Traffic Problems in Mobile Radio Networks

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Recent results of performance analysis studies of existent and future mobile radio networks are presented. The problems considered cover blocking during handover in cellular radio networks, mean progress per successful packet in multi-hop packet radio with transmit power control and directional antennas and modelling and analysis of mobility and impact of synchronization errors on short-range radio networks for inter-vehicle communication. Although most of the results presented were published already, access to them is limited for various reasons.

Verkehrsprobleme in Mobilfunknetzen

Der Beitrag präsentiert neue Ergebnisse der Leistungsanalyse bestehender und zukünftiger Mobilfunknetze. Berechnet werden Kenngrößen wie Blockierwahrscheinlichkeit beim Weiterreichen in zellularen Mobilfunknetzen, mittlerer Fortschritt je erfolgreich übertragenes Paket in multi-hop Paketfunknetzen mit gesteuerter Sendeleistung und Richtantennen, mobilitätsbedingter Verbindungsverlust benachbarter Stationen und mögliche Synchronisationsgenauigkeit in Nahbereichsfunknetzen. Die meisten der hier dargestellten Ergebnisse sind bereits veröffentlicht worden, jedoch überwiegend in schwer zugänglichen Publikationen.

Keywords: Performance analysis, handover, mobility, synchronization, multi-hop packet radio, directional antenna.

1. Introduction

Encouraged by the board of editors of this special issue an overview on traffic problems solved in our research group is presented using queueing theory methods. The results have been obtained recently during performance analysis studies of present and future mobile radio networks, an area of research, which has its early roots in the late seventies. The problems introduced are related to cellular radio for digital voice and data transmission, multi-hop packet radio and short-range mobile radio, considered to support road traffic efficiency, safety and security. Although most of the results presented have been published, access is limited since some publications are available in German only and not so easily accessible.

2. Impact of Mobile Radio on Performance Analysis

Propagation characteristics of radio waves result in a limited coverage of a given service area, due to physical influences on a transmitted signal received at a given location like fading, shadowing and propagation attenuation. The transmission medium is relatively unreliable, but this impact on a radio link can be eliminated quite satisfactorily well through channel coding techniques like combinations of forward error correction, bit-interleaving and error detection. Depending on the code rate applied to improve the reliability of a transmission channel, the resulting bit and block error rate performances can be adjusted to be sufficiently small. Nevertheless, the remaining bit error rate might be too high for a given service, which problem is solved by use of error-tolerant codecs at the receiver in case of voice, and by automatic repeat request (ARQ) protocols in case of data.

From the traffic performance analysis point of view, mobile radio networks differ in three important aspects from ground wired networks:

1) Stations (transmitters, receivers) are mobile. Mobility is not limited to time intervals, during which a silent station (being disconnected from the network) is moving from one to another location: this situation will soon become normal with the conditions of ground wired networks. In wireless networks, instead, stations communicate while being in move. Performance analysis then has to consider, which resources to allocate to a communication link in use and how resources are changed if neccessary (e. g. during handover in a cellular radio network). The handover performance under various channel reservation strategies is addressed in Section 3.1.
Section 3.2 addresses a similar problem related to inter-vehicle communication in future road traffic supporting radio networks, namely reduction of relative mobility of stations to reduce the frequency of handover events. The probability of interference of assigned channels is calculated for uni- and bidirectional motion of vehicles.
2) Frequency bands allocated for transmission are scarce resources, requiring extensive use of a given spectrum, making interferenc of a signal sent from a given transmitter to a receiver by signals of other coexisting transmitters a normal event. The notion collision is in use to characterize a situation, where two or more transmitters concurrently contribute to the signal strength received at a given station, which is not able to decode one of the messages. Apparently,

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performance analysis must distinguish between utilization of a given channel and resulting throughput at a receiver.
In Section 3.3 a packet radio network is considered and directional (small coverage) antennas are compared to omnidirectional ones in a multi-hop environment, where hidden stations contribute to interference. Further, we compare in Section 3.4 the performance of two acknowledgement protocols in a broadcast scenario. Another scenario is that of beacon-to-vehicle communication, where narrow antenna beams are used for dialogue communication with passing vehicles. We calculated the probability of recovery at a mobile station after a first collision in answer to a wake up signal issued by a beacon [1].

3) Synchronization of stations to a common time basis can be reached only to a limited precision, due to the unknown positions of moving stations in relation to a synchronizing master radio clock. Radio link capacity is wasted partly, since e. g. a slot of a TDMA communication system can carry a data burst of smaller length only, the difference being consumed by guard bits neccessary due to synchronization imprecision. In Section 3.5 we illustrate the analysis of a synchronization problem in a scenario, where external synchronization of stations is insufficient in precision and is supplemented by a decentrally operating, network internal adjustment procedure.

The space available to present analysis of these problems is limited. For each problem we therefore briefly present the model and procedure of calculation, followed by a short discussion of the results. More details can be found in the cited papers. Besides the problems discussed so far, we have applied stochastic simulation to investigate throughput and delay performance of the radio link protocol (RLP), the (non)transparent telefax transmission protocols and a new packet radio protocol defined for the Global System for Mobile radio communication (GSM) [2]. Similar studies were performed for the Digital European Cordless Telephone (DECT) [3] and the Trans European Trunked Radio System (TETRA) [4]; since this paper does not focus on simulation and results of mathematical analysis are not yet available, the interested reader might have a look at [5], [6], [7].

3. Models and Results

3.1 Handover with Channel Reservation in Cellular Radio

Handover (HO) is a procedure neccessary in cellular radio, to organize uninterrupted switching of a radio link in use from one serving base station to another, due to degradation of link quality. A HO is initiated usually by a centralized control unit and based on measurements of link related parameters like received signal level and quality observed by both, base and mobile stations. Two important goals have to be mentioned:

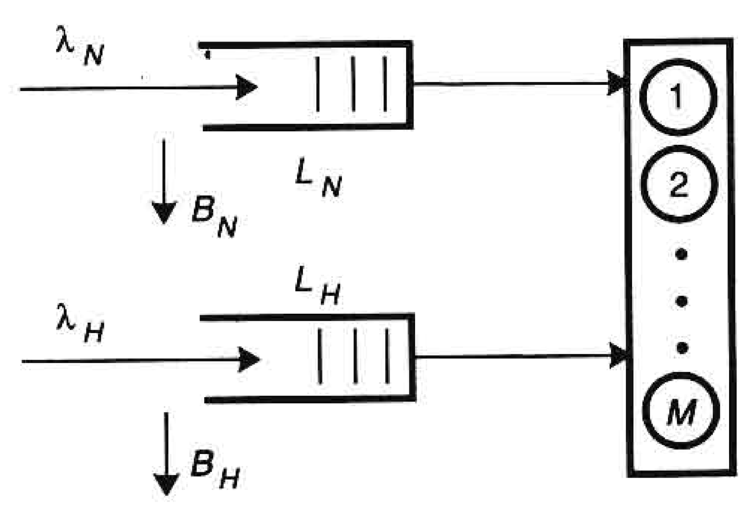


Fig. 1. A general reservation model.

a) a HO must be possible at any time with negligible probability of loss of a connection;
b) the allocation of a mobile to the new base station (a new cell) should be stable.

Sophisticated HO algorithms have been developed [2] to reach goal b). Simulation results can be found in [8], [9], which show e. g. that it is impossible to reach the optimum value of 1 HO per cell change. Instead, mean values of 1.5 up to 5 HO per cell change can be expected until stability is reached. Goal a) mentioned above is met at best if a number of channels from the trunk available in each cell is reserved for HO calls, exclusively. Different reservation strategies were studied so far. In [10], [11] the holding times of normal calls (NC) and of calls entering a cell via HO (HOC) were validated to follow approximately a negative exponential distribution. Since the arrival process of calls can be approximated well by a Poisson process (the traffic sources are independent and uncorrelated), the classical Erlang loss or delay-loss queueing models appear to be applicable. In [10], [11] a modification to these models has been introduced, where a number of channels, say r, is reserved for HOCs and NCs are not accepted at the trunk, if only r or less channels remain idle. The model, Fig. 1, is then suitable for analysis and can be solved using a discrete-state, time-continuous Markov chain where the state variable denotes the number of occupied channels plus queue positions. According to Fig. 1, λ_N and λ_H denote arrival rates of NCs and HOCs, respectively, M is the number of channels in the trunk and μ denotes the service completion rate of any type of call. Queues of delayed calls, which find all accessible channels occupied on arrival, are provided with length L_N and L_H. Most important performance parameters for NCs and HOCs are: probability of loss B, probability of delay, mean wait of delayed calls W and carried traffic Y on the trunk. It was shown in [11] that a queue for HOCs does not contribute much to reduce loss B_H for HOCs since W is nearly independent of r and too large to be acceptable during the HO procedure.

