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On the performance of packet-switched cellular networks for wireless data communications *

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Abstract. Cellular frequency reuse is known to be an efficient method to allow many wireless telephone subscribers to share the same frequency band. However, for wireless data and multi-media communications optimum cell layouts differ essentially from typical solutions for telephone systems. We argue that wireless radio systems for bursty message traffic preferably use the entire bandwidth in each cell. Packet queuing delays are derived for a network with multipath fading channels, shadowing, path loss and discontinuously transmitting base stations. Interference between cells can be reduced by appropriately scheduling transmissions or by 'spatial collision resolution'.

1. Introduction

Over the past several years, wireless communications has seen an explosive growth in the number of services and types of technologies that have become readily available. Systems for cellular telephony, radio paging and cordless telephony have become commonplace and the demand for enhanced capacity is growing. As the available radio spectrum is limited in bandwidth, network operators attempt to maximize the number of circuits that can be supported simultaneously by reusing radio channels as densely as possibly. It is expected that in the near future, wireless data and multi-media services will also become popular and that there will be an increasing need for spectrum-efficient radio networks to support such services.

Driven by spectrum scarcity, radio resource management for bursty traffic is rapidly becoming a major research topic. The problem of managing information and data flows in radio and wireless optical networks appears to be significantly different from existing techniques for wired or 'guided' communication. Decades of research on sharing communication resources among multiple users and services on wired networks has led to a wide variety of techniques for multiplexing, switching and multiple access to communication resources such as coaxial cable local area networks (LANs), e.g. [1–4]. The common goal of these schemes is the dynamic assignment of *bandwidth* during certain periods of *time*. Many of these multiple-access techniques are also used in radio data networks. However, it soon appeared that the performance of many random-access schemes substantially differs for guided (wired) and unguided (radio) channels, being highly dependent on the physical characteristics of the channel. A review is in [5].

Meanwhile, the aspects of *spatially* reusing scarce radio spectrum resources have mostly been addressed separately from allowing multiple users to share the same *bandwidth-time* resources. This is for instance illustrated by the fact that most existing mobile data networks use a cellular frequency reuse pattern, and within each cell a random-access scheme is used independently of the traffic characteristics in other cells. Results on how to dynamically assign the *space-time-bandwidth* resources in radio channels is however not yet well developed.

A crucial aspect in the evaluation and planning of radio networks is the computation of the effect of co-channel interference in radio links. The amount of interference that can be tolerated determines the required separation distance between co-channel cells and therefore also the efficiency of the network. The link performance of cellular telephone networks was first studied around 1980 by Gosling [6], French [7] and Cox [8]. Initial analyses were limited to outage probabilities in continuous wave (CW) voice communication, taking into account path loss and flat (frequency non-selective) Rayleigh fading. In the 1980's the technique for computing outage probabilities was refined step by step, see e.g. [5–17], considering among other things shadowing [7], multiple interfering signals cumulating coherently [9] or, more realistically, incoherently [10], the modulation technique and error correction method [18], and more recently the presence of a dominant line-of-sight propagation path, as it occurs in micro-cellular networks [12,13,18]. The stochastic occupation of nearby co-channel cells according to the traffic laws by Erlang was included in some studies.

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To future data or multi-media services, queuing and retransmission delays are far more important performance measures than outage probability. Messages lost in a fade or due to interference from other cells can simply be retransmitted, so outage probabilities *per sé* may not be an appropriate criterion. Advanced methods to find link performance, as developed for cellular telephony, can still be used, but need to be extended to address the specific Quality of Service requirements for data or multi-media traffic. This paper finds the packet delay performance in the downlink, i.e., from base station to terminals. We show that it is optimum to use the entire bandwidth in each cell. The corresponding high interference power levels from nearby transmitters in adjacent cells require a joint optimization and dynamic management of the spatial frequency reuse and the occupation of spectrum within cells.

The paper analyses generic systems, without making specific assumptions about the frequency bands or propagation environments considered. The assumption of a constant channel transfer function during the transmission of a packet of data is appears realistic for the parameters chosen in most modern VHF or UHF wireless networks. A second assumption, considering a flat transfer function over the transmit bandwidth, is reasonable as long a the symbol time is longer than, say, ten times the rms delay spread. In systems with large cells and high bit rates as in GSM, this assumption may not be satisfied strictly, but the model used here may be sufficiently realistic for the purpose of the paper. If, in future mobile multi-media systems, large cells are used with symbol rates on the order of Megabits per second, frequency selectivity may require special measures to ensure reliable and efficient communication. The design trade-off involving both modulation and multiple access is still subject of current research for mobile multi-media applications. This paper attempts to investigate some of the access issues and shows how the existing models of cellular planning for telephony may no longer be efficient.

Initially this paper reviews and further develops the technique for computing and modelling link performance in cellular networks, which is used later on as a tool to compute the network performance. Section 2 starts with a statistical description of the multipath radio channel. Section 3 shows that Laplace Transforms facilitate some of the analyses. Accurate numerical evaluations can nonetheless be lengthy, but section 4 proposes series expansions that can be used in computationally intensive tasks, such as the planning of practical nets from topographical data bases. Section 5 formulates a model for packet-switched networks. The results in section 6 combine link performance, as computed in sections 3 and 4, with the models of section 5. Section 7 proposes two new schemes that dynamically combine frequency reuse and interference protection with multiple access. Section 8 concludes the paper.

