IMPROVING PERFORMAMCE OF WIRELESS NETWORKS USING COLLISION RESISTENT MODULATIONS

G. Caire, E. Leonardi, E. Viterbo
Dipartimento di Elettronica, Politecnico di Torino
Corso Duca degli Abruzzi 24, 10129 Torino, Italy
Phone: +39 11 564 4000, Fax: +39 11 564 4099
E-mail: {caire,leonardi,viterbo}@polito.it

Abstract

Recent work by the authors presents a novel class of signal space codes called Collision Resistant Modulations (CRM) for bandwidth efficient transmission on a random access collision channel, as in packet-radio applications. Results show that CRMs achieve a significant gain over traditional modulation formats under a Slotted ALOHA protocol. In this paper, we investigate the potentials of using CRM under a partially ordered access protocol like Packet Reservation Multiple Access (PRMA). A system based on Reed-Solomon coded CRM is compared with a more traditional system using the same Reed-Solomon coding concatenated with simple one-dimensional modulation schemes. Results show that the proposed coded PRMA yields significant improvements in terms of both blocking probability and number of established calls (served users), at the expenses of a slight increase in the average transmitted power.

1 Introduction

Several coding techniques aimed at improving the system performance of a wireless fading multiple access channel have been proposed in the last years [1, 2, 3, 4, 5]. These techniques allow to reduce the negative impact of collisions on the system throughput by exploiting channel coding error correcting capability. In [6, 7], the authors present a novel class of signal space codes nicknamed Collision Resistant Modulations (CRM). Results show that it is possible to achieve a significant gain by using CRM instead of traditional modulation schemes under a Slotted ALOHA protocol. The major advantage of this signal space coding over traditional coding schemes is the fact that a coding gain is obtained with no bandwidth increase for the transmission of redundant information.

In this paper, we investigate the potential benefits of using CRMs in conjunction with more complex MAC protocols that involve both random access and collision free transmissions. A simple Markovian model has been developed to evaluate the system performance in the case of real-time voice transmission. Results show that the system performance can be significantly improved by careful use of CRMs, even with partially ordered multiple access.

The paper is organized as follows. In Section 2 the access protocol is described; in Section 3 Collision Resistant Modulations are reviewed; in Section 4 an analytical model for the protocol is developed; finally, a numerical example and conclusions are presented in Section 5.

2 MAC protocol description

We consider a population of N_u users accessing N_W common subcarriers. Time is divided into *frames*. Each frame comprises N_T time slots for each subcarrier. Then, $N_s = N_T \times N_W$ time-frequency slots per frame are available for transmission. Each slot can carry L_s elementary waveforms [8] for the transmission of L_s real dimensions. According to the "$2WT$-Theorem" [9], the total number of real dimensions per frame is $N_s L_s \approx 2WT$, where T is the frame time duration and W is the overall system bandwidth.

Slots in each frame are dynamically partitioned in two classes: *reserved slots* and *random access slots*. Reserved slots can be accessed by a single user only and are assigned from the base station to a particular user after an explicit request. Random access slots can be accessed in a random fashion by all the users that have no reserved slots.

Considering voice services, we suppose that each user, during each talk-spurt accesses a sequence of reserved slots. At the end of every talk-spurt reserved slots are released. Reservation requests are submitted to the base station from users that become active (i.e., at the beginning of each talk-spurt) by transmitting on a random access slot the first voice packet. The base station informs all users about the up-link slot reservation state by transmitting some signaling packets on the down-link channel. All the terminals must keep an updated map of the slots state. The above protocol is a possible implementation of the PRMA [10].

In the following, we consider a slight generalization of the above basic scheme involving coding and interleaving. A (signal-space) code for the Gaussian channel is simply a set $\mathcal{X}$ of sequences $\mathbf{x}$ of real numbers of length n (block length). The code rate is $R = \frac{1}{n}\log_2|\mathcal{X}|$ bit per real dimension. We assume that users encode their information packets by a given code $\mathcal{X}$, so that each transmitted packet correspond to a code word. Code words can be transmitted over a single slot (in this case, $L_s = n$), or *interleaved* over D slots (in this case, $DL_s = n$).

