Guard Zones and the Near-Far Problem in DS-CDMA Ad Hoc Networks

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Abstract—The central issue in direct-sequence code-division multiple-access (DS-CDMA) ad hoc networks is the prevention of a near-far problem. This paper considers two types of guard zones that may be used to control the near-far problem: a fundamental exclusion zone and an additional CSMA guard zone that may be established by the carrier-sense multiple-access (CSMA) protocol. In the exclusion zone, no mobiles are physically present, modeling the minimum physical separation among mobiles that always present in actual networks. Potentially interfering is mobiles beyond a transmitting mobile's exclusion zone, but within its CSMA guard zone, are deactivated by the protocol. This paper provides an analysis of DS-CSMA networks with either or both types of guard zones. A network of finite extent with a finite number of mobiles is modeled as a uniform clustering process. The analysis uses a closed-form expression for the outage probability in the presence of Nakagami fading, conditioned on the network geometry. By using the analysis developed in this paper, the tradeoffs between exclusion zones and CSMA guard zones are explored for DS-CDMA and unspread networks.

I. INTRODUCTION

Direct-sequence code-division multiple-access (DS-CDMA) ad hoc networks are realized by using direct-sequence spreadspectrum modulation while the mobiles or nodes of multiple users simultaneously transmit signals in the same frequency band. All signals use the entire allocated spectrum, but the spreading sequences differ. DS-CDMA is advantageous for ad hoc networks because it eliminates the need for any frequency or time-slot coordination, imposes no sharp upper bound on the number of mobiles, directly benefits from inactive terminals in the network, and is capable of exploiting bursty data traffic, intermittent voice signals, multibeamed arrays, and reassignments to accommodate variable data rates. Furthermore, DS-CDMA systems are inherently resistant to interference, interception, and frequency-selective fading.

The central issue in DS-CDMA ad hoc networks is the prevention of a near-far problem. The solution to the near-far problem in cellular networks is power control [1]. However, the absence of a centralized control of an ad hoc network renders any attempted power control local rather than pervasive. As an alternative to power control, ad hoc networks typically use *guard zones* surrounding mobiles to manage interference. This paper considers two types of guard zones to control the near-far problem: a fundamental *exclusion zone* and an additional guard zone that may be established by the carrier-sense multiple-access (CSMA) protocol; i.e., a *CSMA guard*

zone. In the exclusion zone surrounding a mobile, no other mobiles are physically present. The exclusion zone may be enforced by using information about the locations of a mobile and its surrounding mobiles and is justified by the fact that mobiles will always have a minimum physical separation in actual networks. In the CSMA guard zone [2], [3], [4], which extends beyond the exclusion zone, other mobiles may be present, but they are deactivated by the protocol. The CSMA guard zone offers additional near-far protection beyond that offered by the exclusion zone, but at the cost of reduced network transmission capacity, as shown subsequently.

In contrast to the existing literature (e.g., [5]-[10] and the references therein), a realistic network of finite extent with a finite number of mobiles and uniform clustering as the spatial distribution is modeled. The analysis presented in this paper discards previous assumptions based on stochastic geometry [11], [12] about the spatial distribution of the mobiles. Both the spatial extent of the network and number of mobiles are finite, and each mobile has an arbitrary location. The analysis considers the mobile's duty factor, the shadowing, the possible coordination among the mobiles (through the use of guard zones), and a Nakagami-m factor that can vary among the channels from each mobile to the reference receiver. A recent closed-form expression for the exact outage probability [13] is used for a reference receiver conditioned on the network geometry and shadowing factors. The spatially averaged outage probability, defined as the average over both the mobile locations and the shadowing, is computed by averaging the conditional outage probability with respect to the spatial distribution and the distribution of the shadowing. While this expectation is not generally analytically tractable for finite networks and guard zones, a simple and efficient Monte Carlo method can be used that involves the random placement of mobiles and generation of shadowing factors, but does not require the generation of fading coefficients.

