The Medium is the Message

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Abstract— **In this paper we advocate exploiting channel descriptor information in packet data communication networks to gain transmission capacity. Besides the normal data transmission also the channel descriptor (or character of the channel) can be used to convey data. This novel access technique is suitable for wired as well as for wireless networks. By the example of a wireless spread spectrum system with pseudo–noise spreading sequences, we can report that a gain of nearly an order of magnitude in terms of capacity can be achieved compared to the standard spread spectrum transmission for a given scenario. Our approach is not limited to spread spectrum technologies, but applies to all systems with the property that the number of channel descriptors is larger than the actual number of simultaneously usable resources.**

I. MOTIVATION

In the '60s Marshall McLuhan coined the phrase *The Medium is the Message* claiming that the medium over which information is transported is sometimes more important than the information itself. He was referring to the upcoming importance of television, but still 40 years later this sentence has some importance for the work we are describing in this paper. As we introduce a novel access technology, we would like to motivate our idea by a short example out of the GSM world. At the beginning of the GSM deployment, there was a phenomenon in Italy called *squillo*. People, mostly young people, would just ring each other (hanging up before the other side could pick up) using their mobile phones to say hello or to convey some other predefined messages. This kind of communication was very popular as it was not billed (still in many countries it is not). Inspired by this idea, we envision a scheme where multiple phones could be used to convey data over existing wireless networks using the signalling plane without any additional costs for the user. In Figure 1 a possible setup and example is given. The bits gained are of course paid for by the network provider and far fewer bits are conveyed than the network provider has to invest to make this transmission possible. Therefore it may be referred to as a *trick*. Leaving this example, we raise the questions whether it is possible to convey data by exploiting the channel descriptor (in our example phone numbers) used instead of transmitting data (recall that we did not send any bits at all over the GSM bearer). In the following we would like to investigate this idea in more detail. We will find out that the proposed approach will not lead to any gain if the number of channel descriptors is less or equal than the actual resources that can be used simultaneously. Therefore we are not looking into orthogonal systems but at so called spread spectrum systems with pseudo–noise sequences, where the number of descriptors (all available spreading sequences) is larger than the number of resources (number of actively used spreading sequences with reasonable bit error rates). In contrast to the GSM example, the spread spectrum approach is not based on a *trick*.

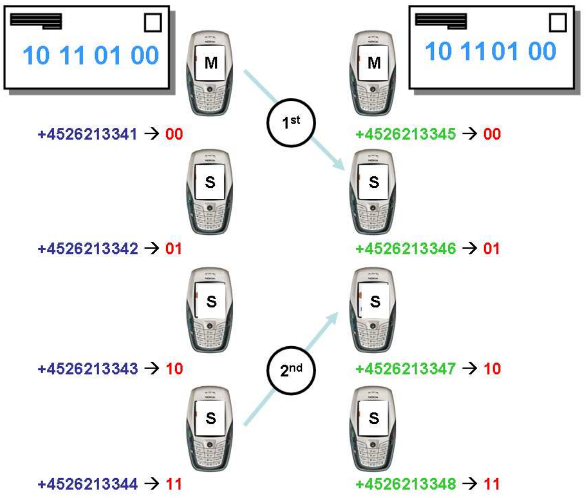

Fig. 1. Data Transmission over the GSM signalling plane with two groups of four mobile phones. Both groups have one master (M) each and three slaves (S) communicating over Bluetooth among group members. One sending phone, acting as a master, has the information to be conveyed to the master of the receiving group. The four sending and receiving phones are identified by their phone numbers and to each entity a two bit address is assigned. This assignment is known to both masters of the group. The sender master will read the digital message and by using the first two bits one phone of the sender group is chosen to call over GSM a phone of the receiver group, which is identified by the second two bit tuple. In this example, first the master itself (**00**) will call the second phone of the receiving group (**01**). The receiving phone, by using the intra group communication, informs the master about the received call (also which phone in the sending group made the call), which the master in turn can demap into four bits of information (**0100**). The second call from phone number four of the sender group (**11**) to the third phone of the receiver group (**10**) will be transformed into the information (**1011**). By each call four bits of information is transmitted.