We observe that the performance of the protocol at hand depends critically on the *blocking probability* (BP), defined here as the probability that the first packet of a talk-spurt is not received correctly. In fact, if a blocking event occurs, no slots are reserved for the transmission of the remaining packets and the user must send the next packet on some random access slot in the next frame, and so on. The resulting voice quality-of-service rapidly degrades as the BP increases. Then, it is reasonable to protect the first packet of each talk-spurt from collisions as much as possible, by using coding and interleaving, while in order to save bandwidth, less error protection is needed for the packets transmitted on reserved slots, since they must cope with noise (and fading) only, and not with collisions.

Hence, we will consider a generalized coded and interleaved PRMA protocol where users transmit with a code $\mathcal{X}_1$ of length $n_1 = L_s D$ over D slots when accessing the channel (at the beginning of each talk-spurt) and with a code $\mathcal{X}_2$ of length $n_2 = L_s K$ over $K \leq D$ slots when transmitting over reserved slots (i.e., during the talk-spurt if the first packet transmission was successful). Since the bit-rate is constant and equal to R_b bit/s, the number of information bits per code word must be equal for the two codes, i.e., $\log_2 |\mathcal{X}_1| = \log_2 |\mathcal{X}_2| = R_b T$. Then, the two codes have different rates $R_1 = R_b T/n_1$ and $R_2 = R_b T/n_2$. This is an example of variable-rate coding used in conjunction with a MAC protocol. Generally speaking, in wireless communications the protocol and the user coding scheme should be jointly designed and optimized.

3 Collision Resistant Modulation

We model the collision channel as an on-off vector channel

$$\mathbf{y} = C(G\mathbf{s} + \mathbf{n}) \qquad (1)$$

where $\mathbf{s} = (s_1, \dots s_D)^T$ is the transmitted signal vector (or "symbol") taken from a signal set S of cardinality $|S|$ in a D-dimensional Euclidean space, $\mathbf{n} = (n_1, \dots n_D)^T$ is the additive white Gaussian noise with $n_i \sim \mathcal{N}(0, N_0/2)$, $\mathbf{y} = (y_1, \dots y_D)^T$ is the received signal, $G = diag(g_1, \dots g_D)$ represents the channel fading gains and $C = diag(c_1, \dots c_D)$, with $c_i \in \{0, 1\}$, is the collision pattern (a 0 represents a collision). As it is apparent from (1), if a component of $\mathbf{s}$ is transmitted over a collided slot it is erased.

We assume that the receiver has perfect channel state information (CSI), i.e., it has perfect knowledge of C and G. The Maximum Likelihood (ML) decision rule is obtained by minimizing, over all $\mathbf{s} \in S$, the following modified Euclidean distance

$$d_C^2(\mathbf{s}, \mathbf{y}) = \sum_{i=1}^{D} c_i (y_i - g_i s_i)^2 \ . \qquad (2)$$

This corresponds to the minimum distance criterion of the received point from the points of a signal set $S(C)$ in an l-dimensional Euclidean space, where $S(C)$ is the projection of S on the subspace generated by the l axes corresponding to the non zero c_i's. According to this detection criterium, to avoid systematic errors, we require that the points in $S(C)$ are all distinct. This observation leads to the following

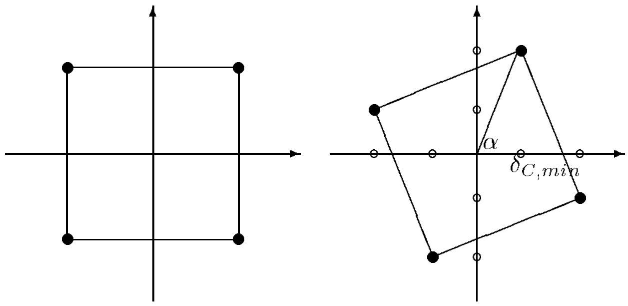

Figure 1: Example of CRM for $D = 2$ obtained by rotation of a 4-PSK signal set.

Definition — A *Collision Resistant Modulation* (CRM) is a D-dimensional signal set S with the property that any projection on any coordinate subspace is a signal set with the same number of distinct points, i.e., $|S(C)| = |S|$ for all non zero C. □

Equivalently, the vectors in S must have all distinct coordinates or, more precisely, the Hamming distance between any pair of vectors must be D. A similar requirement is imposed in the design of *high diversity* signal constellations for the fading channel where the number of distinct components is called *modulation diversity* [11, 12].

The construction of CRMs is discussed in [6, 7]. Here we provide only a simple two-dimensional example ($D = 2$).