II. GUARD ZONES

The IEEE 802.11 standard, which is currently the predominant standard for ad hoc networks, uses CSMA with collision avoidance in its medium-access control protocol [2], [3]. The implementation entails the exchange of request-to-send (RTS) and clear-to-send (CTS) handshake packets between a transmitter and receiver during their initial phase of communication that precedes the subsequent data and acknowledgment packets. The receipt of the RTS/CTS packets with sufficient power levels by nearby mobiles causes them to inhibit their

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own transmissions, which would produce interference in the receiver of interest. The transmission of separate CTS packets in addition to the RTS packets decreases the possibility of subsequent signal collisions at the receiver due to nearby hidden terminals that do not sense the RTS packets. Thus, the RTS/CTS packets essentially establish guard zones surrounding a transmitter and receiver, and hence, prevent a near-far problem except during the initial reception of an RTS packet. The interference at the receiver is restricted to concurrent transmissions generated by mobiles outside the guard zones. The fundamental disadvantage with this CSMA guard zone is that it inhibits other concurrent transmissions within the zone.

A more fundamental guard zone, which is called the exclusion zone, is based on the spacing that usually occurs in actual mobile networks. For instance, when the radios are mounted on vehicles, there is a need for crash avoidance by maintaining a minimum vehicle separation. A small exclusion zone maintained by visual sightings exists in practical networks, but a more reliable and extensive one can be established by equipping each mobile with a global positioning system (GPS) and periodically broadcasting each mobile's GPS coordinates. Mobiles that receive those messages could compare their locations to that in the message and alter their movements accordingly. The major advantage of the exclusion zone compared with a CSMA guard zone is that the exclusion zone prevents near-far problems at receivers while not inhibiting any potential concurrent transmissions. Another advantage of an exclusion zone is enhanced network connectivity because of the inherent constraint on the clustering of mobiles.

When CSMA is used in a network, the CSMA guard zone will usually encompass the exclusion zone. Although both zones may cover arbitrary regions, they are modeled as circular regions in the subsequent examples for computational convenience, and the region of the CSMA guard zone that lies outside the exclusion zone is an annular ring. The existence of an annular ring enhances the near-far protection at the cost of inhibiting potential concurrent transmissions within the annular ring. The tradeoffs entailed in having the CSMA guard zone are examined subsequently.

III. NETWORK MODEL

The network comprises a fixed number of mobiles in a circular area with radius r_{net} , although any arbitrary two- or three-dimensional regions could be considered. A reference receiver is located inside the circle, a reference transmitter X_0 is located at distance $||X_0||$ from the reference receiver, and there are M potentially interfering mobiles $X_1, ..., X_M$. The variable X_i represents both the i^{th} mobile and its location, and $||X_i||$ is the distance from the i^{th} mobile to the receiver. Each mobile uses a single omnidirectional antenna. The radii of the exclusion zone and the CSMA guard zone are r_{ex} and r_{g} , respectively.

The interfering mobiles are uniformly distributed throughout the network area outside the exclusion zones, according to a *uniform clustering* model. One by one, the location of each X_i is drawn according to a uniform distribution within the radius- r_{net} circle. However, if an X_i falls within the exclusion zone of a previously placed mobile, then it has a new random location assigned to it as many times as necessary until it falls outside all exclusion zones. Unlike Matern thinning [14], which silences mobiles without replacing them, uniform clustering maintains a fixed number of active mobiles.

Since there is no significant advantage to using short directsequence sequences, long spreading sequences are assumed and modeled as random binary sequences with chip duration T_c . The processing gain or spreading factor G directly reduces the interference power. The multiple-access interference is assumed to be asynchronous, and the power from each interfering X_i is further reduced by the chip factor $h(\tau_i)$, which is a function of the chip waveform and the timing offset τ_i of X_i 's spreading sequence relative to that of the desired signal [1]. In a network of quadriphase direct-sequence systems, a multipleaccess interference signal with power \mathcal{I}_i before despreading is reduced after despreading to the power level $\mathcal{I}_i h(\tau_i)/G$, where [1], [15]

$$h(\tau_i) = \frac{1}{T_c^2} \left[R_{\psi}^2(\tau_i) + R_{\psi}^2(T_c - \tau_i) \right]$$
(1)

and $R_{\psi}(\tau_i)$ is the partial autocorrelation for the normalized chip waveform. Thus, the interference power is effectively reduced by the factor $G_i = G/h(\tau_i)$. Assuming a rectangular chip waveform and that τ_i has a uniform distribution over [0, T_c], the expected value of $h(\tau_i)$ is 2/3.