The remainder of the text is structured as follows: In Section II a sophisticated survey on spread–spectrum technology extracting the information to explain our novel approach is given. The novel approach itself is explained in Section III; first for the ideal receiver, then for the non–ideal receiver case. A first performance evaluation of our approach is given in Section IV. We discuss our approach in Section V and conclude the work by Section VI.

II. SPREAD–SPECTRUM TRANSMISSION

Spread–spectrum techniques gained their popularity by the needs of military communications. In contrast to narrow–band communication, spread–spectrum techniques were proved to be more resistant to jamming. For a communication system to be considered a spread–spectrum system it has to satisfy the following criteria: (i) The bandwidth of the spread signal has to be greater than the information bandwidth. As this criterion is also satisfied by frequency modulation, pulse code modulation, and delta modulation, spread–spectrum has to fulfill a second condition: (ii) The spread signal is composed of the information signal and the spreading sequence. The spreading sequence has to be independent of the information [1].

In a **D**irect **S**equence **S**pread **S**pectrum *(DSSS)* transmitter (or **D**irect **S**equence **C**ode **D**ivision **M**ultiple **A**ccess (DS–CDMA)) the information signal is directly modulated by a spreading sequence, i.e. the generation of DSSS signals can be achieved by a simple multiplication of the information and the spreading sequence. The spreading sequence consists of a number of spreading chips with time duration T_{c}. The information signal consists of a number of information bits with time duration T_{s}. Spreading is achieved if multiple chips represent one bit. If T_{s} is a multiple of T_{c} the processing gain G can be easily calculated by $G = T_{\mathrm{s}}/T_{\mathrm{c}}$.

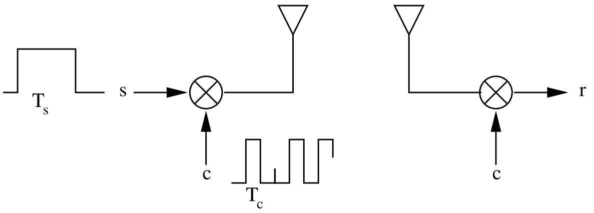

Fig. 2. Standard Spread–spectrum Transmission Approach.

The proper choice of spreading sequences enables multiple access capability for spread–spectrum based wireless communication systems. A sequence is a non–ambiguous identification for a transmitter receiver pair. Spreading sequences can be divided into *orthogonal* and **P**seudo–**N**oise (*PN*) spreading sequences. In this paper we focus on PN sequences. PN sequences are binary sequences, which exhibit random properties similar to noise. Within the class of PN sequences, the most popular representatives are *Maximal Length* sequences, *Gold* sequences, and *Kasami* [2] sequences. All sequences can be generated using a **L**inear **F**eedback **S**hift **R**egister (*LFSR*), which is built by f feedback–taps [3]. Sequences generated with a LFSR having the maximum possible period length for an f–stage shift register are called *Maximal Length* or simply m*–sequences*. The length of an m–sequence can be proven to be $2^f - 1$. The number of possible codes depends on the number of possible sets (also called *primitive* irreducible generators) of feedback–taps. Golomb [3] showed that the overall number of sequences generated by a LFSR of degree f equals

$$N_m(f) = \frac{2^f - 1}{f} \prod_{i=1}^{k} \frac{P_i - 1}{P_i}, \tag{1}$$

where P_i equals the prime decomposition of $2^f - 1$.

Corresponding to N_m for the m–sequences, we give the number of spreading sequences for the Gold and Kasami sequences in Equation 2 and 3, respectively.

$$N_g(f) = 2^f + 1, \tag{2}$$

$$N_k(f) = \begin{cases} 2^{3f/2} & \textbf{if } f = 0 \ (mod 4) \\ 2^{3f/2} + 2^{f/2} & \textbf{if } f = 2 \ (mod 4) \end{cases} \tag{3}$$

Table I provides the sequence length of a given degree f and the resulting number of achievable code sequences (see [4] for higher values of f).