A queue of limited length proved advantageous to improve Y and reduce the loss probability B_N for normal calls, substantially, with still a small mean wait W. Summarizing, reservation of a small number of channels r for HOCs was shown to reduce their loss probability dramatically, with substantial increase of B_N. From a respective state diagram $B_N = \mathrm{P}\{i \geq M - r\}$

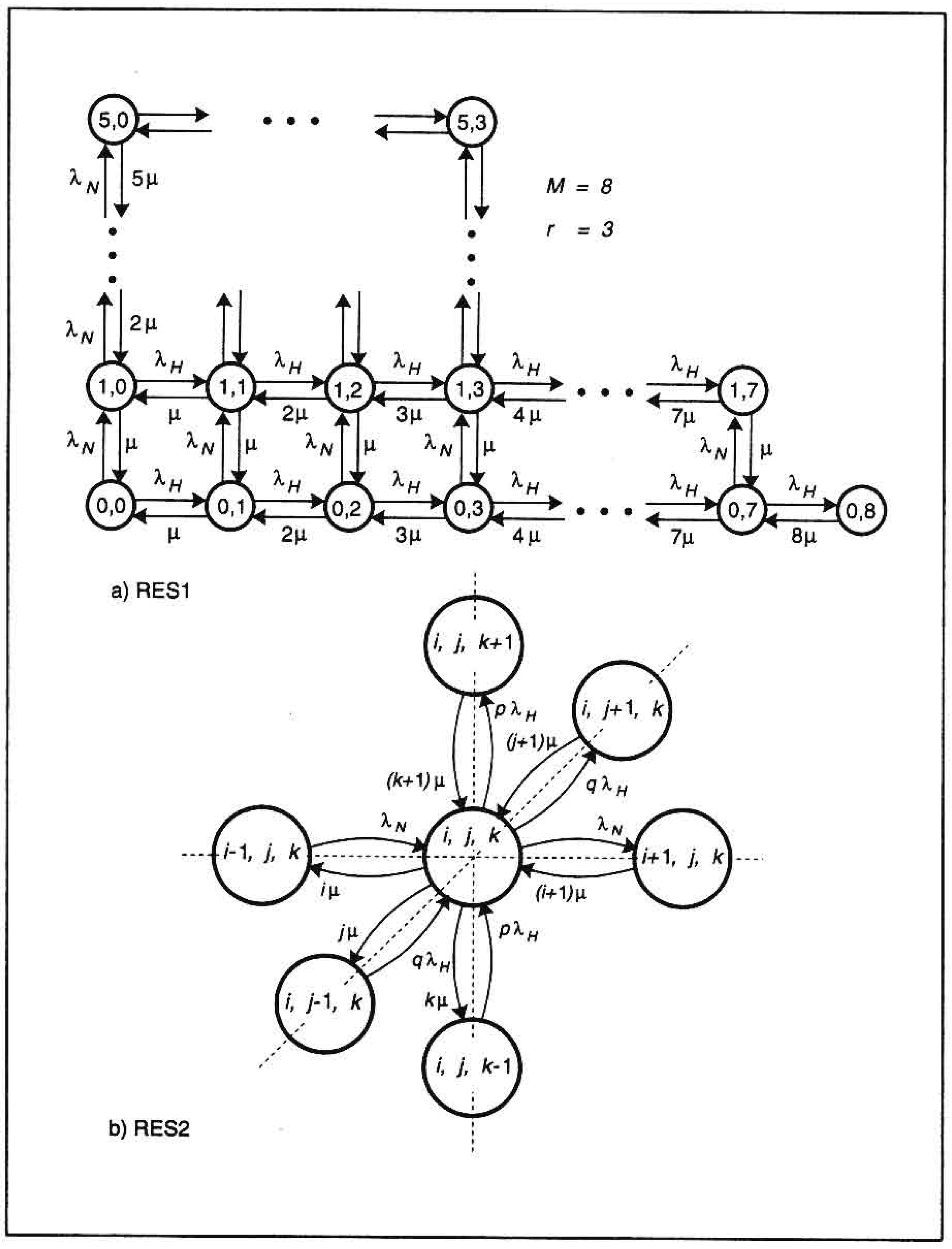


Fig. 2. State diagrams for strategies RES1 and RES2.

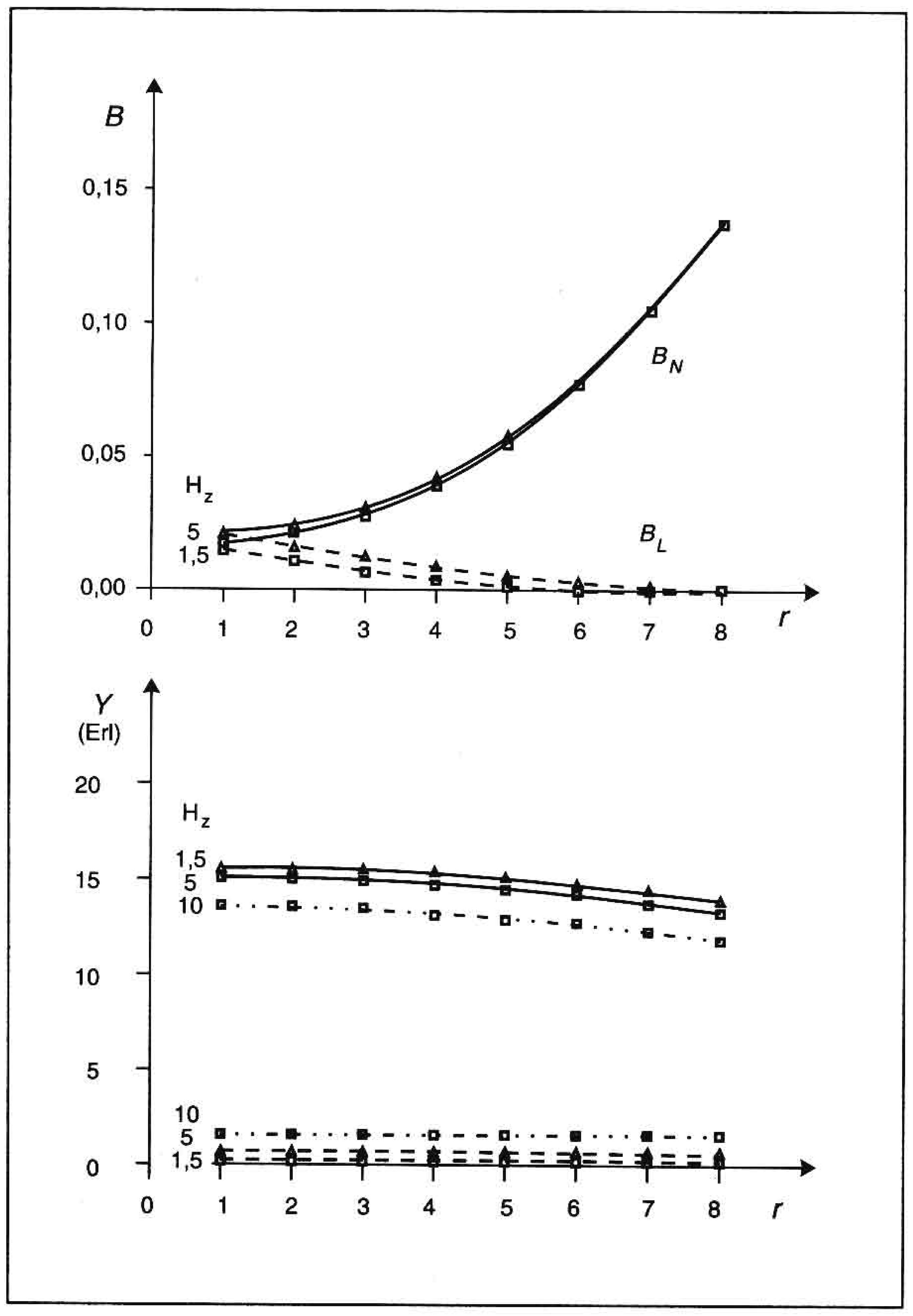


Fig. 3. Loss B and carried traffic Y as a function of the number of reserved channels r for reservation strategy RES2 [8]. Trunk size: $M = 23$.

and $B_H = \mathrm{P}\{i = M\}$ are directly derived with i denoting the state variable.

$$B_N = p_0 A^{M-r} \sum_{i=M-r}^{M} \frac{c^{i-M+r}}{i!}, \qquad (1)$$

$$B_H = p_0 A^{M-r} \frac{c^r}{M!} \qquad (2)$$

is the solution for a loss system [11], with total offered traffic A, offered traffic of HO calls c and probability of an idle system p_0. One might argue that reservation of r channels for HOCs, independent of the actual number of HOCs carried in a trunk, is too capacity consuming, especially for small trunks (e. g. $M = 23$ channels) as expected to be typical with the GSM system.

In [8] a modified reservation strategy RES1 was proposed, analysed and shown to be attractive: the trunk now accepts in total r HOCs only. The state variable now is two dimensional, (n_N, n_H) being the number of NCs and HOCs, respectively, holding a channel. A state diagram is shown in Fig. 2a. Results have been obtained numerically, applying sequential overrelaxation and are, in principle, contained in Fig. 3 ($H_z = 1$). A further refinement has been studied leading to the strategy RES2, including the additional arrivals to the model by HOCs, erroneously allocated to a base station, resulting in a short holding time before being handovered back or to another cell. The holding time of erroneous HOs was assumed in the numeric calculations to be 10% of the normal call holding time. The mean number H_z of HOs neccessary to find a safe change of cell is now included in the model, resulting in a 3-dimensional state diagram, of which one central state is shown in Fig. 2b. A state (n_N, n_{Hs}, n_{Hw}) denotes the combination of n_N NCs, n_{Hs} successfull HOCs and n_{Hw} erroneous HOCs. A HOC is successful with probability $q = 1/H_z = 1 - p$, where p is the probability of allocating calls erroneously. Since a HOC has to change the cell H times, the total loss probability $B_{H\mathrm{tot}}$ of a HOC for given B_H and H is

$$B_{H\mathrm{tot}} = B_H \sum_{i=1}^{H} (1 - B_H)^{i-1}. \qquad (3)$$

Since successful and erroneous HOs both face the same loss probability when trying to enter a cell, B_H is still the correct performance measure. Fig. 3 shows the RES2 results for probability of loss B and carried traffic Y over the number r of reserved channels for a small trunk with $M = 23$ channels. The mean number H_z of HOs neccessary until safe change of a cell is a parameter. (Results for RES1 with $H_z = 1$ differ not much from the curves for RES2 with $H_z = 1.5$). With increasing number H_z of HOs until stable cell change, both types of calls endure a higher loss, which influence is reduced in general with increasing number of reserved channels r. Since the trunking gain depends on the trunk size, loss of NCs increases with r the more dramatic, the smaller a trunk is. The carried traffic Y of HOCs appears independent and that of NCs nearly independent of the number of reserved channels r. The reason for that is the quite bad channel utilization being possible with such relatively small trunks. Main results are, that

a) with a non-optimized handover control strategy, resulting in a mean of 2 or more HOs, and with small trunk sizes M, a large number of channels r must be reserved for HOCs to reach a sufficiently small loss B_H. A consequence is that normal calls (NC) are served with a relatively high probability of loss B_N;
b) the carried traffic of a cellular system is remarkably reduced by a bad HO control algorithm, especially if the trunk size M is small.

