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Editorial

Synchronization in Wireless Communications

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The last decade has witnessed an immense increase of wireless communications services in order to keep pace with the ever increasing demand for higher data rates combined with higher mobility. To satisfy this demand for higher data rates, the throughput over the existing transmission media had to be increased. Several techniques were proposed to boost up the data rate: multicarrier systems to combat selective fading, ultra-wideband (UWB) communications systems to share the spectrum with other users, MIMO transmissions to increase the capacity of wireless links, iteratively decodable codes (e.g., turbo codes and LDPC codes) to improve the quality of the link, cognitive radios, and so forth.

To function properly, the receiver must synchronize with the incoming signal. The accuracy of the synchronization will determine whether the communication system is able to perform well. The receiver needs to determine at which time instants the incoming signal has to be sampled (timing synchronization). In addition, for bandpass communications, the receiver needs to adapt the frequency and phase of its local carrier oscillator with those of the received signal (carrier synchronization). However, most of the existing communication systems operate under hostile conditions: low SNR, strong fading, and (multiuser) interference, which makes the acquisition of the synchronization parameters burdensome. Therefore, synchronization is considered in general as a challenging task.

The objective of this special issue (whose preparation was also carried out under the auspices of the EC Network of Excellence in Wireless Communications NEWCOM++) was to gather recent advances in the area of synchronization of wireless systems, spanning from theoretical analysis of synchronization schemes to practical implementation issues, from optimal synchronizers to low-complexity ad hoc synchronizers.

In this overview of the topics that are addressed in this special issue, we first consider narrowband single-carrier systems, where narrow band means that the RF bandwidth of the system is comparable with the symbol transmission rate of the link. This is, for example, typical for a satellite link. In the paper by Lee et al. the frame synchronization problem in a DVB-S2 link was investigated. The link works at low SNR and uses forward error correction for data detection. Further, the incoming signal is disturbed by a large clock frequency offset. Under these hostile circumstances, the traditional correlation method, that looks for the synchronization sequence available in the frame header to obtain frame synchronization, gives rise to poor performance. To solve this problem, and to make the frame synchronizer more robust, the authors modify the correlation-based estimator with an additional correction term depending on the signal energy.

Besides of time synchronization, phase estimation of the RF carrier used for transmission is also crucial for coherent detection. However, in mass production, to keep the cost of the devices as low as possible, cheap oscillators are used. These low-cost oscillators inherently have instabilities, causing random perturbations in the phase. The resulting phase noise causes a degradation of the system performance.

This phase noise can be tracked by feedback algorithms, like the phase-locked loop, but these algorithms give rise to long transients, such that they are not suitable for burst transmissions. In the paper by Bhatti and Moeneclaey, a feedforward algorithm is proposed where the phase noise is decomposed into its spectral components using a DCT transform. The phase noise is estimated from pilots by determining a few of these DCT coefficients. The paper of Simoens et al. tackles the phase noise problem in a different way. The authors start from the optimal joint estimation of the unknown data and the phase noise. The unknown distribution of the phase noise, needed for this estimation, is obtained in a probabilistic way by applying Monte Carlo methods. Although several approximations are made to reduce the complexity of the algorithm, its performance is close to optimal, both for uncoded and coded systems.

In contrast with narrowband systems, ultra-wideband communication occupies a bandwidth that is much larger than the transmission rate. The data is modulated on very short pulses, making timing synchronization a complicated task. In the paper by Wang et al. a pilot-aided two-stage synchronization strategy is proposed. In the first stage, sample-level timing is obtained together with an estimate of the channel, and in the second stage, symbol-level synchronization is pursued by looking for the header.