2. Radio channel characterization

A typical radio channel exhibits multipath reception, which causes fading. We address narrowband systems, that is, we assume that the channel transfer function is virtually constant over the signal bandwidth. This corresponds to the assumption that Intersymbol Interference does not play a major role in the performance of the radio links. A method to include the effect of channel dispersion on outage probabilities was proposed in [23].

The signal amplitude ρ_i and phase received from user i varies randomly with antenna location and carrier frequency. Several statistical models have been proposed to model the stochastic behavior of the signal amplitude and power. Most commonly accepted is Rician fading, which assumes a dominant line-of-sight component and a large set of reflected waves. The instantaneous power p_i received from the ith user, with $p_i = 1/2\rho_i^2$, has the probability density function (pdf)

$$f_{p_i}(p_i|\bar{p}_i) = \frac{(1+K)e^{-K}}{\bar{p}_i}\exp\left\{-\frac{1+K}{\bar{p}_i}p_i\right\} \times I_0\left(\sqrt{4K(1+K)\frac{p_i}{\bar{p}_i}}\right), \qquad (1)$$

where the Rician K-factor is defined as the ratio of the power in the dominant component and the scattered (multipath) power, $\bar{p}_i$ is the total local-mean power in the dominant and scattered waves, and $I_0(.)$ denotes the modified Bessel function of the first kind and order zero. In the special case that the dominant component is zero ($K = 0$), Rayleigh fading occurs, with an exponentially distributed power with mean $\bar{p}_i$.

Another experimentally verified model for multipath reception is Nakagami fading [19,20]. In this case the instantaneous power has the gamma pdf

$$f_{p_i}(p_i|\bar{p}_i) = \frac{1}{\Gamma(m)}\left(\frac{m}{\bar{p}_i}\right)^m p_i^{m-1}\exp\left\{-\frac{mp_i}{\bar{p}_i}\right\}, \qquad (2)$$

where $\Gamma(m)$ is the gamma function, with $\Gamma(m+1) = m!$ for integer m. The parameter m is called the 'shape factor' of the distribution. In the special case that $m = 1$, Rayleigh fading is recovered, while for larger m the fluctuations of the signal strength are less, compared to Rayleigh fading. For ease of analysis, the Nakagami model is sometimes used to approximate the pdf of the power of a Rician fading signal [20]. Matching the first and second moments of the Rician and Nakagami pdfs gives

$$m = \frac{K^2 + 2K + 1}{2K + 1}, \qquad (3)$$

which tends to $m = K/2$ for large K. However section 4 shows that in contrast to common belief, this approximation is less suitable to model deep signal fades of the wanted signal. The Nakagami model is nonetheless relevant as it models the received signal after m-branch diversity with *maximum ratio combining*. In a Rayleigh-fading channel, this signal becomes m-Nakagami [5,17].

A second propagation effect is shadowing, resulting in a slow variation of the local-mean power as the antenna moves over distances larger than a few meters. Measurements indicate that the received local-mean power converted into logarithmic values, such as dB or neper, has a normal distribution. The local-mean power $\bar{p}_i$ in absolute units (e.g. watts) thus has the log- normal pdf

$$f_{\bar{p}_i}(\bar{p}_i) = \frac{1}{\sqrt{2\pi}\sigma_s \bar{p}_i} \exp\left\{-\frac{1}{2\sigma_s^2}\ln^2\left(\frac{p_i}{\bar{\bar{p}}_i}\right)\right\}, \qquad (4)$$

where σ_s is the logarithmic standard deviation of the shadowing and $\bar{p}_i$ is the logarithmic area-mean power of the i-th user. A typical mobile channel suffers from both shadowing and either Rician or Nakagami fading.

The area-mean power $\bar{\bar{p}}_i$ can be estimated from the distance r_i between the ith terminal and the base station. The most simple path loss model used for analysis of generic radio systems is

$$\bar{\bar{p}}_i = r_i^{-\beta}, \qquad (5)$$

where β is on the order of 2 to 5. Harley [21] suggested

$$\bar{\bar{p}}_i = r_i^{-2}\left(1 + \frac{r_i}{r_g}\right)^{-2} \qquad (6)$$

to improve the accuracy for short-range micro-cellular propagation, where r_g is a turnover distance, often in the range 100 m to 500 m.

3. Method for link evaluation

In certain situations [5–17], it is a sufficiently good approximation to assume that a message is received successfully if and only if the signal-to-interference-plus-noise ratio exceeds a certain threshold z. Typically z is on the order of 2 to 10 (3 to 10 dB). Assuming constant received power during a packet transmission time, the probability that the wanted signal power p_0 sufficiently exceeds the joint interference plus noise power p_t is

$$\Pr(p_0 > zp_t) = \int_{0-}^{\infty} f_{p_t}(x) \int_{zx}^{\infty} f_{p_0}(y)\, dy\, dx, \qquad (7)$$

where we insert the appropriate pdfs of received signal power as presented in section 2. The joint interference signal p_t is the incoherent sum of multiple individual signals. For independent fading, the pdf of the joint interference power is the convolution of the pdf of individual interference powers.

