes d_{sinr} s-distance away from R to ensure that the SINR at R is at least γ_0. For example, in Figure 1, there are four nodes

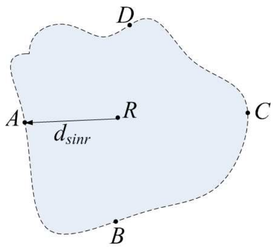


Figure 1. Difference in PRK and SINR based scheduling: receiver oriented view

d_{sinr} s-distance away from R. While SINR model may only need to silence node A to guarantee the SINR threshold I_t, the PRK model will silence all the four nodes d_{sinr} away. Therefore, $\mathcal{S}_{sinr} \subseteq \mathcal{S}_{prk}$. Since $\mathcal{S}_{sinr} \subseteq \mathcal{S}_{prk}$, $I_{prk} \leq I_{sinr}$. SINR based scheduling will ensure that $I_{sinr} \leq I_t$. Thus, $I_{prk} \leq I_{sinr} \leq I_t$ holds.

Similar argument applies to the transmitter T. Thus, $\mathcal{S}'_{sinr} \subseteq \mathcal{S}'_{prk}$, and $I'_{prk} \leq I'_{sinr} \leq I'_t$.

Since $\mathcal{S}_{sinr} \subseteq \mathcal{S}_{prk}$ and $\mathcal{S}'_{sinr} \subseteq \mathcal{S}'_{prk}$, $\mathbb{S}_{sinr} \subseteq \mathbb{S}_{prk}$. $\square$

Now, we are ready to derive the upper bound on the throughput loss in PRK based scheduling as compared with SINR based scheduling. Assuming that each node in grid and Poisson random networks covers an area of A_0 on average, then, by Formulas **??** and **??**, the throughput of PRK and SINR based scheduling, denoted by T_{prk} and T_{sinr} respectively, can be computed as follows:

$$T_{prk} = \frac{T_{R,prk}}{|\mathbb{S}_{prk}| \times A_0} \quad T_{sinr} = \frac{T_{R,sinr}}{|\mathbb{S}_{sinr}| \times A_0}$$

where $T_{R,prk}$ and $T_{R,sinr}$ are the link throughput to R in PRK and SINR based scheduling respectively. From Proposition 2, we know that the average link reliability in SINR based scheduling is no higher than that in PRK based scheduling (since the actual interference incurred in SINR based scheduling is no less than that in PRK based scheduling). Thus, $T_{R,sinr} \leq T_{R,prk}$. Then, we can define the throughput loss T_{loss} in PRK based scheduling as

$$\begin{aligned} T_{loss} &= \frac{T_{sinr} - T_{prk}}{T_{sinr}} = \frac{\frac{T_{R,sinr}}{|\mathbb{S}_{sinr}| \times A_0} - \frac{T_{R,prk}}{|\mathbb{S}_{prk}| \times A_0}}{\frac{T_{R,sinr}}{|\mathbb{S}_{sinr}| \times A_0}} \\ &\leq \frac{\frac{T_{R,sinr}}{|\mathbb{S}_{sinr}| \times A_0} - \frac{T_{R,sinr}}{|\mathbb{S}_{prk}| \times A_0}}{\frac{T_{R,sinr}}{|\mathbb{S}_{sinr}| \times A_0}} = \frac{|\mathbb{S}_{prk}| - |\mathbb{S}_{sinr}|}{|\mathbb{S}_{prk}|} \end{aligned} \tag{6}$$

Let n_b be the node in $\mathcal{S}_{sinr}$ that is s-farthest away from the receiver R, P_0 be the power of signals that reach R from n_b, and N_b be the number of nodes in the network whose s-distance to R is $sd(n_b, R)$. Similarly, let n'_b be the node in $\mathcal{S}'_{sinr}$ that is s-farthest away from the transmitter T, P'_0 be the power of signals that reach T from n'_b, and N'_b be the number of nodes whose s-distance to T is $sd(n'_b, T)$. Then,

PROPOSITION 3. *The expected T_{loss} is less than or equal to* $\frac{1}{|\mathbb{S}_{prk}|}(\min\{\frac{I_t - I_{prk}}{P_0 \times \beta}, N_b\} + \min\{\frac{I'_t - I'_{prk}}{P'_0 \times \beta}, N'_b\})$.