Next, we shift our attention to multicarrier-based broadband transmission systems. Multicarrier modulation is known to be robust to frequency selective channels. However, they are also highly sensitive to carrier frequency offsets, coming, for example, from Doppler shifts, and to phase noise. To have tolerable BER performance degradation, the carrier frequency offset must be sufficiently smaller than the carrier spacing of the multicarrier system, which in turn is (because of the large number of carriers that is typically modulated) much smaller than the bandwidth of the multicarrier system. Several of the papers in this special issue indeed deal with this crucial carrier frequency synchronization but let us first start with the paper from Üreten and Taşıoğlu, which is concerned with the design of timing synchronization waveforms. To avoid the overhead of a separate synchronization sequence, a system is considered where the pilots are embedded in the frequency domain by replacing some of the data carriers by pilot tones. The authors consider both uniform and nonuniform positioning of the pilot tones. With the uniform positioning, the design of the synchronization waveform, that is obtained by considering the time domain signal corresponding to the pilot tones, is simple and easy to analyze. However, because of the large-side lobes in the autocorrelation function related to this synchronization waveform, the timing synchronization will suffer from ambiguities. With the non-uniform positioning, the synchronization waveform becomes aperiodic, such that the autocorrelation function has lower sidelobes and thus results in more precise timing synchronization.

Also the paper by Langowski deals with the design of pilot sequences, although in contrast with the previous paper, the pilot sequence is transmitted as a preamble to the data signal. The author proposes a pilot sequence that is symmetric in the time domain and derive an algorithm that is not only able to obtain the coarse timing estimate, but also the fractional frequency offset with respect to the carrier spacing. The robustness of the proposed algorithm to a frequency selective channel was one of the main concerns of the author. After the initial synchronization based on the pilot sequence, tracking is achieved with a newly designed nondata aided algorithm.

Not only synchronization for standard multicarrier techniques are considered, also several variants of the multicarrier technique are studied. Block interleaved frequency division multiple access (B-IFDMA) is a variation of the OFDMA technique. In IFDMA, compression and repetition are applied on the data and different users are assigned different chip sequences. Before modulating the chips on the carriers, chip interleaving is applied. Therefore, IFDMA can be regarded as unitary precoded OFDMA with interleaved subcarriers. On the other hand, IFDMA can also be seen as a variant on the CDMA technique with orthogonal signature sequences. Similarly as OFDMA, this IFDMA technique turns out to be very sensitive to carrier frequency offsets. To make the technique more robust to carrier frequency offsets, the data of a user is transmitted on blocks of subcarriers that are equidistantly distributed over the available bandwidth, resulting in B-IFDMA. The paper by Simon et al. investigates the sensitivity of two variants of the B-IFDMA system, that is, joint DFT B-IFDMA and added-signal B-IFDMA, to carrier frequency offsets.

Another variant on the multicarrier technique is hexagonal multicarrier modulation. In this technique, the carrier frequencies in odd time slots are shifted over half a carrier spacing as compared to the carrier frequencies in the even time slots. The positions of the carriers in the time-frequency domain can therefore be considered as lying on a hexagonal lattice, in contrast to the rectangular lattice of standard multicarrier modulation. The analysis of the sensitivity to carrier frequency offset, timing offset, and a frequency selective channel in the paper by Xu and Shen shows that hexagonal multicarrier modulation is more robust to these impairments than standard multicarrier modulation.

During the last ten years, researchers have put large efforts in increasing the capacity of wireless systems by equipping devices with more than one antenna-element, resulting in a multiple input multiple output (MIMO) system. By relying on spatial multiplexing, the number of users increases with the number of antenna-elements. Alternatively, one can choose to exploit the spatial diversity of the MIMO channel by using space-time codes, which introduce redundancy in both the spatial and the time domain to increase the reliability of the transmission link. When MIMO systems are used in frequency selective channels, OFDM is considered as the transmission technique of preference, because it facilitates the equalization process. Of course, it is obvious that synchronization in MIMO systems is even more complex than in single-antenna systems, as the number of synchronization parameters to be estimated increases with the number of antennas.