In the special case of a Rayleigh-fading wanted signal, its pdf of signal power is an exponential one. Hence, for probabilities conditional on the local-mean $\bar{p}_0$, the integral over y can be solved analytically. An elegant mathematical framework has been developed by interpreting the result as a Laplace transform of the pdf of joint interference power. For a wanted signal subject to Rayleigh fading, this probability can be expressed in the form [5,14,15,22]

$$\Pr(p_0 > zp_t \mid \bar{p}_0) = \mathcal{L}\{f_{p_t}; s\}\big|_{s=\frac{z}{\bar{p}_0}}, \qquad (8)$$

where $\mathcal{L}\{f, s\}$ denotes the one-sided Laplace transform of the function f at the point s. We will now show that this approach can be applied to a Rician-fading wanted signal, using the series expansion

$$I_0(z) = \sum_{n=0}^{\infty} \frac{1}{(n!)^2}\left(\tfrac{1}{4}z^2\right)^n \qquad (9)$$

for the modified Bessel function I_0. This gives

$$\begin{aligned}\Pr(p_0 > zp_t|\bar{p}_0) &= \sum_{n=0}^{\infty}\sum_{k=0}^{n}\int_{0-}^{\infty}\exp\left\{-K - zx\frac{K+1}{\bar{p}}\right\} \\ &\quad \times \frac{K^n}{n!}\left(zx\frac{K+1}{\bar{p}}\right)^k f_{p_t}(x)\, dx \\ &= \sum_{n=0}^{\infty}\frac{K^n}{n!}e^{-K}\sum_{k=0}^{n}\frac{s^k}{k!}\int_{0-}^{\infty} x^k s^{-sx} f_{p_t}(x)\, dx.\end{aligned} \qquad (10)$$

Using the properties of the laplace transform, this can be written as the series

$$\begin{aligned}\Pr(p_0 > zp_t|\bar{p}_0) &= e^{-K}\sum_{n=0}^{\infty}\sum_{k=0}^{n}(-1)^k \\ &\quad \times \frac{K^n}{n!}\frac{s^k}{k!} d^k ds^k \mathcal{L}\{f_{p_t}(x), s\},\end{aligned} \qquad (11)$$

For a Nakagami-fading wanted signal, a similar method has been proposed by [16, 17]. Inserting the gamma pdf, one obtains

$$\begin{aligned}\Pr(p_0 > zp_t|\bar{p}_0) &= \sum_{n=0}^{m-1}\frac{s^i}{i!}\int_{0-}^{\infty} x^i e^{-sx} f_{p_t}(x)\, dx \\ &= \sum_{n=0}^{m-1}\frac{s^i}{i!}\frac{d^i}{ds^i}\mathcal{L}\{f_{p_t}(x); s\}.\end{aligned} \qquad (12)$$

We conclude that in both cases, this probability can be expressed in the generalized form

$$\Pr(p_0 > zp_t|\bar{p}_0) = \sum_{i=0}^{\infty} a_i s_0^i \frac{(-1)^i}{i!}\frac{d^i}{ds^i}\mathcal{L}\{f_p t; s\}\big|_{s=s_0}, \qquad (13)$$

where Table 1 gives the appropriate coefficients a_i and argument s_0.

Table 1
Coefficients a_i and argument s_0 for link success probability.

Channel fading	a_i	s_0
Rayleigh	$a_0 = 1$; $a_i = 0$ for $i = 1, 2, \ldots$	$\frac{z}{\bar{p}_0}$
Rician	$a_0 = 1$; $a_i = 1 - e^{-K}\sum_{n=0}^{i-1}\frac{K^n}{n!}$	$\frac{z(K+1)}{\bar{p}_0}$
m-Nakagami	$a_i = 1$ for $i = 0, 1, \ldots, m-1$; $a_i = 0$ for $i = m, m+1, \ldots$	$\frac{mz}{\bar{p}_0}$

Typically, terminals with bursty traffic transmit discontinuously, say with probability $\Pr(i_{ON}) = P_{on}$, to minimize interference to other users. Taking this activity factor into account, the Laplace image of the pdf of interference power becomes after some straightforward mathematical manipulations [5],

$$\mathcal{L}\{f_{p_0}; s\} = 1 - \Pr(i_{ON}) \times \left[1 - \frac{1}{\sqrt{\pi}} \int_{-\infty}^{\infty} \frac{\exp(-x^2)\, dx}{1 + s\bar{\bar{p}}_i \exp(\sqrt{2} x \sigma_s)}\right]. \quad (14)$$

The Laplace transform of the pdf of joint interference power, as needed in (13), is the product of the Laplace transforms of individual interfering pdfs, each of the form of (14). The effect of (man-made) noise can also be modelled as a Laplace image [23].

If the wanted signal is subject to both multipath fading and shadowing, area-mean probabilities are obtained by averaging the above conditional probabilities over the lognormal local-mean power of the wanted signal (4). The probability of successful transmission, given the area-mean power, or equivalently, given the propagation distance r_0, is

$$Q(r_0) = \Pr(p_0 > zp_t | r_0) = \int_0^{\infty} \Pr(p_0 > zp_t | \bar{p}_0) f_{\bar{p}_0}(\bar{p}_0 | r_0)\, d\bar{p}_0\,, \quad (15)$$

where the probability in the integrand is of the form of (3). The outage probability equals $1 - Q(r)$.