TABLE I

SPREADING SEQUENCE LENGTH WITH RELATED NUMBER OF MAXIMAL LFSR (DEGREE f) SPREADING SEQUENCES.

f	4	6	8	10	12
P_i	15	63	255	1023	4095
N_m	2	6	16	60	144
N_g	17	65	257	1025	4097
N_k	64	520	4096	32800	262144

The **B**it **E**rror **P**robability (*BEP*) p_s for a standard multi–user spread spectrum communication system is given in Equation 4 using a Gaussian approximation. The Gaussian approximation does not reflect the single auto– and cross correlation among the used spreading sequences. But in real systems, using PN sequences, the communication pair agrees on a very long PN sequence. Shorter PN sequences are extracted from this long PN sequence periodically and used for the spreading. By this approach persistent interference between terminals, which would occur if two terminals were using the same series of PN sequences, is avoided and therefore the Gaussian approximation can be used.

$$p_s = Q\left(\sqrt{\frac{2 \cdot G}{k - 1}}\right) \tag{4}$$

It can be seen that the BEP p_s depends on the system parameter G (spreading factor) and the number of users k communicating at the same time. An improved Gaussian approximation has been derived by Holtzman [5] and applied in [6]. The Holtzman approximation calculates the bit–error rate caused by the multiple-access interference (neglecting the effects of thermal noise) for a system with equal received signal powers and randomly interfering signature sequences. The bit error probability for the improved Gaussian approximation is given in Equation 5. The calculations for the bit error probability are still simple enough but lead to quite accurate results. In [7] it is claimed that the improved Gaussian approximation should be used, if the number of active connections is small or the spreading gain G is large.

$$p_{Holtzman}(k) = \tfrac{2}{3}Q\left(\sqrt{\tfrac{3\cdot G}{k-1}}\right) + \tfrac{1}{6}Q\left(\frac{G}{\sqrt{\frac{(k-1)G}{3}+\sqrt{3}\sigma}}\right) + \tfrac{1}{6}Q\left(\frac{G}{\sqrt{\frac{(k-1)G}{3}-\sqrt{3}\sigma}}\right),$$
$$\sigma^2 = (k-1)\left(\tfrac{23}{360}G^2 + \left(\tfrac{1}{20}+\tfrac{k-2}{36}\right)(G-1)\right). \qquad (5)$$

The **P**acket **E**rror **P**robability (*PEP*) p_p for a packet data unit of the length L [bits] is given in Equation 6. This equation assumes a coding scheme that allows us to correct e bit errors in each packet [8], [9].

$$p_p = 1 - \sum_{i=0}^{e} \binom{L}{i} (1-p)^{L-i} p^i \qquad (6)$$

Equation 7 [10] gives the capacity C for a single CDMA cell as a function of the packet length L, the redundancy R (to correct e bits) and the number of active wireless terminals k.

$$c = (L-R)\cdot k \cdot (1-p_p) \qquad (7)$$

The cell capacity is depicted in Figure 3. Based on the bit error probability, we calculate the packet error probability by considering a simple static FEC as follows. We set the packet length to 1023 bits and employ static forward error correction that can correct up to 30 bit errors. We assume a slotted channel structure. The spreading gain is set to 32. For a small number of active channels the capacity increases linearly. At a specific point the throughput decreases rapidly. The improved Gaussian approximation by Holtzman has an optimal number of seven active channels for this example.

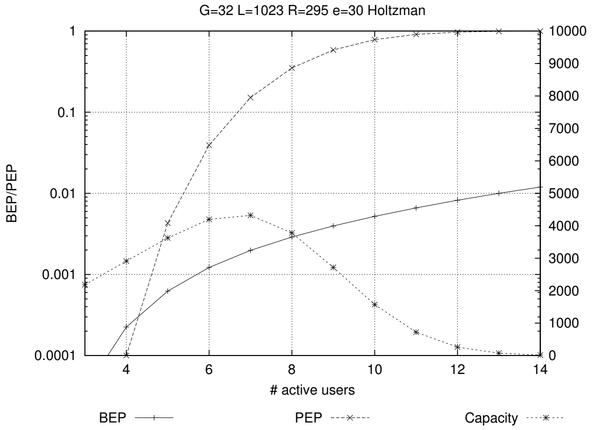

Fig. 3. p, p_p and Capacity versus the number of active users. The optimal number of active users (for G=32, L-1023, R=295,e=30) is 7.

