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Virtual Cellular Network: A New Wireless Communications Architecture with Multiple Access Ports

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Abstract. A "virtual cellular network" (VCN) is proposed to provide wireless random access for bursty multimedia traffic to a fixed backbone infrastructure. A VCN does not use a conventional cellular frequency reuse concept. In a VCN, each terminal sends packets using the entire system bandwidth while any nearby port can pick up the signal. Then, the ports relay the packets to the port server (PS) over a fixed (wired) network. Ports can be simple radio receivers as they do not have to support the same functionality as conventional cellular base stations. The performance is investigated in terms of probability of capture, throughput and delay. Both our analysis and simulation show that despite its simplicity this network has a larger user capacity than conventional cellular reuse patterns.

Keywords: random access, cellular networks, ALOHA, fading channels, frequency reuse, spectrum efficiency.

1. Introduction

Wireless communications attracted much attention especially for applications such as mobile telephony, indoor wireless data network and multimedia wireless computing [1]. New services require significantly larger user capacity and bandwidth efficiency than cellular systems currently offer. In order to achieve high user capacity in a wireless network, the radio spectrum must be used in an efficient manner. Typically the spectrum efficiency is defined as the number of bits successfully transmitted in a given time period, within a given frequency band occupied in a certain area. That is, the system architect aims at optimizing the throughput per $\text{Hz} \cdot \text{sec} \cdot \text{m}^2$, rather than per $\text{Hz} \cdot \text{sec}$ as addressed in most random access schemes proposed for wired networks. This adds a new dimension to design of efficient access schemes.

In the traditional cellular concept, this problem is separated into two independent parts: the available radio channels are *spatially* reused in a regular pattern to ensure that adjacent cells use different channels, while within each cell a *temporal* multiple access scheme is used to organize the traffic from many independent terminals. In most existing cellular networks, the operation of the access scheme is independent from neighboring cells, even if radio resources remain unused in adjacent cells. However, the scarce spectrum resources can be used substantially more effectively if one succeeds to find an integrated approach for dynamically assigning time-bandwidth and area resources [2]. This is fundamentally different from the two-step

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procedure in which at first, portions of the bandwidth are uniquely assigned to particular areas and secondly in each cell the remaining bandwidth is shared by a multiple access protocol.

In this paper, a new cellular communication architecture, called a "virtual cellular network" (VCN) is proposed in order to improve the requirements such as increasing user capacity, simplicity of the protocol to ensure low power consumption and suitability for heterogeneous traffic. We derive the joint throughput of multiple cooperating receive ports and evaluate the performance of the multiple access protocol.

The motivation for this study was the design philosophy used for the "Infopad" system at the University of California at Berkeley, where an indoor wireless multimedia network with portable terminals is developed [1]. In order to minimize the power consumption in the terminal, most of communication protocols and application computations are performed in the backbone network and its compute servers, making the mobile terminal merely an multimedia Input/Output device. The uplink traffic (terminal-to-system) in the Infopad system includes key pad input, voice command and hand-writing (pen) input. As these messages arrive according to a very bursty pattern and require high reliability, a random access protocol, with retransmission of packets lost in collisions can be more effective than a CDMA system [5]. The downlink in Infopad is based on a pico-cellular code division multiple access (CDMA) broadcast system to provide independent video and data information to each mobile terminal within a network area. It is expected that a data rate of 2 Mb/s per user will be needed to support full motion video services. Direct sequence (DS)-CDMA transmission method appears to be significantly more suitable for multiplexed downlink (video) transmission than for uplink random access transmission (of control and key pad data). An analysis was reported earlier in this journal [3]. In the uplink, signals arrive over different channels and with random code synchronization offsets, which erodes the orthogonality of the arriving signals. So, the advantages of CDMA over random access ALOHA with slow frequency hopping appeared less evident [5].

Following this introduction, the concept of VCN and its architecture are described in Section 2. A communication protocol of the VCN is proposed in Section 3. Probability of capturing the VCN and throughput are derived in Section 4, and delay of speech packets is investigated in Section 5. Conclusions are in Section 6. Related work on random access schemes involving multiple cochannel base stations has been reported by Zorzi et al. (e.g. [14, 15]). Their CDPA scheme exploits predictable transmissions attempts in multipacket transmissions, whereas this paper focuses on single packet transmissions.

2. Virtual Cellular Network

The basic concept of the VCN is two held: First, a VCN uses the entire frequency band for each link. Secondly, in a VCN there are no conventional base stations (BS's) which manage channel assignments and handovers. In a VCN, however, simple receiving *ports* are used. It is known that the throughput of a wide-area cellular ALOHA network with multiple receiving base stations is optimized if one takes cluster size 1, i.e., all base stations listen to the same (wideband) radio channel [4, 18]. This throughput gain over conventional seven or nine cell reuse schemes is particularly evident if radio receivers are able to detect signals in the presence of interfering signals from other terminals at a somewhat larger distance. The rationale is that in this case each terminal can use the entire system bandwidth, which shortens the packet duration and consequently reduces the traffic load on the channels.

From an engineering point of view, it can be preferable to split the uplink bandwidth B_u into several, say K, parallel random access channels of bandwidth $B = B_u/K$. Each terminal then randomly selects an uplink frequency for each transmission. This is particularly effective if $B \ll B_c \ll B_u$ where B_c is the coherence bandwidth of the channel. In such case, the ports do not have to perform channel equalization (as $B \ll B_c$). Moreover the random slow frequency hopping (SFH) ensures that the channel fading becomes independent from transmission to transmission. This increases the fairness of the network and enhances the stability as terminals in a bad spot do not produce excessively many retransmissions [13]. SFH would also make the system better suitable for operation in Industrial Scientific and Medical (ISM) bands, for which spreading in mandatory.

In the next section we assume that this SFH scheme is used effectively. As the results do not depend significantly on K, we focus on a network of fixed B_u and omit a further discussion of K.

A *virtual cell* is defined as the area in which the received signal has enough power to capture a port when no other terminal is transmitting any packet within a sufficiently large area to interfere. The size of a virtual cell is determined by the transmit power, propagation attenuation and channel noise, but not by interference from elsewhere in the system. Whenever a terminal sends a packet, a virtual cell for the packet is (virtually) generated during the packet transmission time. A virtual cell does not have a dedicated port, as in a conventional base station, but the group of ports within a virtual cell provide site diversity which helps to combat multipath fading. In contrast to existing cellular systems, the VCN is *not* designed such that signals from outside a virtual cell never interfere with the transmission inside the virtual cell. If multiple users transmit, their virtual cells may overlap to any extent, and it highly depends on the topology of ports and terminals whether none, one, multiple or all of the transmitted signals are received successfully.

A *port server* (PS) concentrates packets from the terminals within the network area, and sends them over a backbone network to their destination. Figure 1 shows the terminals (a, b, ...), ports (A, B, ...), virtual cells (circles) and a PS during a slot time. Each port is connected to the PS via *port network*. A port network may have a passive bus topology, and it should have enough bandwidth to accommodate the traffic generated in the network area.

