$$P\langle error|\omega_i, \alpha_i, p_i, \rho_0\rangle = \frac{1}{2}\mathrm{erfc}\left(\sqrt{\frac{\frac{1}{2}\rho_0^2 T_b \mathrm{Sinc}(\omega_i T_b)}{2\sum_{i=1}^{N}\overline{p_i}(1-2\alpha_i)^2\mathrm{Sinc}(\omega_i T_b) + N_0}}\right) \qquad (13)$$

We have assumed that oscillator drifts are minimal, and hence we can model ω_i as random FM. Due to the reduced angle of elevation and the typically large distance between the receiver and the co-channel interference transmitters, there is a very high chance that the LOS and ground reflected waves are obstructed by other vehicles on the road, it is likely that the interference is Rayleigh fading. The distribution of ω_i as such can be taken to be

$$f_{\dot{\theta}}\left(\dot{\theta}\right) = \frac{1}{2\sqrt{2}}\left(1 + 2\left[\frac{\dot{\theta}}{2\pi f_d}\right]^2\right)^{-3/2} \qquad (14)$$

as discussed in [15]. f_d is the maximum Doppler shift. If the base stations are operated independently, the density of α_i is most likely uniform on $0 < \alpha_i < 1$, in which case

$$P\langle error|\overline{p_i}, \rho_0\rangle = \int_0^{\infty}\int_0^{\frac{1}{2}}\frac{1}{2}\mathrm{erfc}\left(\sqrt{\frac{\frac{1}{2}\rho_0^2 T_b}{2\sum_{i=1}^{N}\overline{p_i}(1-2\alpha_i)^2\mathrm{Sinc}(\omega_i T_b) + N_0}}\right)2f_{\dot{\theta}}\left(\dot{\theta}\right)d\alpha_i d\dot{\theta} \quad . \qquad (15)$$

A more accurate analysis, however, would have to take into account the fact that the instantaneous power of the interfering signal and $\dot{\theta}$ may be correlated [15].

If no bit synchronization offset between contending signals is assumed ($\alpha_i \equiv 0$ for i = 1, 2,3,...,n), then conservative results are obtained because it will overestimate the effect of interference. Moreover, in the case of random α_i, the worst-case interfering BPSK bit sequence $k_{\leftarrow} = k_{\rightarrow}$; i.e., no phase reversal is expected to occur during 50% of the bits in the test packet. This event gives the same probability as the case α_i = 0. Computations in this text assume $\alpha_i = 0$ and $\omega_i = 0$.

Our received signal is hence

$$r(t) = a_0\rho_0\cos(\omega_c t) + \sum_{i=1}^{N}\rho_i\{k_{\leftarrow}\alpha_i + k_{\rightarrow}(1-\alpha_i)\}\cos(2\pi(f_c - f_i)t + \varphi_i) + n(t) \quad (9)$$

where $n(t)$ denotes Gaussian noise, and the user bits a_0 are +1 or -1. The values of the interfering bits before and after reversal during a bit time denoted $k_{\leftarrow}$ and $k_{\rightarrow}$ are +1 or -1. The instantaneous frequency offset f_i is due to random Doppler shifts and transmit oscillator drifts.

At the receiver the decision variable v is obtained from the correlation operation

$$v = 2\int_0^{T_b} r(t)\cos(\omega_c t)\,dt\ . \quad (10)$$

We then get,

$$v = a_0\rho_0 T_b + \sum_{i=1}^{N}\xi_i\{k_{\leftarrow}\alpha_i + k_{\rightarrow}(1-\alpha_i)\}\int_0^{T_b}\cos(\omega_i t)\,dt$$
$$+ \sum_{i=1}^{N}\zeta_i\{k_{\leftarrow}\alpha_i + k_{\rightarrow}(1-\alpha_i)\}\int_0^{T_b}\sin(\omega_i t)\,dt + N_i \quad (11)$$

where, because of fading, the in-phase component, $\xi_i = \rho_i\cos\varphi_i$, and the quadrature component, $\zeta_i = \rho_i\sin(\varphi_i)$, are Gaussian random variables. Their variances are found as $E(\xi^2) = E\left(\zeta_i^2\right) = \overline{p}_i$. Also, $E\left(n_i^2\right) = N_0/T_b$.

The conditional variance of the i-th interfering signal is hence

$$2\overline{p}_i(1-2\alpha_i)^2\mathrm{Sinc}(\omega_i T_b) \quad (12)$$

and we therefore have the conditional probability of error:

[24] R.F. Diesta and J.P.M.G. Linnartz, "Multiple access and spatial collision resolution for IVHS packet radio networks", *IEEE Int. Symp. on Personal, Indoor and Mobile Radio Communications*, The Hague, The Netherlands, Sept. 1994, pp. 1260-1263.

[25] R.F. Diesta and J.-P.M.G. Linnartz, "Spatial collision resolution for packet-switched multiple-access wireless networks", *28th Asilomar Conf. on Signals, Systems, & Computers*, Pacific Grove, California, Oct. 1994, pp. 234-237.

[26] R. Litjens, "Conflict-Free Scheduling of Broadcasts in a Linear Packet Radio Network", Masters Thesis in Econometrics, Tilburg University, August 1994.

[27] N.D. Vvedenskaya, "Performance of stack Algorithm in case of mutually interfereing transmission in two cells ", Benelux IEEE Symposium on Information Theory, Noordwijk, Netherlands, May 1995.

[28] N.D. Vvedenskaya and B.S. Tsybakov, ``Packet delay with multi-access stack- algorithm", Problems of Information Transmission, v.16, (1984).

[29] N. D. Vvedenskaya, "Multiple access stack-algorithm with imperfect feedback," Tr. of Fifth IEEE Int.Symposium on PIMRC'94 , 1126--1128 (1994).

[30] N. D. Vvedenskaya, J.C. Arnbak, B.S. Tsybakov, ``Improved Performance of mobile data networks using stack-algorithms and receiver capture,'' March 1994 Int.Zurich Seminar on Digital Communications,} Springer-verlag, Lecture Notes in Computer Sci., 464-475 (1994).

[31] J. P. M. G. Linnartz and N. D. Vvedenskaya, "Optimal delay and throughput in packet switched CDMA network with collision resolution using stack-algorithm,'' Electronics letters, 1st Sept., No.18, 1470--1471.

5.6 APPENDIX A

5.6.1 An Improved Model for Interfering Signals

Section 4.4 described the mean error probability for BPSK modulation with Rayleigh faded co-channel interference. This assumed that interfering signals are perfectly synchronized with the wanted signal. This assumption may be unrealistic. Also, there are likely to be random frequency shifts due to oscillator drifts and random Doppler shifts. In this section we will analyze their effect

An interfering signal experiences a reversal at $t = (k + \alpha_i) T_b$, where k is an integer, and α_i $(0 < \alpha_i < 1)$ is the synchronization bit offset, normalized to the bit time.

$k_{\leftarrow}$ = bit value for $kT_b < t < (k + \alpha_i) T_b$, and 0 for $(k + \alpha_i) T_b < t < (k + 1) T_b$,

$k_{\rightarrow}$ = 0 for $kT_b < t < (k + \alpha_i) T_b$, and reversed value for $(k + \alpha_i) T_b < t < (k + 1) T_b$

[6] J.P.M.G. Linnartz, *Narrowband Land-Mobile Radio Networks*, Boston: Artech House, 1993.

[7] E. Green, "Pathloss and signal variability analysis or microcells", *5th IEE Intl. Conf. on Mobile Radio and Personal Communication*, Warwick, U.K., Dec. 1989, pp. 38-42.

[8] R.J.C. Bultitude and G.K. Bedal, "Propagation characteristics on microcellular urban radio channels at 910 MHz", *IEEE J. Sel. Areas in Commun.*, vol. 7, no. 1, 1989, pp. 31-39.

[9] D.M.J. Devasirvatham, "Radio propagation studies in a small city for universal portable communications", *38th IEEE Vehicular Technology Conf.*, Philadelphia, June 15-17, 1988, pp. 100-104.

[10] J.G. Proakis, *Digital Communications*, 2nd ed., New York: McGraw-Hill, 1989.

[11] R. Ziemer and W. Tranter, *Principles of Communications - Systems, Modulation and Noise*, 3rd ed., Boston: Houghton Mifflin, 1990.

[12] I.M.I. Habbab, M. Kahvehrad and C.E.W. Sundberg, "ALOHA with capture over slow and fast fading channels with coding and diversity," *IEEE J. Sel. Areas in Commun.*, vol. 7, no. 1, Jan. 1989, pp79-88.

