# Wireless Ad Hoc Networks with Successive Interference Cancellation


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**Abstract**

The transmission capacity of a wireless ad hoc network is defined as the maximum allowable spatial density of transmissions such that the outage probability does not exceed some specified threshold. This work studies the improvement in transmission capacity obtainable with successive interference cancellation (SIC), an important receiver technique that has been shown to achieve the capacity of several classes of multiuser channels, but has not been carefully evaluated in an uncentralized wireless network. This paper develops closed-form bounds for the transmission capacity of CDMA ad hoc networks with SIC receivers. Several design-relevant insights are obtained: *i*) although the capacity gain from perfect SIC is very large, any imperfections in the interference cancellation rapidly degrades its usefulness; *ii*) only a few – often just one – interfering nodes need to be cancelled in order to get the vast majority of the available performance gain.


## 1 Introduction

Our previous work [1] studied the spatial density of transmissions that could be supported in a wireless ad hoc network subject to a constraint on the fraction of attempted transmissions permitted to fail due to excessive interference. More precisely, given a QoS constraint $\epsilon \in (0, 1)$, the transmission capacity $c^\epsilon$ is defined as the maximum permissible spatial density of attempted transmissions such that the probability of outage for a typical transmission attempt is at most $\epsilon$. That work focused on the transmission capacity for frequency hopping (FH) versus direct sequence (DS) CDMA and found that frequency hopping offered superior transmission capacity scaling over direct sequence. In particular, our model predicts a performance improvement on the order of $M^{1-\frac{2}{\alpha}}$, where $M$ is the spreading factor and $\alpha > 2$ is the path loss exponent in the flat fading channel model. The conclusion is that it is easier to *avoid* interference by frequency hopping rather than trying to *suppress* it through spreading. Intuitively, most outages are a result of a single interfering node being close to a receiver, and these occurrences are better handled by


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the receiver and interferer using different channels as opposed to the receiver trying to suppress the interference.

If FH is superior to DS due to its superior ability to suppress "near-field" interference, then this begs the question of how the transmission capacity can be improved through the use of successive interference cancellation (SIC). Indeed, SIC is a mechanism that works best on canceling interference from transmitters where the interference power from that transmitter exceeds the signal power, i.e., near-field interference. This paper will address the impact of SIC on the transmission capacity of wireless ad hoc networks. Our primary findings include the following.

- Most of the performance improvement obtainable through SIC is gained by canceling the single transmitter with the largest interference level; canceling additional transmitters may carry a negligible benefit.
- The performance improvement is very sensitive to the cancellation effectiveness, especially for tight QoS constraints (small $\epsilon$); improving cancellation effectiveness may yield a significant benefit.
- The transmission capacity of DS with SIC versus that of FH depends upon the spreading factor $M$; DS with SIC is superior for small $M$ while FH is superior for large $M$. The crossover point depends upon the SIC effectiveness.

## 1.1 Successive interference cancellation

SIC is especially promising for ad hoc networks since it is well-suited to asynchronous signals of unequal powers [2]; furthermore, only the strongest interfering users would need to be cancelled, reducing the normal latency issue with SIC. We capture the performance impact of an SIC-equipped receiver through a simple model: the interference power of up to $K$ of the nearest interfering nodes is reduced by a factor $\zeta$ provided the interference power exceeds the signal power as measured at the receiver.

Direct incorporation of the $(K, \zeta)$ model into the stochastic geometric framework we employ is problematic. Instead, we consider a model employing a cancellation radius: the interference of all nodes within a radius $r_{\rm sic}$ of the receiver is reduced by $\zeta$. The cancellation radius is chosen so that on average there are $K$ interfering nodes within the cancellation radius. The radius is also constrained to be no larger than the distance from the signal transmitter to the receiver; this captures the effect that only interfering nodes with high interference power are cancellable. This latter framework is much more amenable to analysis, and as will be shown in our simulations, the two models are usually statistically equivalent with respect to the performance metrics of interest.

## 1.2 Related work

There is a large and growing body of work on the capacity of ad hoc networks [3, 4, 5, 6, 7, 8, 9, 10, 11]. Rather than summarize that work, we will focus on the work specifically dealing with the capacity under SIC.