Example 1. — *Rotated cubic constellations* with maximum diversity introduced in [12] are CRMs. These constellations are obtained by applying a particular rotation matrix to the vertices of a D-dimensional hypercube in order to produce the maximum possible *modulation diversity*. A two-dimensional case is shown in Figure 1. ◇

Channel coding schemes like TCM or BCM can be constructed from CRM signal sets [7]. For simplicity, here we consider the concatenation of a Reed-Solomon (RS) code with CRM. Information packets are encoded by the RS encoder. The resulting code words are mapped onto sequences of CRM signals by a simple binary labeling (e.g., Gray labeling of the CRM signal points). On the receiving end, the CRM signals are detected and the resulting sequence of hard-decisions are passed to the RS decoder, which implements simple t-error correcting algebraic decoding. In order to apply a CRM to the MAC protocol described in the previous section we assume that different components of the same D-dimensional signal are transmitted in different slots. This guarantees that collisions affecting different components of the same signal are statistically independent. Then, the transmission of a CRM-modulated RS code word needs D slots. Because of the properties of CRM, a variable-rate coding scheme as described in Section 2 can be obtained simply by transmitting $K \leq D$ components of each signal. As the number of transmitted components per signal decreases, the code rate increases and its ability of coping with channel errors diminishes. Hence, K must be chosen by trading-off spectral efficiency with power efficiency, as it will be apparent from the examples of Section 5.

Example 1 (cont.). — We illustrate the use of the CRM signal set of Fig. 1 with RS coding. Consider the 2-error correcting RS code over GF(16) with parameters $(15, 11, 5)$. Its block length is 15 GF(16) symbols, i.e., 60 bits. This corresponds to 30 CRM signals per code word, or 60 real dimensions per code word, since each 2-dimensional signal carries 2 bits. Users transmit 2 slots of length $L_s = 30$ (slot 1 carries all the first signal components and slot 2 carries all the second signal components) at the beginning of their talk-spurt and only 1 slot of the same length (carrying only the first signal components) for the remaining packets in the talk-spurt, if reservation was successful. The modulation format in each slot is the projection of the signal points on the first or second coordinate axis, which is a sort of 4-level pulse amplitude modulation (4-PAM). Let $\mathcal{E}$ be the transmitted average energy per dimension. Then, the average transmitted power is given by

$$\mathcal{P} = (f_1 2 L_s \mathcal{E} + f_2 L_s \mathcal{E})/T$$

where f_1 is the fraction of frames with random access (first packet of a talk-spurt) and f_2 is the fraction of frames with reserved access. In normal operating conditions, $f_1 \ll f_2$, so that the transmitted power is determined essentially by the voice activity ratio $p = f_1 + f_2 \simeq f_2$ (the fraction of time in which a user is voice-active) and by the instantaneous transmitted power during reserved slots, i.e., $\mathcal{P} \simeq p L_s \mathcal{E}/T$. Fig. 2 shows the packet-error probability (PER) for this example vs. E_b/N_0 in AWGN (for the time being we neglect the possible presence of fading), where the energy per bit is given by $E_b = \mathcal{P}/R_b$. The leftmost curve refers to a random access packet where both slots are not collided. The rightmost curve refers either to a random access packet, where one slot is collided, or to a reserved packet. In both cases, only one slot is received and it is used for decoding. Assuming a desired BP$= 10^{-2}$, we must guarantee that the PER is at least two orders of magnitude less, so that the system performance is interference-limited and not power-limited. From Fig. 2 we get an SNR operating point of $E_b/N_0 \geq 12$ dB for target PER $\leq 10^{-4}$ with a single non-collided slot. The analysis carried out here for this simple example can be extended to more general $D \geq 2$ CRM signal sets and RS codes. Results for a conceptually similar, but more complicated example, will be illustrated in Section 5. ◇

4 The Markovian model

In this section we describe the Markovian model that we used for evaluating the system performance. We consider a voice environment and suppose that the voice activity process of the terminals during a call can be modeled by a two state Markov chain, whose states are labeled as *on-state* and *off-state*. During the *off-state* the terminal is silent, no voice packets are emitted; during the *on-state* (i.e a talk-spurt) voice packets are emitted at a fixed rate (e.g., one in each frame). The transition probabilities between the two states are denoted by $p_{on \rightarrow off}$ and $p_{off \rightarrow on}$.