[13] K. Zang, K. Pahlavan and R. Ganesh, "Slotted ALOHA networks with PSK modulation in Rayleigh fading channels", *Electron Lett.*, Vol 23, No 6, 16th March 1989, pp. 413-414.

[14] A.J. Jong, "Average bit error rates for coherent detection in macro and micro-cellular radio", *IEE International Conference on Mobile Radio and Personal Communication*, Warwick, Dec. 1991 pp. 241-247.

[15] W.C. Jakes (Ed.), *Microwave Mobile Communication*, New York: Wiley, 1974.

[16] R.E. Blahut, *Theory and Practice of Error Control Codes*, MA: Addison-Wesley, 1983.

[17] S.R. Sachs and P. Varaiya, *A Communication System for the Control of Automated Vehicles*, PATH technical memorandum 93-5, 1993.

[18] D.C. Cox and R.P. Leck, "Distributions of multipath delay spread and average excess delay for 910-MHz urban mobile radio paths", *IEEE Trans.on Antennas and Propagation*, vol. 23, no.3, Mar. 1975, pp. 206-13.

[19] J. Walrand, *An Introduction to Queueing Networks,* Prentice-Hall: New Jersey, 1988.

[20] J.P.M.G. Linnartz, "Contiguous frequency assignment in wireless packet-switched networks", *IEEE Int. Symp.on Personal Indoor and Mobile Radio Communications*, Yokohama, Japan, Sept. 1993.

[21] R. Diesta, Internal research Memorandum, U.C. Berkeley, 1993. ZZZZ DATE ????

[22] C.O. Eleazu, *A Study of Base Station to Vehicle Communication for Intelligent Vehicle / Highway Systems*, research project EECS Dept, UCB. 1993.

[23] R.F. Diesta, C.O. Eleazu and J.P.M.G. Linnartz, "Packet-switched roadside base station to vehicle communication for Intelligent Vehicle/Highway Systems", *IEEE Veh. Technol. Conf.*, Sweden, June 1994.

ment. Queues at base stations are modelled as M/G/1, and it is found that, if base statioons do not mutually coordinate transmissions, a cluster size C=2 maximizes throughput while minimizing the queueing delay.

Other computations indicate that it is worthwhile to have directional antennas only if the backward attenuation is reasonably high (25 dB), otherwise interference at the cell edge (the vicinity of the interfering station is too high). Hand-overs, based on average numbers of retransmissions, will tend to occur after the vehicle is well into the next cell, and not at the point when the packet erasure rates from both transmitters are equal. The advantage of increased reliability is hence not fully utilized. Computations show that the advantage of directionality is not significant even for most reasonably directional antennae, and as such omnidirectional antennae will be assumed in our computations

Regarding the uplink, our results show that two-cell system with stack-algorithm used for conflict resolution and the same channel used in both cell can be approximated by one-cell system with two states of the feedback channel and with Markov chain transition from one state to the other.

Our results suggest that in future lightly loaded wireless networks with bursty traffic, it may be advantageous to allow near by cells to use the same channels. The free access algorithms appear robust against high levels of interference from co-channel cells. This is in contrast to conventional cellular frequency reuse used for mobile telephones.

5.5 References

[1] K. Takada, Y. Tanaka, A. Igarashi, D. Fujita, "Road/Automobile Communication System and its Economic Effect," *IEEE Vehicle Navigation and Information System Conf.*, pp. A15-21, 1989.

[2] I. Catling and P. Belcher, "Autoguide - Route Guidance in the United Kingdom," *IEEE Vehicle Navigation and Information System Conf.*, pp. 467-473, 1989.

[3] U. Karaaslan, P. Varaiya, and J. Walrand, *Two Proposals to Improve Freeway Traffic Flow*, PATH research report PRR-90-6, Dec. 1990.

[4] H. Harley, "Short distance attenuation measurements at 900 MHz and 1.8 GHz using low antenna heights for microcells", *IEEE J. Sel. Areas in Commun.*, vol. 7, no. 1, 1989, pp. 5-10.

[5] A. Polydoros, et al, "Vehicle to roadside communications study", PATH research report PRR-93-4, June 1993.

1.0 CONCLUSION

An appropriate model for the IVHS environment which included a narrowband Rician fading signal with Rayleigh fading interference was proposed. The channel was shown to be slowly fading with the major source of error being co-channel interference. A Rician K parameter of 10 was chosen to mode all multipath effects on the highways such ducting with a view to computing packet erasure rates. The effect of shadowing was not included in the model. We postulated that during the transmission of a packet and its retransmission, the loacl mean received power may bre considered constant.

It was concluded that error correction coding would not be as efficient as error detection and subsequent retransmission. Also, directional antennas have been investigated to determine the extent to which they increase the efficiency of the network. It was concluded that there is an improvement over omnidirectional antennae, but on the condition that they provide interference attenuation of up to 25 dB close to the cell edge. The change in cell average packet erasure rates on the channel is found not to be too significant compared to the omnidirectional case, and so omnidirectional antennas are assumed.

With spatial collision resolution as being investigated in [22], [23], there will be no need for reuse factors of greater than 1. Spectral efficiency and queueing delays would then be optimized. In the absence of such a scheme, it is reasonable to conclude that cluster sizes of 2 are sufficient with the use of directional antennae. This conclusion is based on spectrum efficiency and queueing delay considerations.

For instance, with a frequency reuse pattern of 2 and a bit rate of 80 kbps, an average of 200 successful packet transmissions per second can be achieved, each packet containing about 200 bits. This throughput is more than enough to deal with the cell entry rate estimate of 6 vehicles/second assumed in [19]. The corresponding delay of a few milliseconds per packet suggests that the only limitation on the cell size is the efficiency of the hand-over protocol.

Packet erasure rates have been calculated by averaging over a Rician power distribution. A Rician channel model with a two-ray dominant component has been proposed for the IVHS environ-

As in system f no interference from other cells is present, collision resolution can be very efficient. The length of a slot is unity (because C = 1), but the arrival rate per slot is twice the arrival rate in one cell (per slot). So the arrival rates (per slot) in systewm e and f are equal. However, the delays in similar f are half the delays seen in system e. This result is remarkable. It suggests that conventional frequency reuse (system e) is even worse than covering all traffic by a single base station!

System	$\lambda = 0.05$	$\lambda = 0.1$	$\lambda = 0.15$	$\lambda = 0.2$	λ_{cr}
a:	0.22	0.60	1.22	2.54	0.33
b:	1.81	2.39	3.84	10.5	0.23
c:	1.87	2.69	7.22	inf	0.16
d:					
e:	4.16	8.08	55.0:	inf	0.16
f:	2.08	4.04	27.5	inf	0.16

Table 5.T and λ_{cr} for algorithm A

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System	$\lambda = 0.05$	$\lambda = 0.1$	$\lambda = 0.15$	$\lambda = 0.2$	$\lambda = 0.25$	λ_{cr}
a:	0.18	0.47	0.95	1.83	3.79	0.36
b:	1.71	2.06	2.67	3.96	6.77	0.29
c:	1.72	2.09	2.78	4.44	12.29	0.27
d:	1.75	2.19	3.10	7.96	inf	0.2
e:	3.94	6.66	22.69	inf	inf	0.18
f:	2.97	3.33	11.35	inf	inf	0.18

Table 5.T and λ_{cr} for algorithm B

Note, that for algorithm B the delay and the throughput do not depend on z_{01}. In the examples the delay is less for the system with C = 1, even for relatively large z_{01}

one-cell two-state system in which the mean length of busy session L_b is equal to the mean length L_2 of the state "2" (i.e. the system being in the "bad state"). The mean length L_1 of the state "1" (i.e. the system being in the "good state") is assumed to be equal to the mean length of the slots without new packets, $L_1 = \frac{1}{1-e^{-\lambda}}$ Therefore $q_1 = e^{-\lambda}$. For given channel properties the value of L_b can be expressed in terms of the solutions of the linear equations (similar to the computations the value of the delay D); q_2 is found by iterations , to satisfy the equality $L_2 = L_b$.

The results of simulations follow the results of computations (for one-cell system) with 10% accuracy.

For the simulation system and for one-cell system C is equal to 1 . The results for one-channel (C = 1) two-state system with income flow rate λ (i.e. for two-cell system using the same channel) are compared with the results for two-cell system with different channels (C = 2).As each channel only has half the bandwidth, time slots need to be twice as large. Effectively, for a given arrival rate per second, this corresponds to a flow rate of twice λ new packets per slot. However, using different channels has the advantage that interference or "feedback errors" do not occur.