In addition to its simplicity and amenability to implementation [12], SIC is well-justified from a theoretical point of view. Simple successive interference cancellation implementation with suboptimal coding was shown to nearly achieve the Shannon capacity of multiuser AWGN channels, assuming accurate channel estimation and a large spreading factor [13]. Other more recent work has proven that SIC with single-user decoding in fact achieves the Shannon capacity region boundaries for both the broadcast (downlink) and multiple access (uplink) multiuser channel scenarios [14, 15], as well-summarized in [16]. Quantifying SIC's benefit in ad hoc networks is naturally more problematic, but initial evidence for its promise is given in [11]. Since it is well-suited to asynchronous signals of unequal powers [17], and has much lower complexity than most other multiuser receivers, it appears to be a natural fit for a wireless ad hoc networks from the standpoint of both theory and practice.

Accurately modelling and analyzing SIC in ad hoc networks requires some nontrivial extensions from centralized networks. For instance, it has been shown that a particular (unequal) distribution of received powers is needed for SIC systems to perform well, especially when the interference cancellation is imperfect [18, 2]. Achieving such a distribution at each receiver in an ad hoc network is impossible due to the random spatial characteristics of the network. Related to this, to be realistic it should be assumed that only strong signals can be cancelled, hence at any given location in the network, only the nearby interferers are cancellable. In order to accurately quantify SIC's performance in ad hoc networks, Section 2 will develop a realistic (but analytically tractable) model in view of such considerations.

# 2 Mathematical model

## 2.1 Wireless ad hoc network

Our model employs a homogeneous Poisson point process (PPP) $\Pi(\lambda) = \{X_i, i \in \mathbb{N}\}$ on the plane $\mathbb{R}^2$ to represent the locations of all nodes transmitting at some time $t$. The parameter $\lambda$ is the spatial intensity (density) of points on the plane so that $\mathbb{E}[\Pi(\lambda) \cap A] = \lambda\nu(A)$, where $\nu(A)$ is the area of $A$. All transmissions employ a fixed transmission power $\rho$ and fixed transmission distance $r_{\text{tx}}$.

Our channel model considers only path-loss attenuation effects and ignore additional channel effects such as shadowing and fast-fading. In particular, if the transmitted power is $\rho$ and the path-loss exponent is $\alpha > 2$ then the received power at a distance $d > 1$ from the transmitter is $\rho d^{-\alpha}$. We denote the SINR threshold required for successful transmission as $\beta$.

## 2.2 Transmission capacity without SIC

The above model is analyzed in [1] yielding the following upper and lower bounds on the transmission capacity. Let nsic denote "no SIC", meaning the receivers are not equipped with any cancellation technology.

**Definition 1** The *optimal contention density* without SIC, denoted $\lambda^{\epsilon,\text{nsic}}$, is the maximum spatial density of nodes that can contend for the channel subject to the constraint that the typical outage probability is less than $\epsilon$ for some $\epsilon \in (0, 1)$:

$$\lambda^{\epsilon,\text{nsic}} = \sup\left\{\lambda \ : \ \mathbb{P}^0\left(\frac{\rho r_{\text{tx}}^{-\alpha}}{\sum_{i\in\Pi} \rho|X_i|^{-\alpha}} \leq \beta\right) \leq \epsilon\right\}.$$

**Definition 2** The *transmission capacity* without SIC, denoted $c^{\epsilon,\text{nsic}}$, is the density of successful transmissions resulting from the optimal contention density: $c^{\epsilon,\text{nsic}} = \lambda^{\epsilon,\text{nsic}}(1-\epsilon)$.

