Guest Editorial
Signal Synchronization in Digital Transmission Systems

BOTH wireless and wired communications are experiencing an unprecedented worldwide growth due to the ever-increasing demand of new services and to the recent deregulation of the field in many developed countries. This host of new applications relies on a number of sophisticated signaling formats: direct-sequence spread-spectrum (DS/SS) signals to provide code division multiple access (CDMA), discrete multitone (DMT) modulation, and/or orthogonal frequency division multiplexing (OFDM) to combat selective fading, and turbo coding to yield a better quality of the link, just to mention a few samples of this trend. In order to function properly, a digital communication receiver must synchronize itself to the incoming signal. As is well known, there are various facets to the synchronization process. With bandpass modulation, the receiver must achieve *carrier synchronization*, meaning that its oscillator must acquire the same frequency and (for coherent detection) the same phase as the carrier signal at its input. Also, information is needed about the arrival times of the digital data symbols (*symbol timing*), so that the received waveform can be sampled at the right times with a minimum intersymbol interference. Finally, in DS/SS communications, it is necessary to achieve *code synchronization*, i.e., to align the locally generated code sequence with that of the desired user. Synchronization algorithms play a vital function in digital transmissions as their accuracy affects the system performance critically. Also, as they comprise a significant portion of the receiver's hardware and software, they have a considerable weight in the overall receiver cost and design effort. For these reasons it is not surprising that a vast literature has appeared in the recent past dealing with a host of applications, ranging from point-to-point transmissions (wired or wireless), audio and video digital broadcasting, to (radio) cellular systems.

To overview the synchronization problems addressed in this Special Issue we consider first narrow-band point-to-point transmissions over the additive white Gaussian noise (AWGN) channel, which are typical of satellite links. By narrow-band we mean any single-carrier modulations with an RF bandwidth comparable to the information bit-rate of the link. They encompass conventional PSK and QAM and nonlinear schemes like CPM. In all these cases, synchronization amounts to estimating three scalar parameters: carrier frequency, carrier phase (coherent detection only), and symbol timing. At least conceptually, maximum likelihood (ML) estimation methods, or approximations thereof, offer a systematic guide to the derivation of good synchronizers. In this context the paper by Vanelli-Coralli *et al.* represents a case study for the application of per-survivor processing (PSP) to the detection of convolutionally coded data signals. The authors show that, even in the presence of carrier frequency and phase uncertainty, PSP is successful in the demodulation of wideband signals such as those encountered ina future SHF/EHF satellite network for multimedia services. Mosquera *et al.* provide an application-oriented paper in the same field. They focus on a particular satellite-based synchronization technique denoted as "time transfer." They show that in a TDMA satellite scenario with regenerative on-board processing a stable master clock can be obtained on board the satellite making use of short signal bursts from a reference ground station. This result makes it possible to dispense with on-board bulky and expensive (space-qualified) reference oscillators.

Taken together, ML-based and *ad hoc* methods seem to satisfy most of the current needs, although some open problems remain. One instance occurs in applications with highly efficient forward error correcting codes, for example concatenated or turbo codes, where the operating SNR may be as low as 1–2 dB. In such conditions excellent estimation accuracy (close to the Cramér–Rao bound) is required to keep the processing time within acceptable limits. The paper by D'Amico *et al.* deals with the analysis and design of carrier and clock synchronizers for turbo-coded satellite DVB transmission. The receiver architecture proposed by the authors exhibits satisfactory performance for E_b/N_0 values around 1 dB. Frame synchronization is another receiver function whose implementation takes advantage of the code structure. Howlader and Woerner address this problem for packets with convolutionally encoded data. Their technique is also extended to the synchronization of turbo-coded systems. Harris and Rice tackle a different issue in a paper where symbol timing recovery is revisited with a view to low complexity, multirate, and possibly multistandard architectures. The authors describe the use of a polyphase filterbank to implement the interpolations required in a sampled-data receiver.

We now shift our interest to frequency/time-selective channels. Frequency selectivity is ubiquitous in modern communications (for example, terrestrial cellular communications, high capacity radio, and transmission over twisted-pair cable) and has a considerable impact on the receiver architecture. As opposed to the AWGN channel, the receiver must estimate not only the carrier frequency and the symbol timing, but also the channel impulse response (CIR) to perform equalization. In principle, carrier phase is not at stake as it can be incorporated into the CIR. In summary, the scalar parameters have diminished by one but a vector parameter (the CIR) has emerged. Similar issues are encountered with narrowband transmissions over time-selective frequency-flat fading channels. Here the channel man-

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ifests itself in the form of a multiplicative distortion, which must be estimated and compensated for. In this context Baltersee *et al.* investigate the achievable rate of a coherent coded communication system with data-aided channel estimation. A multiple-input/multiple-output channel is assumed and an interleaver is used to combat the bursty nature of the channel. It is shown that linear minimum mean square error channel estimation directly follows from the derivation. The achievable rate is optimized with respect to the amount of training information available.