A PS also performs the duplication resolution protocol (DRP) in order to select only one packet among possibly duplicated packets as more than one port may receive the same packet. This DRP will be described in Section 3.2. By performing the DRP at the PS rather than at a port, the communication protocol of the terminal can be simplified resulting in small power consumption. The traffic in the port network, however, will be increased due to duplicate packets. We can say that the sacrifice of bandwidth in the “wired” port network will improve the bandwidth efficiency in the “wireless” part.

3. Communication Protocol

The communication protocol of a VCN is composed of a wireless multiple access control (MAC) protocol for terminals, and a multiple access protocol in the port network. We will describe the uplink and downlink protocols on the wireless link, and the port network protocol.

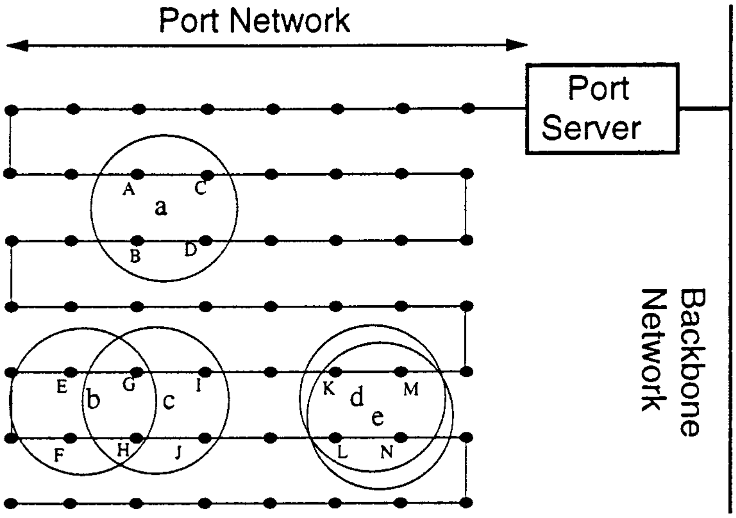

Figure 1. Virtual cellular network: virtual cells (circle) for five simultaneous mobiles (a, b, ..., e) and active ports (A, B, ...) during a slot time.

3.1. Uplink Protocol

The uplink protocol in a VCN is based on a random access protocol, viz. slotted ALOHA, rather than a centrally controlled scheme. The basic advantage of the random access protocol is its simplicity and flexibility. Furthermore, it will be shown that unlike the conventional slotted ALOHA network without capture, the VCN can have high throughput even if the traffic is relatively predictable, as in speech communications.

In a VCN, as illustrated in Figure 1, each terminal transmits packets randomly, according to the slotted ALOHA protocol and retransmits it if no acknowledge arrives within a predetermined time duration. Any packet successfully received at the ports is sent immediately to the PS. Whenever the PS receives a packet, it updates the *active-port table* which includes the following elements:

user-id, *input-port*, *signal-quality*, *received-time*

When b and c transmit packets simultaneously, signals of ports G and H will suffer strong interference, therefore packets from b and c will be sent to PS through port E and I respectively. When a packet from a terminal fails to capture any port it will not be acknowledged through the high speed downlink and will be retransmitted after a backoff delay. We refer to [16] and [17] for optimizations of the retransmission scheme if multiple receive ports are involved and contiguous frequency reuse is applied.

Another function of PS is to trace users based on uplink received signals and to route traffic in the downlink.

3.2. Duplication Resolution Protocol (DRP)

At the PS, a DRP is required to select only one copy of each packet from any terminal. Many schemes can be used for DRP, some of which are modifications to known diversity combining methods. In a very basic implementation, all duplicated packets which arrive after a correct packet will be discarded. This simple algorithm minimizes the processing delay in the PS. In order to distinguish the duplicated packets and a new packet from a user, a sequence number of modulo-M is used. The size of M will depend on the delay characteristics of wired (port) network. For a fast port network, relatively small values of M suffice.

In a second scheme, the PS receives all duplicated packets but chooses the copy with the smallest Hamming distance to a valid code word. The PS, however, does not know the number of duplicate packets in advance. Therefore a timer is required in building the active-port table. The value of the timer will be determined by the maximum latency of the port network. Although this solution exploits macrodiversity more effectively, for simplicity of analysis our mathematical evaluation is based on the former scheme. Further improvements are to carry reliability or soft decision information to PS and to combine information from various ports.

PS also keeps track of the port number from which best signal was received for each user. This channel information can be used for the downlink to select the best (set of) port(s) to transmit packet to terminal.

3.3. Downlink Protocol

The downlink of a VCN can also exploit the virtual cellular concept as in the uplink protocol. However they need not to be symmetric to each other. Ideally the PS should send downstream data through the port which received the best upstream signal. DS-CDMA allows that more than one port is used to “multicast” downstream packets in order to increase the performance [6].

In this paper, we focus on the performance of uplink protocol. The case of an ALOHA channel with a Poisson field of interferers was previously studied, e.g. by [7–11]. For acknowledgment of uplink packets, we assume that there is a reliable downlink channel in a VCN. It is noted that the acknowledgment signal is not originated from the port but from the PS, unlike the conventional cellular network.

3.4. Port Network

The port network interconnects the PS and all ports in the network area covered by the PS, and carries both upstream (from terminal to PS) and downstream (from PS to terminal) data. We assume that there is no direct user data exchange between ports. In view of packet delay and stability, a star topology will be the most appropriate one for a port network. However considering practical installation, a passive bus network will be suitable for the port network. If the IEEE 802.6 Distributed Queue Dual Bus (DQDB) is used, one bus can be exclusively used by the PS for downstream transmission and the other bus will be used for uplink transmission from ports to PS. Another possible advantage of DQDB is its easy interworking with ATM-based backbone network.

4. Performance of VCN

In order to study the performance of a VCN, we will first derive the probability of capture for a simple VCN which has 4 ports, and extend it to a wide-area VCN assuming that ports are arranged in a regular patterns (see Figure 3). We compared it with simulation results. Secondly, the throughput-delay characteristics of speech packets in the VCN are obtained by numerical analysis.

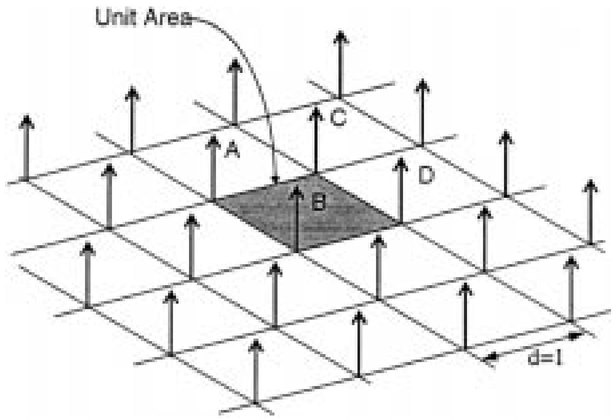

Figure 2. Rectangular pattern of ports in a VCN. Distance between ports, d is normalized to 1.

4.1. NETWORK MODEL

This subsection describes the model for analysis and simulations of VCN. A Rayleigh fading channel is assumed. The received mean signal power, is a function of distance between terminal and port, and is found from Harley's (normalized) expression [12]

$$S(x) = x^{-2}\left(1 + \frac{x}{r}\right)^{-2}, \tag{1}$$

where r is the turnover distance in the path loss model.