PROOF. Let $dist(n_b, R)$ be the s-distance from n_b to R, and $dist(n'_b, T)$ be the s-distance from n'_b to T. Then from the proof of Proposition 2, we know that the s-distance d from every node in $\mathcal{S}_{prk} \setminus \mathcal{S}_{sinr}$ to R is $dist(n_b, R)$ since PRK model silences all the nodes on the boundary of the exclusion region around R. Similarly, the s-distance d' from every node in $\mathcal{S}'_{prk} \setminus \mathcal{S}'_{sinr}$ to T is $dist(n'_b, T)$.

Given the interference tolerance I_t and I'_t at R and T respectively, the set of silenced nodes $\mathbb{S}_{prk}$ is fixed for a tightest tessellation of concurrent transmitters in a specific network and environmental setting. To understand the upper bound on T_{loss}, we need to understand the upper bound on $(|\mathbb{S}_{prk}| - |\mathbb{S}_{sinr}|)$ (*see* Inequality 6). By the definition of $\mathbb{S}_{prk}$ and $\mathbb{S}_{sinr}$, we know that $|\mathbb{S}_{prk}| - |\mathbb{S}_{sinr}| \leq (|\mathcal{S}_{prk}| - |\mathcal{S}_{sinr}|) + (|\mathcal{S}'_{prk}| - |\mathcal{S}'_{sinr}|)$. To upper bound $(|\mathbb{S}_{prk}| - |\mathbb{S}_{sinr}|)$, we analyze in what follows the upper bound on $(|\mathcal{S}_{prk}| - |\mathcal{S}_{sinr}|)$ and $(|\mathcal{S}'_{prk}| - |\mathcal{S}'_{sinr}|)$.

We first derive the upper bound on $(|\mathcal{S}_{prk}| - |\mathcal{S}_{sinr}|)$. Since all the nodes in $\mathcal{S}_{prk} \setminus \mathcal{S}_{sinr}$ are on the boundary of the exclusion region around R and are $dist(n_b, R)$ s-distance away from R, each such node introduces an expected interference of $P_0 \times \beta$ at receiver R. To ensure that the expected interference at R is no more than I_t (a.k.a., the SINR at R is above γ_0), one necessary condition is that the expected interference introduced by nodes in $\mathcal{S}_{prk} \setminus \mathcal{S}_{sinr}$ should be no more than $I_t - I_{prk}$, that is, the number of nodes in $\mathcal{S}_{prk} \setminus \mathcal{S}_{sinr}$ should be no more than $\frac{I_t - I_{prk}}{P_0 \times \beta}$. Note that this upper bound is usually not tight and not a sufficient condition because the interference at R tends to exceed I_t if the interferences from nodes in $\mathcal{S}_{prk} \setminus \mathcal{S}_{sinr}$ reaches $I_t - I_{prk}$. This is because, if we add, for every area of the same size of the exclusion region around R, $\frac{I_t - I_{prk}}{P_0 \times \beta}$ more transmitters on average in SINR based scheduling than in PRK based scheduling, the interference at R will exceed $I_t - I_{prk}$ when the area covered by the network is larger than the exclusion region around R (which is usually the case). Therefore, an upper bound on the number of nodes in $\mathcal{S}_{prk} \setminus \mathcal{S}_{sinr}$ is $\frac{I_t - I_{prk}}{P_0 \times \beta}$. In addition, the number of nodes on the boundary of the exclusion region around R is no more than N_b, thus $(|\mathcal{S}_{prk}| - |\mathcal{S}_{sinr}|) \leq \min\{\frac{I_t - I_{prk}}{P_0 \times \beta}, N_b\}$.

Similarly, we can derive that $(|\mathcal{S}'_{prk}| - |\mathcal{S}'_{sinr}|) \leq \min\{\frac{I'_t - I'_{prk}}{P'_0 \times \beta}, N'_b\}$.

Putting the above analysis together, the expected T_{loss} is no more than $\frac{1}{|\mathbb{S}_{prk}|}(\frac{I_t - I_{prk}}{P_0 \times \beta} + \frac{I'_t - I'_{prk}}{P'_0 \times \beta})$. $\square$

Proposition 3 enables us to compute the upper bound, denoted by T_{lb}, on the throughput loss in PRK based scheduling. For convenience, we let $\Delta X = \min\{\frac{I_t - I_{prk}}{P_0 \times \beta}, N_b\} + \min\{\frac{I'_t - I'_{prk}}{P'_0 \times \beta}, N'_b\}$, and thus $T_{lb} = \frac{\Delta X}{|\mathbb{S}_{prk}|}$. Note that ΔX represents an upper bound on $|\mathbb{S}_{prk} \setminus \mathbb{S}_{sinr}|$, that is, the average number of nodes per exclusion region that are silenced in PRK based scheduling but not in SINR based scheduling. In the next subsection, we numerically analyze the properties of ΔX and T_{lb}.