3.2 Relative Mobility with Intervehicle Communications

To model the mobility of vehicles in road traffic, the following assumptions have been introduced:

a) mobile stations (MSs) are randomly distributed on a line of infinite length, on which they either move in one direction (uni-directional model, UDM) or into two opposite directions (bi-directional model, BDM); MSs move independently of each other and the distance of any two MSs is homogeneously distributed.
b) the number of MSs in a given segment of the line is defined by a Poisson distribution with density λ (MSs per line element).
c) MSs move along the line with a random speed defined by a normally distributed random variable v.

The density of speed distribution $f_{v1}(v)$ for the UDM and $f_{v2}(v)$ for the BDM then is

$$f_{v1}(v) = \frac{1}{\sqrt{2\pi}\sigma} e^{-(v-\xi)^2/2\sigma^2} = N_v(\xi, \sigma), \quad (4)$$

$$f_{v2}(v) = \frac{1}{2} N_v(\xi, \sigma) + \frac{1}{2} N_v(-\xi, \sigma), \quad (5)$$

where ξ and σ are the mean and standard deviation of a normal distribution. A reality near speed distribution on German highways is N_v(115km/h, 20km/h), [12]. $N_v(82,14)$ and $N_v(40,7)$ are assumed to represent rural road and city traffic, respectively. All have in common a coefficient of variance $\sigma/\xi \approx 0.16$.

The model used to analyze mobility on roads is shown in Fig. 4a. Stations move into direction d with positive speeds. S denotes a MS and R represents a radius around S, which can be interpreted as receive or interference radius with respect to another transmitting MS. $K_s = 2R$ is its radio coverage. S′ denotes a MS inside and S″ a MS outside K_s. Two interesting performance parameters of the model are the

- probability p_i that there are exactly i ($i = 0, 1, \ldots$) MSs, which move at time t inside (outside) K_s, respectively move outside (inside) K_s during Δt.
- mean number of MSs E[i], which leave (enter) K_s during a time interval Δt.

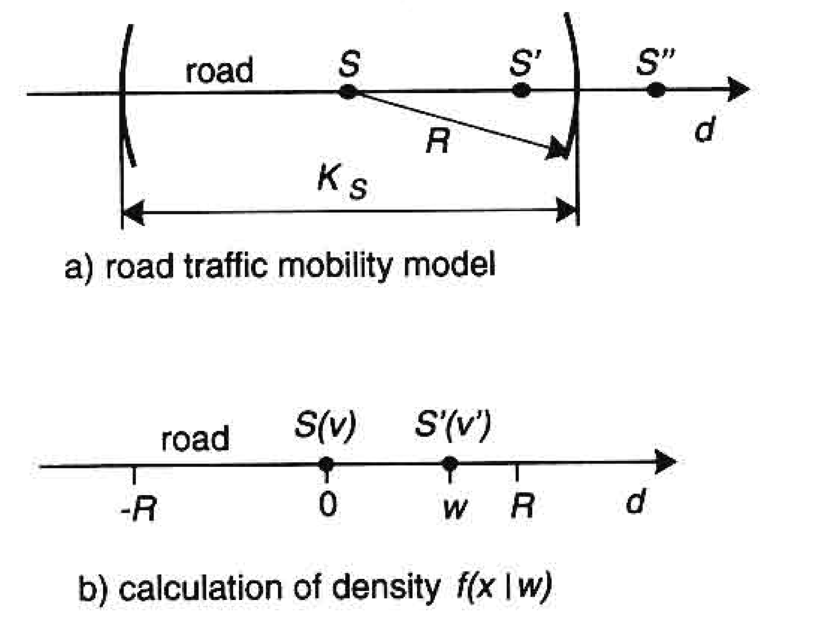


Fig. 4. Mobility model for Mobile Stations (MSs).

Under the assumptions made, p_i is the same for MSs entering and leaving K_s during Δt. Analysis of the model was published in [13] and is briefly repeated here. In a short-range mobile radio network for inter-vehicle communication, E_i defines the number of handovers neccessary after a frame duration Δt in a TDMA radio network, where MSs permanently hold one slot of the frame to transmit their status messages [14].

If n MSs are in K_s, the number of MSs, which leave K_s during Δt, was shown to be binomial distributed [15]. The probability $p_{i|n}$ that i ($i \le n$) MSs leave K_s during Δt is

$$p_{i|n} = \binom{n}{i} p^i (1-p)^{n-i}, \quad (6)$$

$p = \mathrm{P}\{\text{MS in } K_s \text{ at } t \text{ leaves } K_s \text{ during } \Delta t\}$.

Since the probability q_n that there are n MSs in K_s follows the Poisson distribution

$$q_n = \frac{(2\lambda R p)^n}{n!} e^{-2\lambda R p}, \quad (7)$$

we have the unconditional probability p_i that i MSs leave K_s during Δt

$$p_i = \sum_{n=i}^{\infty} p_{i|n} q_n. \quad (8)$$

According to Fig. 4b, let y be the absolute dislocation of S(v) at speed v during Δt, z be the dislocation of S′(v') at speed v' during Δt, $x = z - y$ be the relative distance change of S with respect to S′ during Δt. Further let w be the location of S′ with respect to S at time t. Apparently x, y, z are values of random variables X, Y, Z. Since Y and Z are assumed to be normally distributed, we have for UDM

$$f_{Y1}(y) = N_y(a, b) = f_{Z1}(z), \quad a = \xi\Delta t, \; b = \sigma\Delta t, \quad (9)$$

and for BDM

$$f_{Y2}(y) = \frac{1}{2} N_y(a, b) + \frac{1}{2} N_y(-a, b) = f_{Z2}(z). \quad (10)$$

The distribution density of the relative move x of S′ during Δt under condition w is

$$f(x|w) = \int_{-\infty}^{\infty} f_Y(w + z - x) f_Z(z)\, dz. \quad (11)$$

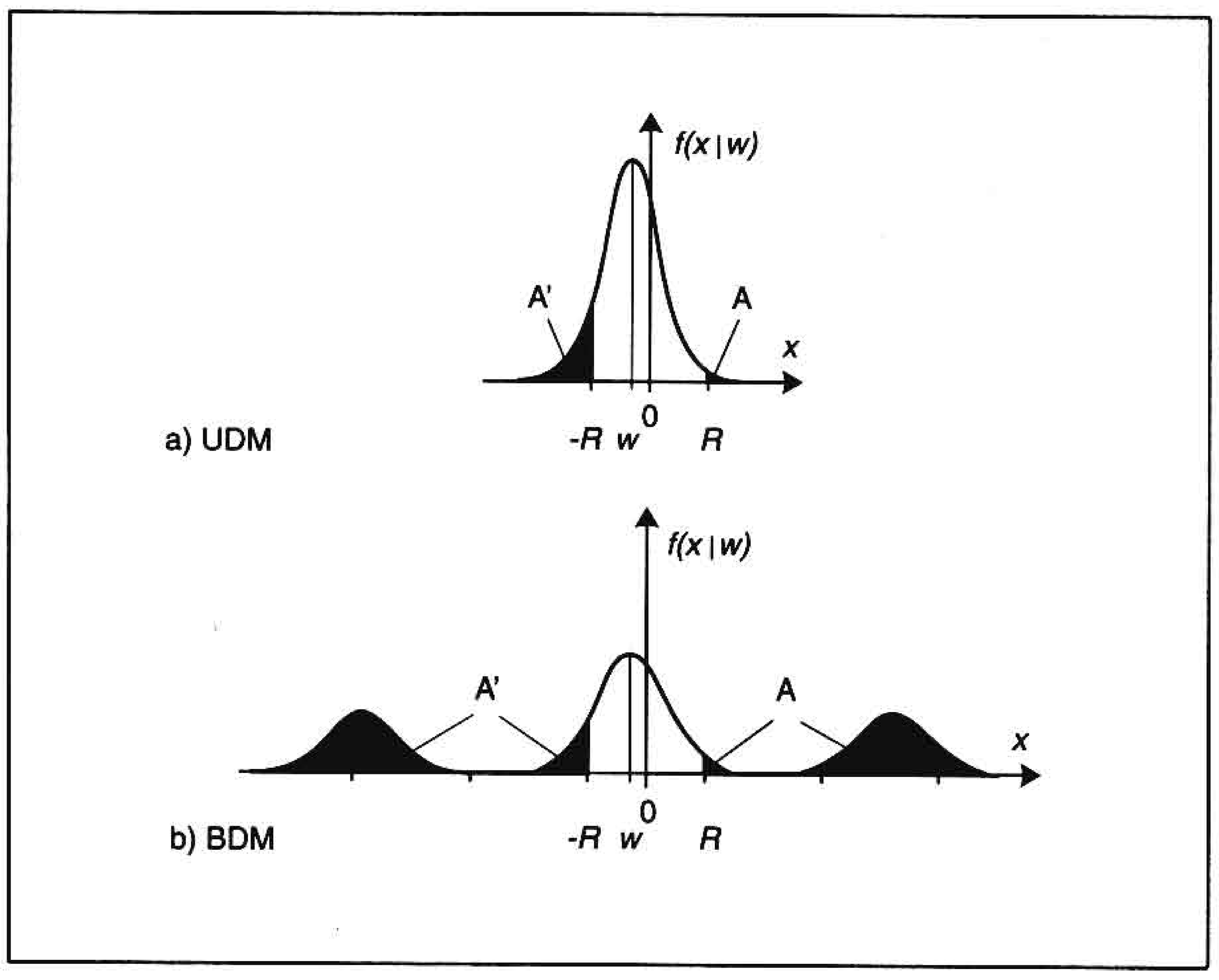


Fig. 5. Densities $f(x|w)$ for UDM and BDM.