Thus, the admission control should take care that not more than seven channels are used. But at the same time, using Gold sequences, a total number of 33 spreading sequences are available. The observation that the number of channel descriptors is larger than the number of resources that can be used simultaneously is exploited in our proposed scheme. Note, that for orthogonal systems the number of channels descriptors is always the same as the number of resources used simultaneously.

III. NOVEL APPROACH FOR SPREAD–SPECTRUM TRANSMISSION

In our proposed scheme we assume that a sender receiver pair has a predefined set of PN sequences for communication. Each PN sequence is referred to as a channel descriptor. This approach is similar to a **M**ulti–**C**ode CDMA (*MC–CDMA*) system. In contrast to a MC–CDMA system our approach will always use only one channel at the time. In Figure 4 the novel spread–spectrum transmission approach is given. If the number of parallel channels per communication pair is denoted as H and the binary message s has to be conveyed to the receiver, the sender will take the first $N_d = log_2 H$ bits of the binary sequence s identifying the channel descriptor to use and send N_s bits over this channel descriptor. Note that the N_d are not sent over the air interface and therefore are not introducing interference to other ongoing transmissions. On the receiver side the ongoing communication on one of the channel descriptors is detected and the N_s bits are received. Before the N_s bits are written into the receiver queue the receiver will add N_d bits, known by the channel descriptor used. From the perspective of ongoing transmissions in the cell, the proposed system will produce interference like a single code CDMA system. As CDMA is interference limited, we claim that our proposed scheme will have no effect on ongoing transmissions and can therefore be evaluated in a stand alone fashion. If we consider multi user scenarios and all receivers are merged in a centralized entity such as a base station then double use of PN sequences among the terminals can be avoided easily. For a distributed system, the PN sequences have to be monitored and if some PN sequences will conflict with each other, they should be replaced.

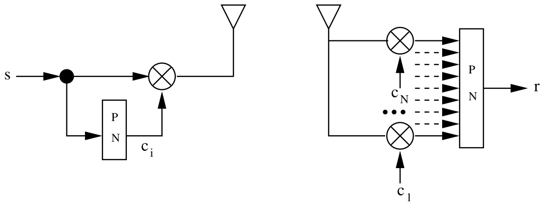

Fig. 4. Novel Spread–spectrum Transmission Approach.

For illustration purpose, we assume $H = 8$ such that $b = log_2 N = 3$ bits are assigned such as given in Table II. Furthermore only $N_s = 2$ bits are transmitted over each channel descriptor at the time and for this time we assume that the spreading code acquisition is perfect. In case the sender has to transmit the binary sequences $s = (001\mathbf{11}101\mathbf{01}001\mathbf{00})$ it would take spreading sequence c_{001} to transmit the bit value 11 in the first slot (using this spreading sequence identifies the first three bits and the value transmitted the bit number four and five), the spreading sequence c_{101} to transmit the bit value 01 in the next slot and the spreading sequence c_{001} to transmit the bit value 00 in the last slot.

TABLE II

SPREADING SEQUENCES ASSIGNMENT FOR H=8.

	spreading sequence	bits assigned
1	c_{000}	000
2	c_{001}	001
3	c_{010}	010
4	c_{011}	011
5	c_{100}	100
6	c_{101}	101
7	c_{110}	110
8	c_{111}	111

In this example we have only transmitted six bits over the wireless channel, but the receiver receives 15 bits of information. Thus the capacity was improved by the factor of 2.5 in contrast to a system where only one channel would have been available transmitting all 15 bits. In general the gain Φ is defined as the ratio of bits sent with the new scheme divided by the bits sent in the old scheme as given in Equation 8.

$$\Phi = \frac{bits_{new}}{bits_{old}} \tag{8}$$

A. Ideal Spread Spectrum System

In case the spreading code acquisition and synchronization is ideal, the gain can be simply calculated as $\Phi = \frac{N_s + N_d}{N_s}$. In the ideal case the capacity of each terminal for the proposed system is Φ times higher than the standard one. The bit error rate remains the same as the cell interference will not change in contrast to the standard transmission case for the transmitted bits. The approach can be also used to reduce the inference by transmitting as much information as before, but transmitting less information over the air interface exploiting our approach. In such a case we can assume that the number of active users is simply divided by the gain Φ. Furthermore, in the ideal case, only the N_s bits are prone to errors, while the N_d bits are error–free. Therefore the bit error probability has to be divided by Φ.