With few exceptions, synchronizers for frequency-selective channels are taken from the AWGN channel shelf. This is not so much because of their good performance but because of lack of better solutions. For example, most frequency synchronizers for the AWGN channel take the "center of gravity" of the received signal spectrum as an estimate of the carrier frequency. In the presence of channel distortions, however, the center of gravity is moved off its original position and the resulting carrier frequency estimate is biased. Some *ad hoc* schemes have been proposed to alleviate the problem, but their effectiveness depends critically on the assumed channel model. Even theoretically, it is not clear whether unbiased estimates can be implemented in the absence of channel state information. Jeong *et al.* describe a least squares approach to this problem. Their estimator is data-aided and does not need channel-state information. Its superiority with respect to existing techniques is significant with fast fading channels. The estimator can be used with transmitter antenna diversity and can be successfully applied to third-generation wireless systems.

Let us turn our attention to DS/SS signaling for CDMA in the return link of a cellular system. The received waveform is the superposition of the desired user's signal, the multiple-access interference (MAI), and the background noise. A conventional receiver separates the desired user's signal from MAI by correlating the incoming waveform with a locally generated replica of the user's spreading code. Proper operation requires good alignment (within fractions of the code chip duration) between the received and the locally generated code. This is achieved in two steps: the synchronizer provides first an approximate alignment (*code acquisition*) and then reduces it within tolerable limits (*code tracking*). Carrier recovery is still necessary while chip timing is inherent in the code tracking process. The paper by Lin deals with code tracking for DS/SS signals. Its novelty lies in the introduction of an easily implementable closed-loop algorithm to perform tracking in the presence of a frequency-selective fading channel. This technique can be embedded into radio modems for 3G CDMA personal communications.

Code acquisition is a crucial task and imposes serious restrictions on the capacity of DS-CDMA networks. It has been argued that system capacity is more limited by a failure to achieve code synchronization than by poor bit-error-rate performance once acquisition is attained. Acquisition methods fall into two categories: serial and parallel schemes. Serial schemes are simple to implement but are inherently time consuming. Vice versa, parallel schemes guarantee short acquisitions but are computationally complex. Complexity arises from the fact that, as acquisition is strongly affected by carrier frequency errors, code alignment and carrier frequency estimation must be performed jointly, which requires a two-dimensional grid search. Current efforts are focused on simple search algorithms that alleviate the effects of MAI. The paper by Burshtein *et al.*investigates a new linear feedback shift register (LFSR) acquisition method. It employs a soft-decoding algorithm for low rate linear block codes. On their turn, Shamain and Milstein discuss the acquisition of direct sequence spread spectrum CDMA signals in the presence of correlated multipath fading. They also address the acquisition issue with wideband multicarrier CDMA and antenna diversity.

Due to the high market demands for advanced wireless communications, third-generation CDMA-based systems like those envisaged by ITU's initiative IMT-2000, have become key technologies in research, development, and international standardization bodies. They are expected to support multimedia services with data rates up to 2 Mb/s and achieve much better capacity than their present counterparts. One way to improve capacity is to employ sophisticated receiver structures. Performance close to the single-user receiver can be achieved through optimum multiuser detection. Unfortunately, this receiver is impractical as its complexity grows exponentially with the number of users. Many suboptimal approximations have been investigated to reduce the implementation cost while keeping most of the benefits of multiuser detection. The proposed schemes depend on substantial side-information about the number of users, code waveforms, signal powers, and channel parameters, i.e., the attenuation and delay of each individual propagation path. The problem of measuring the delays seems crucial since performance degrades rapidly with timing misalignments in excess of a small fraction of the chip duration. The contribution by Fock *et al.* is concerned with the estimation and tracking of the channel parameters of the desired user's signal. The authors explain why conventional single-path tracking algorithms fail in a multipath environment and develop some new trackers that can cope with a multipath scenario. Delva and Howitt approach the DS-CDMA synchronization problem by modifying the PN-code acquisition with the introduction of an auxiliary sequence that can be used to assess the size of the current propagation-delay error. This information is then exploited to guide the search algorithm. Katz *et al.* consider a DS-CDMA receiver equipped with an antenna array. In this context the acquisition problem becomes a two-dimensional search, both in time and angle. Because of the spatial distribution of the users, the MAI in a single delay-angle slot (synchronization cell) is reduced, which implies a better detection probability. However, this does not necessarily mean that the overall acquisition time is smaller since there are more cells to be searched compared with the one-dimensional case. It turns out that, under some conditions, an optimal number of cells exists that guarantees the shortest acquisition. Guenach and Vandendorpe consider timing recovery for DS-CDMA multiuser communication over multipath fading channels. By analysis and simulation they show the effectiveness of a synchronization scheme incorporating multiuser interference mitigation. Third-generation systems will also rely on space–time signal processing to improve quality of service and/or capacity. Space–time processing is useful in key functions such as coding, equalization, and multiple access. The paper by Cheikhvouhou *et al.* investigates the impact of synchronization on a spatio–temporal array-receiver (STAR) and introduces enhancements that reduce complexity and improve performance.