At a port (e.g., port A) we assume that a signal from the k-th terminal captures the port successfully if the received signal power $S_{A,k}$ satisfies the following condition.

$$S_{A,k} > z\left[\sum_{l=1}^{n} S_{A,l} + \nu\right], \tag{2}$$

where $S_{A,l}$ is the received interference power from user l, z is the receiver threshold and n is the total number of interfering terminals within the network area during a slot time (thus the wanted signal k is not included in the summing), and ν is the mean power of additive white noise.

The number of simultaneous users in a network area is large and the packet size is small (e.g., compatible with the ATM cell). We assume that the input traffic, composed of various services, will be Poisson. It is assumed that terminals are uniformly distributed and packets are generated according to a spatial Poisson process.

In this paper, we assume that the slot timing in uplink is perfect. Offering multiple parallel channels with SFH ($K \gg 1$), rather than a single wideband channel facilitates timing reduces the overhead caused by guard times needed to ensure sufficient synchronization.

4.2. PROBABILITY OF CAPTURE

First, we express the probability of capture for a terminal assuming that there are only 4 ports (e.g. ports A, B, C and D in Figure 2). We normalize the size of this rectangular area closed by A, B, C, and D to unity. The probability of capture over wide area can be obtained by periodically repeating the results for a 4-port network. A basic assumption of this approach is that the signal of a terminal located in the unit area closed by A, B, C and D can capture only A, B, C, or D, even though it may capture farther ones.

If the offered traffic per unit area at location $\underline{x}_i$ is given by $G(\underline{x}_i)$ (expressed in packets per slot per area), the probability that the signal from terminal j captures at least one port (A, B, C or D) can be written in the lengthy, but mathematically well-structured form

$$\begin{aligned}
Pr(A_j \cup B_j \cup C_j \cup D_j|\underline{x}_j) &= \exp\left\{-\int\int_{\text{area}} W_{A,i}G(\underline{x}_i)d\underline{x}_i\right\} \\
&+ \exp\left\{-\int\int_{\text{area}} W_{B,i}G(\underline{x}_i)d\underline{x}_i\right\} + \exp\left\{-\int\int_{\text{area}} W_{C,i}G(\underline{x}_i)d\underline{x}_i\right\} \\
&+ \exp\left\{-\int\int_{\text{area}} W_{D,i}G(\underline{x}_i)d\underline{x}_i\right\} - \exp\left\{-\int\int_{\text{area}} W_{A,B,i}G(\underline{x}_i)d\underline{x}_i\right\} \\
&- \exp\left\{-\int\int_{\text{area}} W_{A,C,i}G(\underline{x}_i)d\underline{x}_i\right\} - \exp\left\{-\int\int_{\text{area}} W_{A,D,i}G(\underline{x}_i)d\underline{x}_i\right\} \\
&- \exp\left\{-\int\int_{\text{area}} W_{B,C,i}G(\underline{x}_i)d\underline{x}_i\right\} - \exp\left\{-\int\int_{\text{area}} W_{B,D,i}G(\underline{x}_i)d\underline{x}_i\right\} \\
&- \exp\left\{-\int\int_{\text{area}} W_{C,D,i}G(\underline{x}_i)d\underline{x}_i\right\} + \exp\left\{-\int\int_{\text{area}} W_{A,B,C,i}G(\underline{x}_i)d\underline{x}_i\right\} \\
&+ \exp\left\{-\int\int_{\text{area}} W_{A,B,D,i}G(\underline{x}_i)d\underline{x}_i\right\} + \exp\left\{-\int\int_{\text{area}} W_{A,C,D,i}G(\underline{x}_i)d\underline{x}_i\right\} \\
&+ \exp\left\{-\int\int_{\text{area}} W_{B,C,D,i}G(\underline{x}_i)d\underline{x}_i\right\} - \exp\left\{-\int\int_{\text{area}} W_{A,B,C,D,i}G(\underline{x}_i)d\underline{x}_i\right\}
\end{aligned} \tag{3}$$

where A_j, B_j, C_j and D_j denote the events of successful reception of a packet from terminal j at ports A, B, C and D, respectively. In (3), $\underline{x}_j$ denotes the location of terminal j. This result has been obtained after lengthy but straightforward mathematical operations, which we summarize in Appendix A. The special case of only two receiving base stations has been worked out in [3]. $W_{A,i}$ is a weight function defined by

$$W_{A,i} = \frac{zS_{A,i}}{zS_{A,i} + S_{A,j}}, \tag{4}$$

where $S_{A,j}$ is the local mean power at port A from terminal j, and $S_{A,i}$ is the interfering signal power at port A from terminal at location $\underline{x}_i$ (see (1)). $W_{B,i}$, $W_{C,i}$ and $W_{D,i}$ are defined in the similar manner and the joint weight functions are defined by

$$W_{A,B,i} = W_{A,i} + W_{B,i} - W_{A,i}W_{B,i} \tag{5}$$

$$W_{A,B,C,i} = W_{C,i} + W_{A,B,i} - W_{A,B,i}W_{C,i} \tag{6}$$

$$W_{A,B,C,D,i} = W_{D,i} + W_{A,B,C,i} - W_{A,B,C,i}W_{D,i} \tag{7}$$

In (3), the additive channel noise is assumed to be weak compared to the interfering signals. We assume that the noise floor ν is zero. That is, we only consider the effects of interference.

Equation (3) explicitly expresses the throughput (or more precisely the probability of success) in terms the offered traffic, $G(\underline{x})$. However, in practice the throughput is dictated by the applications and the offered traffic is result of this traffic plus any retransmission traffic. Hence,

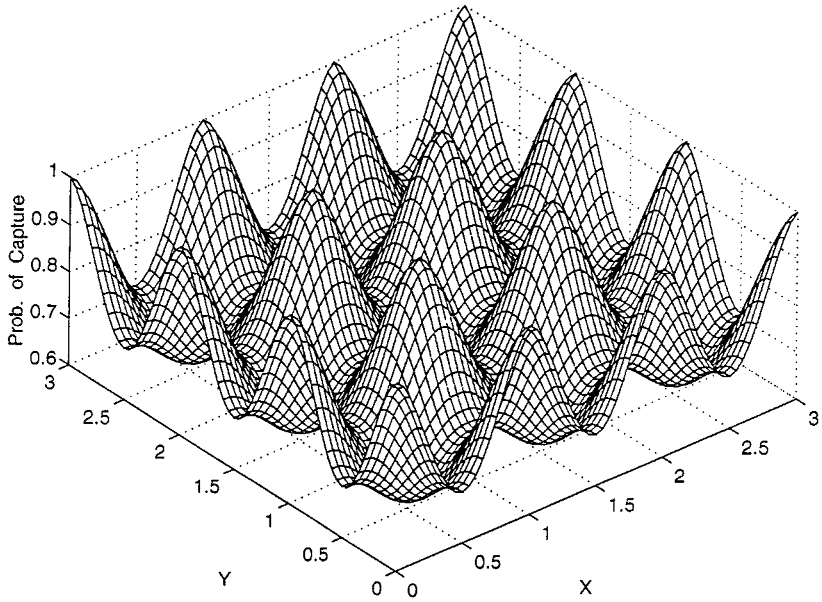

Figure 3.