$$p_n = Q\left(\sqrt{\frac{2 \cdot G}{k/\Phi - 1}}\right) \cdot \Phi^{-1} \tag{9}$$

For the ideal case the BEP versus number of parallel channels and versus active users for the standard and the proposed approach is given in Figure 5. For the proposed scheme we have depicted the bit error probability for the transmitted bits and the overall bits individually. We used the simple Gaussian approximation here. It can be seen that our proposed scheme yields significantly better results than the standard approach. Without going into details we leave the ideal case and investigate the more realistic scenario of the non–ideal receiving process.

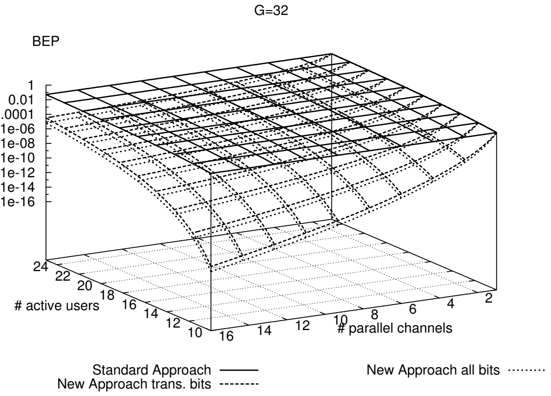

Fig. 5. BEP Versus Number Of Parallel Channels And Versus Active Users For The Standard And The Proposed Approach For The Ideal Case Using The Gaussian Approximation.

B. Non–Ideal Spread Spectrum System

So far we assumed the spreading code acquisition and synchronization are perfect leading to a error-free reception of all N_d bits. In real systems we have to deal with code acquisition and synchronization. Here and hereafter we use the Holtzman approximation to calculate the bit error probability. Code acquisition is needed to achieve a coarse synchronization between sender and receiver. In case the code acquisition fails, no data will be transmitted at all. Two different types of acquisition errors are known, namely a false alarm (incorrect hypothesis to have received a signal) and a miss (not successful detection of a send signal). Possible detection schemes are the *matched filter energy detector* and the *radiometer*. Both approaches are comparing the incoming signal σ with a given threshold γ. Whenever σ is larger than γ a detection is assumed. A large γ will end up in less detection but also less failure and the other way round. The probability for a false alarm p_{fa} and a miss p_m (or its complement the probability of detection p_{de}) are given in [11], [12], [13] for *matched filter energy detector* and the *radiometer* assuming a single code CDMA system. We give here the probabilities for the radiometer as:

$$p_{fa} = Q\left(\sqrt{BT_d}\left[\frac{\gamma}{N_0 B} - 1\right]\right) \tag{10}$$

.

$$p_{de} = Q\left(\frac{Q^{-1}(P_{fa}) - SNR\sqrt{BT_d}}{\sqrt{2SNR + 1}}\right) \tag{11}$$

To calculate the non–ideal BEP $p_{n'}$ of our approach with code acquisition and synchronization errors the fraction of erroneous bits by the total number of bit has to be calculated as:

$$p_{n'} = 1 - \frac{1 - p_1}{2} - \frac{(N_d + N_s(1 - p_s))p_1}{N_s + N_d}, \tag{12}$$

where $p_1 = p_r \cdot (1 - p_f)^{H-1}$ reflects the situation where a signal is detected only on one channel with probability p_r (probability that the signal is detected on the correct channel after the system has been synchronized) and the other channels have no false alarm meanwhile with probability p_f (probability that a false signal is detected on one channel after the system is synchronized). The probabilities set p_r and p_f are much smaller than the set of probabilities p_{de} and p_{fa}, respectively, as the later set gives the probabilities when no synchronization has been established yet. The former set includes the initial synchronization and the ongoing tracking. For completeness, the probability $1 - p_1$ reflects the situation, where multiple detections are assumed, no detection has occurred, or the transmission is not synchronized anymore. For the standard approach the error prone detection is also taken into consideration as given below

$$p_{s'} = \frac{(1-p_1)}{2} + p_1 \cdot Q\left(\sqrt{\frac{2 \cdot G}{k-1}}\right), \qquad (13)$$

where $p_1 = p_r$ (so no false alarm will worsen the situation).