After despreading, the power of X_i 's signal at the reference receiver is

$$\rho_i = P_i g_i 10^{\xi_i/10} f\left(||X_i||\right) \tag{2}$$

where P_i is the received power at a reference distance d_0 (assumed to be sufficiently far that the signals are in the far field) after despreading when fading and shadowing are absent, g_i is the power gain due to fading, ξ_i is a shadowing coefficient, and $f(\cdot)$ is a path-loss function. The path-loss function is expressed as the power law

$$f(d) = \left(\frac{d}{d_0}\right)^{-\alpha}, \quad d \ge d_0 \tag{3}$$

where $\alpha \geq 2$ is the path-loss exponent. It is assumed that $r_{ex} \geq d_0$. The $\{g_i\}$ are independent with unit-mean, but are not necessarily identically distributed; i.e., the channels from the different $\{X_i\}$ to the reference receiver may undergo fading with different distributions. For analytical tractability and close agreement with measured fading statistics, Nakagami fading is assumed, and $g_i = a_i^2$, where a_i is Nakagami with parameter m_i . When the channel between X_i and the reference receiver undergoes Rayleigh fading, $m_i = 1$ and the corresponding g_i is exponentially distributed. In the presence of log-normal shadowing, the $\{\xi_i\}$ are independent zero-mean Gaussian with variance σ_s^2 . For ease of exposition, it is assumed that the shadowing variance is the same for the entire network, but the results may be easily generalized to allow for different shadowing variances over parts of the network. In the absence of shadowing, $\xi_i = 0$.

It is assumed that the $\{g_i\}$ remain fixed for the duration of a time interval, but vary independently from interval to interval (block fading). With probability p_i , the i^{th} mobile transmits in the same time interval as the desired signal. The $\{p_i\}$ can be used to model voice-activity factors, controlled silence, or failed link transmissions and the resulting retransmission attempts. The $\{p_i\}$ need not be the same; for instance, CSMA protocols can be modeled by setting $p_i = 0$ when a mobile lies within the CSMA guard zone of another active mobile, which is equivalent to implementing Matern thinning within the annular ring corresponding to that guard zone.

The instantaneous signal-to-interference-and-noise ratio (SINR) at the receiver is given by:

$$\gamma = \frac{\rho_0}{\mathcal{N} + \sum_{i=1}^M I_i \rho_i} \tag{4}$$

where ρ_0 is the received power of the desired signal, \mathcal{N} is the noise power, and the indicator I_i is a Bernoulli random variable with probability $P[I_i = 1] = p_i$ and $P[I_i = 0] = 1 - p_i$.

Since the despreading does not affect the desired-signal power, the substitution of (2) and (3) into (4) yields

$$\gamma = \frac{g_0 \Omega_0}{\Gamma^{-1} + \sum_{i=1}^M I_i g_i \Omega_i}$$
(5)

where

$$\Omega_{i} = \begin{cases} 10^{\xi_{0}/10} ||X_{0}||^{-\alpha} & i = 0\\ \frac{P_{i}}{G_{i}P_{0}} 10^{\xi_{i}/10} ||X_{i}||^{-\alpha} & i > 0 \end{cases}$$
(6)

is the normalized power of X_i , P_i is the received power at the reference distance d_0 before despreading when fading and shadowing are absent, and $\Gamma = d_0^{\alpha} P_0 / \mathcal{N}$ is the SNR when the reference transmitter is at unit distance from the reference receiver and fading and shadowing are absent.

IV. OUTAGE PROBABILITY

Let β denote the minimum SINR required for reliable reception and $\Omega = \{\Omega_0, ..., \Omega_M\}$ represent the set of normalized powers. An *outage* occurs when the SINR falls below β . Conditioning on Ω , the outage probability is

$$\epsilon = P\left[\gamma \le \beta \big| \mathbf{\Omega} \right]. \tag{7}$$

The outage probability depends on the network geometry and shadowing factors, which have dynamics over much slower timescales than the fading. In contrast, the outage probability of [5] is not conditioned on Ω and therefore is unable to quantify the outage probability of any specific network geometry. By defining a variable

$$\mathsf{Z} = \beta^{-1} g_0 \Omega_0 - \sum_{i=1}^{m} I_i g_i \Omega_i \tag{8}$$

the conditional outage probability may be expressed as

$$\epsilon = P\left[\mathsf{Z} \le \Gamma^{-1} \big| \mathbf{\Omega}\right] = F_{\mathsf{Z}}\left(\Gamma^{-1} \big| \mathbf{\Omega}\right) \tag{9}$$