The results are illustrated by the tables. In Table 1 we present the mean time T a packet spends in the system and the throughput λ_{cr} for stack-algorithm A. In the Table 2 we present the same data for stack-algorithm B.

In the Tables

a : C=1, $z_{0c} = z_{01} = z_1 = 0$; this system does not suffer any harmful interference between cells.

b : C=1, z_{0c} =1/16, $z_{01} = z_1$ =1/4,

c : C=1, z_{0c} =1/9, $z_{01} = z_1$ =1/3,

d : C=1, z_{0c} =1/4, $z_{01} = z_1$ =1/2,

e : C=2, $z_{0c} = z_{01} = z_1 = 0$. This system uses different inbound channels in the two cells, so mutual interference is absent

f : C=1, $z_{0c} = z_{01} = z_1 = 0$. This system uses only one channel and a single receiving base station covers the two cells.

The delay of a packet is defined as the length of a time interval between the start of the packet's first transmission and the start of it's successful transmission. Note, that the time a packet spends in the system includes the random waiting time till the beginning of the first transmission, the delay, and one slot of successful transmission. The mean time T a packet spends in the system is equal to the mean delay D plus a slot duration times 3/2.

If the income flow rate $\lambda < \lambda_{cr}$, all packets are transmitted with finite delay with probability 1, and the mean delay finite. The value of λ_{cr} is called the throughput of the system, λ_{cr} depends on the channel probabilities. For given channel probabilitires the mean delay D can be expressed in terms of the solutions of the linear algebraic equations.

The results of computation for one-cell two-state system are compared with the simulation results for two-cell system. In this system both stations use the same stack-algorithm. The performance of two-station system is defined by the following rules.

Let in cell *i*, *i*=1,2, slot *n* be idle. If in cell *j* with *j* not equal to i, the slot *n* is idle too, then in cell i this slot is reported idle. If in cell *j* there is a capture, then in cell *i* this slot is reported idle with probability 1 - z_{01} and a capture is reported with probability z_{01}. If in cell *j* there is a conflict, then in cell i this slot is reported idle with probability 1 - z_{0c} and a conflict is reported with probability z_c.

Let in cell *i*, *i*=1, 2, slot *n* be a capture. If in cell *j*, with *j* different from *i*, slot *n* is idle, then in cell *i* this slot is reported to be a capture. If in cell *j* slot *n* is not idle, then in cell *i* a capture is reported with probability 1- z_1 and a conflict is always correctly reported with probability z_1. A conflict in cell i is always reported to be a conflict in this cell.

5.4.2 Computational RESULTS

To consider the performance of a one-station system we need to introduce the notion of a busy session. Roughly speaking a busy session is a time interval during which there are some packets in the channel, or in the stack of some vehicle terminal, or both in the channel and in the stack. We want to model a two-cell system with the equal income flow rate λ in both cells. Therefore we consider a

4a. If $l_n > 0$ for a packet and a conflict is reported in slot n, $l_{n+1} = l_n + 1$.

5a. If $l_n > 0$ for a packet and slot n is reported idle, $l_{n+1} = l_n - 1$.

6a. If $l_n > 0$ for a packet and a capture is reported in slot n, $l_{n+1} = l_n$.

Rules 1 - 3 address the behaviour of newly arrivaing packets and those that are being (re-) transmitted, while rules 4-6 address backlogged packets.

Algorithm B

The algorithm uses binary "conflict/no conflict" feedback.

1b-5b are the same as 1a-5a, respectively.

6b. If $l_n > 0$ for a packet and a capture is reported in slot n, $l_{n+1} = l_n - 1$.

Thus algorithm B is more aggressive in retransmitting previously collided packets.

The one-cell system can be in two states. If during slot n the system is in state i, i=1,2, then it will stay in the same state during slot $n + 1$ with probability q_i, and will be in different state with probability $(1 - q_i)$. The mean duration of being in state i is equal to $L_i = 1/(1-q_i)$, i = 1, 2. The probability for a system to be in state i is $Q_i = L_i/(L_1 + L_2)$, i =1, 2 .

Let the system be in state i during a slot n. We model the effect of interference as follows. If the slot n is idle, a capture is reported in this slot with probability z^i_{10}, and a conflict is reported with probability z^i_{0c}. The slot is reported idle with probability $(1- z^i_{01} - z^i_{0c})$. If in the slot n there would be a capture (one packet from that cell was transmitted), a conflict is reported in this slot with probability z^i_1. , and a capture is reported with probability $(1 - z^i_1)$. If in the slot n there is a conflict, a conflict is reported with probability 1. Thus,in our discussion, we cover interference between cells as errors in the feedback, wich would have the same effect.

We assume that the state "1" has a perfect feedback channel, $z^1_{01} = z^1_{0c} = z^i_1 = 0$, and assume that the state "2" has an imperfect feedback channel. For ease of notations, the index "2" is omitted, and the notations are : $z^2_{01} = z_{01} > 0$, $z^2_{0c} = z_{0c} > 0$, $z^2_1 = z_1 > 0$.

5.4.1 Model of Access Scheme

The uplink random access channel is considered to be time slotted and synchronized at time slot level. The slots start at t=1,2,3,... A slot that starts at $t = n$ is called slot n. A packet is transmitted during one slot, and transmission of each packet starts at the beginning of a slot. A new packet is transmitted for the first time in the first slot following packet's arrival (free access). The incoming flow of packets in a cell is a Poisson flow with flow rate λ packets per slot. Each vehicle terminal has a buffer to keep one packet that has to be transmitted. Any packet that captures the receiver leaves the system. Each packet transmitted in a slot without capturing the receiver is either retained in the vehicle terminal's buffer (with probability 1/2) or is retransmitted in the next slot (with probability 1/2). The main idea here is to split the terminals into different smaller groups. the probability of having a message collision in subgroups rapidly vanishes afteer a number of splits. To ensure that each terminal keeps track of the group in which is may transmit, we introduce a stack counter l_n which is associated with the vehicle terminal's buffer and which changes from slot to slot according to the stack-algorithm rules, following the feedback information. Generally, the stack counter increases when a conflict is reported in a slot and decreases when a slot is idle. The idea is that after a collision, all backlogged groups of packets have to wait before the current group has resolved its collision. As the current group splits, a new level is inserted, and all existing groups increase their stack counter.

We address two versions of algorithm [3].

Algorithm A

The algorithm uses ternary "idle slot/success/conflict" feedback.

1a. A packet transmitted in slot n for the first time (i.e. the packet generated in slot n-1) has l_n = 0.

2a. If l_n=0 for a packet, the packet is transmitted in slot n. If $l_n > 0$, the packet is not transmitted in slot n.

3a. If $l_n = 0$ for a packet and a conflict is reported in slot n, $l_{n+1} = 1$ with probability 1/2 and $l_{n+1} = 0$ with probability 1/2.

The proposed algorithm for static strategies with centralized control separates the problem into two parts: (1) the selection of the assignment patterns that are used in the cycle and their frequencies of appearance, and (2) the placement of these patterns in a cycle, aiming to spread the activations as uniformly as possible for each individual base station.

5.4 UPLINK RANDOM ACCESS

As the message traffic offered to the uplink is highly bursty, a random schemme is presumably needed. It was reported in PATH document [27] that it is optimum to use the same inbound frequency in all cells. Next we present some new results on a radio network with two base station receiving packets transmitted by a large population of mobile vehicle terminals. If both stations share the same channel, transmissions in one cell interfere with transmissions in the other cell. Here we discuss a roburst retransmission scheme that avoid instability and migitates the effect of interference between cells. To consider the performance of this two-cell system, we model a one-cell system with time-varying channel properties. If only one station is busy (or if both are silent) the base station is supposed to be in "good state". If both stations are busy the channels are supposed to be in "bad state", due to the mutual interference. Markovian transitions from one state to the other is assumed. For conflict resolution, the stack-algorithm is used [28, 29], which will be explained later on.

Whenever only one base station is busy (or when both stations are silent), this base station is assumed to have a perfect channel (to be in "good state"). When both stations are busy, they interfere, so the channel is imperfect ("bad state"). We approximate these states as Markov transition from one state to the other. The performance of such two-cell system with a common channel (and without any CDMA spreading factor) is compared with the performance of two-cell system with different channels. To avoid the interference in the latter system, 2 different channels would be needed, each with half the bandwidth. That is, the transmission time increases by a factor two. Moreover the arrival rate of packets per time slot increases by a factor of two. Under large traffic loads, this leads to a significant delay.

tions are silenced. This coordination is performed by sending instructions through the fixed backbone infrastructure connecting all base stations. With this algorithm implemented to resolve the interference problem, it will be possible for all stations to transmit at the full bandwidth with hence high spectral efficiencies and minimal delays.