3.2 Numerical analysis

Using the same network and environmental settings of Section **??** and based on Proposition 3, we analyze the throughput loss in PRK based scheduling as compared with the SINR based scheduling. For each of the system configurations we study, more specifically, we first find I_t, I_t', and the minimum K value of PRK model for satisfying certain link reliability requirement, then we compute $|\mathbb{S}_{prk}|$, I_{prk}, and I'_{prk} which in turn enable us to compute ΔX and T_{lb} according to Proposition 3.

Grid network. For each system configuration, we compute the ΔX and throughput loss in PRK based scheduling. For different requirements on packet delivery rate (PDR), Figure 2 shows the boxplot of throughput loss in PRK based

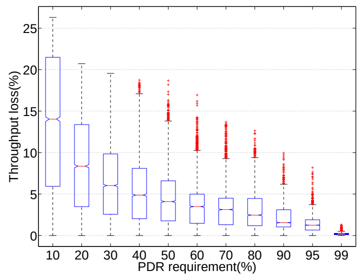


Figure 2. Throughput loss in PRK models: grid networks

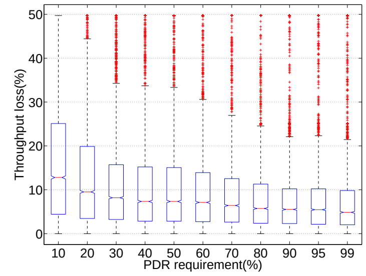
scheduling in different system configurations. We see that the throughput loss is small in general, and it also tends to decrease as the PDR requirement increases. For instance, the median throughput loss is less than 5% when the required PDR is 50%, and the median throughput loss is less than 1% when the required PDR is 90%. These findings imply that PRK model can be used for mission-critical wireless networking (e.g., those for real-time, reliable sensing and control) where PDR requirement is usually high and thus PRK model can enable a performance very close to what is possible with SINR model.

Random network. Figure 3 shows the throughput loss of PRK model in random networks with node distribution density λ being 1.59 and 12.74 respectively (i.e., with the average number of neighbors being 5 and 40 respectively), and Table 1 shows the median throughput loss for differ-

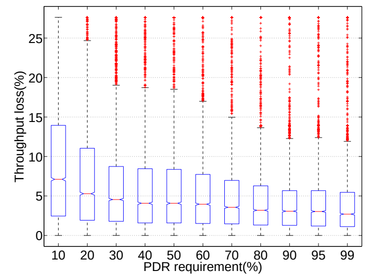
PDR req. (%)	20	40	60	80	99
$\lambda = 3.18$	8.87	7.01	6.25	5.21	4.20
$\lambda = 6.37$	7.60	6.01	5.36	4.46	3.60
$\lambda = 9.55$	6.65	5.26	4.69	3.91	3.15
$\lambda = 12.74$	5.91	4.68	4.17	3.47	2.80

Table 1. Impact of λ and PDR requirement on median throughput loss (%)

ent λ's and PDR requirements. We see that, similar to grid networks, throughput loss decreases as PDR requirement increases. Moreover, we see that throughput loss also decreases as node distribution density λ increases, and this is because larger λ increases the number of silenced nodes in PRK model (i.e., $|\mathbb{S}_{prk}|$).



(a) $\lambda = 1.59$



(b) $\lambda = 12.74$

Figure 3. Throughput loss in PRK model: random networks

4 Measurement study of PRK and SINR based scheduling

Our analytical results show that PRK model serves well as the basis of instantiating ratio-K model in different network and environmental settings and that PRK based scheduling achieves a throughput close to what is possible in SINR based scheduling. To corroborate these results, we experimentally compare the performance of PRK and SINR based scheduling using a testbed of 120 TelosB motes, and we also experimentally verify the tradeoff between reliability and throughput in both PRK and SINR based scheduling.

4.1 Methodology

In our measurement study, we use a 10×12 grid of TelosB motes deployed in an indoor office as shown in Figure 4, where every two closest neighboring motes are separated by 2 feet.