a designer rather expresses offered traffic in terms of throughput than the other way round. For instance, a designer may assume that the input traffic density S_0 will be uniformly spread over the area. If terminals move very slowly, i.e., if retransmissions always occur from the same area, we may write for location $\underline{x}_j$ that $S_0 = G(\underline{x}_j) \cdot Pr(A_j \cup B_j \cup C_j \cup D_j | \underline{x}_j,\ G(\underline{x}_j))$. Using this expression for fixed S_0, we can obtain $G(\underline{x}_j)$ iteratively, for instance by the techniques developed in [7] and [18]. The $(k+1)$st estimate of $G(\underline{x}_j)$ is obtained from

$$G_{k+1}(\underline{x}_j) = \frac{S_0}{Pr(A_j \cup B_j \cup C_j \cup D_j | \underline{x}_j,\ G_k(\underline{x}_j))} \tag{8}$$

which converges rapidly if S_0 is sufficiently below the maximum achievable throughput. We stopped the iteration when the ratio of mean values of $G_k(\underline{x}_j)$ over $G_{k+1}(\underline{x}_j)$ became larger than 0.995. The probability of capture of the VCN is shown in Figure 3 from numerical analysis, and in Figure 4 from simulations (only 3×3 unit area is shown for clarity). The offered traffic $G(\underline{x})$ is shown in Figure 5 for $S_0 = 0.15$ packets per slot per unit of area.

4.3. Throughput

Unlike the case of wired networks with guided communication, the throughput of a VCN depends highly on the spatial distribution of terminals. Figure 6 shows the offered traffic per cell, G versus the input traffic density, S_0 when $z = 4$ (6dB) and $r = 0.1$, 0.5, 1 and 1.5. The results reveal that performance is very critical to the propagation turnover distance r. In the special case of free space loss ($r \to \infty$) the throughput goes zero, because the path loss so slowly increases with distance that the accumulated interference power diverges. This theoretical result appears to generally apply to cellular systems with infinitely extended uniform traffic densities. The maximum achievable S_0 is found by searching the maximum value of S_0 from which $G(\underline{x})$ in (8) converges. Table 1 shows the throughput as a function of r.

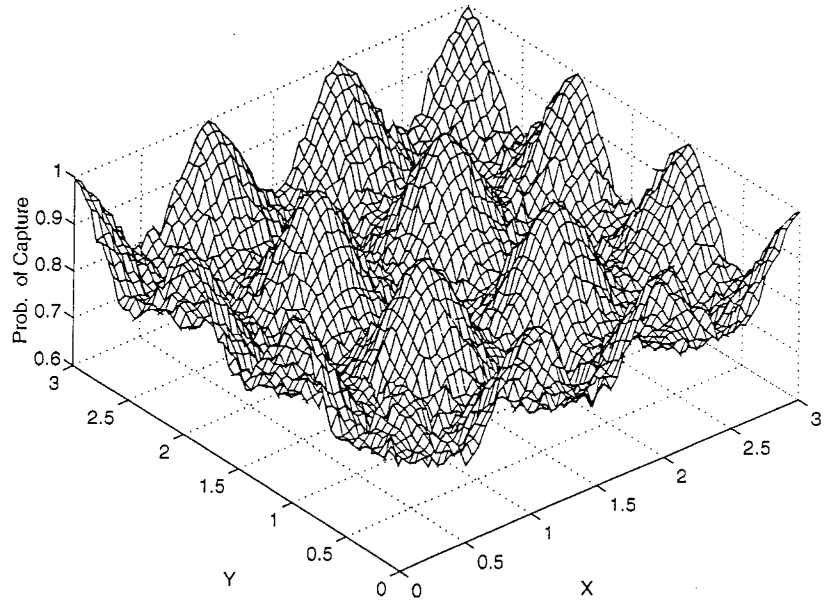

Figure 4.

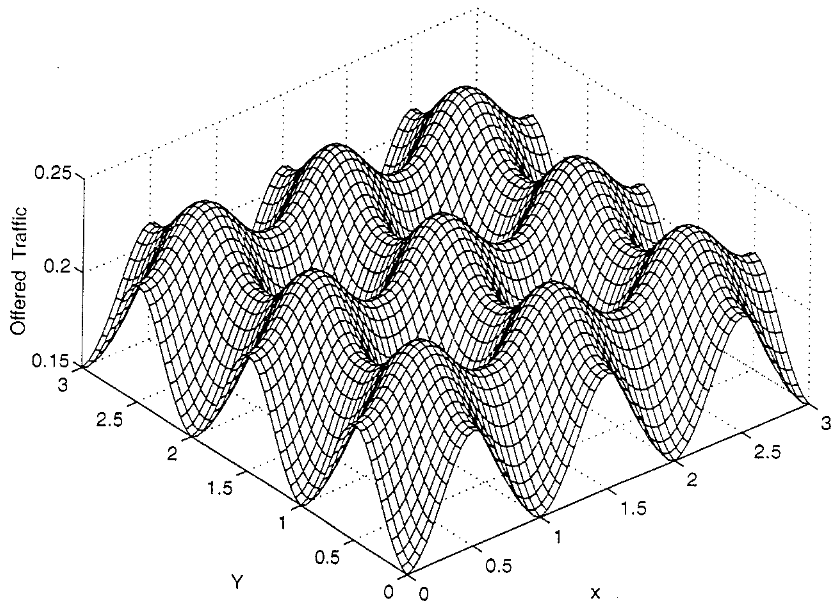

Figure 5.

The minimum value of probability of capture, which occurs at the center of the unit area, is shown in Figure 7. The results give an impression of the expected number of retransmissions that are required.

As an example, assume a propagation environment with path loss break point $r = 0.5$. The maximum throughput of a VCN is $S_0 = 0.175$ packets per slot per area. We compare the throughput of the VCN to a conventional cellular network with a 7 cell reuse pattern, and $r = 0.5$. If all packets are received perfectly, i.e., ignoring intercell interference, the

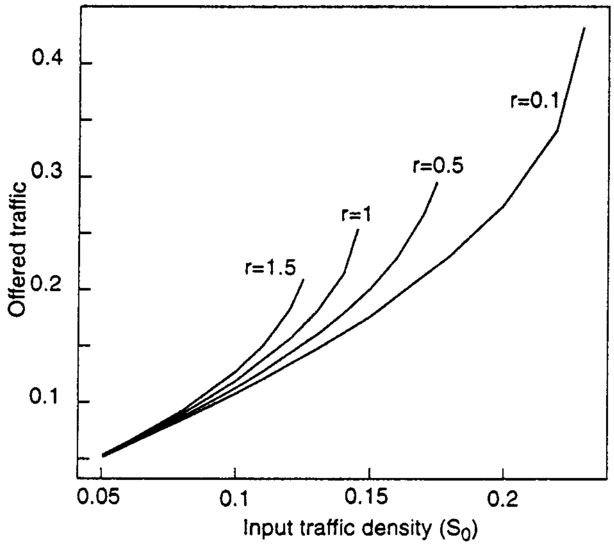

Figure 6. Mean value of calculated offered traffic versus input traffic density. Receiver threshold $z = 4$.