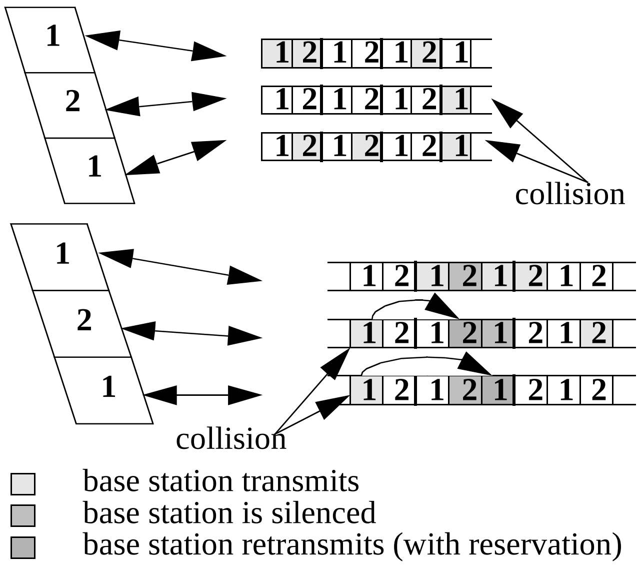


Figure 5.18 Time Slot Usage with Spatial Collision Resolution

To further exploit the benefits of dense frequency reuse, Walrand and Litjens [26] proposed a packet-switched scheme transmitting packets from roadside base stations to vehicles. Arrival processes in the cells are assumed to be homogenuous Poisson processes but with non-identical arrival rates. The proposed scheduling algorithms assign permissions to transmit to the base stations in a conflict-free manner: when a station is activated, its neighbors are silenced, in order to solve the problem of collisions through interference. Both static and dynamic strategies are proposed in [26]. In the former, a fixed broadcast schedule is constructed, describing the time slots in a cycle during which each base station is activated. In the latter, permissions are distributed in each time slot, based on the status (idleness or nonidleness) of all the base stations. A second distinction that is made, is between centralized control, where the network management makes all decisions, and distributed control, where the base stations decide themselves whether or not to transmit, based on the limited information that is exchanged between neighbors.

Extending, if we use perfectly directed antennas (radiating in one direction only so the cell area is $0 < r < 1$ with the base station at the edge $r = 0$), then the spectrum efficiency is increased and we observe that $C = 1$ is optimum. (See Fig. 5.XX)

Cluster Size	SNR = infinity	SNR = 9 dB
C=1	0.020517	0.007107
C=2	0.499960	0.490237
C=3	0.333332	0.329033
Dynamic	0.784922	0.742079

Table 5.1 Spectrum Efficiency (continuously transmitting base stations); SNR specified at cell boundary ($r = 0.5$)

5.3.5 Spatial Collision Resolution

The calculations performed above have assumed that queues at adjacent base stations are independent. This is however also not necessarily true. Firstly, if a message intended for a certain vehicle is not transmitted while it is in the cell, it will have to be added to the queue of the adjacent base station. Secondly, packet transmissions at both base stations cause mutual interference which directly affects the lengths of both queues. Nonetheless, independent service times for packets queued at the same base station have been assumed. Therefore, the previous results may be inaccurate under certain conditions. However, transmissions of base stations may be coordinated to avoid the problem of continued mutual interference.

Performance analyses of ‘spatial resolution schemes’ to resolve collisions in adjacent cells are being performed [22], [23]. In one such scheme all base stations share the same transmit channel which has frames of four time slots. The sections of the highway cover by each base station are assigned a sequence number {1 or 2} according to map-coloring scheme which assures adjacent areas always have a different number. During normal operation, each station may transmit during anytime slot. With some probability a collision occurs, and the interfering power is to strong to allow successful receiver capture. In this case the station will retransmit in its assigned slot while all adjacent sta-

The "number of spectrum resources" that a packet consumes on average for successful transmission is $C/Q(r)$ (Fig. 5.17). Near the base station, very few transmissions are needed. Farther away, more are required especially for C = 1. The results show that, as r varies, the minimum value for $C/Q(r)$ changes between parameter values of C. This leads us to propose a dynamic cluster size which depends on the location of target vehicles within a cell; i.e., if a vehicle is known to be close to the base station, then it receives downlink packets using C = 1. Vehicles which are farther away will receive downlink packets at C = 2 or even C = 3 to minimize the "number of spectrum resources" used. If this dynamic cluster size method is used, then the expected service time becomes

$$E(\lambda) = \frac{L}{\eta_r R B_N} \int_R \min_C \frac{C}{Q(r)} \, dr \qquad (8)$$

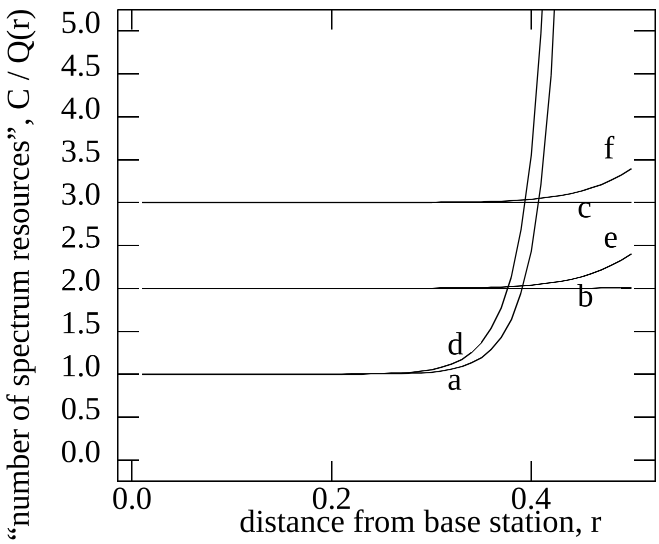


Figure 5.17 "Number of spectrum resources" versus position in cell. (continuously transmitting base stations) No noise: a) C=1, b) C=2, c) C=3; with noise: d) C=1, e) C=2, f) C=3.

The spectrum efficiencies for fixed (C=1,2,3) and dynamic cluster sizes were calculated and the results are shown in Table 1. The spectrum efficiency for C = 1 is close to zero due to excessive retransmissions to vehicles at the cell boundary. For other values of C, the spectrum efficiency approaches the theoretical maximum ($1/C$). For the fixed system, C = 2 gives the best spectrum efficiency, but the dynamic scheme gives even better results. Smaller SNR will diminish SE.

$$E[\lambda^2] = \int_R \frac{2 - P(S|r)}{[P(S|r)]^2} dr \tag{6}$$

The number of packets waiting in a station is modeled as a M/G/1/∞ queue. Assuming immediate retransmissions but nonetheless with independent success probabilities $P(S|r)$, the average delay (using the Pollacek-Khintchine formula) is

$$E(D) = \left(\frac{LC}{\eta_r B_N}\right)\left[\frac{S_0 \cdot E[\lambda^2]}{2(1 - P(busy))} + E[\lambda]\right] \tag{7}$$

The results in Figure 5.XX (normalized to $\eta_r B_N / L = 1$) were computed by letting *P*(*busy*) vary from 0 to 1 and getting throughput and delay from the above expression. For any required throughput, delays are less for *C* = 2 than for *C* = 3. At low throughput, *C*=1 has the least delay, and the delay is inversely proportional to the bandwidth per base station: interference is so low that very few packets need to be retransmitted and delays are close to one packet transmission time. For higher throughput, hence more interference, the delay for *C* = 2 remains less than for *C* = 3 despite the fact that more collisions occur; the delay for *C* = 1 is worse due to many (immediate) retransmissions. A frequency reuse pattern of 2 minimizes delay at high throughput. At low throughput, *C* = 1 has less delay. As we'll report in the nerxt sections, it may be possible to further enhance the spectrum efficiency by using *C* = 1 with an efficient 'collision resolution' algorithm to mitigate the effect of conflicting base station transmissions. This particularly improves the loss of throughput at high offered traffic loads.