4. Practical expressions for outage probability in telephone nets

The above method to find the probability of a signal outage can be significantly faster than brute-force averaging over all pdfs of multipath fading and shadowing, of the wanted and all interfering signals. In hexagonal networks, this may require a 14 fold integration. To the author's best knowledge, no paper endeavors such numerical evaluation. Authors either use approximate methods, particularly the one by Schwartz and Yeh [24], or, as is increasingly often performed in recently published work, use Laplace techniques for Nakagami or Rayleigh channels, e.g. [14–17]. Nonetheless the Laplace method can be time-consuming and a faster method can be developed for the planning practical networks.

The probability of a signal outage at large signal-to-interference ratios ($\bar{p}_0 >> \mathrm{E}p_t$) is found from the behavior of the Laplace expression at small values for s. Expanding the Laplace transform into a McLaurin series gives

$$\mathcal{L}\{f_{p_t}, s\} = 1 - s\mathrm{E}p_t + \frac{s^2}{2!}\mathrm{E}p_t^2 - \cdots. \quad (16)$$

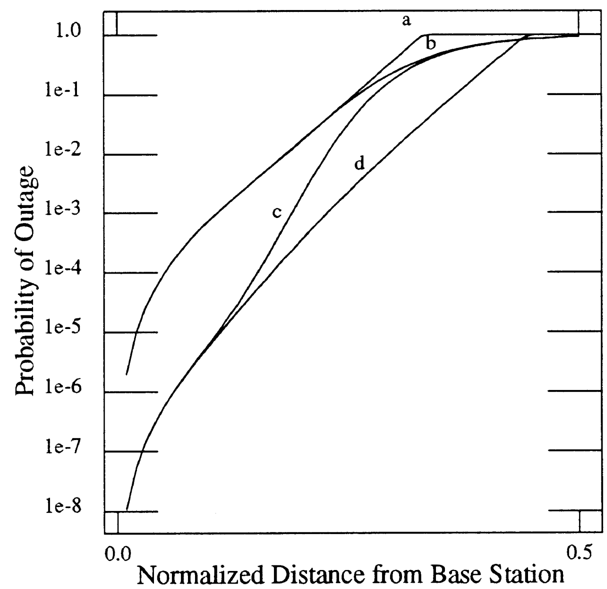

Fig. 1. Outage probability versus the distance between the base station and the mobile terminal. $r_g = 0.1$, $C = 1$, $z = 4$ (6 dB) (a) $K = 4$ MacLaurin (b) $K = 4$, exact (c) $K = 10$ MacLaurin, (d) $K = 10$, exact.

Inserting this in expression gives the outage probability

$$\Pr(\text{out}) = 1 - \Pr(p_0 > zp_t | \bar{p}_0) = \frac{z}{m!}\mathrm{E}p_t^m \bar{p}_0^m + 0\left(\frac{\mathrm{E}p_t^{m+1}}{\bar{p}_0^{m+1}}\right) \quad (17)$$

for Nakagami fading with integer m. For Rician fading, we find

$$\Pr(\text{out}) = se^{-K}\mathrm{E}p_t + (1-K)\frac{s^2}{2}e^{-K}\mathrm{E}p_t^2 + 0\left(\frac{\mathrm{E}p_t^3}{\bar{p}_0^3}\right) \quad (18)$$

with s given in Table 1. The results are strikingly different for m larger than one. As the approximation in (3) was based on the first and second moments, it is likely to be most accurate for values close to the mean. Outage probabilities however highly depend on the tail of the pdf for small power of the wanted signal. We conclude that approximating the pdf of a Rician-fading *wanted* signal by a Nakagami pdf is highly inaccurate: Results differ even in first-order. This is due to fact that Rician-fading signals exhibit relatively deep fades with a non-zero probability density for small received power. This is in sharp contrast to vanishing probability density at zero power for a Nakagami-fading signal if $m = 2, 3, \ldots$. Fig. 1 compares exact results for a Rician fading wanted signal, with a two-term McLaurin approximation. For ranges of practical interest, i.e., outage probabilities on the order of 10^{-2} to 10^{-3}, the expansion appears accurate unless the line of sight is much stronger than the scattered power, say it is suitable for $K < 4$.

5. Queuing delay for packet-switched nets

The previous sections discussed outage probabilities in cellular links. We now apply these to the performance of packet-switched networks, such as the one in Fig. 2. Each base station has a packet queue for messages to be sent to mobile terminals. Packets have a uniform length of L bits, arrive according to a Poisson process, and are destined for terminals uniformly distributed over the cell area. If a packet is received successfully the terminal sends an acknowledgement. If no acknowledgement is received, the base station repeats the packet until successful reception occurs. In a well functioning, stable system, the successful *throughput* of messages over the radio link must be equal to the flow rate of messages into the base station buffer (*arrival rate*). While in our model the arrival rate equals throughput, the *attempted traffic* on the radio channel may be much larger, due to retransmissions. This section computes the attempted traffic for a given arrival rate. We initially assume that all signals experience Rayleigh fading and shadow attenuation, independent of each other and independent from one transmission attempt to the next. The path loss is assumed constant during all retransmission attempts. Interfering signals arrive from base stations in other cells. The area-mean power of these signals is taken from (5). In a hexagonal cell layout, the distance between the centers of two co-channel cells is $R\sqrt{(3C)}$, where R is the cell radius and C is the cluster size, i.e., the number of different frequencies in use. We approximate hexagonal cells of unity size by circular cells of radius $R = 3^{3/4}\sqrt{(2\pi)} \approx 0.91$ [5].