**Theorem 1** As $\epsilon \to 0$, the lower and upper bounds on the transmission capacity subject to the outage constraint $\epsilon$ when transmitters employ a fixed transmission power $\rho$ for receivers that are a fixed distance $r_{\rm tx}$ away are: $c_l^{\epsilon,\rm nsic} = (1-\epsilon)\lambda_l^{\epsilon,\rm nsic}$, $c_u^{\epsilon,\rm nsic} = (1-\epsilon)\lambda_u^{\epsilon,\rm nsic}$, where the (Markov (M) and Chebychev (C)) lower and upper bounds on the optimal contention density are:

$$\lambda_{l,M}^{\epsilon,\rm nsic} = \left(1-\frac{2}{\alpha}\right)\frac{\epsilon}{\pi\left(\beta^{\frac{1}{\alpha}} r_{\rm tx}\right)^2} + O(\epsilon^2), \quad \lambda_{l,C}^{\epsilon,\rm nsic} = \left(1-\frac{1}{\alpha}\right)\frac{\epsilon}{\pi\left(\beta^{\frac{1}{\alpha}} r_{\rm tx}\right)^2} + O(\epsilon^2), \quad \lambda_{u}^{\epsilon,\rm nsic} = \frac{-\ln(1-\epsilon)}{\pi\left(\beta^{\frac{1}{\alpha}} r_{\rm tx}\right)^2}.$$

**Comments on Theorem 1.** Several points are noteworthy:

- As discussed in [1], this model may be specialized to the cases of frequency hopping (FH) and direct sequence (DS) spread spectrum. In order to obtain bounds for FH it suffices to multiply the bounds by $M$; in order to obtain bounds for DS it suffices to replace $\beta$ by $\beta/M$.
- The quantity $\beta^{\frac{1}{\alpha}} r_{\rm tx}$ is a minimum interference-free radius in the sense that a necessary condition for a reception to be successful is that there be no receivers in the ball $b(O, \beta^{\frac{1}{\alpha}} r_{\rm tx})$. The bounds illustrate that transmission capacity has a strong connection with sphere packing: $\pi\left(\beta^{\frac{1}{\alpha}} r_{\rm tx}\right)^2$ is the area of the disk corresponding to the interference-free radius. Note that improving $\beta$, e.g., through DS spreading, reduces the interference-free radius, thereby permitting a larger number of spheres to be packed into the space.

## 2.3 Successive interference cancellation model

As presented in the introduction, an SIC-equipped receiver is capable of reducing by $\zeta$ the interference power of the $K$ nearest interfering nodes located no farther than $r_{\rm tx}$ from the receiver. It is difficult to work with this model in our mathematical framework. Instead, we present a secondary SIC model more amenable to analysis. In particular, define the *cancellation radius*, denoted $r_{\rm sic}$, such that the receiver is capable of eliminating the interference power of any and all transmitters located within distance $r_{\rm sic}$ of it. The cancellation radius is chosen so that there are $K$ interfering nodes falling within the radius on average.

**Definition 3** A $(K,\zeta)$-*SIC receiver* operating in a network with a transmission density of $\lambda$ is capable of reducing by $\zeta$ the interference power for all interfering nodes within distance $r_{\rm sic} = r_{\rm tx} \wedge \sqrt{\frac{K}{\pi\lambda}}$ of the receiver.

**Definition 4** The *optimal contention density* for a network of $(K,\zeta)$-SIC receivers, denoted $\lambda^{\epsilon,\rm sic}$, is the maximum spatial density of nodes that can contend for the channel subject to the constraint that the typical outage probability is less than $\epsilon$ for some $\epsilon \in (0,1)$:

$$\lambda^{\epsilon,\rm sic} = \sup\left\{\lambda : \mathbb{P}^0\left(\frac{\rho r^{-\alpha}}{\zeta \sum_{i\in\Pi\cap b(O,r_{\rm sic})} \rho|X_i|^{-\alpha} + \sum_{i\in\Pi\cap\bar{b}(O,r_{\rm sic})} \rho|X_i|^{-\alpha}} \le \beta\right) \le \epsilon\right\}.$$

# 3 Performance improvement obtainable through SIC

The major result is a set of closed form expressions for lower and upper bounds on the transmission capacity.

