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MIRAGE: A Model for Latency in Communication

Abstract
Mirage is a research effort which attempts to provide a basis for analysis and design of gigabit communications networks. As part of the overall Mirage project, we develop here the Mirage model, a formal model for the design and analysis of high-speed wide-area network protocols. The primary goal of this research is to understand the effects of moving to the gigabit domain in wide-area networks, verifying or disproving the predicted failure of existing protocols, and anticipating potential solutions. A derivative and more fundamental goal is to provide a framework for understanding the effects of latency on communication. In the high-speed, wide-area domain, network inefficiencies are caused by the combined effect of increased channel capacity, without a corresponding decrease in communication latency (due to finite propagation delays). Mirage proposes a view where latency can be compensated by accepting information imprecision (a controlled form of error), thus inverting the problem.

This research is based on suggestions derived from analogies in physics, using a model of state space volume transformations, in an attempt to incorporate the imprecision evident in quantum models into communication protocol analysis. It proposes to extend Shannon's communication theory by accounting for the effects of latency, just as Shannon's accounts for communication errors.

The dissertation we propose will consist of a three phase development of the formal model, providing for its synthesis and examples of its use. The first phase uses the description of a simple, existing protocol, clock synchronization via the Network Time Protocol, to assist in the development of the formal model. In the second phase, we will consider the application of the Mirage model principles towards the analysis of a new protocol, specifically a flow protocol, and the accumulation resetting mechanisms contained therein.

Finally, we will show how Mirage can be useful in the design of new protocols. In particular, we can apply this model toward the design of new distributed cache management protocols. Mirage suggests interesting tradeoffs and optimizations in the protocols used to maintain caches in a distributed shared memory.

Comments
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2 Submitted in partial fulfillment of the requirements of the Dissertation Proposal, towards the
degree of Ph.D. in Computer and Information Science.
ABSTRACT: Mirage is a research effort which attempts to provide a basis for analysis and design of gigabit communications networks. As part of the overall Mirage project, we develop here the Mirage model, a formal model for the design and analysis of high-speed wide-area network protocols. The primary goal of this research is to understand the effects of moving to the gigabit domain in wide-area networks, verifying or disproving the predicted failure of existing protocols, and anticipating potential solutions. A derivative and more fundamental goal is to provide a framework for understanding the effects of latency on communication. In the high-speed, wide-area domain, network inefficiencies are caused by the combined effect of increased channel capacity, without a corresponding decrease in communication latency (due to finite propagation delays). Mirage proposes a view where latency can be compensated by accepting information imprecision (a controlled form of error), thus inverting the problem.

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1. Introduction

Mirage is a research effort which attempts to provide the basis for the analysis and design of high-speed wide-area protocols [ToFa89]. The primary goal of this research is to understand the effects the gigabit domain on wide-area networks, examining the predicted failure of existing protocols, and anticipating potential solutions.

In numerous research projects, the predicted failure of current protocols in the gigabit domain is used to justify the search for new protocol implementations. Most of these efforts focus on the complexity of existing implementations and the impossibility of executing these protocols at the nodes, and attempt to seek simpler protocols or more efficient implementations (e.g. XTP, NETBLT, VMTP). Instead, we seek to understand the distinguishing characteristic(s) of gigabit networks, so that protocols developed via this model will be capable of gigabit rates by design, rather than accommodation.

One characteristic of gigabit wide-area networks which differentiates them from their slower or more proximal counterparts is that latency becomes comparable to bandwidth and node size. It is believed that fixed latency, combined with increasing data transmission rates, will result in network inefficiencies as bandwidth and network sizes scale [Mi90, Pa90]. As such, a derivative and more fundamental goal of this research is to provide a framework for understanding the interacting effects of fixed propagation delay and bandwidth increases on communication networks. This approach is a highly explorative effort which will provide a basis for understanding the characteristics of high-speed wide-area protocols by investigating the effects of fixed latency.

Mirage denotes the difficulty with high-speed, wide-area network protocols, in that by the time requested information arrives, it may no longer be accurate. Nodes in a high-speed network never really "see" each other; rather, they work with (and around) the mirages which high speed and fixed latency conjure before them.

Recent changes in the structure of the national network have required a fresh view of protocols which serve these networks [Gr87, Ra87, Po88]. The primary influence of these changes is a decrease in the large gap between the size of a node and the amount of data caught in network round trip latency. The decrease in this gap is believed to cause conventional protocols to decrease in channel utilization, since many such protocols were designed for file transfer based on sliding window flow control. One possible reason for the deterioration of efficiency in existing protocols is that they operate in a
point model of communication [ShWe63]. Shannon's theory, which describes this point model, indicates methods for reducing channel error by encoding sequences of data; reducing larger channel errors requires encoding over longer data sequences, and results in a trade of error for latency.

In high-speed, wide-area networks, inefficiencies are caused by the effect of increased channel capacity, without a corresponding decrease in communication latency (due to finite propagation delays). The Mirage model proposes a view where latency can be reduced by increasing information imprecision (a controlled form of error), thus inverting the problem. In the inversion, the information of a remote node, formerly represented by a precise point in state space, becomes an imprecise volume in state space. Mirage defines forms of communication as transformations on these state space volumes, also incorporating the effects of time in its transformations on the volumes.