Figure 5.XX Relation between delay and spectrum efficiency for various cluster sizes (*C*=1 ____ , C=2 ...., C=3 - - - -). (r_g = 0.25, K_1 = 10, K_2 = 1.4 x10^7, SNR = 9 dB at cell boundary, 200 bits/packet, no error correction).

$$SE = \eta_r \frac{S_0}{C} \quad (3)$$

expressed in gross user bits per base station per Hz per second. The bit rate per second per Hertz is denoted as η_r. The normalized spectrum efficiency is found from $\eta_r = 1$ bit/sec/Hz.

We will assume that the fading is independent from one transmission to the next, but that the large scale attenuation remains constant during the retransmission delay time. Since the probability of successful packet reception at a given distance $P(S|r)$ decreases with increasing propagation distance *r*, the expected number of transmission attempts $M(r)$ increases with increasing *r*.

The delay $D(r)$ is mainly determined by the queueing of packets in the base station: packets with nearby destinations may have to wait because of the transmission time for packets to remote destinations. The delay is less sensitive to *r* than *M(r)*, and may depend on queueing strategy for retransmission. The following analysis will therefore address the cell-average delays.

The number of packets waiting in the base station is modelled as a Discrete Time M/G/1/∞ queue. The mean service time E[λ] is

$$\mathrm{E}[\lambda] = \mathrm{E}[\mathrm{E}[\lambda|r]] = \frac{1}{R}\int_R \frac{1}{P(S|r)} dr \quad (4)$$

expressed in slots, where the slot time depends on *C*, and *R* is the cell size. Once again we have assumed that the distribution of vehicles within the cell is uniform. (The cell size can be normalized to 1 for simplicity.) The cell throughput is found from

$$S_0 = \frac{P(S)}{\mathrm{E}[\lambda]} = \frac{P(busy)}{R}\left(\frac{1}{R}\int_0^R \frac{dr}{P(S|r)}\right)^{-1} \quad (5)$$

where $P(busy)$ is the probability that the reference station is transmitting vehicle terminal data. It is equal to the probability that the interfering station is transmitting. Also, since we have assumed uniform throughput rather than uniform attempted traffic, $P(S) \neq \int_0^R \frac{P(S|r)}{R} dr$.

Similarly, the variance of the service time is

Figure 5.11 A frequency reuse pattern of 2.

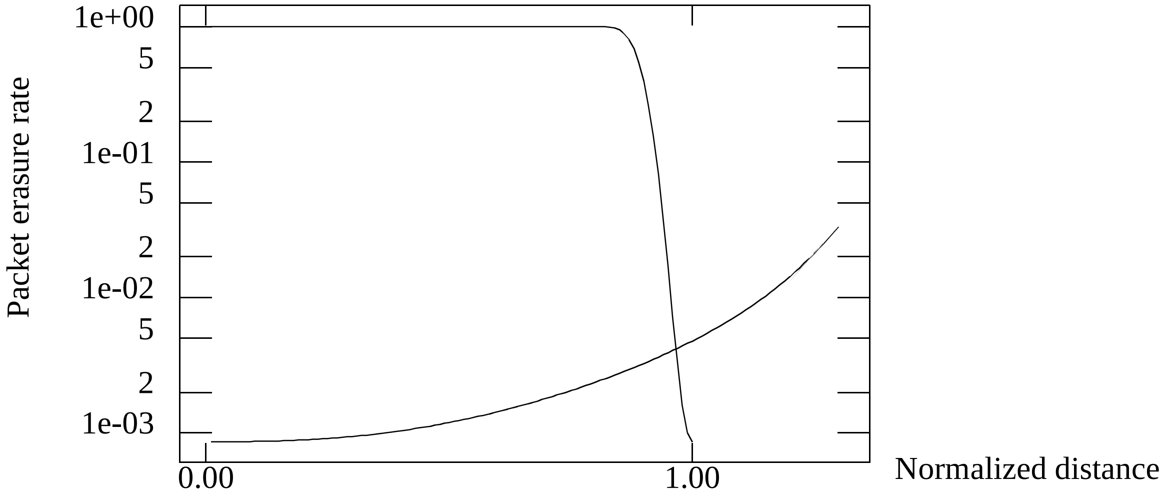
Finally, correct hand-over decisions are an issue. A hand-over should be made at the right point and to the right base station. The local-mean number of retransmissions of packets may be used as an indication of whether a hand-over is necessary.

Figs. 5.6 thru 5.8 indicate that based on reliability considerations, a frequency reuse factor of 2 or 3 is much more reasonable than a reuse factor of 1. The plots however, assume that the interfering base stations are always on. This is a rather conservative assumption, but it indicates that by dividing the bandwidth into 2 as demonstrated in Fig. 5.11, we get a much more reliable channel. It also demonstrates that the additional gain from splitting the total bandwidth into 3 frequency bands is not as significant. It can be concluded based on channel reliability, that a frequency reuse pattern of 2 is the reasonable choice. This is more reliable than a reuse pattern of 1, and in both cases of frequency reuse factor of 2 and 3, the average number of packet transmissions required per message is close to 1.

5.3.4 Maximizing Performance

So far, our analyses suggests that a cluster size of 2, using omnidirectional antennas is sufficient. In this section we study the delays that occur due to retransmissions and queueing in the base station. Ultimately, the goal is to minimize the delay, while utilizing the available spectrum efficiently. By delay we mean the total of the wait until service, and the service time for a packet. The following analysis will reveal that denser reuse is favourable.

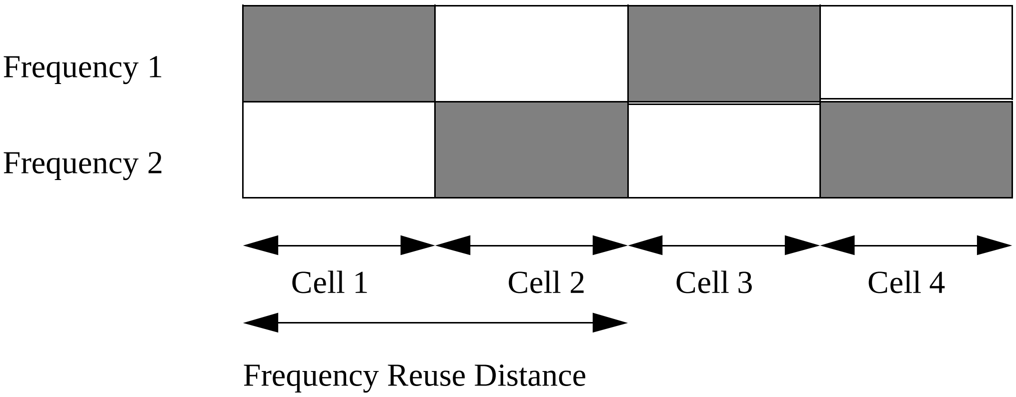
Vehicle traffic is assumed uniform throughout the cell. It would hence be reasonable to model uniform throughput per unit of area throughout the cell. This assumption however differs from assuming a constant attempted packet traffic to all areas, because areas will poor coverage need more retransmission attempts. The successful total throughput per station is denoted as S_0 $(0 \le S_0 \le 1)$ and represents the number of packets per cell per slot that are successfully transmitted. For a cluster size of C (the total allocated bandwidth is shared by C cells), we define the spectrum efficiency (spatial packet throughput density) as



drawback is that the system will not take full advantage of the lower packet error rates resulting from antenna directionality.