Together with eq. (9) we get the conditional probability density of x for the UDM:

$$f(x|w) = \int_{-\infty}^{\infty} N_{z+w-x}(a,b) N_z(a,b)\,dz =$$

$$= \int_{-\infty}^{\infty} \frac{e^{-(z+w-x-a)^2/2b^2} e^{-(z-a)^2/2b^2}}{(\sqrt{2\pi}b)^2} dz =$$

$$= N_x(w, \sqrt{2}b), \tag{12}$$

which proves to be normally distributed and independent of the mean value of speed a. In a similar way we get for the BDM:

$$f(x|w) = \frac{1}{4}N_x(w+2a,\sqrt{2}b) + \frac{1}{2}N_x(w,\sqrt{2}b) + \\ + \frac{1}{4}N_x(w-2a,\sqrt{2}b). \tag{13}$$

According to Fig. 4a,b S′ can leave K_s during Δt under condition w only, if the relative removal x is larger than R or smaller than $-R$. It follows that

$$P_{\Delta w} = \mathrm{P}\{S' \text{ leaves } K_s \mid w' \le w \le w' + \Delta w\} = \\ = \int_{-\infty}^{-R} f(x|w)\mathrm{d}x + \int_{R}^{\infty} f(x|w)\mathrm{d}x, \tag{14}$$

see Fig. 5. Let $f(w) = (2R)^{-1}$ be the density of distance between S′ and S at time t. Then the unconditional probability to eq. (14) is for UDM

$$p = \mathrm{P}\{S' \text{ leaves } K_s\} = \int_w P_{\Delta w}\, f(w)\,\mathrm{d}w = \\ = \frac{1}{R}\int_{-R}^{R}\int_{R}^{\infty} N_x(w,\sqrt{2}b)\,\mathrm{d}x\,\mathrm{d}w, \tag{15}$$

and for the BDM

$$p = \frac{1}{R}\int_{-R}^{R}\int_{R}^{\infty} [\frac{1}{4}N_x(w+2a,\sqrt{2}b) + \\ + \frac{1}{2}N_x(w,\sqrt{2}b) + \frac{1}{4}N_x(w-2a,\sqrt{2}b)]\mathrm{d}x\mathrm{d}w. \tag{16}$$

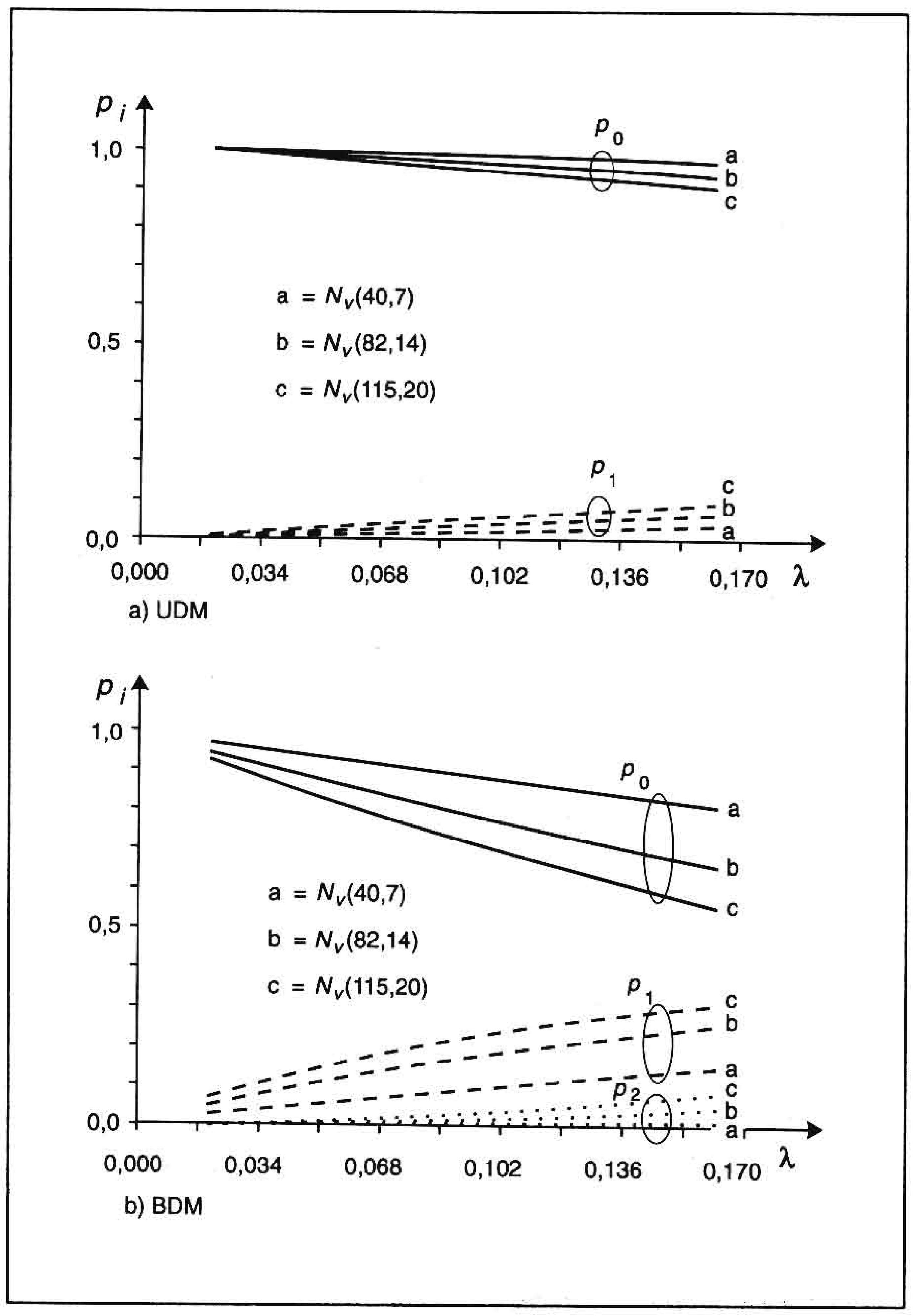


Fig. 6. Probability of connectivity loss p_i during Δt vs. intensity of vehicles λ for UDM and BDM, calculated for $\Delta t = 0.1$s, $R = 100$m. Curve parameter is the speed distribution eq. (4).

Finally, the mean number of MSs leaving K_s during the time interval Δt is

$$\mathrm{E}[i] = \sum_{i=0}^{\infty} i\,p_i. \tag{17}$$

Fig. 6a,b show numerical results for the probability p_i vs. station intensity λ that i MSs leave range K_s during Δt, for unidirectional and bidirectional models. It can be seen that network topology changes in the BDM are significantly more probable than in the UDM. Assume e. g. a speed distribution N(115,20) and $\lambda = 0.04$, $\Delta t = 0.1$, then the probability of a MS loosing radio contact to one of its neighbours in Δt is $p_1 = 0.0242$ for the UDM and $p_1 = 0.122$ for the BDM, which is 6 times larger. This was the reason for proposing the reservation of the subframes in the TDMA frame for MSs moving into different directions [14].

Fig. 7 shows that p_i over Δt changes for the UDM more slowly than for the BDM. For further results on p_i und E[i] see [13].

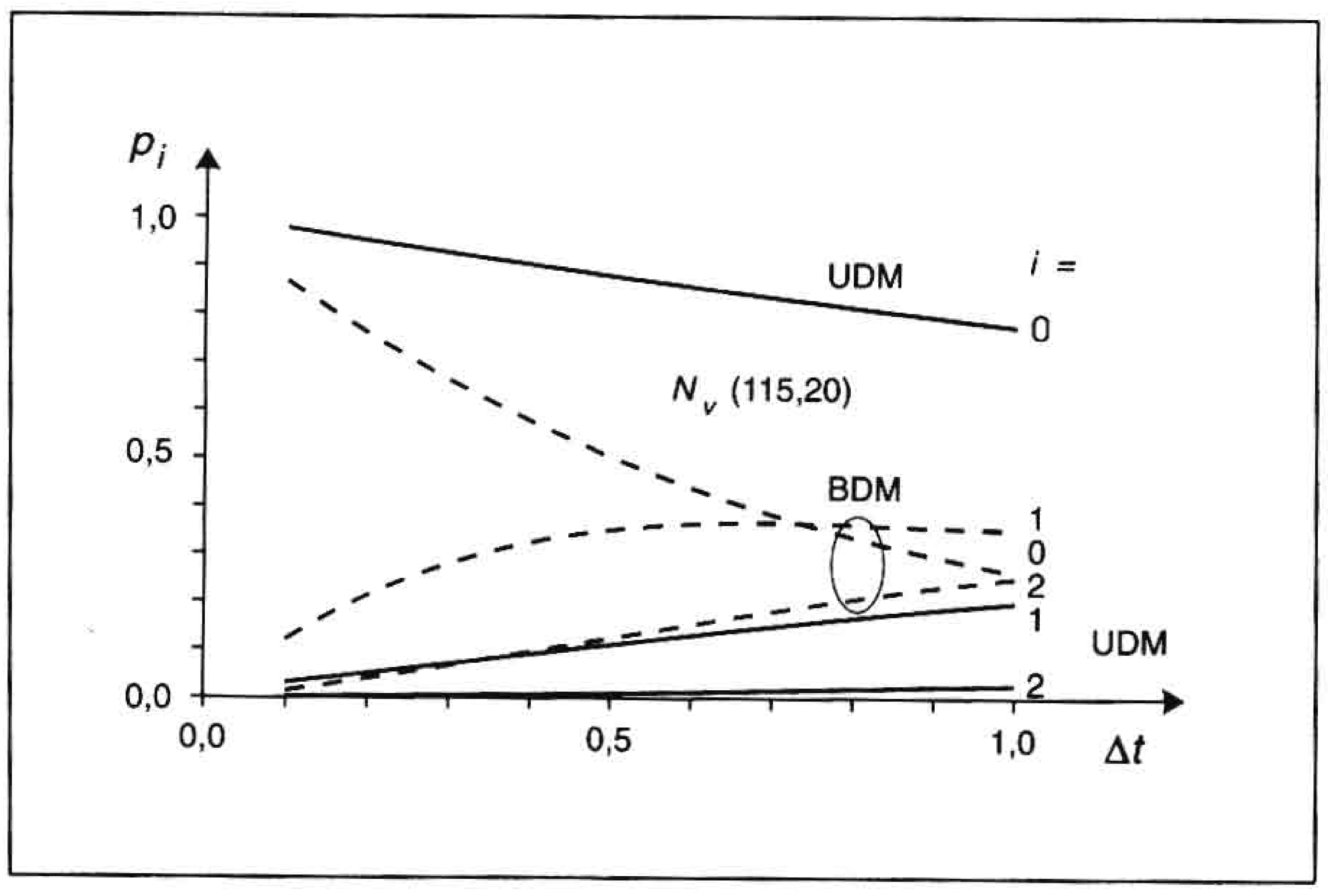


Fig. 7. Probability of connectivity loss p_i vs. Δt for UDM and BDM, calculated for $\lambda = 0.04$, $R = 100$ m.