This section derives packet queuing delays in the base station. Since the probability of successful reception $Q(r)$ decreases with increasing propagation distance r, the number of (re-) transmission attempts, M, statistically increases with increasing r. The service time S per packet is $S = MT_L$ with T_L the duration of a time slot. The bit rate per Hz is denoted as η_r, and the total system bandwidth is B_N. So, $T_L = L/(\eta_r B_T) = LC/(\eta_r B_N)$ where B_T denotes the bandwidth per cell with $B_T = B_N/C$. The maximum effective throughput in user bits per second per base station per Hz is

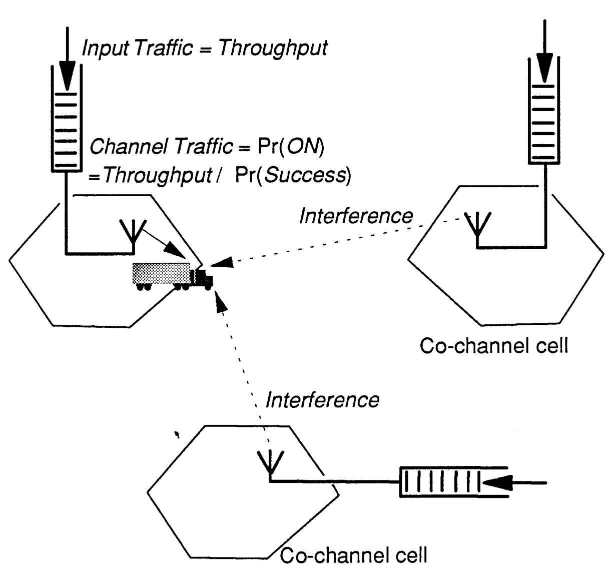

Fig. 2. Cellular packet-switched network configuration.

$$\lambda = \frac{\eta_r}{C\,\mathrm{E}[M]}\,. \tag{19}$$

The probability of successful reception of a data packet depends on the location of the terminal and on the activity of interfering base stations. For discontinuous transmission, the probability that an interfering base station is active is equal to the probability that its queue is non-empty. In a spatially uniform system, this probability is identical for all base stations. The number of packets waiting in the base station is modelled as an $M/G/1/\infty$ queue. Service times conditional on r are geometric with mean $T_L/Q(r)$ but the unconditional distribution of service times is not a closed-form expression. We approximate the service time of successive packets as i.i.d. random variables. This assumption, however, ignores the fact that the service times of successive packets may be correlated. For instance if one packet experiences heavy interference from transmissions by anther base station, it is more likely that the next packet will also see an active co-channel base station. Furthermore, two adjacent base stations may continue to attempt to transmit to terminals at unfavorable locations. We neglect this effect in the following analysis as a more detailed investigation would require us to compute delays in an infinite field of mutually interacting queues. This problem is notoriously hard to solve. But in section 7 we will propose an access scheme that can resolve these potential instability problems. Moreover, appendix A evaluates the effect of correlated retransmissions.

The mean value of the service time, expressed in number of slots and averaged over all locations in the cell is

$$\mathrm{E}[M] = \frac{2}{R^2}\int_0^R \frac{r\,dr}{Q(r)}\,. \tag{20}$$

The second moment is

$$\mathrm{E}[M^2] = \frac{1}{\pi R^2}\int_0^R \frac{1-Q(r)}{Q^2(r)}2\pi r\,dr\,. \tag{21}$$

The expected queuing delay is found from the Pollacek-Khintchine expression for $M/G/1/\infty$ queues, namely

$$D = \frac{LC}{\eta_r B_N}\left[\mathrm{E}[M] + \frac{\mathrm{E}[M^2]}{\mathrm{E}[M]}\,\frac{P_{on}}{2(1-P_{on})}\right]. \tag{22}$$

6. Results

Fig. 3 gives the expected number of required transmission attempts versus terminal location. That is, it depicts $1/Q(r)$, rather than $1 - Q(r)$ as in most other

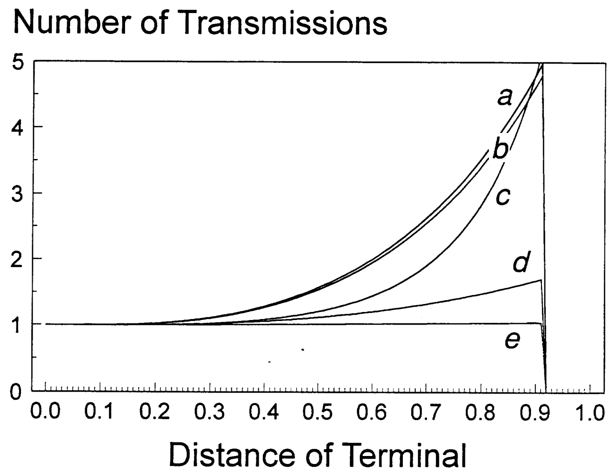

Fig. 3. Expected number of required transmission attempts versus distance for 6 dB fast shadowing. Cluster size $C = 1$, (a) with and (b) without AWG noise floor ($\bar{p}_n = 0.01$), and (c) without shadowing. Comparision with (d) $C = 3$ and (e) $C \to \infty$.

