COMMUNICATION SCIENCES

AND

ENGINEERING

XIII. PROCESSING AND TRANSMISSION OF INFORMATION

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RESEARCH OBJECTIVES AND SUMMARY OF RESEARCH

1. Complexity of Networks and Algorithms

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P. Elias

The complexity theory of switching networks has been explored during the past year by Nicholas Pippenger.[1] He investigated a large variety of problems concerned with connecting networks, and found the order of growth with network size of the number of contacts needed. He also investigated the complexity of the routing algorithms required to set up the connection pattern. One of his results is the first proof that a particular type of connecting network (a partial concentrator) that can rearrange existing calls has a number of switches that grows more slowly with the number of inputs than is the case for a similar network that must maintain old calls while placing new ones. Another result is an improvement on the coefficient of the number of contacts needed for an ϵ-blocking connecting network found by M. J. Marcus.[2] This was obtained by an explicit construction.

If selections from a fixed set of code words are packed adjacent (in space or time) to one another, a receiver or an algorithm accessing memory can unpack them neatly only if no code word in the set is the beginning of another. If the set satisfies this condition, its lengths must satisfy the Kraft inequality; conversely, any set of integers satisfying that inequality is the set of lengths of a set of code words that can be neatly unpacked. These matters have been well known since Kraft[3] completed his Master's thesis. What has not been explored is how complex a device the unpacker has to be. Donna Brown has shown that it requires a number of states which is no worse than quadratic in code-word length, and not much better. Questions of how much further the unpacking complexity can be reduced by making some code words longer than necessary remain open.

References

1. N. Pippenger, "The Complexity Theory of Switching Networks," Technical Report 487, Research Laboratory of Electronics, M. I. T., December 19, 1973.

2. M. J. Marcus, "New Approaches to the Analysis of Connecting and Sorting Networks," Technical Report 486, Research Laboratory of Electronics, M.I.T., March 17, 1972.

3. L. G. Kraft, "A Device for Quantizing, Grouping, and Coding Amplitude-Modulated Pulses," S.M. Thesis, Department of Electrical Engineering, M.I.T., June 1949.

2. Information Theory of Data-Processing Systems

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P. Elias

Information theory ideas and techniques furnish lower bounds to a variety of costs associated with data-processing tasks. When only one such cost is of interest it is usually possible to find a system that attains or approximates the lower bound. When there are several relevant costs, each one is usually minimized by a different system, and trading relations between different kinds of costs must be explored.

For an information storage and retrieval system, two important costs are total bits stored, and bits accessed per retrieval question. A representation and an associated set of retrieval algorithms has been found that is nearly minimal in both kinds of cost for simple files.[1] Similar investigations of other data structures are under way.

A third cost of great practical importance in storage and retrieval systems is the cost of updating a data base. Richard A. Flower[2] has found a lower bound to an informational measure of update cost (bits read plus bits written per update).[2] He has shown that for some simple data structures a single system minimizes all three costs – storage, access, and update – and he has explored trading relations in other cases.

Future lines of investigation include the analysis of a larger variety of different data structures, and the development of models for data structures and for operations on them which are truly representation-independent. Since an informational lower bound is a minimum over all possible representations, it is necessary to have a description of the problem that stays fixed as the representation varies. For static retrieval problems, the set of possible data bases and the partitions induced on that set by the retrieval questions provide such an invariant description. Extensions are needed for other operations on the set of data bases.

References

1. P. Elias, "Efficient Storage and Retrieval by Content and Address of Static Files" (to appear in J. ACM).

2. R. A. Flower, "Computer Updating of a Data Structure," Quarterly Progress Report No. 110, Research Laboratory of Electronics, M.I.T., July 15, 1973, pp. 147-154.

3. Optical Channels

National Aeronautics and Space Administration (Grant NGL 22-009-013)

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We are concerned with the fundamental limitations and efficient utilization of optical channels for communication. Our interests include quantum channels, scattering channels, and the turbulent atmospheric channel. During the coming year the determination of the fundamental limits imposed upon the performance of optical systems by quantum effects and the means of attaining these limits will again be a major concern. We shall also complete an investigation of the limits imposed upon the performance of optical radars by atmospheric turbulence.