As a last item we consider synchronization issues for OFDM and DMT modulations. It is known that multicarrier (MC) modulation is the leading technique when the transmission channel is severely frequency-selective and quasistationary in time. This happens with terrestrial television at VHF/UHF (the family of DVB standards) and with twisted-pair transmission for the access network (xDSL family). MC techniques are also envisaged in future wireless broadband local area networks (WLAN's) where data rates of several megabits per second are needed (for instance, the IEEE 802.16 standard). Communicating at those rates is difficult unless measures are taken to mitigate the effects of multipath propagation. Key tools toward this end are diversity techniques, advanced signal processing algorithms, and suitable modulation formats. Also, MC systems are known to be highly sensitive to frequency offsets caused by Doppler shifts, oscillator instabilities, and phase jitter. As the subcarriers are closely spaced in frequency compared to the channel bandwidth, the frequency offset must be kept within a small fraction of the subcarrier spacing to avoid severe BER degradations. This sensitivity, together with the issue of channel estimation/equalization, has recently stimulated a great deal of research. Some good solutions have been identified but efforts are still going on in search of simpler structures. Timing recovery in high rate MC transmissions over twisted pair cables is treated by Martos-Naya *et al.*who propose all-digital timing correction by means of interpolation in the context of DMT. The interpolator yields a signal-to-distortion ratio exceeding 50 dB for all carriers at low computational cost. The key issue of (joint) carrier frequency and timing recovery is tackled in a number of papers. The twin contributions by Coulson address pilot-symbol-aided methods for OFDM packet detection and synchronization. Algorithms are described for ML estimation of carrier frequency, carrier phase (for coherent detection), and symbol timing. Ma *et al.* adopt a signal-processing approach in their paper on carrier frequency estimation for OFDM signals. They introduce a new nondata-aided technique based on the insertion of *null* "pilot" tones within the OFDM spectrum to ease frequency recovery. This technique does not need prior channel estimation/equalization. Finally, Lu and Wang concentrate on the design of a blind receiver for coded OFDM systems in the presence of frequency offset and a frequency selective fading channel. The receiver iterates between a Bayesian demodulation stage and a maximum *a posteriori* decoding stage. Simulations indicate that the proposed blind turbo receiver achieves good performance and is robust to modeling mismatch.

A recent trend toward the definition of an universal radio interface for the fourth-generation universal wireless system is the combination of MC and SS techniques to achieve multiple access flexibility, high spectral efficiency, and narrow-band interference rejection capability. Steendam and Moeneclaey propose a new multicarrier DS-CDMA method wherein the users can be made orthogonal even when the channel is time-dispersive. In this way the demodulation of a given user is not affected by the presence of other users.

In concluding this Editorial we would like to thank the authors who have enthusiastically responded to the call for papers, as well as the anonymous reviewers who helped us select the better contributions in the lot. We hope that, going through this Special Issue, the reader will gain a better idea of the main current issues on synchronization. They cover a broad range of applications and are bound to play a central role in the improvement of present transmission systems and the realization of the future ones. As compared with their counterparts of two decades ago (see the 1980 Special Issue of the IEEE TRANSACTIONS ON COMMUNICATIONS) they look more complex and diverse, probably due to the ever-growing complexity of the communication techniques. This gives us solid grounds to think that the research activity on synchronization in digital transmissions will be as successful as ever in the *next* 20 years.

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