Robust and Reliable Communication Meets Future Mobile Communication Demands

Alois M.J. Goiser, Samar Khattab
Institute of Communications and Radio Engineering
University of Technology Vienna
Vienna, Austria
Email: alois.goiser@tuwien.ac.at

***Abstract*—Robustness and reliability are more important for future applications than today. This is outlined in this paper. The suitability of the spread-spectrum technology for future wireless applications is investigated. The spread-spectrum technology offers the RAKE receiver structure to mitigate the most harmful type of interference in a mobile application, the multipath interference. To enhance the spectral efficiency multi-code transmission is employed. It is easy and inexpensive to adapt the system to the channel delay spread and avoid expensive channel equalization techniques. The extension from a point-to-point topology to a multipoint-to-point topology is achieved with the code-division-multiple-access concept. The bandwidth efficiency can be further enhanced using multi-user detection. For interference limited environments the multi-carrier code-division multiple access scheme is applied. Special attention is payed to the multi-code transmission and the related improvement in spectral efficiency.**

***Keywords*-Interference Mitigation, Spread-Spectrum Systems, Code-Division-Multiple-Access, Multi-User Detection.**

I. INTRODUCTION

The goal of this paper is to demonstrate that a low complexity transceiver structure for robust and reliable digital communication is necessary for future communication challenges. The transceiver combines the advantage of a low complexity digital design with the advantage of interference reduction in a single step. Further we present the need to move to robust and reliable communication techniques to meet the demands for future applications. As a suitable base technology the spread-spectrum technology is chosen.

The assumption about the future is based on the fact, that it is impossible today to precisely predict the kind of services needed nor the kind of the interference present. Therefore the transceiver scheme must be equipped with the following properties: (a) it must operate in a mobile and hostile/harsh environment, (b) it must be from low complexity to be cheap (economic) and less power consuming (mobile use), (c) the concept must be very flexible for changing service demands, (d) the detection algorithm must be fast adapting to follow rapidly changing waveforms, (e) it must accept information from higher layers. Some of the assumptions above are fulfilled partly from schemes that are published today. What was not published up to today is a concept that can cope with all the mentioned goals with low complexity.

The general topic about interference reduction (IR) is covered in many papers. We like to emphasize some of the key papers. It starts with the famous paper from Claude Shannon [1] which presents the key tools to combat interference. Some excellent tutorial papers are covered in [2], [3], [4], [6]. For an introduction to the global view of IR see [8].

We start with a brief description of robustness and reliability in Section II. In Section III we emphasize the interference reduction mechanism of the spread-spectrum technology in general. Implementation issues are treated in Section IV. Mainly the structure of the used spread-spectrum signal, with its excellent multipath interference reduction capability, is responsible for the popularity of the spread-spectrum technology. The receiver structure that is close to optimum in a multipath interference environment is the RAKE receiver structure, outlined in Section V. The necessary bandwidth expansion to receive the processing gain for a suitable bit-error-probability (BEP) is mitigated by using multi-code transmission (MCTr). The accompanying spectral efficiency is treated in Section VI. A future wireless system must be able to support a multi-user environment. This is achieved with the code-division-multiple-access (CDMA) concept. The necessary orthogonality for the individual users is achieved in the code-space. The code-space is formed by a suitable number of spread-spectrum signals fulfilling the orthogonality relation within the set. The CDMA philosophy is outlined in Section VII. The bandwidth efficiency can be further enhanced for multi-user transmission using multi-user detection (MUD) receiver structures. The idea of multi-user detection is explained in Section VIII. The Section IX deals with multi-carrier CDMA (MC-CDMA). The benefits are listed and the properties are applied to terrestrial mobile communication. The last section focuses on the flexibility of the spread-spectrum concept which is valuable for the radio resource management.

II. ROBUSTNESS AND RELIABILITY

Prior to the discussion of robust communication schemes we compare the optimum communication system with the robust communication system and highlight the differences.

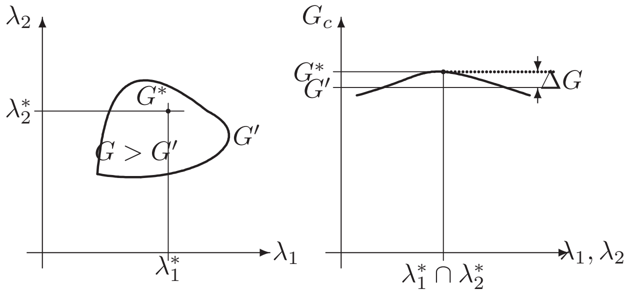

Figure 1. Comparison between optimal communication and robust communication in a 2-dimensional parameter-plain $G(\lambda_1, \lambda_2)$. G is the chosen figure of merit.