When a terminal switches from the *off* to the *on-state*, it transmits the first voice packet of the talk-spurt by filling D non reserved slots of the first incoming frame. The transmitted packet is interpreted by the base station as a reservation request. If the base station is able to "correctly" decode the transmitted information (i.e., at least K non collided components are received by the base station[1]) starting from the following frame K slots will be reserved to the terminal for the following voice packet transmissions.

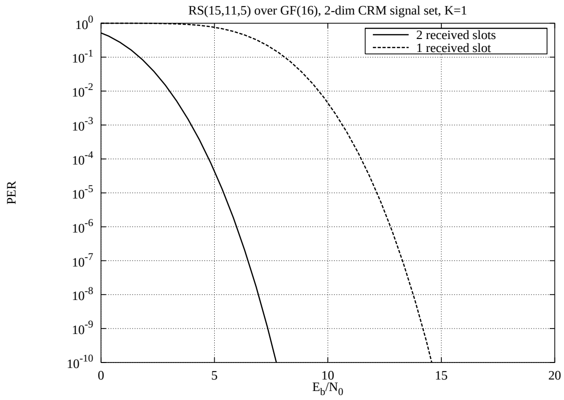

Figure 2: PER over a Gaussian channel for different numbers of collisions, for the RS-encoded 2-dimensional CRM scheme with $D = 2$ and $K = 1$ of Example 1.

If more than K collisions occur the base station is not able to reserve any slot. As a consequence, also the following voice-packet of the talk-spurt will be transmitted on non reserved slots. The terminal will go on in transmitting packets using non reserved slots until it will manage to successfully transmit a packet.

When the terminal switches to the *off-state*, it signals the base station to release the reserved slot by using the last incoming reserved slot.

We model the voice activity dynamic and the slot reservation dynamic of N_u calling terminals. For this purpose, we use a discrete time Markov chain whose state descriptor is a pair of integers (i, j), with $0 \leq i \leq N_u$ and $0 \leq j \leq N_r = min(N_u, \lfloor N_s/K \rfloor)$ and $j \leq i$, representing, respectively, the number of active terminals (i.e., the number of terminals in the *on-state*) and the number of reserved slots (i.e., number of terminals to whom a slot has been reserved).

Transitions probabilities from state $(i, j) \rightarrow (k, l)$ are given by:

$$p_{ij \rightarrow kl} = \sum_{x=0}^{x \leq min(N_{na}, i)} \sum_{y=max(0, x-\alpha)}^{y \leq min(x, j)} p_a(\beta + x, N_{na}) \times$$

$$p_d(y, j) p_d(x - y, \alpha) p_r(\eta + y, \delta + y, N_f + y)$$

for $k \geq i$, while for $k < i$:

$$p_{ij \rightarrow kl} = \sum_{x=0}^{x \leq min(N_{na}, i)} \sum_{y=max(0, x-\alpha+\beta)}^{y \leq min(x+\beta, j)} p_a(x, N_{na}) \times$$

[1] We neglect the noise effects since the system works at a SNR operating point so that the PER is negligible with respect to BP if at least K non collided components are received.

$p_d(y,j)p_d(x-y+\beta,\alpha)p_r(\eta+y,\delta+y,N_f+y)$

where:

$$p_a(x,y)=\binom{y}{x}p^x_{off\rightarrow on}(1-p_{off\rightarrow on})^{y-x}$$

is the activation probability and represents the probability that x among y non active terminals switch from *off* to *on-state*,

$$p_d(x,y)=\binom{y}{x}p^x_{on\rightarrow off}(1-p_{on\rightarrow off})^{y-x}$$

is the deactivation probability and represents the probability that x among y active terminals switch from *on* to *off state*,

$$p_l(x,y,z)=$$

$$\begin{cases}\binom{y}{x}p_{succ}(y,z)^x[1-p_{succ}(y,z)]^{y-x} & x\geq 0, y\geq 0\\ 0 & otherwise\end{cases}$$

is the reservation probability and represents the probability that x packets will be successfully transmitted among the y packets transmitted in the z random access slots, where $p_{succ}(y,z)$ is the probability that the transmitted information arrives not corrupted at the receiver (i.e at least K components are non collided):

$$p_{succ}(y,z)=\sum_{i=K}^{i=D}\binom{D}{i}(1-p_{col}(y,x))^i p_{col}(y,z)^{D-i}$$

where $p_{col}(y,z)$ represents the collision probability for each transmitted component:

$$p_{col}(y,z)=\left(1-\frac{D}{z}\right)^{D(y-1)}$$

Additionally we have set:

N_{na}	$=$	N_u-i	non active terminals
α	$=$	$i-j$	active non allocated terminals
β	$=$	$\lvert k-i\rvert$	change of active terminals
δ	$=$	$k-j$	minimum number of contending terminals
η	$=$	$l-j$	difference in allocated slots between two successive frames
N_f	$=$	N_s-j	free slots

5 Results and conclusions

In this section we present numerical results showing some remarkable performance improvements obtained by CRMs over conventional 1-dimensional modulation schemes. Most of the presented results were obtained by means the analytical Markovian approach described in the previous section. A simulation tool was also developed to validate the analytical model. The simulation and analytical results are in a very good agreement. For brevity, we report only some of the simulation results, however analytical results always fall within the simulation confidence interval that was fixed at 10% (the confidence level was fixed at 0.99).

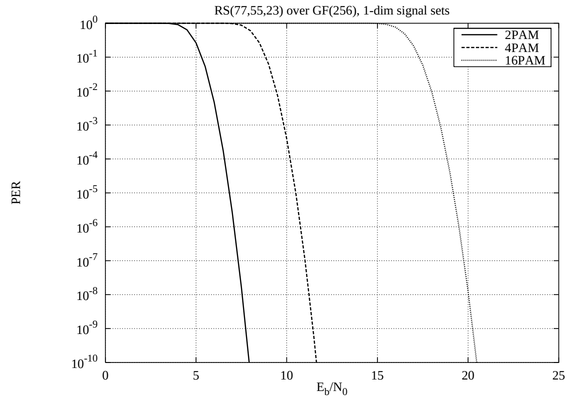

Figure 3: PER over a Gaussian channel for RS-encoded PAM schemes.

Baseline conventional system. We assume data packets are 55 bytes long (two bytes of Wireless MAC control header and 53 bytes of payload, as in a wireless ATM application). Data packets are encoded by a $(77,55,23)$ Reed-Solomon code over $GF(256)$ (each RS symbol is represented by a 8-tuple of bits, i.e., it can be considered as a byte). The simple 1-dimensional modulation formats considered here are 2-PAM, 4-PAM and 16-PAM, carrying 1,2 and 4 bit/dimension. Each RS code word is mapped onto a sequence of 1-dimensional signals by Gray labeling and transmitted over a single slot for both random access packets and reserved packets ($D=K=1$). The resulting slot lengths are $L_s=8\times 77$, 4×77 and 2×77 for 2-PAM, 4-PAM and 16-PAM, respectively. We consider systems with the same $2WT$ product. The number of slots in the 2-PAM case is $N_s^{(2)}=2WT/(8\times 77)$. This was set to 40 in our examples. The number of slots in the case of 4-PAM and 16-PAM is then $N_s^{(4)}=80$ and $N_s^{(16)}=160$, respectively.

Fig. 3 shows the PER vs. E_b/N_0 for the RS encoded 2-PAM, 4-PAM and 16-PAM over reserved slots or, equivalently, over non-collided random access slots. From these curves, for desired PER at 10^{-4} we get the SNR operating points of the three conventional systems approximately at 7 dB, 10.5 dB and 19 dB, respectively.

System based on CRM. In this case, the RS code is the same of before but the RS code words are mapped onto sequences of $D=4$-dimensional signals from a CRM signal set with 16 points presented in [7]. Each signal carries 4 bits, for the same spectral efficiency of 2-PAM, i.e., 1 bit/dimension. The number of signals per code word is 2×77, since each byte is mapped onto a pair of signals. The resulting block length is 8×77 real dimensions. As illustrated previously, our scheme uses 4 slots of length $L_s=2\times 77$ for each random access packet, while it uses only $K\leq 4$ slots of the same length for reserved packets. The number K of slots to be used depends on the desired PER and SNR operating point.