To decrease the impact of the code acquisition error, we advocate a joint detection (JD) of the signal. So far we left it up to each channel to compare the incoming signal strength σ with a given threshold γ individually to check for detection, a situation which we refer to as single detection (SD). In contrast to the SD approach we take the highest value of σ of all channels and take this as a detection, referring to this as the JD approach. This is possible as the receiver knows that the sender will always use only one descriptor at the time. To decrease the impact of the synchronization, code concatenation can be used as proposed in Figure 6. In this case the communication pair is identified by the spreading sequence c_{WT} and the channel descriptor is chosen by a set of codes c_i, i=1 … H. The receiver can then track the ongoing transmission by de–spreading the information with c_{WT} and postprocess the channel descriptor later by sequential search using c_i, i=1, …, H. We claim that this setup is less error prone as the de–spreading with c_{WT} will take place H times more often than on separate multiple channels. Therefore the synchronization can be maintained more easily as the clock of c_{WT} can be used by the later de–spreading with c_i. Furthermore when we detect a signal with c_{WT}, we can be sure that one and only one of c_i, will detect the signal in the second level. With this approach the error probability of the transmitted bits is equal to that of the standard one.

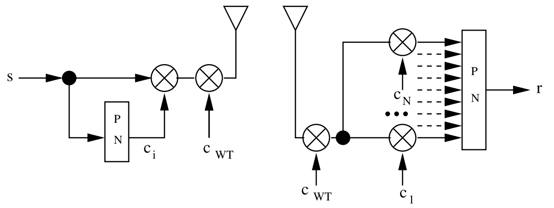

Fig. 6. Novel Spread–spectrum Transmission Approach With Code Concatenation.

With the new architecture the probability p_f is set to zero. Equation 14 has to be rewritten to

$$p_{n''} = 1 - \frac{(1-p_r)}{2} - \frac{(N_d + N_s(1-p_s))p_r}{N_s + N_d}. \qquad (14)$$

IV. PERFORMANCE EVALUATION

For the performance evaluation we assume $p_r = 99.9\%$ and $p_f = 0.1\%$ with a spreading gain $G = 32$. Up to $e = 30$ bits can be corrected in a $L = 1023$ bit word using $R = 295$ bit of redundancy. We analyze the different number of $H = 1, 2, 4, 8$ leading to values of $N_d = 0, 1, 2, 3$. N_s is set to one. The standard approaches (ideal and non-ideal) are given by solid lines, while our proposed approaches are reflected by dashed and dotted lines. The single detection case (SD) has non-filled points, while the joint detection (JD) is given with filled points. In Figure 7 the BEP versus the number of active users for the standard and the proposed approaches with code acquisition errors are given. In that comparison also the standard communication system is prone to errors due to the code acquisition. In Figure 7 the BEP curves of the JD approach are the best and the more channels that are available, the better the performance will be. It seems that the performace is only limited by the number of available descriptors per communication pair. The non ideal standard approach yields better results in terms of the BEP values than the SD approach as the number of users are smaller than 6, 9, and 12 for H equal 2, 4, and 8 respectively.

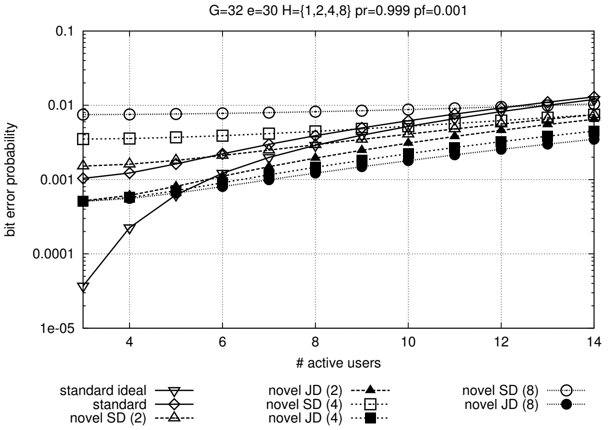

Fig. 7. BEP Versus Number Of Active Users For The Standard And The Proposed Approaches With Code Acquisition Errors.