5.3.3 Choosing a Reuse Patter n

There are three issues to consider in choosing a reuse pattern. The reliability of the channel is a very important consideration: it would be ideal not to have too many retransmissions of packets. Another important factor is the number of vehicle terminals that can be served per unit cell per unit time. Transmitting at full bandwidth obviously would be optimum if the number of serviced customers per unit time were the only issue. It has however been shown that interference causes unreliability if all stations transmit at full bandwidth. Even with a highly directional antenna, interference will cause many packet erasures when the cluster size is 1. Transmitting at the full bandwidth in every cell hence requires a more innovative approach..



advantage of directionality is not significant even for most reasonably directional antennae, and as such omnidirectional antennae will be assumed in subsequent computations

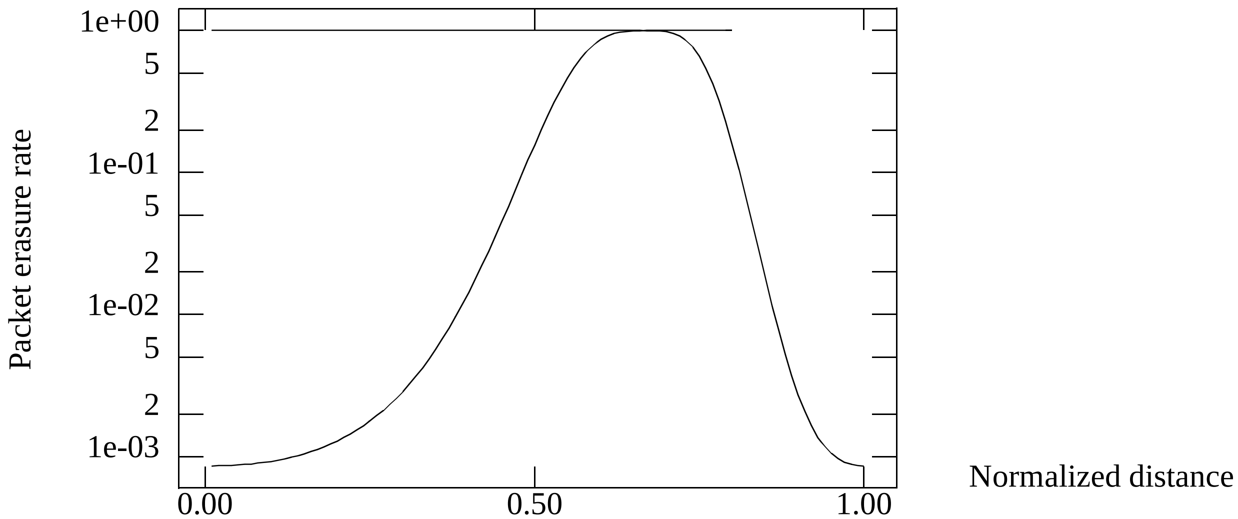


Figure 5.9 Packet erasure rate versus normalized distance from directional transmitter with 25 dB back attenuation for reuse distance of 1.

Figure 5.10 Packet erasure rate versus normalized distance from directional transmitter with 25 dB back attenuation for reuse distance of 2.

Another important inference can be made from Figs. 5.7 and 5.8. They indicate that if packet retransmissions are used as an indication of a vehicle or platoon's position relative to base stations, hand-overs will be made fairly late. In the case when a reuse factor of 2 is used, hand-overs will be made at normalized distances 0.2 and 1.2 for example, if the maximum allowable average number of retransmissions is 2. This result is for 10 dB back attenuation on the directional antenna. If the directionality is increased, the hand-over points will be further skewed relative to the base stations. The

Packet erasure rate

Normalized distance

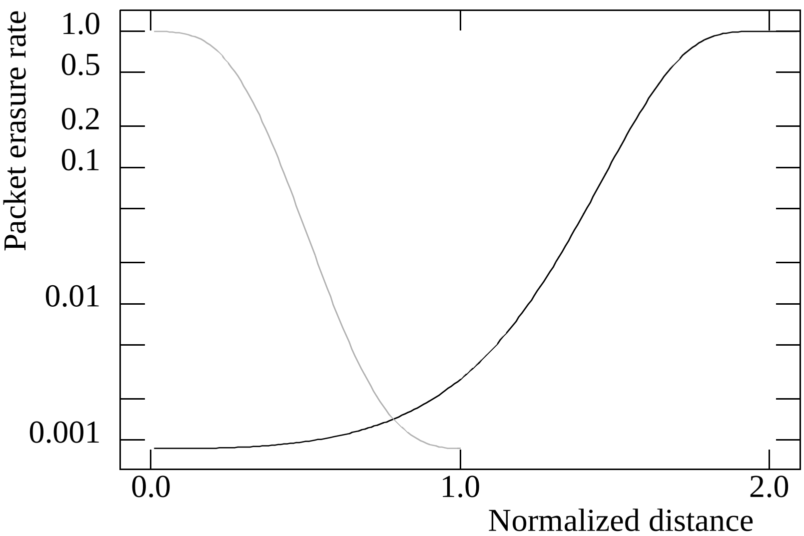


Figure 5.8 Packet erasure rate versus normalized distance from directional transmitter with 10 dB back attenuation for reuse distance of 3.

Fig. 5.9 shows packet erasure rates for a directional antenna with 25 dB back attenuation and for a frequency reuse distance of 1. One interferer is facing the opposing direction, and its power is attenuated by 25 dB. This station still appears to cause unreliability in transmission when the cluster size is 1, even with directional antennae. In Fig. 5.10 we see packet erasure rates for a frequency reuse pattern of 2. There is a slight improvement in cell average packet erasure rates. We conclude that the

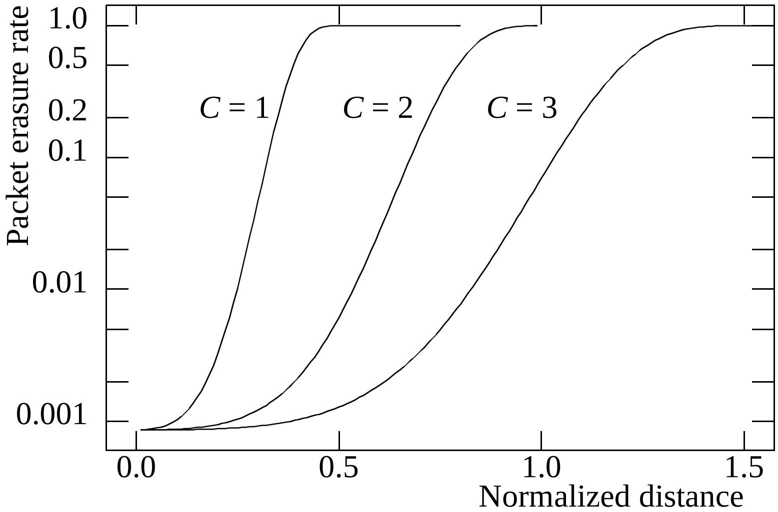
the reference and second base station (i.e. the one to which a handover will be performed). Ideally, in the omni-directional case, a hand-over should occur at $r = 0.5$. In order to maintain channel reliability, the optimum hand-over should take place at about $r = 0.8$. The packet erasure rate at this position is comparable to that at $r = 0.5$ in the omnidirectional case. The directionality of the antenna as such seems only to shift the hand-over point without making a significant difference in cell average packet erasure rates. It is hence seems only worthwhile to have directional antennae if the backward attenuation is reasonably high. The goal should be attenuating interference such that the packet erasure rate approaches the limit due to the noise floor as in Fig. 5.4 (about 25 dB attenuation).

Packet erasure rate

Normalized distance

Figure 5.6 Packet erasure rate versus normalized distance from directional transmitter with 10 dB back attenuation for reuse distance of 1.

Figure 5.7 Packet erasure rate versus normalized distance from directional transmitter with 10 dB back attenuation for reuse distance of 2.



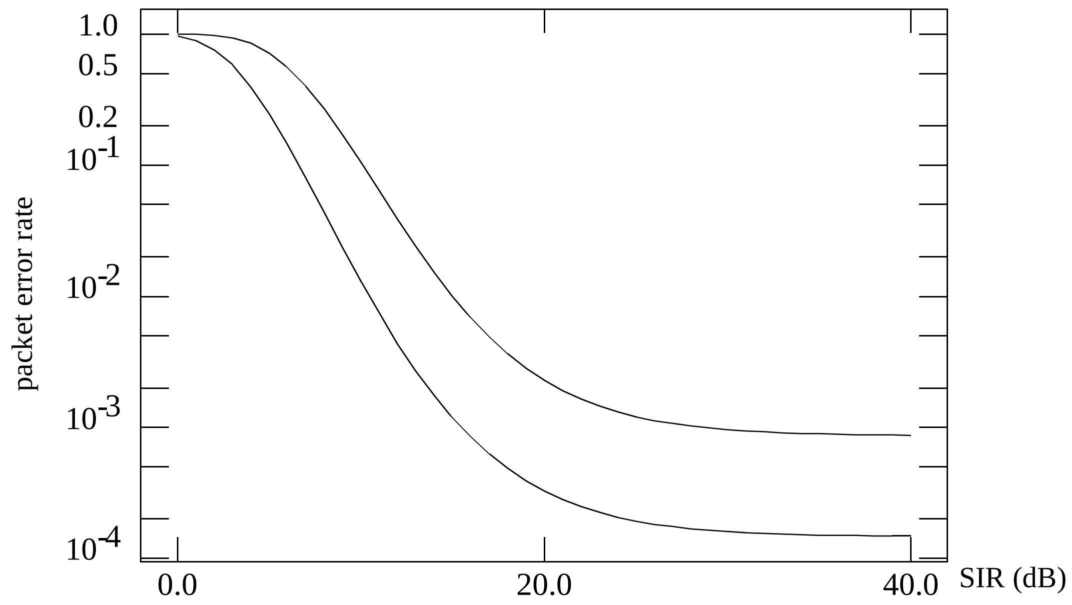
between adjacent stations = 1, omnidirectional antennas, 200 bit packets, no error correction.