Table 1. Throughput of VCN ($z = 4$).

r	max S_0
0.1	0.23
0.5	0.175
1.0	0.145
1.5	0.125
∞	0

maximum throughput ($S_0 = 1$) could be obtained within a cell by a perfect scheduling MAC protocol. However, the bandwidth efficiency over the entire system bandwidth will then be $S_0/C = 1/7 = 0.143$, all because of frequency reuse. This implies that the VCN with random traffic can obtain a spectrum efficiency equal to or at least as good as usual cell layouts with continuous-wave voice communications. With discontinuous voice transmission or with more bursty multimedia traffic, the VCN will achieve a throughput close to the results of Figure 6.

If the number of ports per unit area is increased by 4 in a VCN with $r = 0.5$, the effective propagation turnover distance r will be changed to $r = 1$ which gives maximum $S_0 = 0.145$. Retaining the same reference unit of area, the new maximum throughput will be 4 times 0.145, which equals 0.58 packets per slot per unit area. This implies throughput is increased by 0.58 over 0.175, or approximately 3.31 if we install 4 times as many ports.

5. Delay Characteristics for "Periodic" Messages

Various types of traffic streams are to be accommodated in the VCN network, including both random and predictable, periodic message patterns. The VCN concept differs from conventional cellular networks by not applying fixed reuse patterns or fixed TDMA time slots

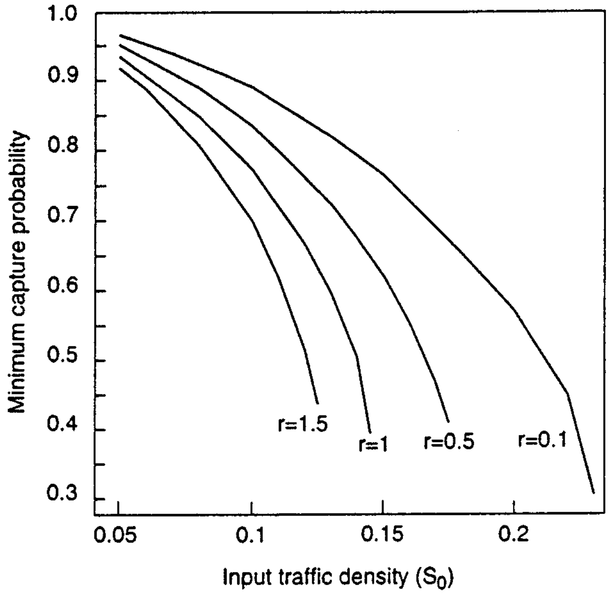

Figure 7. Minimum value of the probability of capture versus input traffic. Receiver threshold $z = 4$.

assigned to particular users. As terminals have to compete for resources in an ALOHA random access scheme, the VCN may be less efficient for periodic traffic, such as voice during speech bursts, pen data packets while drawing on the screen, or uplink video.

The total delay in a VCN is composed of delay in wireless part, delay in port network access, duplicate resolution delay and delay in backbone network. Considering radio spectrum scarcity, the delay in the wireless part will be the dominant component. In this section we derive the delay distribution of speech packets in the wireless part by using a Markovian model and we investigate the outage probability because real-time speech requires a constant small delay.

In the following analysis, we focus on periodic traffic patterns, in which the terminal generates a message exactly once every N time slots. As results show, the VCN concept, although primarily optimized for random bursty traffic, also outperforms a typical conventional cellular design for periodic traffic. In a VCN carrying conversational speech, the "deadline failure probability", i.e., the probability that a particular packet is not received successfully within a certain delay limit, determines the signal outage probability experienced by the user.

5.1. Periodic Traffic Model

Let a packet of a single user arrive in the terminal transmit queue once every N time slots. Figure 8 shows the timing diagram of the transmission model. N is determined by the wireless channel capacity, source coding rate and slot size in the VCN. A numerical example of N will be given for the case of speech transmission in subsection 5.2. We assume that (in steady state operation) the queue length probability mass function is independent for time shifts of the integer multiples of N, thereby we can model the transmission system as a Markov process. The state defines the length of the queue at the time just before a speech packet arrives the queue. The transition of states occurs at every N-th time slot and the state diagram is shown in Figure 9.

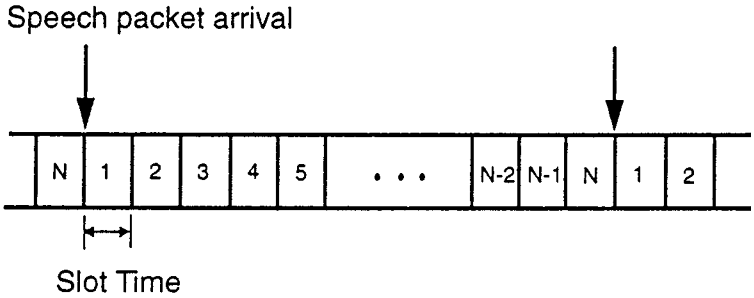

Figure 8. Timing diagram for speech packet transmission. Speech packet arrives at every N time slot, and is transmitted at every time slot.

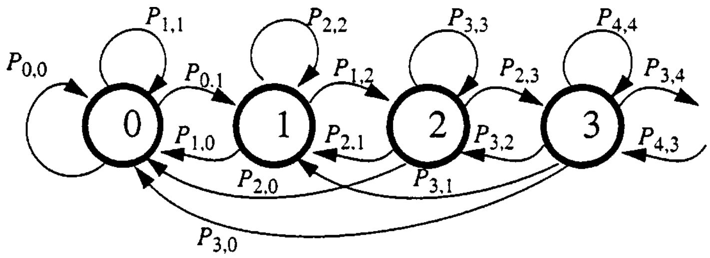

Figure 9. State diagram of speech transmission queue for a single user. State denotes the queue size.

The state transition rate matrix P is shown below, where $P_{i,j}$ denotes state transition rate from state i to j and B is the transmit buffer size.

$$P = \begin{bmatrix} P_{0,-} & P_{0,1} & 0 & \bullet & 0 \\ P_{1,0} & P_{1,1} & P_{1,2} & \bullet & 0 \\ \bullet & \bullet & \bullet & \bullet & P_{B-1,B} \\ P_{B,0} & P_{B,1} & \bullet & P_{B,B-1} & P_{B,B} \end{bmatrix} \tag{9}$$

We assume that the arrival process of interfering packets is a stationary Poisson process. The range where this assumption is reasonable has been studied in [13]. The following subsection further verifies this assumption by simulation of the VCN. For stationary interference, the probability of capture is a time-constant Pc, but its depends on the location $\overline{x}$. If a packet arrives at the buffer when buffer is empty, it is successfully transmitted at the next time slot with probability Pc. If the packet fails to capture any port (with probability $1 - Pc$) it will be retransmitted after a backoff delay. We also assume that when there are one or more packets in the queue, the new packet will follow the retransmission policy, i.e., when it reaches the first position in the queue it is transmitted with probability Pr. We assume a geometric distribution for the backoff delay, with Pr being the retransmission probability at each slot time. It is assumed that the acknowledgment for the transmitted packet is arrived within a time slot. This requires a reliable and high speed downlink channel as it is provided in the Infopad concept where one needs to support downlink real-time video. However, if K is large, this assumption becomes optimistic.