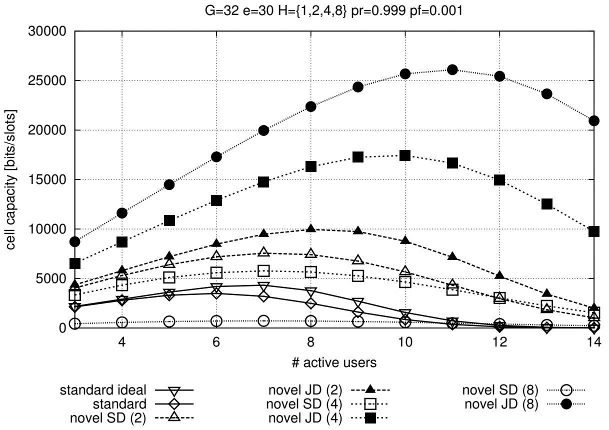

Fig. 8. Capacity Versus Number Of Active Users For The Standard And The Proposed Approaches.

In Figure 8 the capacity versus number of active users for the standard and the proposed approaches are given. Here a more detailed discussion about the performance can be made. Obviously the JD approach yields better results than any other approach. The performance increases with an increasing number of H as for the BEP. The SD approach yields the best performance for $H = 2$, as a larger number of H will degrade the performance due to many false alarms. For $H = 8$ the performance is even worse than the standard approach (for fewer than 11 users). The maximum cell capacity is achieved with six users in the cell for the standard and with seven users for the SD approach. For the JD approach the optimal number of users is 8, 10, and 11 when H equals 2, 4, and 8 respectively. For illustration purposes we present two kinds of cell gain. $Gain_S$ defines the cell gain of a given approach divided by the standard approach with the same number of users, while $Gain_{S,opt}$ defines the cell gain of the proposed approach divided by the capacity of the standard approach with each approach using its own optimal number of users. The results are given in Table III. As we can see, Single Detection reaches its maximum of 2.16 when $H = 2$, and Joint Detection reaches its maximum of 7.46 when $H = 8$.

TABLE III

GAIN AT THE OPTIMAL WORKING POINT.

no. users	Approach	H	Capacity [bits]	$Gain_S$	$Gain_{S,opt}$
6	Standard	1	3497	1.00	1.00
7	SD	2	7425	2.36	2.16
7	SD	4	5775	1.80	1.65
7	SD	8	724	0.22	0.21
8	JD	2	9960	3.99	2.84
10	JD	4	17437	20.34	4.98
11	JD	8	26101	71.34	7.46

V. DISCUSSION

In the discussion two points are highlighted, namely whether our system still meets all of the requirements for a spread spectrum system and the possibility of changing the PN sequences on the fly. Referring to the definition of the spread spectrum system given in Section II, the spreading information and the transmitted information should be uncorrelated. This requirement still holds as the transmitted information has no impact on the choice of the spreading code. The second point deals with the feasibility of changing the PN sequence on the fly. Here we are referring to the implementation in an IS–95 [14] system, where long PN sequences are assigned and subsets of this long PN sequence are extracted to spread the information streams. While in IS–95 the subsets are taken out step by step, we are modulating our information onto the choice of smaller PN sequences. Therefore we claim that our approach is as complex as any standard system and that changing PN sequences is a solved problem. Furthermore in IS–95 systems the usage of multiple channels was already addressed by the LIDA [15] and BALI [16] approach.

VI. CONCLUSION

We have introduced a new access technique based on the exploitation of channel descriptor information. We are exploiting the medium over which partial information is conveyed to code additional information. Following McLuhan, we say the medium is the message or the medium is part of the message. By the example of spread spectrum we have shown the way our approach works and have given a first performance evaluation. The cell gain will vary depending on the system but in our example, using realistic receiver architectures, our technique gave an improvement of nearly one magnitude over the standard one (both with the optimal number of users). In this paper we used the spread spectrum technology to illustrate our approach. Other technolgies can be found and will be named here in our final paper. In our future work we will apply this approach to further communication systems which are not limited to spread spectrum technology.

VII. ACKNOWLEDGEMENTS

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