5.3.2 Directional Antennas

By using directional antennae at the base stations, reception at the vehicles may be enhanced. End fire arrays or simple metal reflectors may be used to create directivity in the antenna beam. The advantages of directional antennas are due to increased backward attenuation and improved cell confinement.

Directional antennas decrease the amount of co-channel interfering energy because it attenuates propagation to sections of the highway that are behind the antenna. Other studies have also shown that there is a greater confinement of energy in the forward direction on the highway when directionality is introduced to the transmitting antenna [5]. We will investigate the advantages of antenna directionality.

Figures 5.6 thru 5.8 show erasure rates for transmission of packets with directional antennas having a backward attenuation of 10 dB. The plots are for frequency reuse distances of 1, 2, and 3. The results in Fig. 5.6 indicate that there is still a sizeable portion of the cell for which packet transmission is very unreliable for a frequency reuse distance of 1 as was observed in the omnidirectional case. The only difference is the positioning of the reliable region relative to the transmitter. Figs. 5.7 and 5.8 show the packet error rates for frequency reuse factors of 2 and 3, respectively, with respect to



200 bit packets): (a) no error correction, (b) 4 bit error correction.

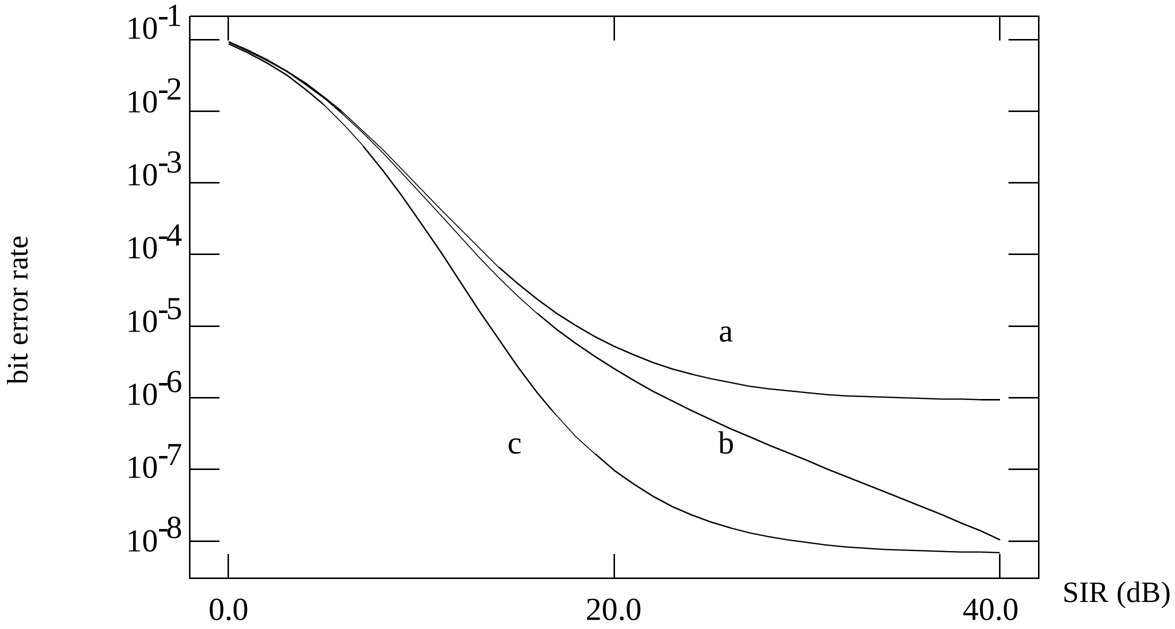
5.3 SPECTRUM EFFICIENCY

In this section, we address the performance of the base station-to-vehicle link in terms of the number of vehicle terminals that may be serviced per unit area, and the delay involved in servicing vehicles.

5.3.1 Packet Erasure Rates as a Function of Distance

The packet erasure rate has been assessed as a function of distance. Fig. 5.5 shows the results of the computation for cluster sizes (frequency reuse distances) of 1, 2, and 3 respectively. The distance between base stations has been normalized to 1, and the reference base station is at 0. Omnidirectional antennae are assumed, and (large scale signal attenuation) is used with path loss turnover distance $r_g = 0.25$ to compute the Signal-to-Interference ratio. The case of cluster size 1 shows a packet erasure probability close to unity at the halfway point between base stations. A reuse distance of 2 will yield packet erasure rates of about 0.007 at the cell edge. With a reuse distance of 3, packet erasure rates are very low: just over 10^{-3} at the cell edge (r=0.5) and about 0.1 at the position of the next base station (r=1.0).

Figure 5.5 Packet erasure rate versus normalized distance from transmitting station. Distance



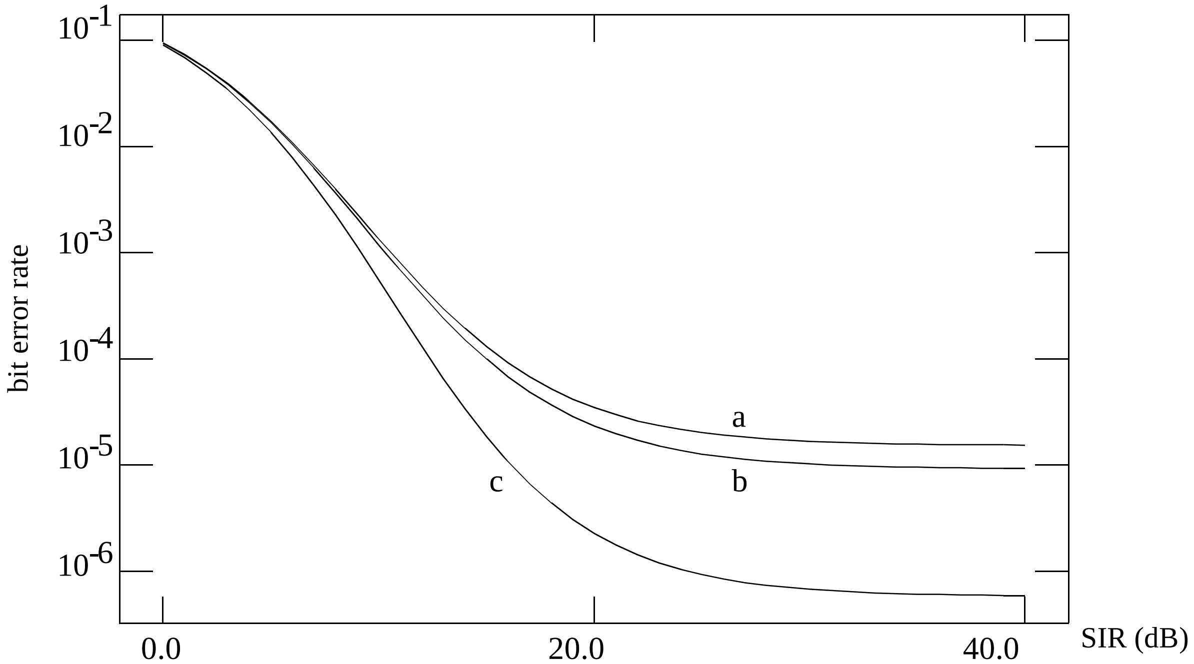


Figure 5.3 Local-mean bit error rates vs. signal-to interference ratio (17 dB SNR) (a)K_1 = 10, K_2 = 1.4 x 10^7; (b) K_1 = 10, K_2 = infinite; (c) K_1 = 16, K_2 = 1.4 x 10^7.

Figure 5.4 Packet error rate vs. signal-to-interference ratio (K_1 = 10, K_2 = 1.4 x 10^7, 17 dB SNR, nificant sources of interference. (See Fig. 5.1) Numerical results were obtained for the local-mean packet erasure rates with no error correction (M = 0). If the interferers are always on, then we have:

$$Q(r) = P(S|r, on) = \int_0^\infty f_p(p|\bar{p}) P\langle S|p, \bar{p}_t \rangle dp \, . \qquad (2)$$

The interfering sample is assumed to be Gaussian distributed with mean $\bar{p}_t$. Moreover, interference samples between successive bits are assumed to be statistically independent.