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Figure 4. Testbed

4.2 Scheduling algorithms

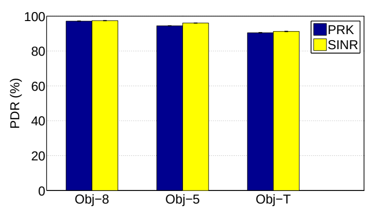
Optimal SINR and ratio-K based scheduling are NP-complete in general [3, 20], thus we use the greedy, approximate scheduling framework, denoted by ALG_0, that has been used to compare different wireless interference models in [13]. In addition to interference model, ALG_0 takes as input the link demand vector $f = (f_1, f_2, \ldots, f_L)$ for L number of links, where the demand f_i for the i-th link is the number of packets to be transmitted across the link. The output of ALG_0 is a schedule $S = \{S_1, S_2, \ldots, S_\tau\}$, where S_j is a set of links scheduled in the j-th time slot. ALG_0 works as follows to generate the output schedule:

1. Order and rename links such that $f_1 \geq f_2 \geq \ldots \geq f_L$.
2. Set $i = 1, S = \emptyset, \tau = 0$. (Note: initial schedule is empty.)
3. Schedule link i in the very first available time slot to which link i can be added based on certain scheduling objective (e.g., guaranteeing certain minimum link reliability or maximizing network throughput) and interference model. If no such slot exists, increment τ and schedule link i in the newly created slot. (Note: incrementing τ is equivalent to creating a new empty slot at the end of the current schedule.)
4. Repeat step 3 f_i times.
5. Increment i. Go back to step 3 until $i > L$.

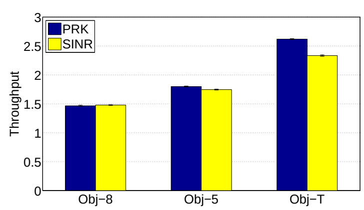
...

4.3 Experimental results

Using the scheduling algorithms ALG_{prk} and ALG_{sinr}, we have measured the performance of PRK and SINR based scheduling using the methodology discussed in Section 4.1. Figures 5 and 6 show the PDR and throughput of PRK and SINR based scheduling in the grid network and the random network respectively, with the error bars representing the 95% confidence intervals (which are very small) of the corresponding metrics. The PDR is defined as the number of successfully delivered packets divided by the number of packets transmitted in a schedule; the throughput is defined as the number of successfully delivered packets divided by the schedule length (i.e., number of slots used in a schedule). Note that the throughput is not that high because of the limited concurrency allowed in the testbed which is in turn due to the wide transitional region of wireless communication as can be seen from Figure **??**. For instance, Table 2 shows the probability of having different number of concurrent links in a slot in PRK based scheduling for the random network and the *Obj-8* objective.

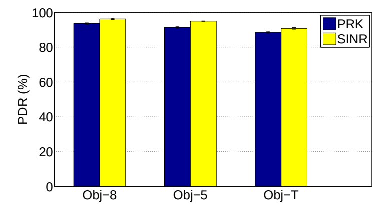


(a) PDR

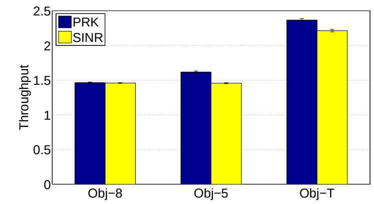


(b) Throughput

Figure 5. PDR and throughput in the grid network



(a) PDR



(b) Throughput

Figure 6. PDR and throughput in the random network

# of Concurrent Links	1	2	3
Probability	0.46	0.51	0.03

Table 2. Probability of having different number of concurrent links in a slot: random network, PRK, *Obj-8*

...

5 Related work

The seminal work of [8] used both ratio-K and SINR models in analyzing the capacity of wireless networks. Since the paper did not focus on MAC protocol design, it did not study the impacts of different factors on optimal ratio-K model, the tradeoff between reliability and throughput, and the optimality of correctly instantiated ratio-K model.

[13] and [16] have studied the benefits of SINR model as compared with ratio-K model. On the other hand, [3] found that ratio-K based scheduling can improve the throughput of SINR based scheduling too. Without studying the impact of different factors and the tradeoff between reliability and throughput in instantiating ratio-K model, however, these work did not explain the causes for the inconsistent observations on the relative goodness between ratio-K and SINR based scheduling, and they did not study how to best use ratio-K model either. Our work complements the aforementioned studies by examining the impact of different network and environmental factors on the optimal ratio-K model, by studying the tradeoff between reliability and throughput in ratio-K model instantiation, by identifying the PRK interference model which addresses the challenge of adapting K to potentially unpredictable network and environmental dynamics, and by studying the optimality of PRK based scheduling through analysis, simulation, and testbed based measurement.