**Theorem 2** Let $\epsilon \in (0,1)$. As $\epsilon \to 0$, the lower and upper bounds on the transmission capacity when receivers are equipped with imperfect SIC ($\zeta \in (0,1)$) are:

$$c_l^{\epsilon,\text{sic}} = (1-\epsilon)\lambda_l^{\epsilon,\text{sic}}, \qquad c_u^{\epsilon,\text{sic}} = (1-\epsilon)\lambda_u^{\epsilon,\text{sic}}. \tag{1}$$

The upper bound on the optimal contention density is:

$$\lambda_u^{\epsilon,\text{sic}} = \begin{cases} \frac{-\ln(1-\epsilon)}{\zeta^{\frac{2}{\alpha}}\pi\left(\beta^{\frac{1}{\alpha}} r_{\text{tx}}\right)^2} & \epsilon \leq 1 - e^{-K\zeta^{\frac{2}{\alpha}}} \\ \frac{K - \ln(1-\epsilon)}{(1+\zeta^{\frac{2}{\alpha}})\pi\left(\beta^{\frac{1}{\alpha}} r_{\text{tx}}\right)^2} & \text{else} \\ \frac{-\ln(1-\epsilon)}{\pi\left(\beta^{\frac{1}{\alpha}} r_{\text{tx}}\right)^2} & \epsilon \geq 1 - e^{-K\zeta^{-\frac{2}{\alpha}}} \end{cases} \tag{2}$$

The Markov (M) lower bound on the optimal contention density is:

$$\lambda_{l,M}^{\epsilon,\text{sic}} \geq \sup_{(\epsilon_u,\epsilon_f):\epsilon_u+\epsilon_f=\epsilon} \left\{\lambda_u^{\epsilon_u,\text{sic}} \wedge \lambda_{f,M}^{\epsilon_f,\text{sic}}\right\}, \tag{3}$$

where

$$\lambda_{f,M}^{\epsilon,\text{sic}} = \begin{cases} \frac{\alpha-2}{2}\frac{\beta^{\frac{2}{\alpha}}}{(1-\zeta)\beta+\zeta\beta^{\frac{2}{\alpha}}}\frac{\epsilon}{\pi\left(\beta^{\frac{1}{\alpha}} r_{\text{tx}}\right)^2}, & \epsilon \leq \epsilon_{c,M}^{\text{sic}} \\ \textit{see below}, & \epsilon_{c,M}^{\text{sic}} \leq \epsilon < \epsilon_{k,M}^{\text{sic}} \\ \frac{\alpha-2}{2}\frac{\epsilon}{\pi\left(\beta^{\frac{1}{\alpha}} r_{\text{tx}}\right)^2}, & \epsilon > \epsilon_{k,M}^{\text{sic}} \end{cases} \tag{4}$$

*and* $\lambda_{f,M}^{\epsilon,\text{sic}}$ *for* $\epsilon_{c,M}^{\text{sic}} \leq \epsilon < \epsilon_{k,M}^{\text{sic}}$ *is the unique solution for* $\lambda$ *satisfying equation:*

$$\frac{2\pi\lambda\beta}{(\alpha-2)r_{\text{tx}}^{-\alpha}}\left[(1-\zeta)\left(\frac{K}{\pi\lambda}\right)^{1-\frac{\alpha}{2}} + \zeta r_{\text{tx}}^{2-\alpha}\beta^{\frac{2}{\alpha}-1}\right] = \epsilon. \tag{5}$$

The constants are given by:

$$\epsilon_{c,M}^{\text{sic}} = \left[(1-\zeta)\beta + \zeta\beta^{\frac{2}{\alpha}}\right]\frac{2K}{\alpha-2}, \quad \epsilon_{k,M}^{\text{sic}} = \frac{2K}{\alpha-2} \tag{6}$$

**Comments on Theorem 2.** Several points are noteworthy:

- The performance improvement due to SIC is very sensitive to the cancellation effectiveness parameter $\zeta$ as $\zeta \to 0$, especially for small $\epsilon$. Looking at the upper bound, for example, we see that for small $\epsilon$: $\frac{d}{d\zeta}\lambda_u^{\epsilon,\text{sic}} \propto -\zeta^{-(1+\frac{2}{\alpha})}$, which means $\lim_{\zeta\to 0}\frac{d}{d\zeta}\lambda_u^{\epsilon,\text{sic}} = -\infty$. Thus our model suggests that technology improvements which improve cancellation effectiveness may yield large increases in the transmission capacity.