3.3 S-ALOHA Multi-Hop Packet Radio: Throughput and Delay with Directional Antennas

Multi-hop packet radio is considered to be applicable to vehicle-to-beacon and inter-vehicle communication in future road traffic applications. One possible scenario is that

- external synchronization is available at all mobile stations (MSs);
- antenna coverage of MSs is circular, defining mobile cells with radius R and with radio connectivity between MSs if their cells overlap;
- MSs communicate by means of asynchronous data bursts (packets), transmitted in slots of a common radio channel under control of the S-ALOHA access protocol;
- the distribution of MSs in the plane is homogeneous with a constant intensity of vehicles;
- MSs communicate multi-hop under shortest path routing, relaying packets if neccessary;
- source-destination relationships between any MSs are equally probable;
- MSs always have a packet to transmit;
- MSs control their transmit power just to reach the next MS in distance $r \leq R$ on a route.

A model for the analysis of this scenario was introduced and analysed in [16], [17] based on the following assumptions:

- The interference model is simplified assuming a MS in distance r from a transmitter being able to receive, if any other concurrent transmitter has a distance greater than r from it. Otherwise a collision is assumed and the packet lost.
- A random distribution of identical MSs with intensity λ in the plane is presumed, resulting in a Poisson distributed number of MSs with mean $N = \lambda\pi R^2$ in a circle of radius R.
- Mobility is modeled assuming a new configuration of MSs after each slot.
- MSs transmit a packet with probabilty p per slot; acknowledgements are neglected.
- Packets are routed most forward within R.
- The arrival process of packets at MSs results from new packets, generated at a MS with probability p and relay packets, received from neighboured MSs. Clearly the system becomes unstable, if p exceeds a certain limit [18].

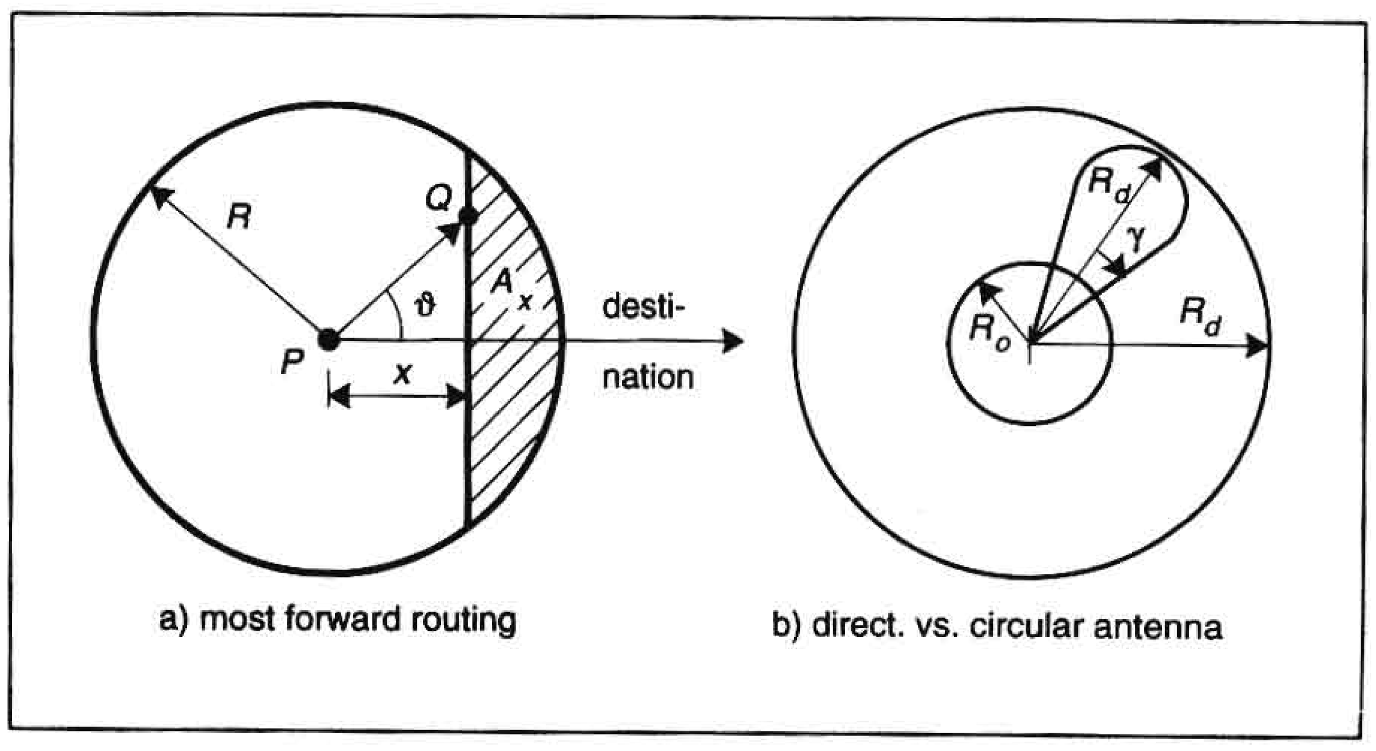


Fig. 8. Routing and antenna coverage models.

3.3.1 Performance Measures

The *one-hop throughput* $\mathrm{E}[S_1]$ is the mean number of successfully received packets per MS and slot. Computation of the mean source-destination throughput requires knowledge of the distribution of the needed number of hops h, which has been calculated in [18]. The *mean one-hop progress* $\mathrm{E}[Z_1]$ of a packet per slot to its final destination is suitable to compare different models and parameter settings [17]. ($\mathrm{E}[S_1]$ increases with decreasing mean number N of neighbours, but then requires more hops per source destination route). The *mean backlog time* $\mathrm{E}[D_1]$ of a packet counts from a first collision until successful transmission. For the complete analysis see [19].

3.3.2 Omnidirectional Antennas and Adjusted Transmit Power

The one-hop throughput S_1 of a MS, conditioned on the number i of neighbours, and the probability that i other MSs are in the random receive range r of a receiving MS are

$$S_1 = p(1-p)(1-p)^{i-1}, \tag{18}$$

$$P(i|r) = \frac{(\lambda\pi r^2)^i}{i!}\mathrm{e}^{-\lambda\pi r^2} \tag{19}$$

giving

$$\mathrm{E}[S_1|r] = p(1-p)\mathrm{e}^{-\lambda\pi r^2}. \tag{20}$$

From Fig. 8a the probability can be derived that a receiver is in distance r with angle ϑ towards the final destination

$$\mathrm{P}\{r < r' < r + dr, \vartheta < \vartheta' < \vartheta + d\vartheta\} = \\ = \mathrm{e}^{-\lambda A_x}\lambda r\, \mathrm{d}r\, \mathrm{d}\vartheta. \tag{21}$$

The area A_x contains no stations

$$A_x = R^2 a(t,\vartheta), \quad t = r/R, \quad g = t\cos\vartheta, \\ a(t,\vartheta) = \arccos g - g\sqrt{1-g^2}\,, \tag{22}$$

where r and ϑ are continuous random variables. Eq. (20) is unconditioned by integration over area A_x

$$E[S_1] = \int_0^R \int_0^{2\pi} \lambda r E[S_1|r' = r] \, e^{-\lambda A_x} \, d\vartheta \, dr =$$
$$= p(1-p)\frac{2N}{\pi} \int_0^1 \int_0^{\pi} t \, e^{-(pNt)^2} e^{-a(t,\vartheta)N/\pi} d\vartheta \, dt,$$
$$N = \lambda \pi R^2. \tag{23}$$

Following the notation of [16] the normalized mean progress of a packet is

$$E[Z_1]\sqrt{\lambda} = \left(\frac{2N}{\pi}\right)^{3/2} p(1-p) \cdot$$
$$\cdot \int_0^1 \int_0^{\pi} t^2 \, e^{-pNt^2} e^{-a(t,\vartheta)N/\pi} \cos\vartheta \, d\vartheta \, dt. \tag{24}$$

Assuming that the scenario of neighbouring stations does not change until the successful transmission of a collided packet, the mean backlog time $E[D]$ is calculated by taking the known expression of a fully meshed network [16]

$$E[D|i] = \frac{1-(1-p)^{i-1}}{p(1-p)^{i-1}}. \tag{25}$$

Multiplying it with the probability of occurrence $P(i|r)$ eq. (19) in the multi-hop network and summing up:

$$E[D|r] = \sum_{i=0}^{\infty} E[D|(i+2)] P(i|r), \tag{26}$$

which results in

$$E[D|r] = \frac{1}{p}\left(\frac{e^{-\pi\lambda p r^2/(1-p)}}{1-p} - 1\right). \tag{27}$$

Integration removes the condition

$$E[D] = \frac{2N}{p\pi} \int_0^1 \int_0^{\pi} t \left(\frac{e^{-pNt^2/(1-p)}}{1-p} - 1\right) \cdot$$
$$\cdot e^{-a(t,\vartheta)N/\pi} \, d\vartheta \, dt, \tag{28}$$

see the definitions in eq. (22).