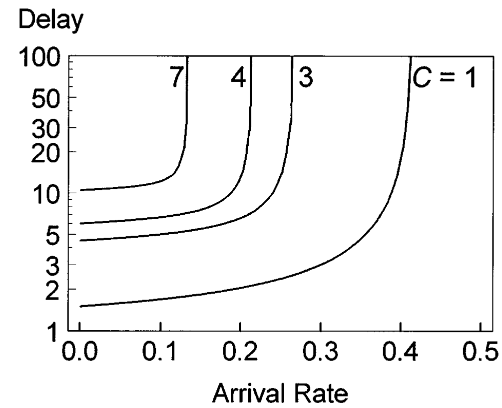

Fig. 4. $M/G/1/\infty$ delay, normalised to slot duration in network with $C = 1$, versus normalised spectrum efficiency for various cluster sizes. 6 dB of fast shadowing. Receiver threshold $z = 4$ (6 dB). UHF groundwave propagation ($\beta = 4$).

papers, which study outage probabilities relevant to circuit switching. We address a typical modulation technique with receiver threshold $z = 4$ (6 dB), UHF groundwave propagation with $\beta = 4$ and shadowing with a spread of 6 dB ($\sigma_s = 1.36$). Service times in seconds can be obtained by multiplying results in Fig. 3 by $L/(\eta_r B_N)$.

Fig. 4 gives the queuing delay in the base station as a function of the message arrival rate λ/η_r per cell. It shows that $C = 1$ is optimum. The relatively high bandwidth in each cell allows the base stations to empty their queues fairly rapidly, which reduced interference to other cells.

In contrast to the assumptions in the above analysis, shadow attenuation can be highly correlated for small antenna displacements. In such case shadow attenuation is likely to be almost identical during all retransmission attempts. Moreover, at high traffic loads the busy periods of each co-channel base station are likely to be much longer than the service time experienced by an individual packet. For the limiting case of identical shadow attenuation and identical interference situations during all retransmission attempts, $E[M]$ is derived in Appendix A. Table 3 shows that under heavy traffic, $C = 1$ does not give favorable performance.

For 3 dB of slow shadowing, $C = 3$ is found as an optimum cluster size. For more severe shadowing, the network becomes very spectrum-inefficient if one requires that the base stations must continue to perform transmission attempts to terminals in deeply shadowed areas. For 6 dB of slow shadowing, a cluster size as large as $C = 19$ would be required. In practice, this would be unacceptable and dynamic interference protection may be needed. Also we see that for relatively small cluster sizes, it is more efficient to ensure that each base station is not fully loaded with traffic, i.e., $P_{ON} < 1$ for optimum throughput. This is contrast to the results for independent shadowing, where the throughput monotonically increases with P_{ON}.

7. Spatial radio resource management

According to the results in the previous sections, in high-capacity spectrum-efficient packet-switched networks, adjacent base stations preferably *compete* for non-disjoint (i.e., interfering) spectrum resources. The

Table 2
Maximum throughput S per base station for various cluster sizes C.

C	λ/η_r	Service time	
		$C\mathrm{E}[M]$	$C\mathrm{E}[M \mid r = 0.91]$
1	0.40	2.49	5.00
3	0.26	3.87	5.10
4	0.21	4.76	5.88
7	0.13	7.70	8.54
9	0.10	9.63	10.4
∞	0	∞	∞

Table 3
Maximum achievable throughput λ/ρ_r with slow shadowing for various cluster sizes C. Receiver threshold $z = 4$ (6 dB). UHF groundwave propagation $\beta = 4$. Shadowing is 3 and 6 dB.

	Shadowing: 3 dB		6 dB	
C	λ/η_r	P_{ON}	λ/η_r	P_{ON}
1	0.23	0.5	–	–
3	**0.29**	1	0.004	0.07
4	0.23	1	0.012	0.10
7	0.14	1	0.025	0.27
9	0.11	1	0.034	0.42
12	0.08	1	0.045	0.7
13	0.07	1	0.049	0.9
19	0.05	1	**0.050**	1
21	0.04	1	0.046	1

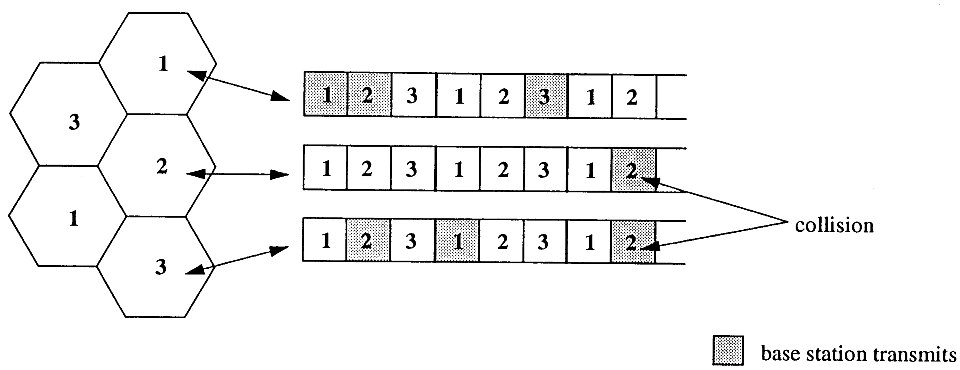

Fig. 5. Cellular packet data network with $C = 1$ under normal contiguous frequency assignment (CFA) operation, i.e., if no destructive collision occurs. Any base station can transmit in any time slot, accepting the risk of excessive interference from cochannel transmissions in nearby cells.