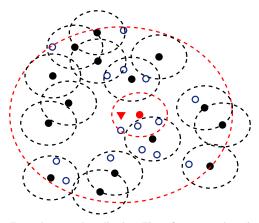


Fig. 1. Example network realization. The reference receiver (indicated by the \checkmark) is placed at the origin, and the reference transmitter is at $X_0 = 1/6$ (indicated by the \bullet to its right). M = 30 mobiles are placed according to the uniform clustering model, each with an exclusion zone (not shown) of radius $r_{\text{ex}} = 1/12$. Active mobiles are indicated by filled circles while deactivated mobiles are indicated by unfilled circles. A guard zone of radius $r_{\text{g}} = 1/4$ surrounds each active mobile, as depicted by dashed circles. When CSMA guard zones are used, the other mobiles within the guard zone of an active mobile are deactivated.

which is the cumulative distribution function (cdf) of Z conditioned on Ω and evaluated at Γ^{-1} .

Define $\overline{F}_{Z}(z) = 1 - F_{Z}(z)$ to be the complementary cdf (ccdf) of Z. Restricting the Nakagami parameter m_0 of the channel between the reference transmitter and receiver to be integer-valued, the ccdf of Z conditioned on Ω is [13]

$$\bar{F}_{\mathsf{Z}}(z|\mathbf{\Omega}) = e^{-\beta_0 z} \sum_{s=0}^{m_0-1} (\beta_0 z)^s \sum_{t=0}^s \frac{z^{-t} H_t(\mathbf{\Psi})}{(s-t)!}$$
(10)

where $\beta_0 = \beta m_0 / \Omega_0$,

$$\Psi_{i} = \left(\beta_{0} \frac{\Omega_{i}}{m_{i}} + 1\right)^{-1}, \quad \text{for } i = \{1, ..., M\}, \quad (11)$$

$$H_t(\boldsymbol{\Psi}) = \sum_{\substack{\ell_i \ge 0\\\sum_{i=0}^M \ell_i = t}} \prod_{i=1}^M \mathsf{G}_{\ell_i}(\boldsymbol{\Psi}_i), \tag{12}$$

the summation in (12) is over all sets of indices that sum to t, and

$$\mathsf{G}_{\ell}(\Psi_{i}) = \begin{cases} 1 - p_{i}(1 - \Psi_{i}^{m_{i}}) & \text{for } \ell = 0\\ \frac{p_{i}\Gamma(\ell + m_{i})}{\ell!\Gamma(m_{i})} \left(\frac{\Omega_{i}}{m_{i}}\right)^{\ell} \Psi_{i}^{m_{i} + \ell} & \text{for } \ell > 0. \end{cases}$$
(13)

V. EXAMPLES

In the examples, all distances are normalized to the network radius so that $r_{net} = 1$, and the reference receiver is located at the center of the network unless otherwise stated. As shown in Fig. 1, the reference transmitter is at coordinate $X_0 = 1/6$ and M = 30 potentially interfering mobiles are placed according to a uniform clustering model with a radius $r_{ex} = 1/12$ exclusion zone surrounding each mobile. Once the mobile locations $\{X_i\}$ are realized, the $\{\Omega_i\}$ are determined by assuming a path-loss coefficient $\alpha = 3.5$ and a common transmit power $(P_i/P_0 = 1 \text{ for all } i)$. Both unshadowed and shadowed environments are considered. Although the model permits nonidentical G_i , it is assumed that G_i is a constant

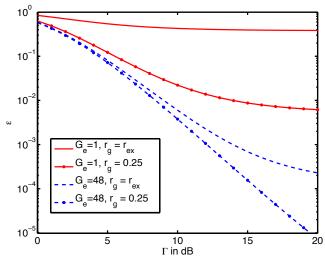


Fig. 2. Outage probability as a function of SNR, conditioned on the network shown in Fig. 1 with mixed fading and no shadowing. Dashed lines are with spreading ($G_e = 48$) while solid lines are without. Curves marked with \bullet indicate performance with a CSMA guard zone of radius $r_g = 1/4$ while curves without markers indicate performance without CSMA guard zones.

equal to G_e (the *effective* spreading gain) for all interference signals. Both spread and unspread systems are considered, with $G_e = 1$ for the unspread system and $G_e = 48$ for the spread system, corresponding to a typical direct-sequence waveform with G = 32 and $h(\tau_i) = 2/3$. The value of $p_i = 0.5$ for all active X_i , and the Nakagami parameters are $m_0 = 3$ for the desired signal and $m_i = 1$ for the interfering mobiles (i.e., Rayleigh fading). Using two different Nakagami factors (i.e., *mixed* fading) is justified by the fact that the reference transmitter is usually within the line-of-sight of the receiver while the interferers are not and, therefore, are subject to more severe fading. The SINR threshold is $\beta = 0$ dB, which corresponds to the unconstrained AWGN capacity limit for a rate-1 channel code, assuming complex-valued inputs.

