Abstract

Machine-type communications (MTC) encompass a broad range of applications—such as smart metering, industrial IoT, and autonomous vehicles—that require the reliable transmission of short to moderate-length packets under stringent energy, latency, and complexity constraints, often in networks with thousands to millions of intermittently active devices. In this regime, any protocol overhead—such as preamble or pilot insertion—impacts significantly the overall system performance, sharply reducing both spectral and energy efficiency. Although Shannon's capacity theorem, derived in the limit of large packets, establishes fundamental performance limits, it does not account for these finite-length effects. To address this gap, non-asymptotic finite-blocklength bounds have been developed and shown to be remarkably tight down to very short packets. Nevertheless, practical coding schemes—such as low-density parity check and turbo codes, which perform well at moderate to large blocklengths—suffer substantial performance degradation when blocklengths fall below a few hundred bits. The resulting losses are further emphasized in massive scenarios. Against this backdrop of massive connectivity and short-packet overhead, this dissertation tackles three important challenges in MTC system design: (1) channel coding optimized for short packets, (2) uncoordinated multiple-access protocols that scale to massive device populations, and (3) frame synchronization methods for direct-sequence spread-spectrum links.

Chapter 3 investigates the concatenation of convolutional codes with outer polynomial codes (poly+CC) of CCSDS telemetry recommendations and LTE control channels. By analyzing the trellis of the corresponding poly+CC and computing its distance spectrum, tight upper bounds on the block-error probability under maximum-likelihood decoding are derived. The analysis yields an approximate 3 dB coding gain for the maximum-likelihood decoding of poly+CCs over Viterbi decoding of the convolutional code alone. Numerical evaluations for both CCSDS telemetry and LTE systems demonstrate that list-Viterbi decoding of the poly+CC scheme can recover a large fraction of the theoretical 3 dB coding gain, with moderate list sizes and practical decoder complexity.

Chapter 4 adapts the enhanced spread-spectrum ALOHA (E-SSA) protocol—widely used in satellite MTC—for the unsourced multiple-access channel (UMAC) framework. A wrap-around framing model permits direct comparison with finite-blocklength UMAC achievability bounds. Modifications in the E-SSA protocol include the integration of short low-rate polar codes with outer polynomial codes and the exploitation of the transmission timing as an auxiliary error-detection channel. Performance comparisons show that the optimized E-SSA approaches state-of-the-art UMAC schemes for moderate numbers of active users, while retaining a simple transmitter architecture and a receiver whose complexity scales linearly with the number of users.

Chapter 5 formulates sequential frame synchronization in direct-sequence spread-spectrum systems as a binary hypothesis test under coherent and non-coherent additive white Gaussian noise channel models. The optimal likelihood-ratio test is derived via the Neyman-Pearson criterion, and simplified metrics are proposed. Compared to traditional detectors based on preamble-only detection, the new metrics that incorporate spreading sequence information into the synchronization process significantly improve detection accuracy. Moreover, the simplified tests maintain robust performance while offering reduced implementation complexity, in low-SNR regimes and in the presence of phase uncertainty in non-coherent scenarios. When embedded into the E-SSA receiver, the new frame synchronizer is capable of working with a shorter preamble length, which results in improved energy and spectral efficiency, while achieving up to 20% fewer channel-decoder calls, and while reducing the necessary per-user signal-to-noise ratio by 0.4 dB to meet a target per-user error probability and a 33% increase in supported simultaneous users under moderate load.

Taken together, the coding, access-protocol, and synchronization methods developed in this work advance the design of energy- and spectrally-efficient MTC systems, helping to approach the finite-blocklength performance limits with feasible implementation complexity.