This research is based on suggestions derived from analogies in physics. Communication theory already incorporates physics analogs, most notably that between information and negative entropy; here we investigate other analogies as well. The Mirage model, of state space volume transformations, is an attempt to incorporate the concept of imprecision evident in quantum models into communication protocol analysis.

2. What has changed?

We have previously built networks where the bandwidth*delay product was small compared to the size of the nodes participating in the protocols. In existing window-based protocols, utilization is optimal only where the buffer space is larger than the round trip data delay; when smaller, the utilization is proportional to the ratio. Graphing the three factors of node size, which determines the number of buffers available, round trip time, and channel bandwidth, we see that we have previously been operating on the plateau of a curve, and are rapidly approaching the cliff, where utilization drops dramatically even for subtle variation in parameter values [Figure 1].

In existing protocols and models, latency is treated differently than we propose, because the mismatch between node size and round trip delay was not manifested until the emergence of gigabit wide-area networks. Here we want to extend communication theory to provide a formal basis, and create a framework for understanding latency which is both analytic and predictive. We expect existing protocol solutions to be verified, if we use our model to analyze conventional networks, in which latency is negligible.
The dissertation we propose develops components of the overall Mirage research, especially those related to the theoretical basis for the project. The following is a brief description of some Mirage model principles, including expression of state spaces as volumes rather than points, trading error for latency (as a possible extension to Shannon's model), and the use of guarded messages (akin to guarded commands). We also introduce an instance of the model as applied to Petri Nets, called Meta-Petri Nets, as a concrete domain where state space volumes and virtual knowledge (similar to quantum interactions) can be developed further.

3.1. Shannon’s Model - Extensions for High Speed

Shannon’s mathematical model of communication defines channel bandwidth and capacity, and analyzes the capacity of the channel under the constraint of transmission error [ShWe63]. In his model, the channel is viewed as a pipe between the communicating nodes [Figure 2]. Bandwidth is a unit of volume of flow in this pipe - bit width x signal.
duration. Note that the propagation delay (latency) of this volume as it traverses the pipe is ignored; Mirage will add this component, in its extension of this model.

Figure 2: Shannon's communication channel

Shannon's model is based on denoting the state of a node as a point in state space, implying that the values at the node are known precisely at remote nodes. This is implicit in the communication model, which attempts to emulate the transitions of the transmitter by equivalent transitions in the receiver [Figure 3].

Figure 3: State space point transformation (translation of a point)

As latency is a characteristic of wide-area networks, we consider how to extend Shannon's model to account for latency, as it already accounts for error. One constraint of our extension is that, in cases where latency is negligible, it should reduce to the original model. Other constraints are that the model be useful, i.e. that it describe the new domain of high bandwidth*delay products effectively and that it enable the derivation of new protocols which account for this increased latency.

One of the fundamental results of Shannon’s theory is that any amount of channel error (below 100%) can be removed by sufficient encoding. The effect of error compensation and reduction is to require encoding, which also requires delaying the symbol stream by the length over which encoding is performed. As such, error reduction is traded for an increase in propagation delay. Here we examine the complement of this, in which we will reduce latency by increasing the error across the channel; the error will be exhibited by the imprecision of information about remote nodes in the network.
4. The Mirage model

Mirage is a research effort which attempts to provide a basis for protocol analysis and design, in high-speed, wide-area network environments [ToFa89,ToFa90]. It is based on representing remote nodes as volumes in state space, where data transmission and reception, as well as time evolution, are modelled as transformations on those volumes.

Inherent in the Mirage model is the notion of latency as a measurable entity. We can extend the Shannon model of a communication channel by including the latency measurement [Figure 4]. Here we assume that the latency will be either constant or predictable (other cases may be considered later). If we describe flow in the Shannon model as a volume along the communication pipe, then latency is a measure of the length of the pipe. As such, incorporation of latency into the model reveals a spatial aspect to the formerly topographic Shannon model.

![Mirage communication channel](image)

Figure 4: Mirage communication channel

In Shannon’s model, information about remote nodes is modelled as a point in state space, and any operations which affect this information translate the point in space [Figure 3]. Here information is modelled as a volume in state space, where operations become transformations of that volume. Time expands the volume of a space, transmission logically OR’s the volume with a transformed copy, and reception contracts the volume to a smaller region of space [Figure 5].

Mirage provides for distinct transformations on the state space volumes for each of transmission, reception, and time lapse, as contrasted to the conventional single transformation of a point (i.e. translation) as used for all three. In each transform, there exist constraints formulated from the link bandwidth and transmission latency, expressing the imprecision of the volume as entropy. Mirage also indicates a stability condition, where network information is either conventionally or entropically stable. This stability criterion forms the constraint under which the model optimizes communication [ToFa90].
Mirage works with three types of information, introducing the third to protocol models. The first two are *Real Direct* and *Virtual Direct*; the former is explicit communication, the latter is common knowledge, i.e. information derived from communication with others in a group when global group constraints are known [HaMo84]. Here we also utilize *Virtual Indirect* communication, information known from a combination of prior constraints and the absence of explicit communication [ToFa89].