Most closely related to our work is Shi *et al*. [21] who, in parallel with our study, independently examined the effectiveness of protocol interference model from the perspective of frequency scheduling (together with routing and power control). Having not focused on distributed protocol design, however, [21] left it as an open problem how to choose optimal K in instantiating ratio-K model. Through detailed study of the sensitivity of and the inherent tradeoff between throughput and reliability in ratio-K based scheduling, we discover the simple, distributed, link reliability based approach to selecting the optimal K, and we propose the PRK model which has both the locality of ratio-K model and the high fidelity of SINR model. Our work also complements [21] by examining the effectiveness of ratio-K model from the perspective of time scheduling and distributed protocol design, by studying in Section 3 why PRK/ratio-K based scheduling can be very close to the performance of SINR based scheduling, by examining the issue in a wide range of network and environmental settings (e.g., [21] did not study scenarios of different path loss exponent), and by corroborating the analytical and simulation results with testbed based measurement. Together, [21] and our work show that ratio-K model, if correctly used, may well help simplify cross-layer optimization and distributed protocol design, and it will be worthwhile to explore this direction further.

Other approximate interference models such as hop-based model [19] and range-based model [24] have also been used in the literature, but they are either similar to ratio-K model or perform worse than ratio-K model [13]. Therefore, we did not study those approximate models in detail in this paper. [10] studied the feasibility of local interference model, where only nodes in a local neighborhood (with diameter ρ) need to coordinate with one another to ensure minimum SINR at each receiver. But it did not study the impact of various factors on the optimal ρ, nor did [10] study how to correctly instantiate ρ in dynamic, potentially unpredictable network and environmental settings. [20] and [24] studied TDMA scheduling based on ratio-K model. But [24] only considered the case where K is 1, and the study of [20] did not exam the impact of traffic load and node distribution on the optimal K. The simulation study of optimal K in [20] is also based on approximate instead of optimal scheduling.

Spatial reuse control based on the concept of *exclusion region* has been studied in [15, 25, 11, 12, 6, 17] too. Nonetheless, the issue of optimal K in different scenarios and the comparison between ratio-K and SINR models were not studied in these work. [15] also used the Matern Hard-core Process to analyze the distribution of interferers in a random field; but it did not consider the impact of traffic load on optimal spatial reuse, it only focused on the exclusion region around the receiver (but not the sender), and it did not study how the tradeoff between reliability and throughput affects optimal spatial reuse. The analysis in [25] and [11] used the honey-grid model which assumes the existence of a node at every point in space. [25] did not study the impact of traffic load on optimal spatial reuse, [11] only focused on exclusion region around the receiver (and not the sender) in controlling transmission power and carrier sensing threshold. [12] and [17] only considered the case of single interferer (and did not consider additive interference from multiple interferers) in controlling parameters such as carrier sensing range and transmission power. [6] only considered the case of K = 1 in transmission power control.

[5] showed that additive interference from multiple interferers significantly affect link properties, especially for links of medium-to-high quality. [14] and [22] studied the additivity of interfering signals (i.e., whether the aggregate signal strength of multiple interfering signals is the sum of the strength of the individual signals) for TelosB and MICA2 motes respectively, and it was found that measurement errors may affect the conclusions.

Several studies (e.g., [7] and [9]) recently proposed mechanisms for interference cancellation where a single receiver can simultaneously receive packets from multiple senders. These results challenged the traditional paradigm where a receiver can only receive one packet at a time, and they suggest new ways of interference control. Nonetheless, interference still needs to be controlled due to the constraints of these interference cancellation mechanisms. For instance, ZigZag decoding [7] works the best when the number of interferers is small (e.g., less than 6). How to build interference models for these interference cancellation mechanisms should be an interesting problem to study, but the detailed study is beyond the scope of this paper.

6 Concluding remarks

Through detailed analysis of the impact of different network and environmental factors (e.g., traffic load and wireless signal attenuation) on the optimal instantiation of ratio-K model, we showed that the performance of ratio-K based scheduling is highly sensitive to the choice of K and that it is important to take this into account in both protocol design and performance evaluation. We then comparatively studied the performance of PRK and SINR based scheduling and showed that, if correctly instantiated, ratio-K based scheduling can achieve a close-to-optimal performance. Moreover, our results on PRK model and the inherent tradeoff between reliability and throughput suggest that ratio-K model can be correctly instantiated through link reliability based adaptation of K which is readily amenable to distributed, local implementation. These findings explained the seemingly inconsistent observations about ratio-K model in the literature, showed the feasibility of integrating the high fidelity of SINR model with the locality of ratio-K model, and suggested new approaches to MAC protocol design in dynamic, unpredictable network and environmental settings. We will study the issue of how to apply PRK model to protocol design and systems analysis in our future work.

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