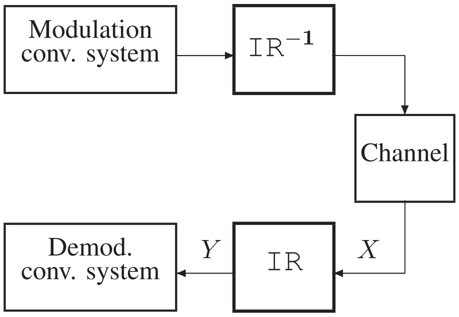

Figure 2. Overall structure of the investigated robust and reliable communication system. IR ... interference reduction.

In general a communication system is a system described by a process with a certain amount of parameters λ_i. The parameters are summarized in a set of parameters and expressed as a parameter vector $\boldsymbol{\lambda} = [\lambda_1, \ldots, \lambda_i, \ldots, \lambda_N]$. The communication system is fully specified for a specific situation with a certain set of parameters. Some of these parameters are controllable others are not. The parameters of the channel are the most important one, because they introduce the randomness in the communication link. Some of these parameters are estimated prior to detection others are not. If no attempt is made to estimate the composition of the interference it is termed a ”blind” concept.

The design process for a communication engineer is to adjust the parameters in such a way that a specific behavior of the communication system is achieved. More precisely we have to choose a suitable optimization criteria and adjust the parameters to maximize these quality conditions. In other words we have a parameter surface over which the quality function G is drawn. The quality function is also denoted as figure of merit. Without loss of generality we reduce the parameterset to two parameters $\boldsymbol{\lambda} = [\lambda_1, \lambda_2]$. The quality function is then $G(\boldsymbol{\lambda})$ and forms a quality surface. For simplicity we assume that the extent of the surface is not bounded.

An optimum system is a system for which the parameterset $\boldsymbol{\lambda}$ maximizes the quality condition (1). It is notable that this condition is only meet by a single parameterset $\boldsymbol{\lambda}^*$.

$$G \mapsto G^* = \max\{G\} \qquad \ldots \text{ Optimum System} \tag{1}$$

The optimum system in additive white gaussian noise (AWGN) is the well known matched-filter receiver (correlation receiver). This type of receiver do not take care about the interference waveform. The performance is only dependent on the energy of the desired signal and the spectral density of the undesired signal. Is the nature of the interference non-gaussian, then a different structure of the receiver is optimal. Therefore we conclude that an optimum system is only optimum for a specific parameter set $\boldsymbol{\lambda}^*$ of the involved signals. This is indicated in Figure 1 with the two specific parameters $\boldsymbol{\lambda}^* = [\lambda_1^*, \lambda_2^*]$.

The derivative of the optimum system is based on stationary parameters. That means that the involved interference processes are stationary and their parameters do not change with time. That is restricted to situations where the interference environment is stable.

If we broaden our view about the interference environment in that way that we allow the interference to undergo some changes with time we open our discussion to a more tolerant class of receivers that are termed *robust receivers*.

A robust communication system is a system that is insensitive to some degree of change in the interference environment. Sometimes the changes are really dramatic when the type of interference is also allowed to change. Robust systems have the inherent capability to reduce the impact of unpredictable types of interference. This is visualized in Figure 1 that the operating point for an optimum system (single point) is spread out to some extend forming an area. Within that area the figure of merit fulfills the inequality that it is always above a predefined quality measure G'.

$$G \mapsto G \geq G' \qquad \ldots \text{ Robust System} \tag{2}$$

We like to note that a robust system includes the optimum system. Generally speaking, a robust communication system is a system that is more insensitive to interference changes.