above computations showed that spectrum efficiency is optimal if the full system bandwidth can be used in all cells. However, continuing interference between transmissions from adjacent base station may severely affect the performance of such networks. This suggests that efficient, coordinated resolution of collisions between packet retransmissions in adjacent cells is necessary to guarantee efficient performance of wireless data and multi-media networks. We now propose two schemes that help mitigating the effect of continued collisions in packet-switched radio data networks with dense frequency reuse:

1. Spatial collision resolution in the downlink: All base stations share the same transmit channel, which has frames of three time slots. The areas covered by each base station are assigned a sequence number 1, 2 or 3 according to a map-coloring scheme which ensures that adjacent areas always have a different number. In normal operation, a base station can transmit in any time slot regardless of its number (Fig. 5). If base stations in adjacent areas happen to transmit simultaneously, most signals may nonetheless 'capture' their intended receiver. With some probability however, interference erases some messages involved in this 'collision'. In the latter case, the base station will retransmit the lost message in the slot of the next frame with the corresponding number. During this retransmission, all adjacent base stations are silenced to prevent another collision (Fig. 6). This coordination can be performed by protocols using the fixed backbone infrastructure, connecting all base stations.

A scheme that completely avoids simultaneous transmissions in adjacent cells was proposed in [27]. Base sations transmit according to a pattern that is chosen in accordance with the arrival rates in all cells.

2. Space time reservation multiple access (STRMA) in the uplink. This scheme is a spatial extension of the packet reservation multiple access (PRMA) concept developed at Winlab, e.g. [25]. PRMA is a framed access scheme with frames of a fixed number of slots. If a terminal has a series of packets or speech segments to transmit, it competes for access in any free slot. If it successfully captures the base station, the terminal gains reservation in the corresponding slots of the next frames, until it releases the reservation. In PRMA, adjacent cells use different carrier frequencies according to a cellular reuse plan, but in STRMA they all use the same channel. We synchronize base stations and term-

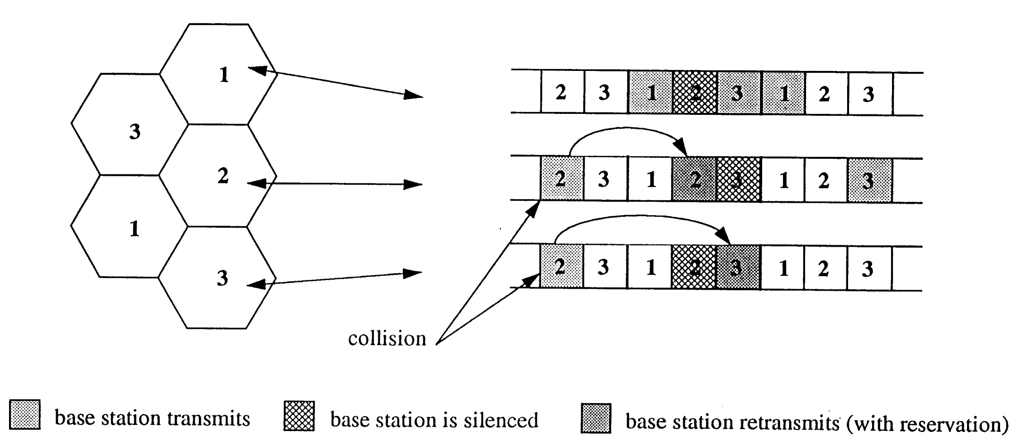

Fig. 6. Spatial collision resolution (SCR) in cellular packet data network. Base stations only transmit in the time slots with the corresponding sequence number. During retransmissions, all adjacent base stations must refrain from transmitting.

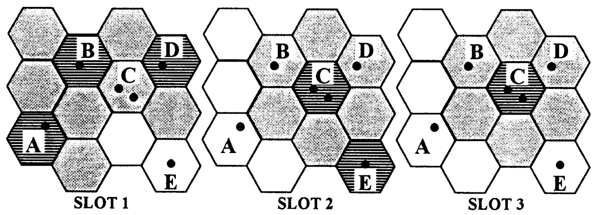

Fig. 7. Sample of three slots in Space time reservation multiple access (STRMA) frame with 6 terminals and 12 cells. • mobile terminal, grey: inhibited slot to avoid co-channel interference, white: free slot in which access competition may take place, ≡: slot reserved for transmission.

inals at slot level. Time slots are common to all cells, and all cells use the same carrier frequencies. However if a terminal gains a reservation in one cell for certain time slots, the base stations of the first tier of surrounding cells inhibit all other terminals to use the same time slots. Hence reservations occur not only in time domain, as in PRMA, but also in space. Fig. 7 illustrates a possible reservation sample for the case of three slots per frame, with active terminals in cells A, B, ..., E. A fixed frequency reuse pattern would not have been able to accomodate this particular distribution of active users. Initial simulations by Van den Broek [28] at Delft University of Technology revealed that for a uniform distribution of speech terminals, STRMA with frames of 21 slots outperforms a PRMA with system with 7 slots per frame and a three cell reuse pattern. A system with 5 erlang per cell was address, with a speech activity of 0.4 (40%) according to a Markovian on-off process with average duration of speech burst of 1 second and average length of a gap of 1.35 seconds. The speech clipping probability for PRMA was about 0.5% and 0.2% for STRMA, while both systems use the same spectrum bandwidth. With non-uniform distributions of users, we expect a further performance gain over PRMA. The STRMA system remained efficient, also at higher message traffic loads.