$P_{0,1}$ is the probability that there was no packet in the queue just before a new speech packet arrived at the transmit queue and no packet has been transmitted successfully during N time slots to make the queue size to 1. That is, the first transmission fails with probability $1 - Pc$ and all the following $(N - 1)$ retransmissions also failed. That is

$$P_{0,1} = (1 - Pc)\,(1 - PrPc)^{N-1} \tag{10}$$

$$P_{0,0} = 1 - P_{0,1} = 1 - (1 - Pc)\,(1 - PrPc)^{N-1}. \tag{11}$$

Generally, for $1 \leq i$, $P_{i,i+1}$ is the probability that there has been no successful retransmission during N time slots, so

$$P_{i,i+1} = (1 - PrPc)^N \qquad (1 \leq i \leq B). \tag{12}$$

$P_{i,i}$ is the probability that there has been only one successful retransmission during N time slots, with

$$P_{i,i} = \binom{N}{1} (PrPc)(1 - PrPc)^{N-1} \qquad (1 \leq i \leq B). \tag{13}$$

The probability that $k+1$ packets are successfully transmitted during N slot time is given by

$$P_{i,i-k} = \binom{N}{k+1} (PrPc)^{k+1}(1 - PrPc)^{N-k-1} \qquad (1 \leq i \leq B,\ 0 \leq k < N). \tag{14}$$

Finally, from the fact that the sum of all transition probabilities from any state is 1, we have:

$$P_{i,0} = 1 - \sum_{m=1}^{B} P_{i,m} \qquad (1 \leq i \leq B). \tag{15}$$

Let $W = [w_0, w_1, \ \ldots,\ w_B]$ be the state probability of the system shown in Figure 9. The size of the buffer B is chosen to be sufficiently large to ignore overflow in the calculations. However, practically B may be limited depending on the maximum allowable delay in the link.

5.2. Deadline Failure Probability

From the probability distribution of the transmit queue length, we can calculate the delay distribution of packets as follows. We define the random variable D as the waiting time (expressed in slots) in the transmit queue. The probability mass function of D is given by

$$P_D(d) = \begin{cases} w_0 Pc & d = 1 \\ w_0(1 - Pc)\,(PrPc)\,(1 - PrPc)^{d-2} & \\ + \displaystyle\sum_{i=1}^{d-1} w_i \binom{d-1}{i} (1 - PrPc)^{d-i-1}(PrPc)^{i+1} & d = 2, 3,\ \ldots \end{cases} \tag{16}$$

It is noted that $w_m = 0$ for $B + 1 \leq m$. From (16) we can calculate the 99th percentile $D_{0.99}$, which is defined by

$$\sum_{d=0}^{D_{0.99}} P_D(d) = 0.99\,. \tag{17}$$

Most conventional cellular systems are designed for a 1% outage probability by sufficiently separating co-channel cells. For a virtual cellaulr network with retransmission of missing packets, packets are lost if retransmission would imply that the delay exceeds a particular limit. We interpret $D_{0.99}$ as the delay incurred if one requires that less than 1% of all packets

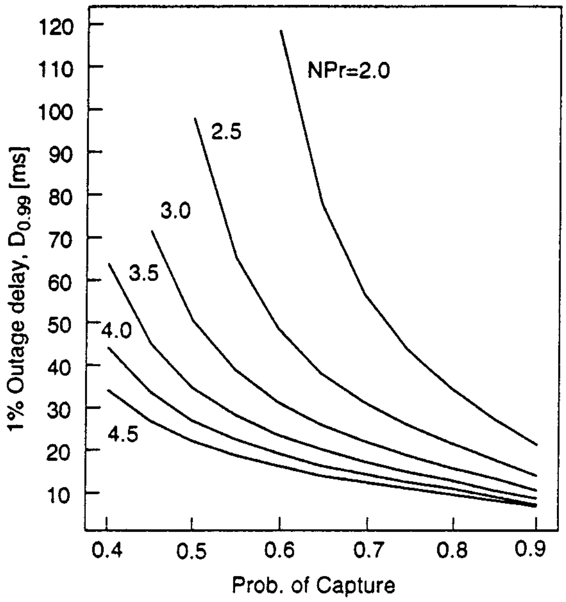

Figure 10. $D_{0.99}$ as a function of Pc for various value of NPr. Buffer size $B = 30$. 1 Mbps wireless channel and 32 kbps speech coding are assumed.

exceed this limit. In a virtual cellular network the total traffic load must be sufficiently low to satisfy such a requirement.

As a numerical example, let's consider a VCN carrying (continuous) speech with system parameters such as: wireless channel $C = 1$ Mbps, packet size $L = 60$ bytes, payload length $L_p = 44$ bytes and speech coding rate is 32 kbps. Hence, the slot duration is $T_s = C/L = 0.48ms$ and the speech packet arrival interval is

$$T_p = L_p/(32\text{kbps}) = 11.04ms \approx 22.9T_s\,. \tag{18}$$

We used $N = 23$ in our numerical example.

Figure 10 shows $D_{0.99}$ as a function of Pc for various values of NPr. If the allowed delay of speech packets in the wireless network is 50 ms for 1% of outage, minimum value of Pc should be 0.66 when $NPr = 3$. Here, NPr means "the expected number of retransmissions during N time slots". To ensure stability of the transmit queue, we require $NPrPc > 1$, so certainly NPr should exceed unity. On the other hand for stability of the network, Pr should be sufficiently small [13]. In our simulation with $NPr = 3$ with N on the order of 20 we did not experience instability problems. For a more detailed evaluation of stability in ALOHA nets with capture we refer to [13] and the references therein. Figure 10 can be used as a guideline to determine Pr given N and delay requirement.

From the probability of capture which is presented as a function of location (see Figure 3), we can find $D_{0.99}$ as a function of location. Figure 11 shows the delay $D_{0.99}$ which ensures a 1% deadline failure probability for $NPr = 3$ when $S_0 = 0.15$, turnover distance $r = 0.5$ and receiver threshold $z = 4$.