To be more flexible in the notation of wanted and unwanted signals we term the signal of interest (SOI) and the signal of no interest (SONI). The overall structure of the investigated robust and reliable communication system is outlined in Figure 2. As conventional modulation scheme a binary keying technique (bipolar) is used. For interference reduction the spread-spectrum technology (direct-sequence) is used. The $\mathtt{IR}^{-1}$ indicates spread-spectrum modulation and `IR` indicates spread-spectrum demodulation. This indication is related to the fact, that the channel signal is hardened with the spread-spectrum signal to protect the information bearing

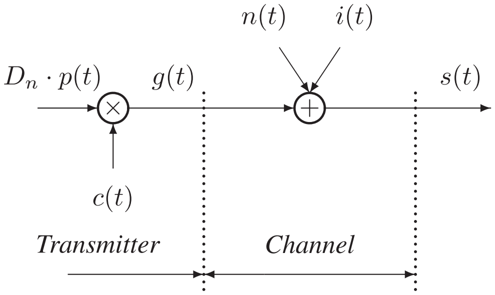

Figure 3. Transmitter and channel model. $p(t)$ ... unite rectangular pulse, D_n ... n-th databit, $c(t)$ ... spread-spectrum signal, $g(t)$ ... SOI, $n(t), i(t)$ ... SONI, $s(t)$ ... received signal.

signal from the conventional modulator from the magnitude attacks of the interference at the channel.

III. Spread-Spectrum Concept

In this section the interference reduction mechanism of the spread-spectrum technology is outlined, which is the basis for all benefits of this technology. Other benefits of spread-spectrum technology are: (a) Additional error-control coding techniques up to the spread-spectrum bandwidth are possible without increasing the bandwidth further. (b) Due to the spreading operation the spectral density of the channel-signal is significantly reduced to fulfill national and international EMC regulations. (c) The design of the spread-spectrum signal allows to protect the signal from unauthorized utilization.

The description of the interference reduction mechanism uses the baseband model of a direct-sequence spread-spectrum system sketched in Figure 3. The n-th databit D_n is presented to the transmitter. This databit is multiplied with the spread-spectrum signal $c(t)$. Bold letters indicate vector notation. The channel adds an interfering signal $i(t)$. The summation of the spread-spectrum modulated databit and the interference is forwarded to the receiver. The spread-spectrum receiver uses the correlation principle to detect the databit. To achieve this, the receiver multiplies the incoming signal with a stored replica of the spread-spectrum signal. The decision variable is given in (3). Due to the linearity of the correlation the decision variable can be split into two terms corresponding to the wanted signal or signal of interest Z_s and the interfering signal or signal of no interest Z_i. The correlation between $\boldsymbol{x}$ and $\boldsymbol{y}$ is denoted in vector notation: $[\boldsymbol{x}, \boldsymbol{y}] = \boldsymbol{x} \cdot \boldsymbol{y}^T$.

$$Z_1^{(n)} = D_n \cdot \underbrace{[\boldsymbol{c}, \boldsymbol{c}]}_{\equiv 1} + \underbrace{[\boldsymbol{i}, \boldsymbol{c}]}_{\rightarrow 0} = D_n + I^{(n)} = Z_s + Z_i \tag{3}$$

It is easy to verify that the first term in the decision variable delivers the polarity of the databit ($D_n = \{+1, -1\}$) and the second term averages to zero. Additionally to this simple interference reduction mechanism another property of a spread-spectrum system is important if multipath interference is present. This property is the two valued correlation function corresponding to the pseudo-noise property of the spread-spectrum signal. This property was originally included to reduce the spectral density of the transmitted signal and to synchronize the spread-spectrum receiver [3]. Synchronization is the process to align the phase of the incoming spread-spectrum signal with the locally stored spread-spectrum signal. The two valued correlation function guarantees synchronization and offers the possibility to distinguish the transmitted signal with a delayed version of it self if the delay is greater than two chip durations. In other words the correlation detection (single correlator case) of a spread-spectrum signal in a multipath environment treats the delayed version of itself as interference and combats it with the processing gain. This single correlation receiver type is referred as multipath rejection receiver (MRR).

These advantages are achieved with an increase in bandwidth. The increase in bandwidth can be mitigated using multi-code transmission. The above mentioned layout of a spread-spectrum system could be termed: single-user or single-code system (SCoTr). This is the simplest architecture of a spread-spectrum system. The ultimate figure of merit is the processing gain. The processing gain (G_p) is the ratio of the signal-to-noise power at the spread-spectrum detector output related to the signal-to-noise power at its input. This ratio is directly related with the bandwidth of the spread-spectrum signal (B_{ss}) to the bandwidth of the information signal (B_d). More specific it relates the symbolrate (R_s) to the channel bandwidth (B_{ch}) and equals the chips available (L) in the direct-sequence signal. A chip is the fundamental pulse of the spread-spectrum signal [3]. The channel bandwidth is equal to the spread-spectrum bandwidth. The processing gain was chosen on the basis of the necessary signal-to-noise ratio at the detector input to guarantee a suitable bit-error probability.

