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A Theory for Distributed Signal Detection and Data Fusion

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Abstract

This research attempts to develop a fundamental understanding of the issues involved in the design and performance analysis of distributed detection schemes. Such knowledge is currently lacking. This is especially true for cases with statistically dependent observations from sensor to sensor, a practical case on which this research focuses. Some emphasis is being devoted to developing design algorithms and on applications. The goal of these studies is to produce tools and techniques for pressing practical problems. We classify our efforts into four basic areas: properties of dependent observations cases, design algorithms, applications and image fusion.

1 Properies of Dependent Observations Cases

Very little was known about the properties of optimum distributed detection schemes for cases with dependent observations. For centralized detection cases, likelihood ratio tests are always optimum. This suggested an interesting question. When are likelihood ratio tests optimum at distributed sensors? For the case of correlated Gaussian noise, we were able to obtain conditions under which this must occur and conditions under which this can not occur [1, 2]. NonGaussian noise cases were considered in a later series of papers [3, 4, 5, 6], where we found the problem is considerably more complex, however the optimum detectors follow a pattern which can be used to predict the general forms of the optimum processing without complex computations.

We are very excited about the latest results we have obtained [7]. Given a distributed scheme which uses a given number of bits for the decisions at all but the last sensor, we can show that the last sensor should not use more than a certain number of bits in its decision. If more bits are used at the last sensor, then the same performance can be obtained by using less bits which implies lower speed communications. The results in [7] are extended in [8, 9] for cases with more than two hypothesis. In [8, 9], we further show that in some common cases, the maximum number of bits that should be used at each sensor is much less the number given in [7]. This is true for the important case of known signals in uncorrelated Gaussian noise. It is even true in many cases with correlated Gaussian noise. We also investigate how a finite number of quantization levels should be allocated across the sensors in [8, 9].

2 Design Algorithms

The Neyman Pearson criterion has been a subject of much controversy and confusion when studied for distributed detection cases. For example, several researchers have claimed some results produced by other researchers are incorrect. While none of our papers were involved in this controversy, the exchanges of the other researchers motivated us to attempt to uncover the truth. In a very recent series of papers [10, 11], we have finally clarified the confusion and proved some Theorems that clearly describe the true situation. The Theorems describe methods for finding optimum distributed detection systems. The proofs draw on our previous research [12] while adding some critical new ideas, including new efficient numerical algorithms for finding optimum schemes. In a second series of papers [13] we finally show that randomization is generally necessary to achieve optimum performance at the fusion center. Further, we provide the first correct algorithm for finding optimum fusion rules employing randomization [13]. A general approach for updating the fusion rule is provided that is also applicable to Bayesian problems.

New efficient algorithms for finding Bayesian optimum distributed decision rules for cases with dependent observations were recently given in [7]. These algorithms are based on a new discretized Gauss-Seidel approach. The convergence of these algorithms is also proven in [7]. In particular, we have shown that these algorithms converge in a finite number of iterations and that as the discretization step sizes approach zero the solutions approach person-by-person optimum solutions. A person-by-person solution is one that can not be improved by changing only one decision rule at a time.

3 Applications

Investigating practical applications of distributed signal detection is a topic1¿ to which we have devoted considerable effort. One application involves fusing the data obtained from multiple surveillance systems to achieve improved performance. Testbeds have been constructed at a number of DoD laboratories. Another important application involves the design of wireless communication receivers. I have recently obtained some analytical results [14] which suggest that distributed processing techniques can reduce the complexity of *wireless communication* receivers without any significant loss in performance. Our initial investigations [14] have focused on frequency shift keying modulation. More recently, we have considered more complicated modulation schemes, including frequency hopped spread spectrum approaches [15]. Our latest investigations in this area involve considering multiuser distributed detection problems [16, 17]. We appear to be the first group to consider this topic which appears to have important applications in ad-hoc networks, a hot new research area. Our investigations into distributed multiuser detection have also led to some contributions to centralized multiuser detection theory [18, 19, 20, 21, 22]. We developed a new multiuser detection algorithm [18, 19] that appears to perform better than any existing suboptimum algorithms with complexity which grows linearly in the number of users. In fact, in a large set of interesting cases its performance is almost indistinguishable from optimum. We have also developed [20, 21, 22] some highly efficient iterative multiuser detection algorithms for turbo coded CDMA signals. Our algorithms provide excellent performance while yielding the lowest possible complexity of any similar algorithms we have seen. These schemes are even applicable to nonGaussian noise cases using a new approach we developed [23, 24, 22, 25, 26] which uses the expectation maximumization algorithm to fit the parameters of a Gaussian mixture model.