Example #1. Suppose that CSMA is not used, and therefore there is no guard zone beyond the fundamental exclusion zone; i.e., $r_{\rm g} = r_{\rm ex}$. All 30 potentially interfering mobiles in Fig. 1 remain active and contribute to the overall interference at the reference receiver. The outage probability for this network is shown in Fig. 2 by the two curves without markers, corresponding to the unspread ($G_{\rm e} = 1$) and direct-sequence spread ($G_{\rm e} = 48$) networks. Without direct-sequence spreading, the outage probability is quite high, for instance $\epsilon = 0.4$ at $\Gamma = 20$ dB. Spreading reduces the outage probability by about three orders of magnitude at high SNR, although this comes at the cost of increased required bandwidth.

Example #2. The outage probability can be reduced by using CSMA to impose guard zones beyond the fundamental exclusion zone. Suppose that a guard zone of radius $r_g = 1/4$ is used, as shown in Fig. 1. Potentially interfering mobiles are deactivated according the following procedure, which is equivalent to Matern thinning. First, the reference transmitter X_0 is activated. Next, each potentially interfering mobile is considered in the order it was placed. For each mobile, a check is made to see if it is in the guard zone of a previously placed active mobile. Since mobiles are indexed according to

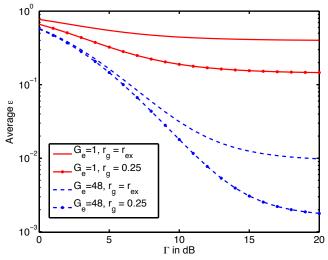


Fig. 3. Outage probability in mixed fading as a function of SNR averaged over 10,000 networks drawn under the same conditions as the one shown in Fig. 1. For each network, shadowing with $\sigma_s = 8$ dB is applied.

the order of placement, X_1 is first considered for possible deactivation; if it lies in the guard zone of X_0 , it is deactivated, and otherwise it is activated. The process repeats for each subsequent X_i , deactivating it if it falls within the guard zone of any active X_j , j < i, or otherwise activating it.

In Fig. 1, active mobiles are indicated by filled circles and deactivated mobiles are indicated by unfilled circles. The guard zone around each active mobile is indicated by a dashed circle of radius r_g . The reference receiver has not been assigned a CSMA guard zone, which reflects the fact that it has none while it is receiving the initial RTS. In the given example, 15 mobiles have been deactivated, while the remaining 15 mobiles remain active. The outage probability of the network with deactivated mobiles is shown in Fig. 2 for $G_e = \{1, 48\}$ by the two curves with markers. The performance of the unspread network improves dramatically with a guard zone, being reduced by two orders of magnitude at high SNR. The DS-CDMA network, which already had superior performance without CSMA, has improved performance, but the improvement only becomes significant at a high SNR.

VI. SPATIAL AVERAGING

Because it is conditioned on Ω , the outage probability will vary from one network realization to the next. The conditioning on Ω can be removed by averaging $\bar{F}_{Z}(z|\Omega)$ over the network geometry. This can be done analytically only under certain limitations [13]. However, the outage probability can be estimated through Monte Carlo simulation by generating many different Ω , computing the outage probability of each, and taking the numerical average. Note that generating each Ω involves not only placing the mobiles according to the uniform clustering modeling, but also realizing the shadowing and deactivating mobiles that lie within the CSMA guard zone of active mobiles.