3.3.3 Directional Antennas and Adjusted Transmit Power

The receiver antenna is still assumed circular; the transmitter uses a lemniscate type antenna pattern, Fig. 8b

$$\text{Lemniscate}: \; r_1^4 = R_d^2(x^2 - y^2) = R_d^2 r_1^2 \cos 2\gamma,$$
$$\text{Area}: \; A(t) = \frac{t}{\sqrt{\pi}}, \quad t = r/R. \tag{29}$$

Throughput and one-hop progress with spot-beam antennas are computed from eqs. (23) and (24).

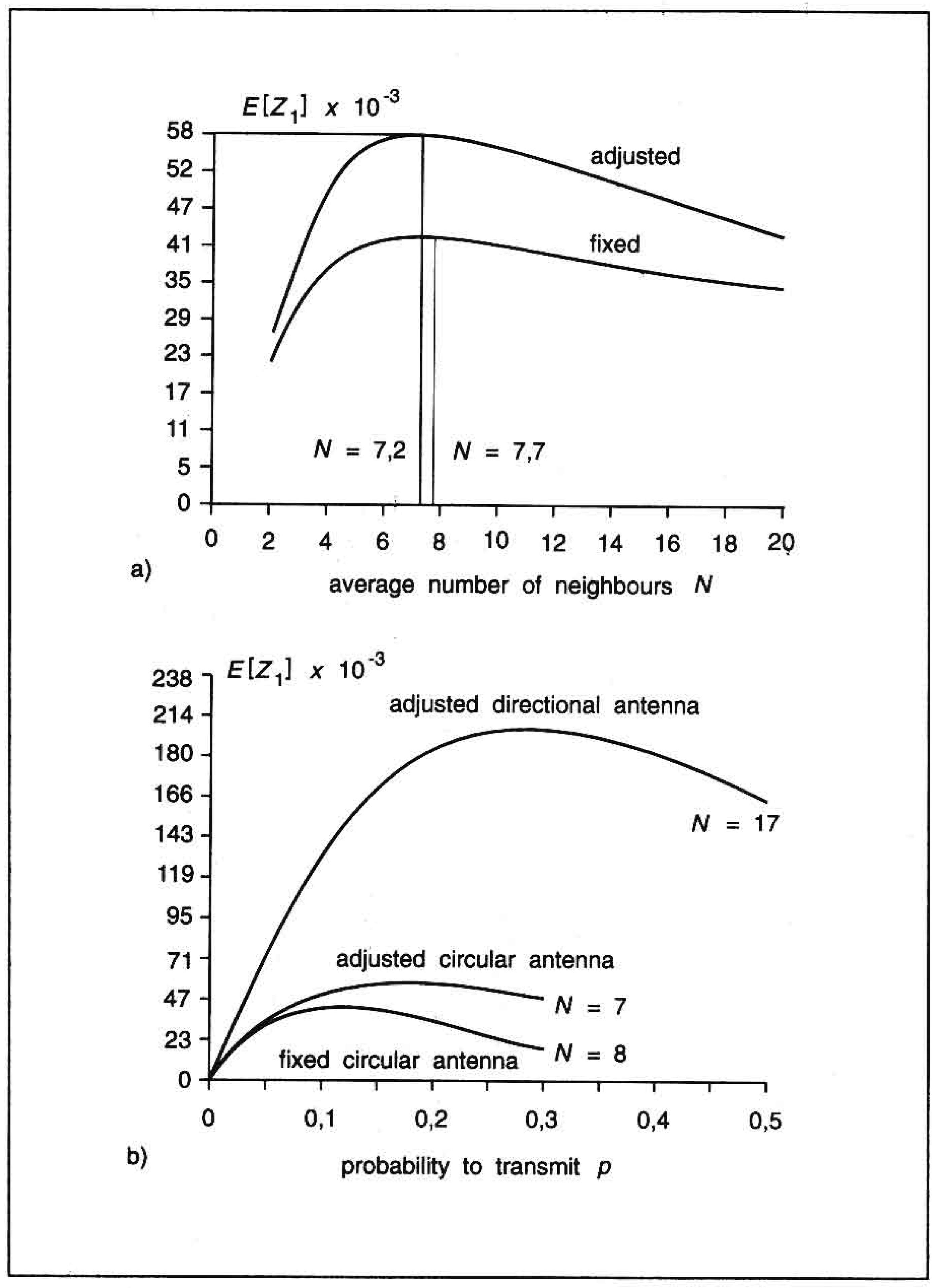


Fig. 9. Mean progress $E[Z_1]$ eq. (24).

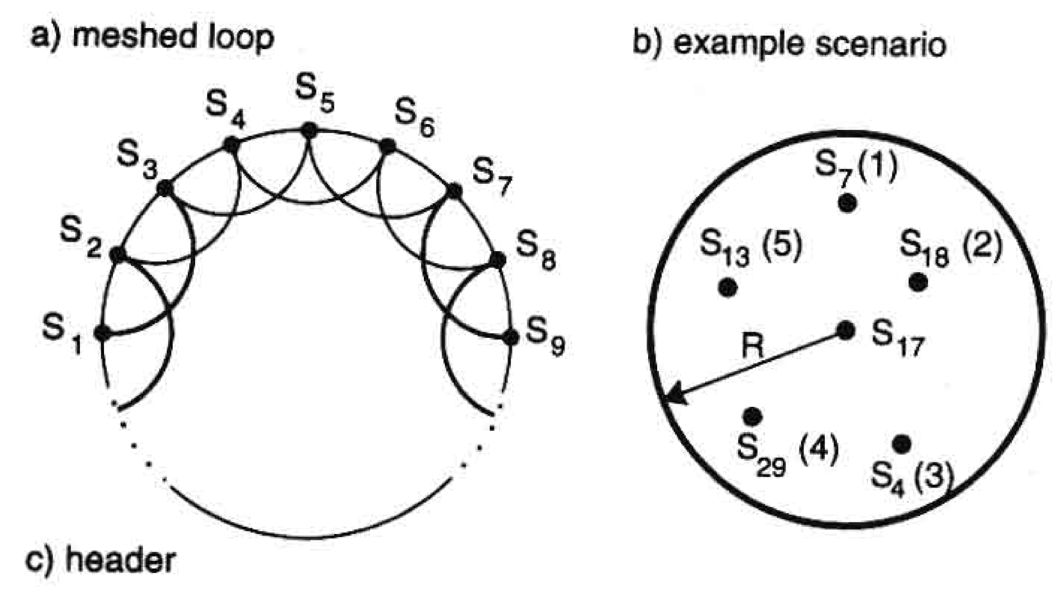
3.3.4 Numerical Results

It is well-known [17], that the mean progress $E[Z_1]$ of a packet per slot is maximized, if a station has a mean of $N = 7.7$ neighbours. Fig. 9a shows $E[Z_1]$ vs. N for both, fixed and adjusted transmit power. Adjusted power appears advantageous and the optimum value of N is shiftet to $N = 7.2$. The mean backlog time $E[D]$ is reduced with adjusted power, see [19]. With directional antennas and adjusted transmit power, the one-hop progress is much higher than with circular antennas, Fig. 9b. $N = 17$ proved to be optimum for the spot-beam antenna, eq. (29).

3.4 Echo- and Multiple-ACK in a Multi-Hop Environment

Automatic repeat request (ARQ) protocols are used in datacommunication applications. We consider a multi-hop packet radio network, like the one discussed in Section 3.3, but now concentrate on the performance taking acknowledgement (ACK) of packets on a per hop basis into account, assuming omnidirectional antennas. A deterministic network structure is assumed, but results are available also for a random network structure [20].

The echo ARQ scheme was analyzed in [21] by simulation: a MS, say S_1, after having transmitted a packet to another MS, say S_2, keeps the packet until S_2 is observed to repeat the packet during its attempt to forward



Header				S_7	S_{18}	S_4	S_{29}	S_{13}	
ADR	SZ (S_{18})	POS=2	S=5	4	4	0	1	6	data

Fig. 10. ACK-model assumptions.

it (whereby an implicit ACK is gained), otherwise, the packet is retransmitted by S_1 after a time-out T_0 has expired. Most of the ACKs are gained implicitly, there. The advantages of this protocol are accompanied by some drawbacks:

- the time-out T_0 must be chosen sufficiently large to reach a high probability that S_2 forwards the packet, whereby a fixed delay per retransmission is introduced;
- concurrent transmissions of MSs S_2 and S_1 result in a collision of the echo packet;
- an explicit ACK by S_2 is required, if S_2 is the final destination of a packet.

3.4.1 Analysis of the Echo-ACK Protocol

We consider a meshed loop with N being the number of neighbors which a MS reaches in one hop, see Fig. 10a. Packets are generated by stations with probability q_e per slot, resulting in a geometric arrival process of new packets at a station. Due to multi-hop communications, any station receives with probability q_r per slot a packet to be relayed. Any packet generated by a MS or received by a neighbor to be relayed is buffered, until a receipt for successful transmission was gained. Packets in a queue of MSs are transmitted with probability p.