Our most recent work has focused on using antenna arrays at the transmitter also, originally in distributed detection based systems. In particular we have been investigating space-time coding which involves coding spatially across the antenna array in addition to coding across time. Space-time coding is an excellent way to combine diversity gain and coding gain. We were the first group to publish a journal paper suggesting serially concatenated space-time codes using a recursive inner code to achieve significant interleaver gain [27, 28, 5]. A highly efficient iterative receiver employing a Turbo decoding algorithm was outlined in [27, 28, 5]. These investigations convinced us that a systematic space-time code design procedure was lacking so we developed a new procedure for computing and bounding diversity and coding gain for flat, slow fading channels in [29, 30]. This procedure was used to find new optimum codes in [31, 32]. The performance of these codes was compared to that for popular existing codes in [31, 32]. These comparisons show the excellent performance of the codes in [31, 32], illustrating the utility of the theory in [29, 30]. Our most recent investigations on this topic consider multiple trellis coded modulation [33, 34]. An efficient design approach for both slow and fast fading cases is proposed in [33, 34]. The resulting codes outperform existing space-time codes. The combination of CDMA with space-time coding is investigated in [35, 36, 22]. The main contribution is a very low complexity receiver that performs the decoding, demodulation, and multiuser detection in an iterative fashion using a successive cancellation approach.

4 Image Fusion

The objective of image fusion is to combine information from multiple images of the same scene. The result of image fusion is a single image which is more suitable for human and machine perception or further image processing tasks. In our research [37, 38, 39], a generic image fusion framework based on multiscale decomposition is studied. This framework provides freedom to choose different multiscale decomposition methods and different fusion rules. The framework includes all of the existing multiscale-decomposition-based fusion approaches we found in the literature which did not assume a statistical model for the source images. Different image fusion approaches are investigated based on this framework. Some evaluation measures are suggested and applied to compare the performance of these fusion schemes. The majority of the research focuses on fusing same sensor images. In particular, visual images are used in the majority of the tests. The comparisons indicate that our framework includes some new approaches which outperform the existing approaches for the cases we consider. The topic of image fusion has also been studied for an interesting new camera, the omni camera in [40]. At a more basic level, we have studied algorithms to measure fusion quality [41, 39]. These algorithms are suitable for many applications, but they are particularly well suited for image fusion. A study of new registration methods for image fusion was also undertaken [39].

5 Contributions

The project has made significant contributions to the field of Electrical Engineering and in particular to the study of distributed signal processing systems. The main contributions have been towards developing the fundamental theory of this topic, which has been lacking. Such studies should stimulate future breakthroughs. Although we did realize this theory was not in place, even we were amazed at the basic nature of some of our results. It was surprising that results of this type were new. This illustrated to us how little is really known about the underlying theory of distributed signal processing. For example, prior to our work it was not known that the number of sensor decision bits used at one sensor can limit the number that should be used at another sensor. This is a very basic property that relies heavily on the nonuniqueness of the overall decision rule realized by a particular set of sensor rules and a fusion rule. Although the result makes sense to us now, even we were surprised by this finding. We were also surprised by the number of errors and misconceptions in the existing theory for Neyman-Pearson optimum distributed signal detection. We believe that our work on this topic will lead to numerous new developments and theory. Prior to this the theory of Neyman-Pearson optimum distributed schemes was thought to be extremely hard to develop for dependent observation cases. Our recent results indicate this theory may not be so difficult to develop.

Since our results are at such a basic level, we believe they have contributed to many disciplines and in particular to the broad topic of data fusion which spans many areas of science and engineering. We outline here the areas we expect will benefit from this research. The theory of distributed decision making is important in many areas outside Electrical Engineering. It has applications in any area involving team decision making by groups of smart machines or humans. Particular application areas include financial institutions, air-traffic control, oil exploration, medical diagnosis, military command and control, electric power networks, weather prediction, manufacturing, computer-based navigation systems, law enforcement, robotics, and industrial organizations. Our basic theory on how to design distributed decision making systems should influence developments in these application areas. We should mention that our topic is closely related to an important type of data fusion, called decision fusion, that has its roots in robotics, artificial intelligence, mathematics, information theory and computing. We have been interfacing with these communities through the Fusion conferences (Fusion 98 and Fusion 99) which have been held the last few years. We have been active in running this conference and in organizing a multidisciplinary Data Fusion Society.

We have trained PhD level researchers for the signal processing, communications and computing industries, areas where highly trained personnel are desperately needed. Wherever possible, we have encouraged these researchers to consider faculty positions. In cases where interest exists the student has been trained and mentored specifically for this purpose since we believe developing highly qualified faculty members is an important role for a University. It is also very important for the future success of our nation. Thus far four

PhD students have graduated who were at least partially supported by this research grant (or by Lehigh's matching funds). Two more PhD students who were partially supported by this research grant will grauate next year.

Clearly we are proud of our strong theoretical contributions, but we are also proud of the more practical contributions we have made. We have developed practical design algorithms for distributed signal detection systems and we have demonstrated the applications of our theory to wireless communication receivers. We are aware of several experimental surveillance systems constructed at several laboratories. The designers have struggled due to a lack of theory for the design of these systems. Our results should be helpful in this regard. In fact, we have also convinced personnel at Lucent Technologies [15] that our ideas could be applied in the implementation of practical communication receivers.

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