$$G_p = B_{ch}/B_d = R_s \cdot B_{ss} = L \tag{4}$$

$$R_d = R_s \tag{5}$$

$$\eta = R_d/B_{ss} = 1/B_{ss} \tag{6}$$

The spectral efficiency (6) is very low as expected. The primary reason of the inventors [5] of this architecture was to communicate reliable in a military environment. For that environment the interference reduction capability and covered communication was the major goal and not the spectral efficiency. For commercial applications the spectral efficiency is more important than hiding the signal and the necessary changes are covered in sections VI to IX.

A remark on spectral efficiency: In the single-user case the bitrate equals the symbolrate. We assume that a single databit is represented by a single spread-spectrum signal of equal duration. The spectral efficiency is defined as the ratio of the bitrate to the occupied channel bandwidth. For the spread-spectrum concept, the spectral efficiency is represented by the instantly used spread-spectrum signals within the spread-spectrum bandwidth. If more complex signal mappings are used, better spectral efficiencies can be achieved. For further reading we refer to [4].

IV. SYSTEM IMPLEMENTATION

The system can be implemented analog with continuous time and magnitude scale with the known problems from analog signal processing. The most flexible way is a digital architecture with the following advantages: (a) simple and cheap signal processing, (b) a limited word-length for the information construction, (c) easy to store, easy channel-coding and encryption. The core of the receiver is the digital correlator for data-detection. The word-length of the necessary analog-to-digital conversion prior to the correlation defines the complexity of the digital receiver. The most coarse quantization is achieved with a hard-limiter. In AWGN-interference, the reduction in signal-to-noise ratio (SNR) prior to detection is about 2 dB which can be accepted. In a narrowband interference the degradation in SNR can be more than 7 dB, which is not acceptable. Multibit quantization raises the complexity which is not our goal. A solution to this problem is a sophisticated quantization procedure [7]. From a complexity point of view we have only 2-bit quantization that keeps the complexity low. But the quantization is adaptive with a fixed sign-threshold at the average level of the received signal and an adjustable pair of magnitude thresholds centered around the fixed sign-threshold. Usually the coarse quantization leads to a loss of information of the SOI. But in our case it reduces the information of the SONI. This offers the potential capability to enhance the SNR prior to detection. How this advantage can be invested are shown in the next sections.

V. RAKE RECEIVER

The RAKE receiver structure is a special structure offered by the spread-spectrum technology to combat multipath interference. The multipath rejection receiver, explained in the introduction, treats the echos as interference and reduce it with the processing gain. Now we go a step further. The energy in the delayed components can be included in the decision variable using as many correlations as significant components in the multipath signal are present. An indicator for that is the multipath profile. The multipath profile delivers the information about the delays and the energies contained in the echos. The multipath profile is efficiently derived from the PN-property of an unmodulated spread-spectrum signal. This signal is referred to as pilot signal (pilot channel). If the delays are known than for each delay a single correlator is necessary to recover the energy in each path. The weighted sum of all the components led to the RAKE receiver [4] structure. Equal gain combining is achieved if the weighting is related to the signal strength of the multipath components.

VI. MULTI-CODE TRANSMISSION

The multi-code transmission (MCTr) is used to enhance the spectral efficiency [4]. Multi-code transmission is based on the orthogonality relation of the spread-spectrum signal set. The signal set contains K orthogonal signals. The signal set is applied to only one physical node (user). For this type of transmission a synchronous transmission can be guaranteed. This means that the databits are from equal length and start at the same time instant. This simplifies the detection of the databits at the receiver side and delivers better performance measured with the bit-error probability. The processing gain is roughly the same as in the single-code case and dictated from the necessary signal-to-noise ratio at the detector input to maintain a certain quality of service (QoS). But the overall data throughput is enhanced (7) with the number of orthogonal spread-spectrum signals used. This has two consequences: (a) As mentioned before the spectral efficiency (8) is enhanced and (b) the databit duration can be adapted to the channel delay spread. The second property allows a cheap receiver design, because it avoids complicated, power consuming and expensive equalizers at the receiver.

$$R_d = K \cdot R_s \tag{7}$$

$$\eta = R_d / B_{ss} = K / B_{ss} \tag{8}$$

Under realistic conditions the orthogonality of the code set is not perfect and the capacity is limited. More on capacity is treated in the next section. But what was overseen so fare is that multi-code transmission offers a substantial advantage in shorten the mean synchronization time. This is achieved due to a majority voting philosophy to declare synchronization. That is a very important improvement in the overall performance of the spread-spectrum concept.