In the paper by Schellmann and Jungnickel, a spacial-division multiple access (SDMA) technique is considered in combination with OFDM. In the uplink, the multiantenna basestation receives the signals from the different users, transmitted on the same frequency resources. As these signals are generated by the carrier oscillators from the different users, each signal is affected by a different carrier frequency offset, impairing the orthogonality between the different users. The authors analyze the effect of the carrier frequency offsets on the performance. Assuming coarse carrier frequency synchronization is obtained by using the information from the downlink signal, a low-complexity compensation technique for fine carrier frequency synchronization in the uplink is proposed.

Many of the algorithms in the literature for synchronization are based on ad hoc methods. Although maximum likelihood (ML) estimation methods will give rise to better performance than ad hoc algorithms and can perform closer to the theoretical Cramer Rao lower bound on the mean squared error, their complexity is typically much higher. However, approximations on the ML method offer good suboptimal algorithms. In the paper by Morelli et al. the pilot subcarriers are selected such that the training sequences have a repetitive structure in the time domain. A low-complexity frequency offset estimation algorithm is proposed, where the integer part (with respect to the carrier spacing) of the carrier frequency offset is estimated based on an approximation of the ML method, whereas the fractional frequency offset estimate is obtained from a correlation-based approach.

In the paper of Ribeiro and Gameiro, a similar problem is tackled. The pilot symbols are regularly spread over the OFDM symbols to be able to estimate the channel coefficients between the different transmit and receive antennas. To minimize the pilot overhead, the same pilot subcarriers are used for the different transmit antennas. The pilot symbols per transmit antenna are phase-shifted to reduce the amount of cochannel interference. Based on this pilot structure, the authors propose an algorithm to jointly estimate the CFO and the channel.

In the two previous papers, pilot tones were embedded in the multicarrier signal to estimate the channel and CFO in a data-aided way. In the paper by Nguyen-Le et al., an algorithm to jointly estimate the CFO, timing, and channel impulse response is discussed for turbo-coded burst transmission. The estimates are obtained iteratively in a soft decision-directed way, where information is exchanged between the joint estimator and the turbo decoder. No pilots are transmitted during the data segment, but a preamble containing pilots is added to derive initial estimates.

As a last item, we consider timing synchronization in networks. When the timing in the different cells of a cellular network is aligned to a common reference instant, the throughput is increased as compared to an asynchronous network. This slot synchronization can be obtained by using the global positioning system (GPS) to acquire a reference clock, or to use the backbone connection. Both methods have drawbacks: the first method needs a GPS receiver at each basestation, and the second one does not provide sufficiently accuracy. The paper by Tyrrell and Auer describes a decentralized solution to obtain slot synchronization, a solution that is based on synchronization in biological systems. In this method, two synchronization words are used to synchronize: one transmitted by the basestations, and one transmitted by the user stations, and each group helps the other to synchronize. Even when the basestations are located hundreds of kilometers apart, introducing large propagation delays, the decentralized slot synchronizer is able to obtain a timing accuracy of a fraction of the propagation delay.

The paper by Xiong and Kishore considers global time synchronization in wireless sensor networks. One class of algorithms that is used for this time synchronization is the distributed consensus time synchronization method, where a global consensus is obtained by averaging the pairwise local time information in the different network nodes. In most algorithms, only the current timing information is considered, resulting in a first-order system. The paper in this special issue extends the first-order system to a second-order system, where also the timing from the previous iteration is taken into account, resulting in a faster convergence and higher accuracy than a first-order system.

As a conclusion of this Editorial, we would like to express our appreciation to the efforts of the authors, who have enthusiastically responded to the call for papers, and the reviewers, who helped us to select the papers in this special issue. Without them, this special issue would have never existed. We hope that this special issue helps the reader to have a better idea of the current issues in synchronization for wireless systems. The topics of this special issue cover a broad range of applications; they can stimulate improvements in present transmission systems and can help in the realization of future ones. As the transmission systems have become more and more complex as compared to 20 years ago, also the synchronization algorithms have grown more complex and diverse. This trend has introduced the expectation that the next 20 years, research on synchronization will be as successful as today.

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