As an example, Fig. 3 shows the average outage probability computed over a set of 10,000 networks, each generated the same way as the Examples given in Section V. For $r_g = r_{ex}$,

 TABLE I

 AVERAGE OUTAGE PROBABILITY WHEN THE RECEIVER IS AT THE CENTER

 $(\bar{\epsilon}_c)$ AND AT THE PERIMETER $(\bar{\epsilon}_n)$ OF THE NETWORK.

e)					
Ge	α	r_{ex}	r_{g}	$\bar{\epsilon}_c$	$\bar{\epsilon}_p$
1	3	0	1/12	0.5298	0.3056
			1/4	0.2324	0.1683
		1/12	1/12	0.5234	0.2592
			1/4	0.2256	0.1528
	4	0	1/12	0.4129	0.2388
			1/4	0.1453	0.1228
		1/12	1/12	0.3869	0.1774
			1/4	0.1313	0.1026
48	3	0	1/12	0.0644	0.0391
			1/4	0.0181	0.0172
		1/12	1/12	0.0308	0.0199
			1/4	0.0173	0.0165
	4	0	1/12	0.0842	0.0494
			1/4	0.0177	0.0174
		1/12	1/12	0.0335	0.0209
			1/4	0.0165	0.0163

each network was generated by placing M = 30 mobiles with exclusion zone $r_{\text{ex}} = 1/12$ according to a uniform clustering model. For $r_{\text{g}} = 1/4$, the same set of networks was used that was already generated with $r_{\text{ex}} = 1/12$, but in each network, potentially interfering mobiles were deactivated if they were in the guard zone of an active mobile. Log-normal shadowing with $\sigma_s = 8$ dB was applied, and all other system parameters are the same used in Section V.

In a finite network, the average outage probability depends on the location of the reference receiver. Rather than leaving the reference receiver at the origin, Table 1 explores the change in performance when the reference receiver moves from the center of the radius- r_{net} circular network to its perimeter. The SNR is $\Gamma = 10$ dB, all channels undergo mixed fading $(m_0 = 3 \text{ and } m_i = 1, i \geq 1)$ with lognormal shadowing $(\sigma_s = 8 \text{ dB}), M = 30, \beta = 0 \text{ dB}, \text{ and } p_i = 0.5 \text{ for the}$ active interferers. For each set of values of the parameters G_{e} , α , r_{ex} , and r_{g} , the average outage probability at the network center $\bar{\epsilon}_c$ and at the network perimeter $\bar{\epsilon}_p$ were computed by averaging over 10,000 network realizations. The interferers were placed according to the uniform clustering model, and the reference transmitter was placed at distance $||X_0|| = 1/6$ from the reference receiver. Two values of each parameter were considered: $G_{e} = \{1, 48\}, \alpha = \{3, 4\}, r_{ex} = \{0, 1/12\},\$ $r_{g} = \{1/12, 1/4\}$. The table indicates that $\bar{\epsilon}_{p}$ is considerably less than $\bar{\epsilon}_c$ in the finite network. This result cannot be predicted by the traditional infinite-network model, which cannot differentiate between $\bar{\epsilon}_c$ and $\bar{\epsilon}_p$. The reduction in outage probability is more significant for the unspread network and is less pronounced with increasing G_{e} . Given a small exclusion zone with $r_{ex} = 1/12$, both direct-sequence spreading and CSMA make the average performance less dependent on the location of the reference receiver inside the network.

VII. TRANSMISSION CAPACITY

While the outage probability is improved with CSMA due to the deactivation of potential interferers, the overall network becomes less efficient due to the suppression of transmissions. The network efficiency can be quantified by the *transmission capacity* (TC) [5]:

$$\tau = (1 - \epsilon)\lambda b \tag{14}$$

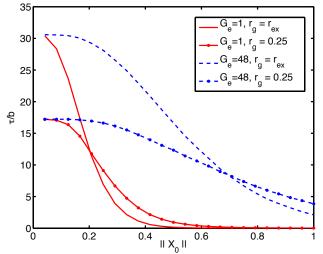


Fig. 4. Transmission capacity for different transmit distances $||X_0||$. The channel model is the same as in Fig. 3 at $\Gamma = 10$ dB.

where λ is the network density, which is the number of active mobiles per unit area, and b is the link throughput in the absence of an outage, in units of bps. The TC represents the network throughput per unit area. Increasing the size of the guard zone generally reduces TC due to fewer simultaneous transmissions.

For a given value of M, the density without a CSMA guard zone remains fixed since all interferers remain active. However, with a CSMA guard zone, the number of active interferers m is random with a value that depends on the value of r_g , the locations of the interferers, and their order of placement, which affects how they are deactivated. As with outage probability, Monte Carlo simulation can be used to estimate TC.