Fig. 4 shows the PER vs. E_b/N_0 for $K=1,2,3,4$ of the proposed scheme. Notice that the PER for a given K is also the PER of a random access packet

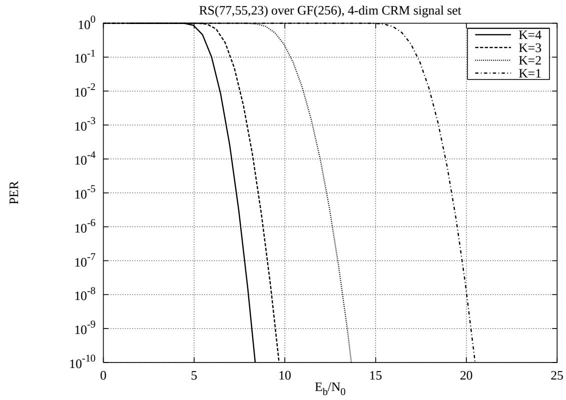

Figure 4: PER over a Gaussian channel for different number K of transmitted slots, for a RS-encoded 4-dimensional CRM scheme.

where $D - K$ slots are collided. Then, by fixing the operating point so that K slots are sufficient to meet the PER target, our system can afford $D - K$ collisions on the random access slots without suffering a blocking event. This explains intuitively the potential gain of this method over conventional schemes. For target PER at 10^{-4} we obtain the required SNRs of 7 dB, 8 dB, 12 dB and 19 dB for $K = 4, 3, 2, 1$ respectively.

As measure of the system performance we chose the *blocking probability* for admitted calls, i.e the probability that the base station is not able to reserve slots to a terminal that has switched from the *silent period* to the *talk period* because of a bad reception of the data packet transmitted on a contention slot, or because of the lack of available channel bandwidth. The average period talk-spurt is set to 50 frames where the frames are supposed to last a 20 *ms*. The mean duration of the talk-spurts is 1*s* and the average silent period is instead set to 100 frames. As a consequence $p_{on \to off} = 0.02$, and $p_{off \to on} = 0.01$.

In Table 1 the blocking probability for an ordinary 2-PAM modulation is reported. Results shown in the first column were provided by the analytical model described above; the results obtained by simulation are reported in the second column for validation. In Table 2, instead, the blocking probability for a 4D-4-CRM system (a 4D-CRM in which $K = 4$) is reported. Both systems operate at 7dB of SNR, however the traditional 2-PAM based system allows a larger number (about 60) to be accommodated by keeping the BP lower than 10^{-2}. The use of CRM modulation, in this case, does not bring any benefit, on the contrary it leads to a waste of the system bandwidth.

If a 4D-3-CRM (i.e., a 4D-CRM system in which $K = 3$) system is used, however, up 88 users can be accommodated in the system (see Table 3). As already said, the 4D-3-CRM operates at 8 dB of SNR, as a consequence, a really significant improvement of the system throughput can be achieved by using a 4D-3-CRM instead of a 2-PAM modulation at the cost of a power penalty of just 1 dB.

In the first column of Table 4, the blocking probabilities are shown, for the 4D-2-CRM modulation where only two different components of a 4-dimensional CRM symbol, are transmitted by each user on reserved slots ($K = 2$). In the second column of Table 4 results are shown for a system in which a 4-PAM modulation is used. The spectral efficiency of both systems is the same (we refer to packet transmission on reserved slots). Also in this case a larger throughput (150 users instead of less than 110) can be achieved by using 4D-2-CRM instead of a 4-PAM modulation. To this end, about 2 dB power penalty (12 dB against 10 dB) must be paid.

In the first column of Table 5, finally, are shown the blocking probabilities for the 4D-1-CRM modulation where only one component of a 4-dimensional CRM symbol, is transmitted by each user on reserved slots ($K = 1$).

In the second column of Table 5 results are shown for a system in which a 16-PAM modulation is used. Also in this case a larger throughput (300 users against less than 220) can be achieved by using 4D-1-CRM instead than a 16-PAM modulation. In this case no power penalty must be paid in this case (19 dB for both systems are needed).

The above results show that adaptive CRM schemes are an effective technique to increase the system capacity at no expense of bandwidth. The only price to pay is an additional demodulator complexity which needs to process higher dimensional symbols and a moderately larger power consumption in some cases.

We conclude by addressing some directions of research. *i)* First of all we are currently investigating the case of fading. Some preliminary results show that the high modulation diversity which is implicit in the CRMs provides good performance over the fading channel. In fact the receiver can consider a deep fade in a slot just like a collision and erase it. *ii)* In this work we have implicitly assumed that power control keeps all the users at the same SNR. An interesting case to analyze is when no power control is added and the *capture* effect is considered. *iii)* Another possibility to be analyzed in the absence of power control is a different adaptive scheme dependent on each user SNR's, i.e., users with high SNR transmit only one dimension of the CRM and users with low SNR transmit more components accordingly. This variable-rate coding scheme replaces the power control one.