5.2.2.3 Numerical Results

Figures 5.2 and 5.3 show results for bit error rates as a function of the Signal-to-Interference Ratio (SIR) for different (average) Signal-to-Noise Ratios (SNR). The bit error rates are clearly rather sensitive to the value of K_1 which hence must be modelled appropriately. Figure 5.2 indicates that the first resolvable reflection and the excessively delayed component (their relative powers indicated by K_1 and K_2 respectively) are the limiting factors in a noiseless channel. In Fig. 5.3, the average ratio E_b/N_0 is taken to be 17 dB where E_b is the energy per bit, and N_0 is the one-sided spectral density of the noise. This choice of SNR was made to ensure that channel not be rendered unreasonably unreliable for AVCS purposes while at the same time not being unrealistically high. With a SNR of 17 dB, the bit error rates are of course generally higher than the noiseless case, but still acceptable in practical situations. Further, the bit error rates are less responsive to changes in SIRs above 30 dB because the system is limited by the Gaussian noise. The lowest bit error rate achievable as the Signal-to-Interference ratio diminishes in the noiseless case is over 1/10 times that when the SNR is 17 dB. The system is as such noise limited for reasonable SNRs.

In Fig. 5.4, the packet error rates for packets of 200 bits are calculated assuming slow fading and a SNR of 17 dB. This is a reasonable assumption, at 80 kbps and vehicle speeds of 65 miles/hour (11.3 m/sec), where a packet is transmitted during 6 cm of motion.

Figure 5.2 Local-mean bit error rates vs. signal-to interference ratio (noiseless channel): (a) K_1 = 10, K_2 = 1.4 x 10^7; (b) K_1 = 10, K_2 = infinite; (c) K_1 = 16, K_2 = 1.4 x 10^7.

5.2.2.1 Fast Fading

With fast fading, the duration of the packets is substantially longer than the time constants of the multipath fading. Further, we assume that during one bit time, the channel characteristics do not change. During reception of a packet, each signal is expected to experience several fades. If it can be assumed that the received amplitude and phase of all signals are statistically independent from bit to bit even though the receiver remains perfectly locked to the wanted signal, the probability of undetected packet errors for BPSK.

5.2.2.2 Slow Fading

For packets of sufficiently short duration, the received amplitude and carrier phase may be assumed to be constant throughout the duration of the packet. This condition is satisfied if the motion of the mobile terminal during the transmission time of a block of bits is negligible compare to the wavelength..

The interference power is the sum of powers from individual interfering base stations, found from the large scale path loss equation and using the appropriate distances and antenna gain factors. In a spatially uniform network with identical base station traffic loads and discontinuous transmission, the transmitter utilization $P(busy)$, i.e., the probability that its packet queue is nonempty, is equal to $P(on)$, the probability that a station's transmitter is switched on. If on the other hand a station transmits continuously even with an empty packet buffer, then $P(on) = 1$. Given the interferer locations or local mean received interference powers, the joint loacl mean interference power p_t becomes a discrete random variable because of random message traffic loads. The probability of successful reception (event S) at distance r from the test base station becomes:

$$P(S|r) = \sum_{\{\bar{p}_t\}} P(\bar{p}_t) \int_0^{\infty} f_p(p|\bar{p}) P\langle S|p, \bar{p}_t\rangle dp \quad (1)$$

where we averaged over all possible values of p_t and we relate the loacl-mean power p of the wanted signal to the location r. We consider the four nearest co-channel base stations as the most sighundred meters, propagation may well be approximated by a path loss law of the form a proposed by Harley. Some fades may occur becuse of wave cancellation of the line-of-sight and a (ground) reflection near the base station, but these effects do not substantially affect the coverage of cells or the handover process that takes place at cell boundaries.

We model the (delayed) scattered waves in two ways: early reflections with delays much less than the symbol duration. These scatters lead to Rician fading of the wanted signal. Measurements have indicated that for channels comparable to the short range channel addressed here, the Rician K factor may vary from 4 to 1000 (6 to 30 dB) [7]. From Bultitude and Bedal [8], we know that K = 7 dB ($K \approx 5$) is reasonable for most micro-cellular channels. In agreement with [5], computations in here assume K_1 = 10 (or 10 dB), where K_1 represents the Rician factor for early scatters.

On the other hand, late reflections cause intersymbol interference, which we approximate as a Gaussian source of interference, of power $1/K_2$ relative to the dominant line-of-sight. If we consider the excessively delayed components to have an exponentially distributed power delay profile with mean value of about $T_{rms} \sim 800$ ns, we find K_2 to be on the order of 1.4×10^7. This delay spread is a somewhat high estimate for some microcellular networks in an urban environment [9], so it presumably also overestimates channel dispersion in a highway propagation environment. As delay spread is modeled to cause Intersymbol Interference, our results tend to be on the pessimistic side. We'll show that its effect is nonetheless small.

For interfering signals, the propagation distance is significantly larger, and because of the relatively low antenna height, a line-of-sight component may not be present. In such cases, Rayleigh fading appears to be a reasonable model.

5.2.2 Probability of Packet Erasure

A packet erasure occurs when errors occur in excess of the correcting capabilities of error correction coding (assuming it is employed). 'Slow' and 'fast' Rayleigh fading of the wanted signal are considered using the same conditional expressions of bit errors.

5.1 INTRODUCTION

This text is concerned with the design, analysis, and computation of results for transmission across the physical channel, as well as specifying requirements to optimize spectral efficiency on the link between roadside stations and the vehicles. An optimum frequency reuse factor will be proposed to maximize network throughput and to minimize average queueing delays: the frequency reuse can be substantially more dense than is acceptable for cellular telephony networks. Studies on the communication requirements [17] for the link between vehicles and base stations indicate that generally, throughputs on the order of 5 to 80 kbps per cell are acceptable for the uplink, and more than sufficient for the downlink in Automated Vehicle Control Systems (AVCS). Also, frame sizes of 77 to 130 bits are typical, and delays on the order of a few seconds are acceptable for AVCS. In this text these parameters are used to study the performance of the roadside base station to vehicle link, with the physical limitations of the short-range highway propagation environment also being accounted for. Frequency reuse and antenna directionality are investigated in an effort to optimize spectrum efficiency and queueing performance at the base stations.

Section 5.2 describes the parameters of that were considered in this study.

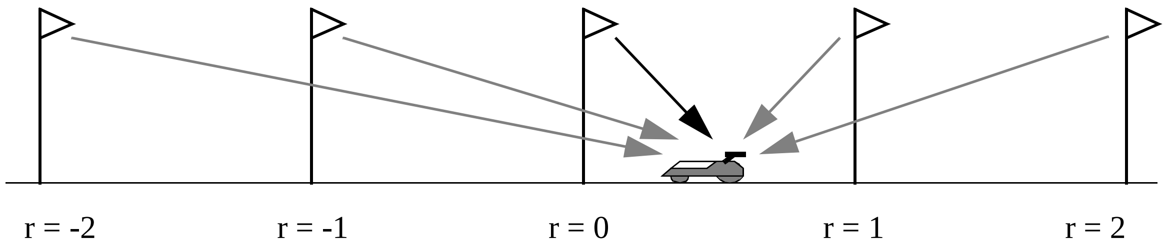


Figure 5.1 Model of base station to vehicle link for frequency reuse distance of one.

5.2 TRANSMISSION CONSIDERATIONS

5.2.1 Some Channel Parameter s

We assume that in a dispersive Rician fading channel. The effect of a strong ground reflection is not modelled explicitly. Our motivations here is that beyond a certain teurnover distance of a few

BASE STATION TO VEHICLE COMMUNICATION

This text addresses roadside-to-vehicle communication via radio channels. The access schemes and the radio transmission techniques have to be designed in order to minimize the adverse effects of Rician multipath reception. The limited availability of bandwidth and the need to accommodate the foreseen traffic make co-channel interference another important factor. Vehicle-to-base station communication involves initial competition for access to the base station. Once access to the station is secured a short communication session in which data is exchanged will follow. Base stations, on the other hand, are initially assumed to transmit independently of other co-channel stations. This text is concerned with the design, analysis, and computation of results for transmission across the physical channel, as well as specifying requirements to optimize spectral efficiency on the link between roadside stations and the vehicles. An optimum frequency reuse factor of 2 is proposed to maximize network throughput, and to minimize average queueing delays. We hence find that frequency reuse would be substantially more dense than is acceptable for cellular telephony networks.