The efficiency of multi-code transmission shown in Figure 5 is based on the assumption that the transmitted power is constant (power of the SOI at the channel input is constant). For verification the channel-capacity of a binary channel, the bit-error-probability (BEP) for a non spread-spectrum system and the bit-error-probability for a plain spread-spectrum system (single code transmission, SCoTr) are included. We have used a single PN-sequence for interference reduction (whitening operation) and the orthogonal walsh-sequence family in Figure 4 for the orthogonal transmission of the information. The results in Figures 5 and 6 are derived with (7), (8) and monte-carlo simulations.

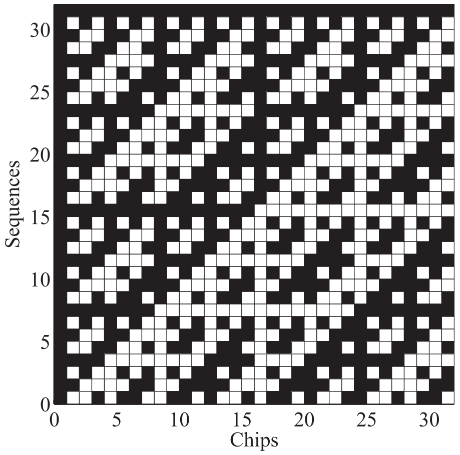

Figure 4. Walsh-family used for multi-code transmission. L=32 chips.

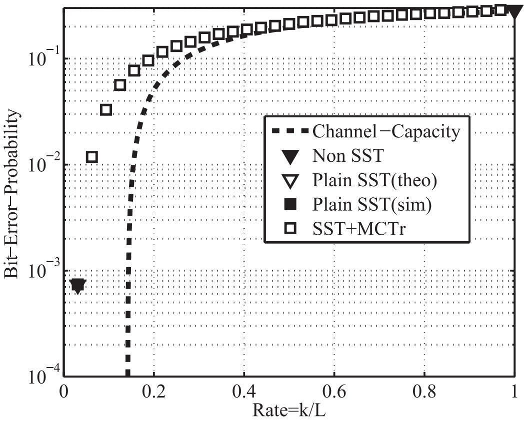

Figure 5. Spectral Efficiency of Multi-Code Transmission in AWGN. L=15dB, SNR=-5dB.

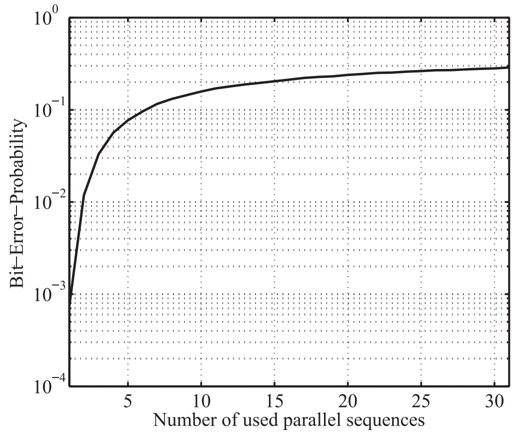

Figure 6. Performance of Multi-Code Transmission in AWGN. L=15dB, SNR=-5dB.

VII. CDMA-CONCEPT

In CDMA the orthogonal signals are assigned to different physical nodes. Each physical node represents a different user in the system. A major difference to multi-code transmission is that each user need his own PN-signal for interference reduction. Due to the two extreme assignments (a) the whole signal set to one physical node and (b) assigning each signal one physical node, also a mixture between both can be arranged. This shows the flexibility of the spread-spectrum concept which is valuable for the radio resource management. The decision variable (9) contains K terms corresponding to K active users. The first term contain the databit of the desired user. The remaining terms are the contribution from the other users and are interference in nature. The collection of the remaining terms is referred too as multi-user interference (MUI).

$$\begin{aligned} Z_1^{(n)} &= D_1^{(n)} \cdot \left[\boldsymbol{c}^{(1)}, \boldsymbol{c}^{(1)}\right] + \cdots + D_K^{(n)} \cdot \left[\boldsymbol{c}^{(K)}, \boldsymbol{c}^{(1)}\right] \\ &= D_1^{(n)} + \mathrm{MUI}_1^{(n)} \end{aligned} \tag{9}$$

