Thesis title:

Efficient Receiver-end Synchronization and Over-the-Air Beamforming Aided Distributed Wireless Transmission

Abstract:

Recent advancements in wireless communication technologies have led to the widespread deployment of systems such as 4G, 5G, and wireless sensor networks. These networks enable large-scale applications ranging from enhanced Internet access and the Internet of Things to industrial automation and environmental monitoring. Despite this progress, practical deployments face persistent challenges: individual radios have limited transmission range, weak or noisy channels reduce the signal-to-noise ratio (SNR), fading undermines link stability (especially under mobility and multipath), sparse or infrastructure-less topologies complicate connectivity, and most devices operate under strict energy constraints. As networks expand, traditional schemes struggle to coordinate efficiently, and energy demands scale unfavorably.

Collaborative communication among distributed nodes has emerged as a promising direction. If N distributed transmitters send the same signal such that they arrive at a receiver synchronized in time, frequency, and phase, the received power can scale up to N2 compared to a single transmitter. This gain can be used to extend range, increase data rates, improve resilience to fading, or reduce per-node transmit power to conserve energy. Such collaboration is useful not only for wireless information transfer, but also for wireless power transfer and simultaneous wireless information and power transfer, particularly in remote or infrastructure-less settings populated by low-cost, battery-powered devices. Enabling collaboration at scale requires practical synchronization strategies that are feasible within energy and complexity constraints; however, this problem remains unaddressed in the literature.

This dissertation addresses the phase synchronization problem in energy- and processing-constrained distributed collaborative networks with unknown node locations. The objective is to minimize the two dominant energy cost contributors: (i) synchronizing communications (e.g., pilots, exchanges, or feedback used to align phases) and (ii) computational processing for phase estimation and correction, while ensuring scalability to large collaborative networks and robustness to fading.

First, this work develops a receiver-end phase synchronization method, Rx-DBF, that achieves phase alignment with one transmission per transmitter and no receiver feedback or pilots, thus achieving zero synchronization-communication overhead. Power gain is achieved solely through receiver-end processing with one-shot resolution of accumulated errors from various phase offsets. Average and worst-case power gains are derived analytically, and it is shown that the proposed method yields fading-agnostic near-perfect power gain at the receiver.

Second, to minimize energy consumption in receiver-end processing, two energy-efficient methods, called the reduced search space (RSS) method and the extended RSS (extRSS) method, are proposed that uniquely leverage the non-uniformity in the Nakagami-m fading channel's phase distribution under balanced conditions (symmetric fading). The search space for phase corrections is reduced to a finite set of values per transmitter, irrespective of the fading parameter m. Closed-form power gain expressions are derived through judicious approximations of the Nakagami-m phase distribution for the case of $m > 1$ and $m < 1$. The power gain is shown to be close to near-perfect power gain in strong LOS ($m \gg 1$) for RSS; while extRSS is shown to achieve fading agnostic (m-independent) and scalable near-perfect power gain even under fast

fading conditions through judicious addition of search points over the RSS set. Both methods are shown to have significantly better energy efficiency compared to the closest competitive approaches in literature.

Then, a generalized Nakagami-m model with channel parameters (m, p) is studied, and the presence, location, and sensitivity of high-probability phase regions have been characterized. Leveraging these insights, an adaptive, channel-aware method (adaptiveRSS) has been devised to align the reduced search space with the high-probability areas under channel unbalanced conditions (widely prevalent asymmetric fading scenarios). Analytical derivations are shown to provide peak locations as explicit functions of (m, p) and average gain expressions under multiple asymmetric regimes, using judicious distributional approximations for tractability. It is shown that the adaptiveRSS improves power gain over non-adaptive baselines under asymmetric fading while maintaining blind operation, gain stability, and energy efficiency for large collaborative transmissions.

For applications that require RF-domain beamforming for rectification at the receiver antenna, such as wireless power transfer and simultaneous wireless information and power transfer, the thesis introduces a transmitter-end scheme that achieves beamforming over the air. Intermittent single broadcast feedback is shown to be sufficient to enable sustained beamformed reception over extended periods by tracking the beamformed output. Energy accounting shows that the intermittent feedback strategy yields N-fold gains over the beamformed interval with small overheads, and, in comparison with competitive transmitter- or receiver-end strategies, it is still more energy-efficient.

Across the chapters, the methods are designed for feasibility under harsh wireless conditions, tight energy budgets, and practical scalability. They remain useful when receiver feedback is unavailable (e.g., no transmission capability) or unreliable, and they can be applied to infrastructure-less deployments such as ad hoc wireless sensor networks for environmental monitoring, disaster response, and surveillance. The concept can also extend to energy-constrained cell-free multiple-input-multiple-output (MIMO) settings where distributed low-power nodes must cooperate without heavy feedback or centralized control.

In summary, this thesis presents a cohesive receiver-end design for blind, energy-efficient phase synchronization to achieve power gains similar to distributed beamforming. It advances the domain by lowering synchronization and processing requirements, maintaining robustness under varied (including asymmetric) fading, and supporting scalable operation in energy-constrained distributed collaborative networks.