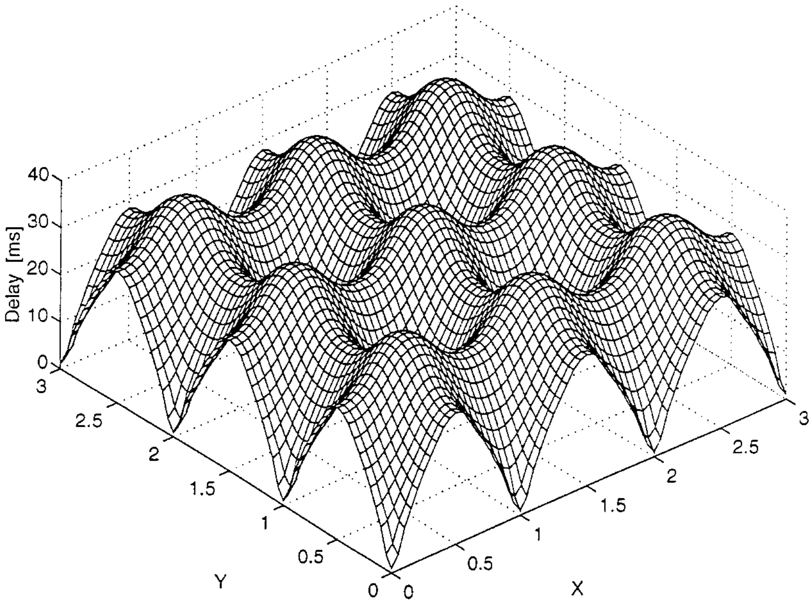

Figure 11.

6. Conclusion

This paper described the concept of a VCN and investigated its performance in terms of probability of capture, throughput and delay both for Poissonian arrivals of short packets and for speech packets. The performance evaluation for the speech outage can be used to estimate the performance of other isochronous traffic modes through a wireless network (VCN).

Advantages of a VCN include increased throughput, a simple protocol at each terminal, easy installation of ports, smooth handoff and resistance against multipath fading. It is noted that if more ports are installed the maximum throughput will be increased without substantially increasing the complexity. In conventional cellular networks, however, increasing the number of BS's requires complex control schemes and signalling. Our experience from simulation shows that the uplink protocol in the VCN is very stable due to site diversity and capture.

Appendix A

The derivations in this appendix extend previous analyses of capture probabilities in Rayleigh fading channels. We refer to publications such as [7, 18] for a primer on the weight function approach and focus here on extending this to express the capture probability with site diversity using multiple ports A, B, .. at locations $\underline{x}_a$, $\underline{x}_B$, $\ldots$ The positions of the $N+1$ terminals (1, 2, $\ldots$ N, j) are denoted as $\underline{x}_1, \underline{x}_2, \ldots, \underline{x}_N, \underline{x}_j$. In our numbering scheme, the user j transmits a reference (or "wanted") signal, and is not an element of the set of interferers $\{1, 2, \ldots, N\}$. In the following expressions, we will use indexes i and k for interferers, so $i \neq j$ of $k \neq j$. However in the last section of this appendix, the conceptual distinction between wanted and interfering users vanishes as all signals are wanted and contribute to the throughput. This appendix shows how essential probabilities used in this paper can be expressed in a relatively convenient analytical form.

The event that the *C/I*-ratio of a packet signal from terminal j at receiver A is above the receiver threshold z is denoted as A_j. It occurs with probability [11]

$$Pr(A_j) = \iint\limits_{O-xz}^{\infty\infty} f_{A,t}(x) f_{A,j}(y) dy dx \,, \tag{A.1}$$

where $f_{A,j}(y)$ is the probability density function of the signal power $S_{A,j}$ from terminal j at receiver A and $f_{A,t}(x)$ is the probability density function of the total interference power $S_{A,t}$ at receiver A. We assume incoherent power addition:

$$S_{A,t} = \sum_{k=1}^{N} S_{A,k} \,. \tag{A.2}$$

In a propagation environment with pathloss and Rayleigh fading, the locations of all terminals $\underline{x}_j, \underline{x}_l, \underline{x}_2, \ldots, \underline{x}_N$ relative to the receive port determine the local-mean received powers $\overline{S}_{A,j}$ and $\overline{S}_{A,1}, \overline{S}_{A,2}, \ldots, \overline{S}_{A,N}$. It has been shown previously see e.g., [7] for an analysis), at the probability of capture in a Rayleigh-fading channel where such local-mean values are known, with a finite population of *N* terminals can be written simply as

$$Pr(A_j | \underline{x}_j,\ \{\underline{x}_i\}_{i=0}^{N}) = \prod_{i=l}^{N} 1 - W_{A,i} Pr(i_{ON}) \,, \tag{A.3}$$

where the weight factor $W_{A,i}$ is given in the main body of this paper (Equation (4)). $Pr(i_{ON})$ is the probability that interferer i is active, either due to a new transmission or a retransmission. We assume that this probability is ergodic and independent from slot to slot. This assumption implies that we simplify the effect collisions and retransmissions, which complicates the activity of terminals. The effect of mutual influences and correlations has been discussed in [13, 16].

Next we explore the a posteriori information provided by the event A_j about the activity of the other terminals.

Lemma: Given all locations $\underline{x}_i (i = 1, 2, \ldots, N)$ and $\underline{x}_j$, the a posteriori probability that interferer k was active (event $k_{ON}, k \in \{1, 2, \ldots, N\}$) given that j captured receiver A is independent of the presence of any other interfering terminal, and is equal to

$$Pr(k_{ON} | A_j, \underline{x}_j, \{\underline{x}_i\}) = Pr(k_{ON} | A_j, \underline{x}_j, \underline{x}_k) = \frac{1 - W_{A,k}}{1 - W_{A,k} Pr(k_{ON})} Pr(k_{ON}) \,, \tag{A.4}$$

We use $\{\underline{x}_i\}$ to denote the set of all locations of the interferers, thus without explicitly mentioning $(i = 1, 2, \ldots, N)$.

Proof: The probability $Pr(k_{ON} | A_j)$ that a terminal k has transmitted an interfering packet, given that the wanted voice segment (of terminal j) captures port *A*, is found from Bayes rule

$$Pr(k_{ON} | A_j, \underline{x}_j, \{\underline{x}_i\}) = \frac{Pr(A_j | k_{ON}, \{\underline{x}_i\})}{Pr(A_j | \{\underline{x}_i\})} Pr(k_{ON}) \,, \tag{A.5}$$

where $Pr(a_j | k_{ON}, \{\underline{x}_i\})$, is the probability that a wanted segment from j is received successfully at A, given that interferer k was active, given all locations of the terminals. So,

$$Pr(A_j | k_{ON}, \underline{x}_j, \{\underline{x}_i\}) = \{1 - W_{A,k}\} \prod_{i=l, i \neq k}^{N} 1 - W_{A,i} Pr(i_{ON}) \,, \tag{A.6}$$

where i_{ON} denotes the event that interferer i is active. The conditional probability of activity of k can be expressed as

$$Pr(k_{ON}|A_j, \underline{x}_j, \{\underline{x}_i\}) = \frac{\{1 - W_{A,k}\} \prod_{i=l, i \neq k}^{N} 1 - W_{A,i} Pr(i_{ON})}{\prod_{i=l}^{N} 1 - W_{A,i} Pr(I_{ON})} Pr(k_{ON}) . \tag{A.7}$$

Here, the summing in the numerator involves uncertainty about the activity of all N interfering signals except interferer k, who is known to be active. The denominator addresses the unconditional probability of success, so its sum includes the a priori $Pr(k_{ON})$. The wanted signal j does not lead to a specific term in these products. However, the location of j affects the value of the weight factors. In the above expression, $N - 1$ terms cancel, which concludes the proof. ■