Synchronization of base stations at time slot level may require some implementation effort. All base station clocks could be slaved to a (satellite) master clock, similar to the concepts used for synchronzation of CDMA or DECT base stations. Alternatively, base stations could find a common synchronization by listening to each others transmissions. However, the self-organizing properities of 'loosely coupled oscilators' [26] are still relatively unexplored for wireless communicaton networks and pratical realizations are rare.

8. Concluding remarks

To the knowledge of the author, only few results are available on (dynamic) frequency reuse schemes for packet-switched networks with bursty traffic. This paper revealed that efficient mobile packet data transmission requires entirely different spectrum reuse than telephone nets. To optimize spectrum efficiency, user capacity and network performance, presumably a new class of access schemes is needed that dynamically combine random access within one cell with protection against interfering signals from other cells. Dynamic channel allocation (DCA) is known to provide a means to share bandwidth-time-space resources in a more dynamic and efficient way. However, DCA primarily works on a session by session basis, whereas bursty teletraffic is presumably best supported through access schemes that assign radio resources on a packet by packet basis, or at least on a burst by burst basis.

Under certain assumptions, contiguous frequency assignment (CFA), i.e., cluster size $C = 1$, can support approximately 0.4 bit/s/Hz/cell. This appeared substantially more efficient than cellular frequency reuse with $C = 3, 4, 7, \ldots$. CFA also provides the smallest packet delay at a given spatial packet throughput intensity. This suggests that, in order to ensure minimum delay at maximum user capacity, mobile radio data networks should be designed with much denser frequency reuse than typically used to ensure an outage probability on the order of 10^{-2} or 10^{-3}. This, however, results in low signal-to-interference ratios and large packet loss probabilities, which have to be addressed by appropriate data-link protocols.

In extreme cases, that transmissions to a particular terminal always see the same interfering base stations, so the number of required transmission attempts may become prohibitively large for certain terminals. This could have a detrimental effect on the entire network performance and it has motivated us to start developing new 'spatial' random access protocols. Performance analysis is topic of our current research.

The results of this paper have been derived from link outage and success probabilities computed with the use of Laplace Transforms. This technique was recognized previously for Rayleigh and Nakagami fading channels. We showed in this paper that the method can be generalized further: it can also be used successfully in Rician-fading channels. Of practical relevance is also the development of series expansions that facilitate link evaluation in cell planning.

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Appendix A

Number of transmission attempts with slow shadowing

In contrast to the assumptions in the main body, we assume identical interference situations during all retransmission attempts of a particular packet. The number of interfering co-channel base stations I is treated as a binomial random variable ($I = 0, 1, \ldots, 6$) with mean $6P_{ON}$, where I is constant during the service time of an individual packet. Given the local-mean powers of the wanted and all active interfering signals, the expected number of retransmissions is

$$\mathrm{E}\Big[M|\bar{p}_0, \{\bar{p}_i\}_{i=1}^{I}, I\Big] = \prod_{i=1}^{I} \frac{p_0 + zp_i}{\bar{p}_0} . \tag{23}$$

If the local-mean powers of signals from interfering base station are i.i.d. log-normally distributed, we find, after solving the I-fold integration,

$$\mathrm{E}\Big[M|\bar{p}_0, \{\bar{\bar{p}}_i\}_{i=1}^{I}, I\Big] = \prod_{i=1}^{I} 1 + \frac{z\bar{\bar{p}}_i e^{\sigma_s^2/2}}{\bar{p}_0} . \tag{24}$$

Rewriting the product into a sum of I-terms and using the property that in a log-normal channel

$$\mathrm{E}\big[\bar{p}_0^{-n}\big] = \bar{\bar{p}}_0^{-n} \exp\left(\frac{\sigma_s^2 n^2}{2}\right) \quad n = 0, 1, \ldots , \tag{25}$$

we find the closed-form expression

$$\mathrm{E}\Big[M|\{\bar{\bar{p}}_i\}_{i=1}^{I}, I\Big] = \sum_{k=0}^{I} \binom{I}{k} \left(\frac{z\bar{\bar{p}}_i}{\bar{\bar{p}}_0}\right)^k \exp\left\{(k + k^2)\frac{\sigma_s^2}{2}\right\} , \tag{26}$$

which we average over the binomial probability mass function of I. If the position of the receiving mobile is uniform within the cell, the expected number of (re-) transmissions per message is

$$\mathrm{E}[M] = \sum_{I=0}^{6} \sum_{k=0}^{I} \frac{6! P_{ON}^{I} (1 - P_{ON})^{6-I}}{(6 - I)!(I - k)!k!} z^k (3C)^{-\beta k/2} \times \exp\left\{(k + k^2)\frac{\sigma_s^2}{2}\right\} \frac{2R^{\beta k}}{\beta k + 2} . \tag{27}$$

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