The accomplishments of the past year are listed as follows.

1. We demonstrated that information rates of kilobits per second per watt transmitted can be achieved over scatter propagation distances of 10 miles in visibility as low as 3 miles.

2. We proved, with others, that the usual characterization of quantum measurements by Hermitian operators is inadequate to determine the fundamental limits imposed upon the performance of optical systems.

3. We showed that the very general description of quantum measurements by operator-valued measures, without loss of performance, can be replaced by a description in terms of overcomplete measurement states.

4. We established the structure and performance of the optimum quantum receiver for the M-ary quantum-limited coherent channel problem.

5. We discovered a new receiver for the binary quantum-limited coherent channel problem.

6. We formulated and began to analyze a class of receivers that are feasible to implement and that appear to offer important improvement in performance over others previously considered.

7. We initiated a fundamental investigation of the extent to which a receiver specified by an operator-valued, or Hermitian, measurement can be realized, and the means of realizing it.

8. We developed techniques for improving the performance of direct detection systems using photodiode detectors.

9. We explored the limitations imposed by atmospheric turbulence upon the performance of optical radar systems.

a. Scatter Communication

Our earlier theoretical and experimental investigations of over-the-horizon optical scatter communication culminated in the design and testing of two communication systems for the 11-mile M. I. T. (Cambridge)-Lincoln Laboratory scatter link. Both systems were designed for daytime operation, which was made possible by modifying the transmitter for Q-switched operation.

The transmitter power was ~10 W average and 10 kW peak, the transmitter repetition rate was in the range 1000-5000 pulses per second.

One system for digital inputs employed on-off signaling with a direct detection receiver, a relatively large receiver field of view, and large, but low-quality, receiving optics (searchlight reflector of 2 ft diameter). The other system, for analog inputs, employed delta modulation, a smaller receiver field of view and smaller, but higher quality, receiving optics (a 24 in. telescope).

Both systems provided reliable operation when the visibility on the 11-mile link exceeded a critical minimum value. For the large-aperture system, this minimum value was approximately 3 miles; for the smaller aperture system it was approximately 7 miles. In both instances the minimum visibility was significantly less than the operating range, as we had expected.

b. Quantum Communication Theory

The quantum aspects of the communication problem have been of increasing concern to us. During the past year we have demonstrated that the usual characterization of quantum measurements by observables, defined on the space of the system to be measured, does not provide an adequate characterization of the class of optical receivers that are consistent with physics. Simply stated, if we adjoin an apparatus to the system, consider an observable on the combined system, and then attempt to describe the resulting measurements in terms of the original system alone, we find that an observable is not adequate to the task, and an operator-valued measure must be employed. This is significant, in that improved system performance may be attained by using a receiver not characterized by an observable — a possibility that we plan to explore.

On the other hand, we have shown that only a restricted class of operator-valued measures need be considered, specifically those characterized by sets of overcomplete states. Thus the search for improved system performance is narrowed. We have also shown that, for the quantum-limited M-ary pure state channel, with linearly independent states, the optimum receiver is characterized by an observable and we have determined the structure of the resulting optimum receiver and its performance in terms of a nonlinear matrix equation. Examples solved thus far demonstrate that, at high information rates, the limitations imposed by quantum noise are not as severe as is usually assumed; a result that is suggested by the performance of PPM with a direct detection receiver.

In an even more specific result, we have found a new receiver for the quantum-limited binary coherent state channel. This receiver offers a 3-dB performance improvement over direct detection receivers, heterodyne receivers, and homodyne receivers. The structure of this near optimum receiver suggests a broader class of receivers that may be superior in more general situations. That class is now being explored. A fundamental investigation of the relationship between the abstract description of quantum measurements and the means of implementing them is also in progress.