Using this result, the conditional probability that the packet from terminal j captures port B given that it also captures port A is found as

$$\begin{aligned} Pr(B_j|A_j, \underline{x}_j, \{\underline{x}_i\}) &= \prod_{k=1}^{N} 1 - W_{B,k} Pr(k_{ON}|A_j, \underline{x}_j, \{\underline{x}_i\}) \\ &= \prod_{k=1}^{N} 1 - \frac{1 - W_{A,k}}{1 - W_{A,k} Pr(k_{ON})} W_{B,k} Pr(k_{ON}) , \end{aligned} \tag{A.8}$$

Combining the results of the foregoing analysis, we find that we can express the probability of capturing both A and B as

$$Pr(A_j \cap B_j|\underline{x}_j, \{\underline{x}_i\}) = Pr(A_j) Pr(B_j|A_j, \underline{x}_j, \{\underline{x}_i\}) = \prod_{i=l}^{N} 1 - W_{A,B,i} Pr(i_{ON}) , \tag{A.9}$$

where we introduced the joint weight function

$$W_{A,B,i} = W_{A,i} + W_{B,i} - W_{A,i} W_{B,i} . \tag{A.10}$$

$W_{A,B,i}$ can be interpreted as a factor weighing the disturbance caused by a interfering packet signal from position $\underline{x}_k$ to a reception of a data packet by terminal j at the two ports A and B simultaneously. The probability that a packet from terminal j captures at least one of the two ports $(A_j \cup B_j)$, given the position of all terminals, equals

$$\begin{aligned} Pr(A_j \cup B_j|\{\underline{x}_i\}, \underline{x}_j) = \; & Pr(A_j|\{\underline{x}_i\}, \underline{x}_j) + Pr(B_j|\{\underline{x}_i\}, \underline{x}_j) \\ & - Pr(A_j|\{\underline{x}_i\}, \underline{x}_j) Pr(B_j|A_j, \{\underline{x}_i\}, \underline{x}_j). \end{aligned} \tag{A.11}$$

We now extend our analysis to three receiving ports. The probability $Pr(k_{ON}|A_j \cap B_j)$ that a terminal k has transmitted an interfering packet, given that the test packet is received correctly by port A and B, is found from Bayes rule

$$Pr(k_{ON}|A_j \cap B_j) = \frac{Pr(A_j \cap B_j|k_{ON})}{Pr(A_j \cap B_j)} Pr(k_{ON}) , \tag{A.12}$$

We further condition on the locations of all terminals. A similar analysis as before gives

$$Pr(k_{ON}|A_j \cap B_j, \{\underline{x}_i, \underline{x}_j\}) = \frac{1 - W_{A,B,k}}{1 - W_{A,B,k}Pr(k_{ON})} Pr(k_{ON})\,. \tag{A.13}$$

The probability of capturing all three ports simultaneously can be expressed as

$$Pr(C_j \cup a_j \cup B_j|\{\underline{x}_i\}, \underline{x}_j) = \prod_{k=1}^{N} 1 - W_{A,B,C,k}Pr(k_{ON}) \tag{A.14}$$

$$Pr(C_j \cup A_j \cup B_j|\{\underline{x}_i\}, \underline{x}_j) = \prod_{k=1}^{N} 1 - W_{A,B,C,k}Pr(k_{ON})\,, \tag{A.15}$$

where we introduced the joint weight factor

$$\begin{aligned} W_{A,B,C,k} &= W_{C,k} + W_{A,B,k} - W_{A,B,k}W_{C,k} \\ &= W_{A,k} + W_{B,k} + W_{C,k} - W_{A,k}W_{B,k} \\ &\quad -W_{B,k}W_{C,k} - W_{A,k}W_{C,k} + W_{A,k}W_{B,k}W_{C,k}\,. \end{aligned} \tag{a.16}$$

Extension to four or more ports can be worked out analogously.

Capture Probability with Poisson Field of Terminals

Up to now we conditioned all expressions on the location of the terminals. Next, we will randomize the locations of the interferers, but fix the location of the user sending the wanted signal. To find the probability of capturing at least one port with *N* terminals known to transmit but with unknown locations, we average over all possible positions of the *N* interferers. So

$$\begin{aligned} &Pr(A_j \cup B_j \cup C_j|\underline{x}_j) = \\ &\iint_{\text{area}} \cdots \iint_{\text{area}} Pr(A_j \cup B_j \cup C_j|\{\underline{x}_i\}, \underline{x}_j) f_{\underline{x}_l}(\underline{x}_l) \ \ldots \ f_{\underline{x}_N}(\underline{x}_N) d\underline{x}_l \ \ldots \ d\underline{x}_N\,. \end{aligned} \tag{A.17}$$

As we have shown before, the probability in the integrand is of the form of the sum of probabilities for capturing combinations of ports. Each term in this sum is of the form of the product of *N* terms. Since each of the integration variables $\underline{x}_i$ occurs only in one factor of each of the products, one may interchange product and integration. Hence,

$$\begin{aligned} Pr(A_j \cup B_j \cup C_j|N, \underline{x}_j) &= \left[\iint_{\text{area}} \{1 - W_{A,i}\} f_{\underline{x}_i}(\underline{x}_i) d\underline{x}_i\right]^N \\ &+ \left[\iint_{\text{area}} \{1 - W_{B,i}\} f_{\underline{x}_i}(\underline{x}_i) d\underline{x}_i\right]^N + \left[\iint_{\text{area}} \{1 - W_{C,i}\} f_{\underline{x}_i}(\underline{x}_i) d\underline{x}_i\right]^N \\ &- \left[\iint_{\text{area}} \{1 - W_{A,B,i}\} f_{\underline{x}_i}(\underline{x}_i) d\underline{x}_i\right]^N - \left[\iint_{\text{area}} \{1 - W_{A,C,i}\} f_{\underline{x}_i}(\underline{x}_i) d\underline{x}_i\right]^N \\ &- \left[\iint_{\text{area}} \{1 - W_{B,C,i}\} f_{\underline{x}_i}(\underline{x}_i) d\underline{x}_i\right]^N + \left[\iint_{\text{area}} \{1 - W_{A,B,C,i}\} f_{\underline{x}_i}(\underline{x}_i) d\underline{x}_i\right]^N \end{aligned} \tag{A.18}$$

For an infinite population of terminals, data packets are transmitted with a spatial distribution $G(\underline{x})$, where $\underline{x}$ is the position in the cell area and $f(\underline{x}) = 2\pi|\underline{x} - \underline{x}_A|G(\underline{x})/G_t$ with G_t the total offered traffic in the system. Since we accumulated all traffic from all terminals on a single channel, it may be reasonable to model the interference as a (spatially non-uniform) Poisson process. For N Poisson distributed, the capture probability becomes a sum of exponential functions, viz.,

$$Pr(A_j \cup B_j \cup C_j|\underline{x}_j) = \sum_{N=0}^{\infty} \frac{G_t^N}{N!} e^{-Gt} \; Pr(A_j \cup B_j \cup C_j|N, \underline{x}_j)\,. \tag{A.19}$$

Using the series expansion of the exponential function for each term in the probability of capture, this can be written in the lengthy but elegantly structured expression (3) given in the main body of the paper for the case of four ports.

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