N_u	BP	BP by symul.
45	0.006129	0.006087
50	0.007396	0.007381
55	0.008892	0.009010
60	0.010693	0.010167
65	0.012924	0.012812
70	0.015862	0.016034
75	0.020325	0.021345

Table 1: Blocking probability for an ordinary 2-PAM modulation

References

[1] M. B. Pursley, "Frequency-Hop Transmission

N_u	BP	BP by simul.
55	0.063654	0.063259
60	0.075448	0.075250
65	0.090118	0.089310
70	0.108141	0.107155
75	0.131028	0.130847

Table 2: Blocking probabilities for a 4D-4-CRM modulation

N_u	BP
72	0.005280
80	0.007384
88	0.009818
96	0.016810
104	0.034495

Table 3: Blocking probabilities for a 4D-3-CRM modulation

for Satellite Packet Switching and Terrestrial Packet Radio Networks," *IEEE Trans. on Information Theory*, pp. 652–667, vol. 32, no. 5, Sept. 1986.

[2] S. W. Kim and W. Stark, "Optimum Rate Reed-Solomon Codes for Frequency-Hopped Spread-Spectrum Multiple-Access Communication Systems," *IEEE Trans. on Communications*, pp. 138–144, vol. 37, no. 2, Feb. 1989.

[3] E. Lutz, "Slotted Aloha Multiple Access and Error Control Coding for Land Mobile Satellite Networks," *Int. J. of Satellite Communications*, pp. 275–281, vol. 10, 1992.

[4] S. Laufer and J. Snyders, "Short Coding for the Collision Channel Without Feedback," *Proceedings of the 1994 IEEE International Symposium on Information Theory*, p. 292, Trondheim, Norway, June 27 – July 1, 1994.

[5] R. M. Alrumaih, "(L,K) CDMA/ALOHA Multiple-Access System," *Proceedings of the 1997 IEEE International Symposium on Information Theory*, p. 53, Ulm, Germany, June 29 – July 4, 1997.

[6] G. Caire, E. Leonardi, and E. Viterbo, "Collision Resistant Modulation," *proceedings of*

N_u	BP(4-PAM)	BP(4D-2-CRM)
90	0.005431	0.000121
100	0.007850	0.000182
110	0.010101	0.000283
120	0.011891	0.000428
130	0.013549	0.000689
140	0.016562	0.001374
150	0.020091	0.004025

Table 4: Blocking probabilities for a 4-PSK and a 4D-2-CRM modulation

N_u	BP(16-PAM)	BP(4D-1-CRM)
180	0.006428	0.000005
200	0.008634	0.000011
220	0.010401	0.000023
240	0.012531	0.000042
260	0.015124	0.000074
280	0.018181	0.000171
300	0.022032	0.001117

Table 5: Blocking probability for a 16-PAM and a 4D-1-CRM modulation

ICT'98 pp. 438–444, Porto Carras, Greece, June 22 – June 25, 1998.

[7] G. Caire, E. Leonardi, and E. Viterbo, "Modulation and Coding for the Gaussian Collision Channel," submitted to *IEEE Trans. on Information Theory*, May 1998.

[8] J. K. Proakis, *Digital Communications,* Mc Graw Hill, 1995.

[9] T. Cover and J. Thomas, *Elements of information theory.* New York: J. Wiley & Sons, 1991.

[10] D. J. Goodman, R. A. Valenzuela, K. T. Gayliard, and B. Bamamurthyi, "Packet Reservation Multiple Access for local wireless communications", *IEEE Trans. on Communications*, pp. 885–890, vol. COM-37, August 1989.

[11] J. Boutros, E. Viterbo, C. Rastello, and J. C. Belfiore, "Good lattice constellations for both Rayleigh fading and Gaussian channel," *IEEE Trans. on Information Theory*, pp. 502–518, vol. 42, no. 2, March 1996.

[12] J. Boutros, E. Viterbo, "Signal Space Diversity: a power and bandwidth efficient technique for the Rayleigh fading channel," *IEEE Trans. on Information Theory*, vol. 44, n. 4, pp. 1453-1467