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Optimization of Distributed Detection Systems in the Presence of Wireless Channel Uncertainty

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We study data fusion in a distributed detection system, consisting of several geographically dispersed signal detectors and a fusion center (FC), that is tasked with solving an underlying binary hypothesis testing problem (e.g., detection of a signal source or a target in a field being monitored). Each detector makes a binary local decision based on its local observation, where each local decision has a certain reliability index, determined by the observation quality. These local decisions are modulated and transmitted over wireless channels to neighboring detectors and/or the FC. The FC is tasked with fusing the data received from the detectors and making a global binary decision. The challenge in data fusion is that the binary local decisions would be corrupted due to wireless channel effects (i.e., additive Gaussian noise and multipath fading). These effects further limit the reliability of the global decision. This raises a key question: Aiming to maximize the reliability of the global decision, what is the optimal distributed detection system design in the presence of wireless channel uncertainty? To address this question in this thesis, we identify and address three subproblems as the following:

P1) Suppose the topology (i.e., the wireless connections between the local detectors and the FC that are used for transmission of local binary decisions) of the distributed detection system is adaptive and can be selected based on the observation and communication channel qualities. What are the best network topology and the best signal processing schemes (i.e., local decision rules and data fusion rules)? How are the best topology and the best signal processing schemes related to the reliability indices of the local decisions, channel noise and fading? Our results indicate that the optimality of widely used parallel topology, in which the local detectors directly communicate with the FC, is limited. We also demonstrate the average performance gain of topology adaptation compared with a fixed topology system.

P2) Channel estimation is an integral part of most of today's wireless communication systems. Via transmitting known training symbols, the local detectors enable the FC to estimate the unknown fading channel, which is used for recovering data symbols. Considering a distributed detection system with a parallel topology, in which the local detectors transmit training symbols, followed by their local binary decisions, and assuming an average transmit power constraint, we ask: What is the best data fusion rule at the FC? How is this fusion rule affected by channel estimation error, transmit power allocation between training and data symbols, and the communication reception mode at the FC (i.e., coherent versus noncoherent)? Our study shows that with noncoherent reception, the detection performance of the FC is maximized when no training symbol is transmitted and all transmit power is spent for only data symbols. This performance is attainable with statistics-based likelihood-ratio-test (LRT) rule for random channels and generalized LRT (GLRT) for deterministic channels. With coherent reception, however, the optimal power allocation depends on the fading model. For Rayleigh fading model, the total detection probability and error exponent are maximized when half of the transmit power is spent for training symbols. Whereas, for Rician fading model, the optimal power allocation depends on the operating signal-to-noise (SNR) and Rice factor.

P3) Suppose the distributed detection system is tasked with detecting a Gaussian signal source, where in its presence, local observations are statistically correlated samples of the signal source, corrupted by an additive Gaussian noise. We ask: What is the best linear data fusion rule at the FC? How is this fusion rule affected by the statistical correlation, the reliability indices of the local decisions, transmit power constraints at the local detectors, communication multiple access scheme (employed by the local detectors to communicate with the FC), the communication reception mode at the FC, channel noise and fading? We show that statistical correlation degrades the detection probability of the system. We also find the optimal power allocation for different communication multiple access schemes, subject to several transmit power constraints, in terms of observation and wireless channel qualities.