Since the network topology is known, the mean number of hops of a packet, presuming random source-to-sink relationships, is

$$H_{n,N} = \frac{K+1}{n-1}\left(\frac{KN}{2} + n - 1 - KN\right), \qquad (30)$$

where $K = \mathrm{Int}[(n-1)/N]$ is the number of direct neighbors to a MS. Since $q_r = q_e(H_{n,N} - 1)$, and an explicit ACK is needed from the sink during T_0, the source transmission probability per slot of a MS is

$$q_s = (H_{n,N} + 1)\, q_e\,. \qquad (31)$$

Due to collisions, a packet is successful only with probability

$$P_s = (1 - q_s)^N = 1 - Q_s\,, \qquad (32)$$

where Q_s is the probability to collide. A packet needs j repetitions until success with probability

$$\mathrm{P}\{J = j\} = Q_s^j P_s\,,$$

with mean number of repeats

$$\mathrm{E}[J] = Q_s / P_s\,. \qquad (33)$$

The mean number of transmission attempts of a source MS is

$$E\,[S] = E\,[J] + 1 = (1 - q_s)^{-N}. \qquad (34)$$

The mean number of transmissions of a destination MS, until receipt of an explicit ACK is [20]

$$E\,[D] = \sum_{i=1}^{\infty}\{i + (i-1)E\,[S]\}Q_s^{i-1}P_s. \qquad (35)$$

The mean number of transmission attempts of a relay MS is calculated, considering the probabilities of all possible combinations of transmissions and receipts of implicit ACKs [20]

$$E\,[R] = P_s^2 + \sum_{i=2}^{\infty} iA + \sum_{i=2}^{\infty} BA + {} + \sum_{i=2}^{\infty} iQ_s^i P_s + \sum_{i=2}^{\infty} BQ_s^i P_s\,, \qquad (36)$$

where

$$A = Q_s^{i-1}P_s^2, \quad B = \{i + (i-1)\mathrm{E}[S]\}.$$

From that, the total transmission probability of a MS per slot can be derived

$$q_{\mathrm{tot}} = \frac{E\,[S] + (H_{n,N} - 1)E\,[R] + E\,[D]\, q_s}{1 - H_{n,N}}. \qquad (37)$$

3.4.2 Specification and Analysis of the Multiple-ACK Mechanism

The packet header structure of Fig. 10c was designed for the multiple ACK protocol. The address ADR of a neighbor MS, followed by the sending MS's transmit counter SZ with respect to that MS, followed by an indicator POS giving the position of the receive counter of the addressed MS, occupy the first three fields of the header. Field four contains the total number of receive counters contained in the header, the respective couter values follow then. The transmit and receive counters are both used as usual with the HDLC protocol. A receiving MS, implicitly gets an ACK via its own receive counter observed in the packet. The ACK might be positive or negative with respect to the last or even earlier packets. To keep buffers small, counters are incremented mod 8, as usual. A formal specification of the protocol, together with a description of its drawbacks and advantages, compared to the Echo protocol, is contained in [22]. The length of the time-out T_0 is assumed to be m slots. During the time-out, the mean number of transmits of a MS is

$$\mathrm{E}[V] = m\, q_{\mathrm{tot}}. \qquad (38)$$

The mean number of negative ACKs, say NAKs, and of positive ACKs is [20]

$$E[T_{\mathrm{nak}}] = m q_{\mathrm{tot}} \left[1 - (1 - q_{\mathrm{tot}})^N\right], \quad (39)$$

$$E[T_{\mathrm{ack}}] = (P_1 + m q_{\mathrm{tot}})(1 - q_{\mathrm{tot}})^N - m q_e,$$

with P_1 the transmission probability of a packet during m slots under transmission probability p

$$P_1 = 1 - (1 - p)^m. \quad (40)$$

Fig. 11a shows analytic and simulation results of the mean values $E[T_{\mathrm{ack}}]$ and $E[T_{\mathrm{nak}}]$ transmitted by any MS, vs. the source transmission probability q_e with the time-out length m as a parameter for clusters of size $N = 6$. Not all packets are received by neighbor MSs. According to eq. (40), the mean number of received positive and negative ACKs are

$$E[R_{\mathrm{nak}}] = E[T_{\mathrm{nak}}](1 - q_{\mathrm{tot}})^N, \quad (41)$$

$$E[R_{\mathrm{ack}}] = E[T_{\mathrm{ack}}](1 - q_{\mathrm{tot}})^N. \quad (42)$$

Fig. 11b shows analytic and simulative results of $E[R_{\mathrm{ack}}]$ and $E[R_{\mathrm{nak}}]$, over q_e with m as a parameter over source transmission probability q_e. Time-out length is m and cluster size is $N = 6, p = 0.35$.

As can be seen, the mean number of NAKs increases substantially with increased q_e, while the ACK curves have a maximum dependent on m. The mean one-hop throughput S of acknowledged packets of a MS is shown in Fig. 11c

$$S = q_{\mathrm{tot}}(1 - q_{\mathrm{tot}})^N. \quad (43)$$

Although for the Echo protocol throughput values can be computed for $q_e > 0.005$, the simulated network is unstable there and no throughput is possible. The multiple-ACK protocol is stable up to $q_e = 0.01$ and a maximum throughput about twice that of the Echo protocol is possible. The overhead bits needed by the header consume about 4 % of the transmit capacity, if a packet size of 1 kbit is assumed.

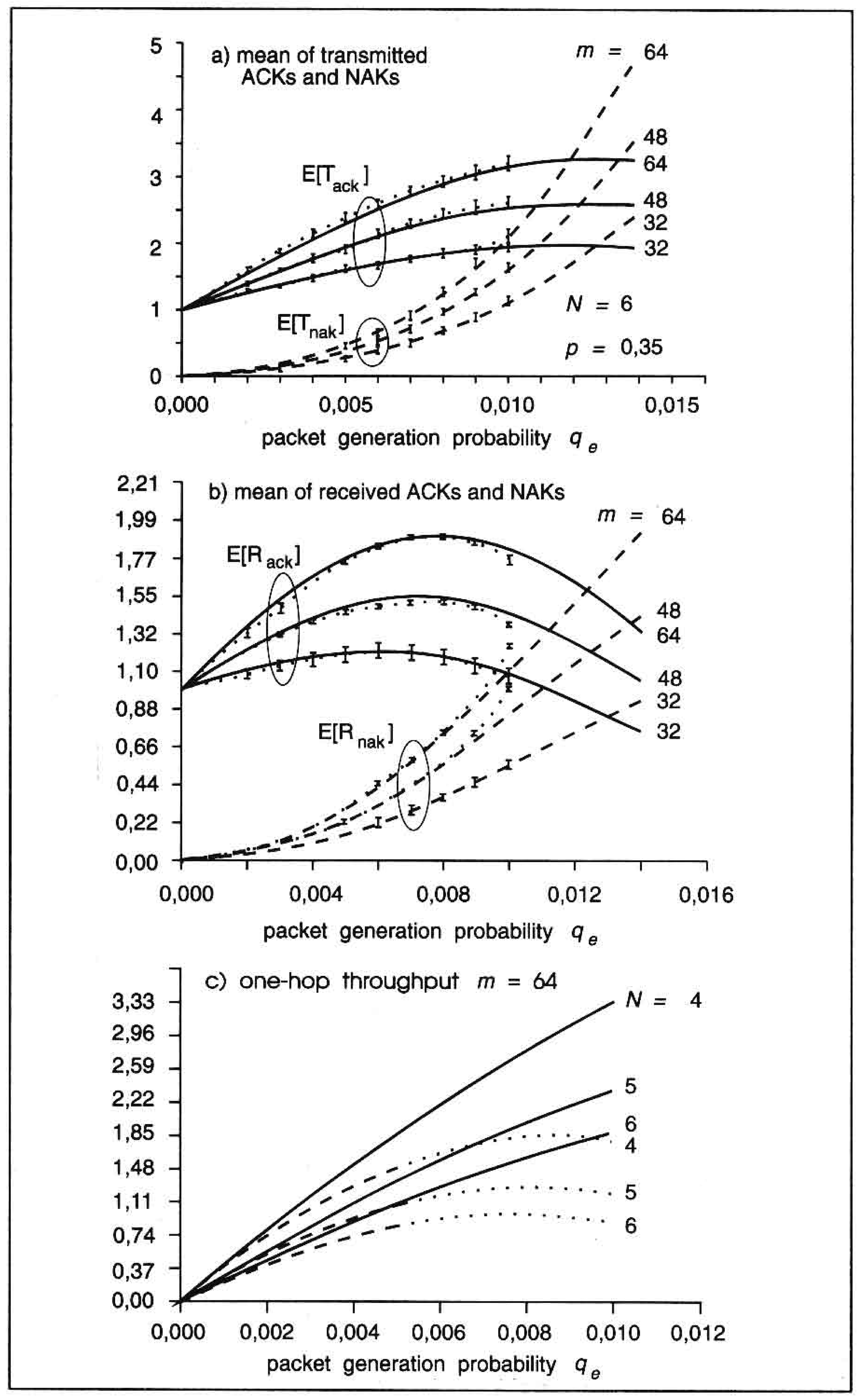


Fig. 11. Multiple-ACK results.

3.5 Synchronization with Global Clock and Local Adjustment

The problem considered is related to the short-range mobile radio networks mentioned in Section 2. A synchronous TDMA transmission system was designed [14] to provide a trunk of some hundred TDM-channels to be independently used for continuous broadcast of MS's status 10 times/s. MAC protocols to organize interference free operation of the channels were introduced in [14], [15]. The proposed TDM-frame length is 100ms and the slot duration is some hundred μs. Apparently, a synchronization precision up to some μs is required, at least for MSs being within their respective interference ranges, since otherwise their slots would overlap. We propose to use a radio clock transmitter to externally synchronize, whereby a precision of about 1ms is reached, and to decentrally adjust the clock to the precision desired [23]. Two facts were taken into account:

a) the transmit radius of a MS in the network is quite below 1km, equivalent to a propagation delay of 3.3 μs,

b) the carrier frequency of the radio clock signal is 77.5 kHz, with a period of about 12.7 μs.