The multi-user interference is a consequence of the spread-spectrum philosophy. The spread-spectrum concept is not a collision avoidance system as other multiple-access schemes. Therefore the capacity of a CDMA system is interference limited. The capacity of a CDMA system is defined as the number of simultaneously supported spread-spectrum users within the spread-spectrum bandwidth with a nominal bit-error probability at the same location. If necessary the capacity could be increased temporarily allowing more active users as nominally designed at the expense that the overall bit-error probability is also increased. This effect is referred to as soft capacity limit. The orthogonality in the signal set could be enhanced using hadamard code words. Hadamard code words are generated from the original spread-spectrum signals multiplied with walsh-signals. The multiplication is done in the digital domain and therefore very simple and costs no additional bandwidth. In this case the advantages add up (pseudorandom property from the spread-spectrum signal and the orthogonal property of the walsh signal) and the disadvantage is harmless. A further mitigation of the multi-user interference leads to the multi-user detection receiver structures.

VIII. MULTI-USER DETECTION

The interference introduced from the other users (MUI) in a CDMA environment limits the capacity of the system. The multi-user receiver structure resolve this disadvantage at the expense of a more complex receiver design. The multi-user detectors gain their advantages from the known correlation behavior of the spread-spectrum signal set. The multi-user detector performs all correlations from all active users. A comparison between the performances of a conventional CDMA system with a multi-user detection system shows the following principal behavior. The performance is measured in bit-error probability over the number of active users starting with the single-user case. The baseline of comparison is the CDMA system. If we add in the CDMA case more active users the bit-error probability increases due to impairments in the orthogonality of the signal set. In the ideal case of a multi-user design the bit-error probability should be the same as that of the single-user case, regardless how many users are active. The reality is that the multi-user concept can support some active users close to the bit-error probability of the single-user case. If further active users are added to the system the bit-error probability of the multi-user system also increases and approaches the behavior of the CDMA system. The behavior of the multi-user receiver is dependent on the processing gain and the signal set design. Multi-user receivers are primarily used at the base station in a terrestrial cellular structure.

IX. MULTI-CARRIER CODE TRANSMISSION

The limiting factor in the capacity of a CDMA system is the multi-user interference. Another possibility than using multi-user detection is to use multi-carrier code-division-multiple-access (MC-CDMA). In this concept the multi-user interference is reduced by introducing the collision avoidance principle into the spread-spectrum philosophy. The idea behind is the merging of the orthogonal frequency-division multiplex (OFDM) scheme with the CDMA scheme. Each orthogonal frequency-channel represents a CDMA channel with its unique carrier frequency and spread-spectrum bandwidth. The necessary spread-spectrum bandwidth is dictated from the necessary processing gain. A property of that mixture is that if the delay spread of the channel is too large compared to the databit duration, the databit can be mapped into two symbols of double databit duration. Each symbol is transmitted via a different CDMA channel. This trick avoids equalization of the received signal. On the basis of equal bit-error probability the energy of the symbols on each sub-carrier is reverse proportional to the used sub-carriers. This property is used in power-limited channels.

X. RADIO RESOURCE MANAGEMENT

The radio resource management is very easily done with the spread-spectrum technology, because it has so many degrees of freedom. If you follow all the previous sections it is apparent that the flexibility is present and the overall system performance can be enhanced. One circumstance should be outlined. It is often desirable to use a variable processing gain and/or spreading factor for inhomogeneous applications like video transmission. This can be achieved via different mechanisms. (a) it is possible to use the orthogonal-variable spreading-factor (OVSF) sequences [9], (b) multi-code transmission with a fixed but coarse granularity of the processing gain or (c) partitioning of a long PN-sequence in segments for each user which offers a fine granularity of the processing gain.

XI. CONCLUSION

In this paper we have shown that the spread-spectrum technology is ready for future wireless applications. The large bandwidth of the spread-spectrum signal guarantees an accurate time resolution which is beneficial in resolving the multipath components of the channel for RAKE receiver reception. Due to the high flexibility of the system architecture the spread-spectrum technology can cope with applications that are defined in the future. One indication that the spread-spectrum technology is ready for the future is that it has survived for so many years and it was applied successfully for very different applications ranging from military to commercial. Due to the deregulation of the telecom-marked we need a communication system that can cope with unpredictable types of interference and is very flexible in the design of new services. These are properties of the spread-spectrum concept.

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