Table 1: Simulation Parameters (unless otherwise noted)

| Symbol | Description | Value |
|---|---|---|
| $\alpha$ | Path loss exponent | 4 |
| $M$ | Spreading factor | 16 |
| $\beta = \frac{3}{M}$ | Target $SINR$ (DS-CDMA) | $\frac{3}{16}$ |
| $r_{\text{tx}}$ | Transmission radius | 10m |
| $K$ | Max. no. cancelable nodes | 10 |
| $\zeta$ | Cancellation effectiveness | $\frac{1}{10}$ |
| $\epsilon$ | Target outage probability | 0.1 |

- For small $\epsilon$ it is straightforward to show that the bounds are reasonably tight. In particular,

$$\lambda_{l,M}^{\epsilon,\text{sic}} = \frac{(\alpha-2)\beta^{\frac{2}{\alpha}}}{2(1-\zeta)\beta + (2\zeta+\alpha-2)\beta^{\frac{2}{\alpha}}} \frac{\epsilon}{\pi\left(\beta^{\frac{1}{\alpha}} r_{\text{tx}}\right)^2} + O(\epsilon^2),$$

  with a corresponding bound ratio of

$$\frac{\lambda_{l,M}^{\epsilon,\text{sic}}}{\lambda_u^{\epsilon,\text{sic}}} = \frac{(\alpha-2)\left(\beta\zeta\right)^{\frac{2}{\alpha}}}{2(1-\zeta)\beta + (2\zeta+\alpha-2)\beta^{\frac{2}{\alpha}}} + O(\epsilon^2).$$

  Note that as $\zeta \to 1$ we recover the bound ratios for the nsic case, while as $\zeta \to 0$ the bound ratios go to zero.

- The above expressions also demonstrate that for small $\epsilon$ the lower bounds are independent of $K$. Recall our SIC model: up to $K$ interfering nodes within $r_{\text{tx}}$ are cancelled. For small $\epsilon$ the transmission capacities supporting that QoS are such that it is unlikely for more than 1 interfering node to be within $r_{\text{tx}}$ in the first place. Thus increasing $K$ may not have any effect. Of course in regimes with high transmission densities having a higher $K$ will be of great value, but this regime will not support a small $\epsilon$ QoS level.

# 4 Numerical and simulation results

In this section we present some numerical and simulation results. Two types of simulations were performed: one where up to the first $K$ nodes within $r_{\text{tx}}$ are cancelled by a factor of $1-\zeta$ and one where all nodes within $r_{\text{sic}}$ are cancelled by a factor of $1-\zeta$. The former aims to approximate the *actual* SIC system, while the latter is our stochastic geometric approximate *model* of the SIC system. The terms *Simulation (actual)* and *Simulation (model)* are used to differentiate the results from these two simulators. Both have 90% confidence intervals.

Table 1 lists the nominal values used for the numerical and simulation results, which are based as closely as possible on realistic parameters for a typical indoor wireless ad hoc network. The target SINR of $3 \approx 5$dB assumes the existence of error correction codes. For conciseness, we restrict our attention to comparing performance of three representative scenarios: *i*) no SIC ($K=0$ and $\zeta=1$), *ii*) perfect SIC with $K=10$ ($\zeta=0$), and *iii*) imperfect SIC with $K=10$ and $\zeta=\frac{1}{10}$.

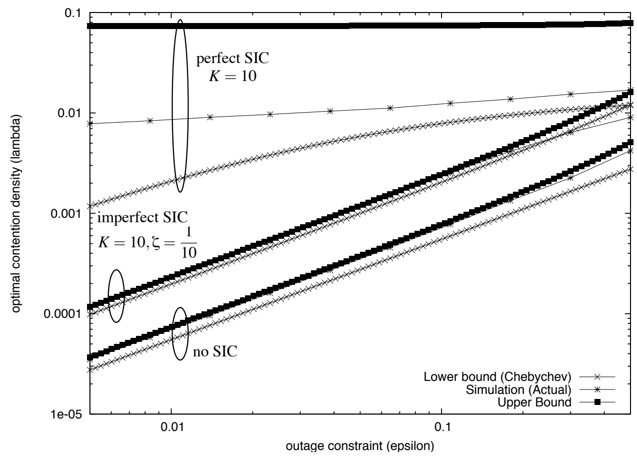


Figure 1: Optimal contention density $\lambda^\epsilon$ versus the outage constraint $\epsilon$ for the no SIC, imperfect SIC, and perfect SIC scenarios.