MSs are assumed able not only to detect the falling shoulder (about 1ms in length) of the periodic 1s signal of the radio clock, but also to quantize it by the period $T = 12.7\ \mu$s of the carrier, resulting in a large number of discrete time instants as possible synchronization points for a frame start, say SP. Any MS is assumed to select the synchronization point SP′ "in the middle" of the shoulder as an operating point for frame start and to reserve one slot of the frame to be exclusively used as a TDM-channel, according to the MAC protocol applied in the network [14], [15]. According to facts a) and b) mentioned above, any MS hearing any other MSs is able to decide with sufficient precision, which SPs were chosen by the other MSs. One global rule suitable, to synchronize all MSs being in their respective receive ranges is to follow that MS, having chosen the earliest SP. This would result in a "subnetwork" containing a random number of MSs, each of which is connected at least via one MS to some others. Apparently, different subnetworks cannot be expected to be synchronized to each other. The problem analyzed in the sequel is, how large the size of the synchronization error of different subnetworks is. The answer is neccessary to dimension the data burst length transmitted in a slot, leaving sufficient spare guard time to be able to coexist with concurrent subnetworks.

A better global rule, currently under investigation, is to apply a decentrally controlled voting algorithm of MSs inside a subnet, aiming at approaching the middle of the radio clock's impulse shoulder; this rule was found to reduce the synchronization error of subnetworks substantially [23].

3.5.1 Analysis

In the analysis, due to W. Zhu, two assumptions were made:

- a SP′ in the middle of a shoulder selected by a MS (out of k possible SPs on the radio clock signal shoulder) follows a discrete probability function $P(p)$ with the shape of a normal distribution

$$P(p) \approx N_\xi(p) = \frac{1}{\sqrt{2\pi}\sigma} e^{-(p-\xi)^2/2\sigma^2}, \quad p = 1, 2, \ldots, k, \quad G_\xi(\beta) = \sum_{j=\beta}^{k} N_\xi(j), \tag{44}$$

  where p counts in multiples of T and $G_\xi(\beta)$ is the compl. distribution function.
- the receive range is set equal to the interference range.

The mean difference $E_1[d]$ between SP′ and the optimum synchronization point SP_0 ("mean synchronization error") is given by

$$E_1[d] = \sum_{p=1}^{k} d\, P_{\xi p} \tag{45}$$

with

$$P_{\xi p} = P\{|\xi - p| = d\} = \begin{cases} P\{\phi_{-p}\} + P\{\phi_{+p}\}, & d \neq 0, \\ P\{\phi_0\}, & d = 0. \end{cases}$$

$$P\{\phi_\alpha\} = P\{\text{Net with } n \text{ MSs has } \xi + \alpha \text{ as a SP}\},$$

$$P\{\phi_0\} = N_\xi(p) \sum_{i=1}^{k} \left[G_\xi^{n-i}(p) \cdot G_\xi^{i-1}(p+1)\right]. \tag{46}$$

The mean difference $E_2[d]$ of SPs ("mean synchronization error") chosen by two subnetworks approaching each other, comprising a number of n and m MSs, respectively, is given by

$$E_2[d] = \sum_{d=0}^{k} d\, P\{|p_n - p_m| = d\}, \tag{47}$$

where p_n and p_m are the respective random variables of the subnetworks according to eq. (44). The probability $P\{|p_n - p_m| = d\}$ is given by the expression

$$P\{|p_n - p_m| = d\} = \sum_{p_n=0}^{k} \Big\{ N_\xi(p_n + d) \cdot \sum_{i=1}^{m} \left[G_\xi^{m-i}(p_n + d) \cdot G_\xi^{i-1}(p_n + d + 1)\right] + N_\xi(p_n - d) \sum_{i=1}^{m} \left[G_\xi^{m-i}(p_n - d) \cdot G_\xi^{i-1}(p_n - d + 1)\right]\Big\} \cdot N_\xi(p_n) \sum_{i=1}^{n} \left[G_\xi^{n-i}(p_n) \cdot G_\xi^{i-1}(p_n + 1)\right]. \tag{48}$$

Fig. 12a shows the mean synchronization error of the chosen SP (counted in carrier periods T), depending on the number n of MSs in a subnetwork, according to eq. (45) with σ as a parameter. The larger σ is, the larger is the mean error with respect to the ideal synchronization point SP_0. Of interest is the synchronization error of two subnetworks introduced by the decentral adjustment algorithm. Fig. 12b shows the mean synchronization error over the size n of one subnetwork in case of $\sigma = 2, k = 77$ according to eq. (47). The size m of the other subnetwork is a parameter. What can be seen is that the error is the larger, the more the networks differ in size. E. g. two networks with $n = 50$ and $m = 2$ have a mean error of about $3.5T = 45.5\mu s$, which is quite large. From Fig. 12a it is clear that the deviation from SP_0 of the SP chosen in a subnetwork increases with increasing number of MSs. If a subnetwork is defined "complete" comprising at least $N = 10$ MSs, i. e. no additional MSs joining the subnetwork are allowed to change the current SP used, but are forced

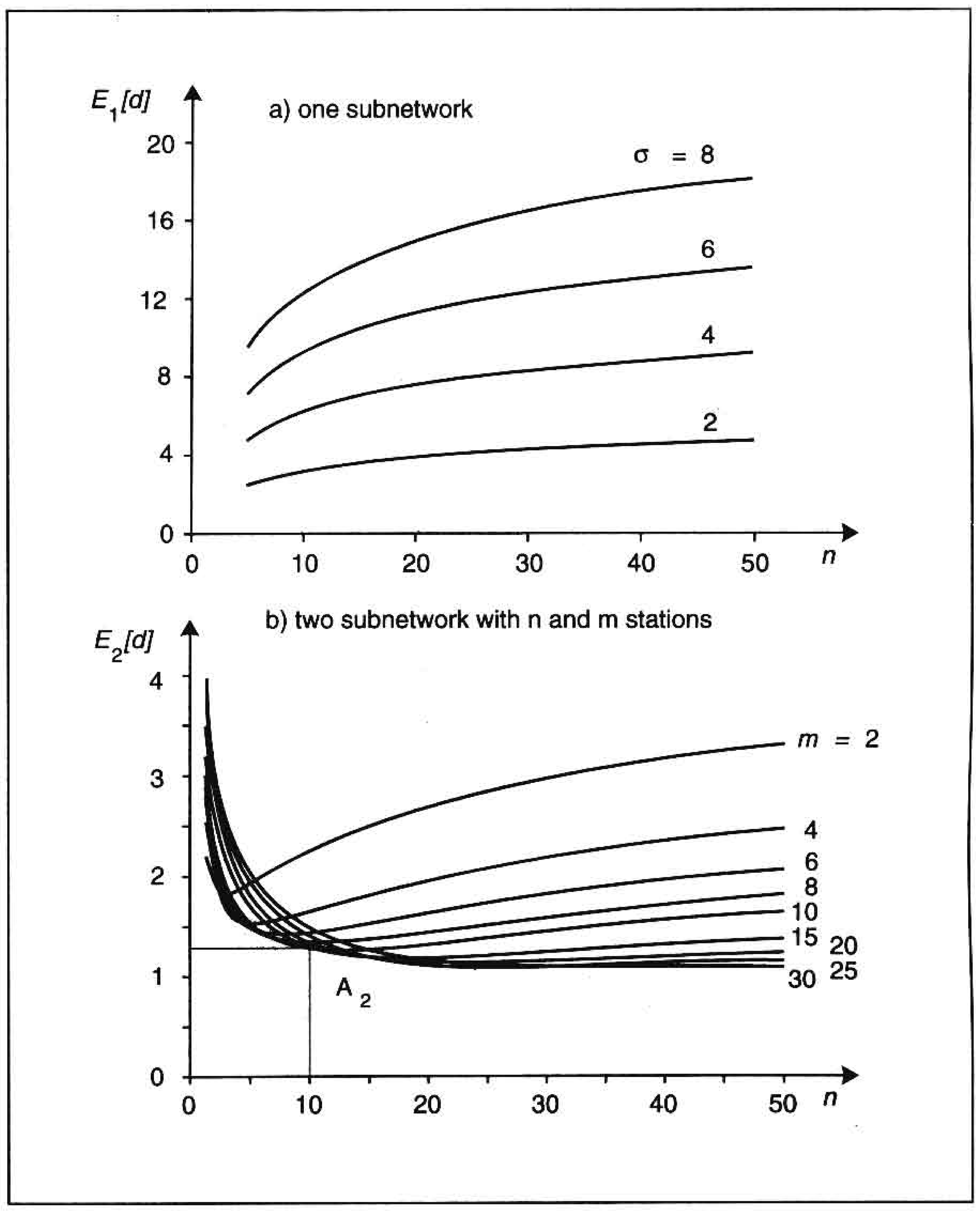


Fig. 12. Mean normalized synchronization error versus number of MSs in one subnetwork.

instead to follow the actual SP, the mean synchronization error between subnetworks is reduced to a value of about 1.5 carrier periods, see point A_2 in Fig. 12b.

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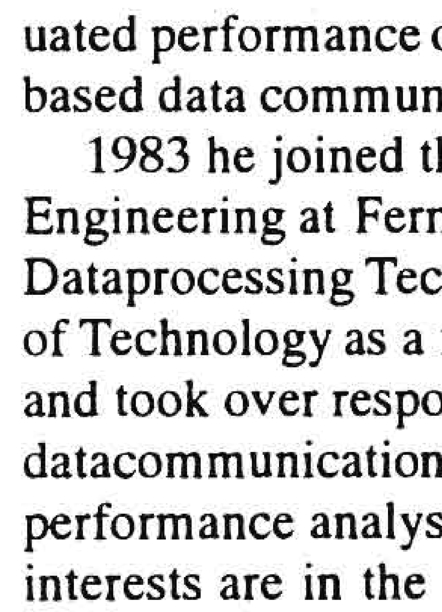

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