A. Effect of Transmitter Distance

The previous examples assume that the distance between the reference transmitter and receiver is fixed. However, performance will depend on this distance. Fig. 4 shows τ/b , the normalized TC as a function of the distance $||X_0||$ between the reference transmitter and receiver. Except for the value of $||X_0||$, the plot was created using the same conditions and parameters used to produce Fig. 3 at SNR $\Gamma = 10$ dB. It is observed that increasing the transmission distance reduces the TC due to the increase in the number of interferers that are closer to the receiver than the reference transmitter. However, the degradation in performance is more gradual with the spread system than the unspread one. The degradation is made more gradual by the use of CSMA, and at extreme distances, the spread system with CSMA outperforms the spread system that does not use CSMA.

B. Effect of r_{ex} and r_{g}

The exclusion-zone radius r_{ex} and guard-zone radius r_{g} influence the TC of the network. To study this relationship, the TC was determined over a range of r_{ex} and r_{g} . With the exception of the values of r_{ex} and r_{g} , the same conditions and parameters used to produce Fig. 3 are again used, with

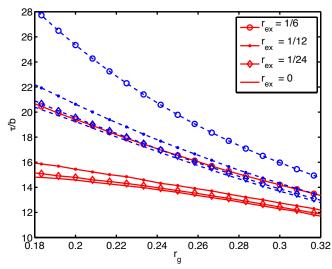


Fig. 5. Transmission capacity as a function of $r_{\rm g}$ for several values of $r_{\rm ex}$. Dashed lines are with spreading ($G_{\rm e} = 48$) while solid lines are without ($G_{\rm e} = 1$). The channel model is the same as in Fig. 3 at $\Gamma = 10$ dB.

 $\Gamma = 10$ dB. In Fig. 5, the guard-zone radius $r_{\rm g}$ was varied over $1/6 \leq r_{\rm g} \leq 1/3$. For each $r_{\rm g}$, the transmission capacity was found for no exclusion zone ($r_{\rm ex} = 0$) and exclusion zones with $r_{\rm ex} = \{1/24, 1/12, 1/6\}$. While transmission capacity was better with larger $r_{\rm ex}$, the transmission capacity of larger values of $r_{\rm ex}$ diminishes quickly with increasing $r_{\rm g}$. Although the reference transmitter was placed at distance $||X_0|| = 1/6$ from the reference receiver in Fig. 5, the results remain qualitatively the same for a wide range of values of $||X_0||$.

C. Effect of the Number of Interferers

In the previous figures, a fixed number of interferers (M = 30) was placed prior to CSMA deactivation. In Fig. 6, the number of interferers is varied from 2 to 60, and the transmission capacity computed for each value of M for a representative set of G_{e} and r_{g} . Except for the value of M, the plot was created using the same conditions and parameters used to produce Fig. 3 at $\Gamma = 10$ dB. As observed previously for just M = 30, the transmission capacity of the DS-CDMA network is higher than that of the unspread network, and using a CSMA guard zone reduces transmission capacity. The transmission capacity of the DS-CDMA network increases roughly linearly with M in the absence of a guard zone while the increase is sublinear for the unspread network or when a guard zone is used. At M = 60, the transmission capacity of the unspread network is approximately the same with and without a guard zone.

VIII. CONCLUSIONS

The analysis developed in this paper allows the tradeoffs between exclusion zones and CSMA guard zones to be explored for DS-CDMA and unspread networks. The advantage of an exclusion zone over a CSMA guard zone is that since the network is not thinned, the number of active mobiles remains constant and higher transmission capacities can be achieved. If the processing gain is sufficiently large, a CSMA guard zone is largely ineffective in that it only slightly improves the

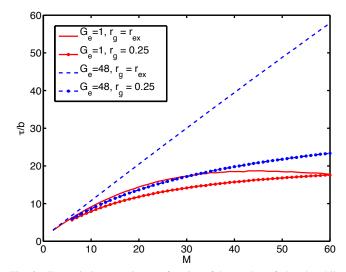


Fig. 6. Transmission capacity as a function of the number of placed mobiles M. An exclusion zone of $r_{ex} = 1/12$ is used. Performance is shown both with spreading ($G_e = 48$) and without spreading ($G_e = 1$), and both with a CSMA guard zone ($r_g = 1/4$) and without an additional CSMA guard zone ($r_g = r_{ex}$). The channel model is the same as in Fig. 3 at $\Gamma = 10$ dB.

outage probability at the cost of a considerable decrease in the transmission capacity.

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