## 4.1 Optimal contention density versus outage constraint

Figure 1 shows the optimal contention density $\lambda^\epsilon$ versus the outage constraint $\epsilon$ for the no SIC, imperfect SIC, and perfect SIC scenarios. For each scenario we show the Chebychev lower bound, the *actual* simulation results, and the upper bound. The dramatic difference between perfect SIC and imperfect SIC are apparent, again highlighting the sensitivity of the optimal contention density to the cancellation effectiveness parameter $\zeta$. Also apparent is the fact that the no SIC and imperfect SIC bounds are tight while the perfect SIC bounds are loose. Finally, we see that the optimal contention density is linear in the outage constraint $\epsilon$ over a wide range of values of $\epsilon$, thus validating our linear approximations for small $\epsilon$.

## 4.2 Optimal contention density versus number of cancelable interferers

Figure 2 shows the optimal contention density $\lambda^\epsilon$ versus the number of cancelable nodes $K$ for the no SIC, imperfect SIC, and perfect SIC scenarios. Of course the no SIC scenario is independent of $K$, but also apparent is the insensitivity for the imperfect SIC scenario. Recall that $K$ is the *maximum* number of cancelable interferers; the insensitivity can be explained by the fact that fewer than $K$ nodes typically lie in the disk $b(O, r_{\text{tx}})$ around a receiver at the optimal contention density. Note that the perfect SIC results highlight how loose the bounds are for this scenario, and that the optimal contention density levels out first for $K \approx 5$. Finally, note that the imperfect SIC case demonstrates an improvement over no SIC by a factor of about 3.

## 4.3 Optimal contention density versus cancellation effectiveness

Figure 3 shows the optimal contention density $\lambda^\epsilon$ versus the cancellation effectiveness parameter $\zeta$ for the no SIC, imperfect SIC, and perfect SIC scenarios. Of course the no SIC and perfect SIC results are independent of $\zeta$: they are shown to confirm that these results are in fact special cases of the imperfect SIC model for $\zeta = 1$ and $\zeta = 0$ respectively. The plot is significant because it demonstrates the great sensitivity of the

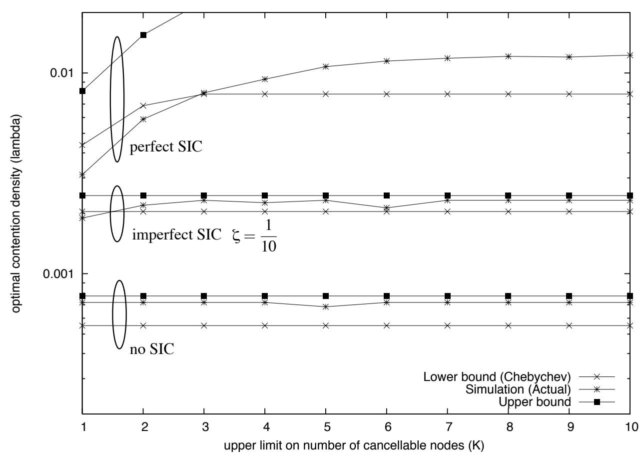


Figure 2: Optimal contention density $\lambda^\epsilon$ versus the number of cancelable interferers $K$ for the no SIC, imperfect SIC, and perfect SIC scenarios.

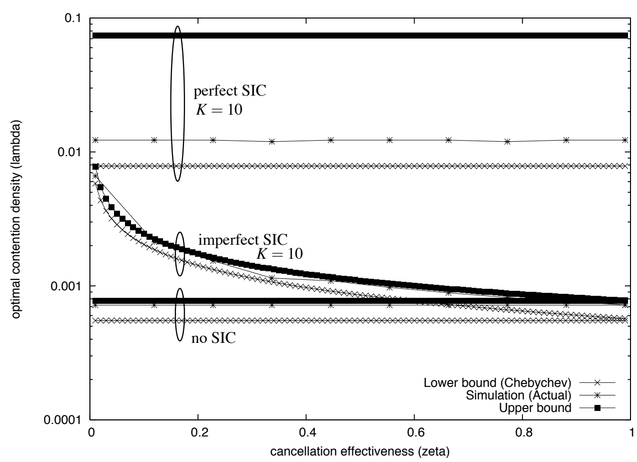


Figure 3: Optimal contention density $\lambda^\epsilon$ versus the cancellation effectiveness parameter $\zeta$ for the no SIC, imperfect SIC, and perfect SIC scenarios.

optimal contention density to $\zeta$ for small $\zeta$. This sensitivity is why there is such a difference between the perfect SIC ($K = 10, \zeta = 0$) results and the imperfect SIC results with similar parameters ($K = 10, \zeta = \frac{1}{10}$). This sensitivity suggests that SIC receiver designers might find significant performance improvements by focusing their efforts on improving the cancellation effectiveness.

## 4.4 Spectral efficiency versus spreading factor

Figure 4 shows a plot of the spectral efficiency $\lambda^\epsilon/M$ versus the spreading factor $M$. Note that the optimal contention density $\lambda^\epsilon$ is increasing in $M$ but this increase comes at the cost of increased resource (spectrum) utilization, hence normalizing by $M$ gives an indication of the efficiency measured in terms of the spatial density per Hz. Four scenarios are shown: the three DS-CDMA scenarios used above, i.e., no SIC, imperfect SIC, and perfect SIC, and a FH-CDMA scenario. Note that, by Theorem 1, FH-CDMA is linear in $M$ and hence the spectral efficiency is constant in $M$. Also, DS-CDMA with no SIC is sub-linear in $M$ and hence the spectral efficiency is decreasing in $M$.

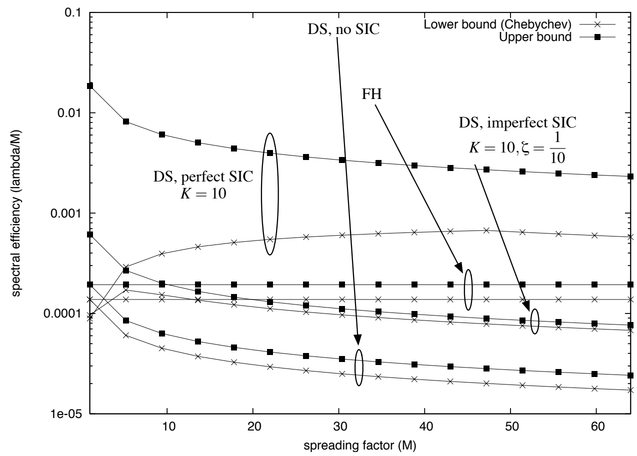


Figure 4: Spectral efficiency $\lambda^\epsilon/M$ versus the spreading factor $M$ for four scenarios: DS-CDMA with no SIC, DS-CDMA with imperfect SIC, DS-CDMA with perfect SIC, and FH-CDMA.

These results are discussed at more length in [1]. As expected the use of imperfect or perfect SIC increases the optimal contention density, and hence the spectral efficiency above that of DS-CDMA with no SIC. Perhaps surprising is the fact that imperfect SIC offers improvements in spectral efficiency above FH-CDMA only for small $M$, in this case $M \leq 10$. The perfect SIC DS-CDMA offers improvement above FH-CDMA for all values of $M$ shown. The plots indicate that the cancellation effectiveness parameter can be very significant in determining whether DS-CDMA with SIC will over or under perform FH-CDMA.

# 5 Conclusion

The primary contribution of this work is a tractable framework for analyzing the performance improvement obtainable through the use of successive interference cancellation in wireless ad hoc networks. Through the use of stochastic geometric models and analysis we are able to obtain (in most cases) reasonably tight closed form expressions for the transmission capacity in terms of the fundamental SIC parameters, i.e., the number of cancelable nodes $K$ and the cancellation effectiveness $\zeta$. Our analysis and simulation results support the claims that $i$) performance is highly sensitive to the cancellation effectiveness parameter but less sensitive to the number of cancelable nodes, and $ii$) the spectral efficiency of DS-CDMA with SIC is always higher than DS-CDMA without SIC, but may not always exceed that of FH-CDMA.

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