### 4.1. Guarded messages

The Mirage model also utilizes guarded messages, similar to guarded commands, as used in programming languages. Since the perception of a remote node can be a volume in state space, we can send messages labelled with various regions of that volume, thus emitting multiple messages for a single desired action. The remote node compares its current local state to the label of the incoming message, and acts on the received information only if they match. It thus becomes possible to send *information redundant* messages. In current protocols, it is common to send identical copies of data, to reduce loss due to corruption. In this model, two messages with null-intersecting guards can be information redundant, when constructed to have equivalent results on the receiving node. They are thus data distinct, but information redundant [ToFa89].

Guarded messages permit the expansion of the state space of a transmitting node to be constrained sufficiently to remain tractable. The information redundancy used by these replicate communication paths also provides a use for the additional bandwidth provided by the high speeds of the problem domain. In effect, we then utilize part of the phenomenon which causes the effect (high bandwidth*delay product) to compensate for it, by using the latent transmission to store information redundant replicates.
4.2. Petri Net Representation

We need to recast an existing protocol model, one based on the Shannon point model, to use state space volumes. We also require a notation for describing an instance, in order to discuss the model's implications in the definite. For this purpose, we have selected Timed Petri Nets [MeFa76], a variation of Petri Nets [Pete77, Petr62]. We extend these nets to describe the state transformations of Mirage, being careful to preserve the graphical/formal properties of the original nets.

We begin with the Timed Petri Net (TPN) of a protocol. The set of markings of this TPN, and the valid transitions between these markings, is called its equivalent Token Machine (TM). Consider the new Timed Petri Net whose places correspond to the states of the TM, and whose transitions correspond to the arcs of the TM. This is also a valid model of the protocol; we call this a Meta-Petri net, or MPN. The MPN has a single token, which begins in the state representing the initial marking of the TPN, and moves along the MPN to represent the TPN's current (single) marking. Transformations on the MPN can also enable the MPN to model multiple TPN markings, under certain conditions; the number of tokens in the marking of a MPN thus reflects the entropy of the state of the node being modelled.

In an MPN where nondeterminism exists, an advantage can be gained by running the MPN into the 'future', with virtual tokens. A virtual token is one of a set created which describes nondeterminism in a MPN. Where a branch occurs in the MPN, rather than having a lone token continue on a single path, a virtual token is created for each path possible. These tokens then belong to a codependant set. Later, if any of these tokens is to be considered real, all codependants of that tokens set, and all ancestors of all tokens in that set, must be destroyed. A token is real only if it is the lone token in an MPN. These operations may appear similar to the virtualization which occurs in Feynman diagrams, which is appropriate, as they were patterned after concepts from quantum physics. Token virtualization and realization can be introduced by a graph transformation in the MPN. The messages emitted in the transformed MPN are guarded messages, in which the conditional label (guard) on a message indicates which of the virtual tokens caused that message.
5. Comparisons to other models

Some existing protocols or protocol variations incorporate some aspects of the Mirage model, but none is as complete. Mirage attempts to unify aspects of several types of models, from distributed operating systems, partitioned databases, and general feedback and control systems. The following is a preliminary analysis of the Mirage components in relation to existing work.

5.1. Cybernetics / control theory

Mirage contains constraints of stability derived from fundamental work in cybernetics [As64, Wi61]. These are also related to feedback and control theory, which relate to method in which Mirage attempts to describe synchronization - the extent to which remote processes can communicate and share information, given feedback latency.

5.2. Models of communication

As previously stated, Mirage also attempts to extend Shannon’s communication theory to account for latency, and to compare the conjugate spaces of error and latency. In addition, there are aspects of existing protocol analysis that Mirage utilizes; specifically, aspects of common and distributed knowledge, which extend Shannon’s theory to account for Virtual Indirect communication as well [HaMo84, Go88]. The Mirage model is not suitable for direct emulation; however equivalent substructures of the model may be suitable, by a coarse-grained partitioning of the state space via equivalence relations, as in protocol projections [La82, Sh82] and partitions [ChMi86].

Constraints on communication links have been examined in the determination of optimal window sizes in windowed flow control schemes, especially where the interdependence between local link windows and global (overall network input/output) network windows is examined [Ak88, Lu88]. Mirage attempts to extend this search for optimal interdependency values to multi-dimensional systems. In particular, the issue of transmitter/receiver feedback as anticipating state space expansion has been used successfully in windowed flow control schemes, albeit in a discrete and restricted fashion, as contrasted to our continuous time axis. The expansion of state spaces upon data transmission, and their contraction upon message receipt, has been examined in the
design of buffer "barriers", a modified flow control which attempts to equalize the uncertainty of communication among transmitter and receiver [Fr88].

Time in protocols normally is modelled either by boundaries or by finite time-steps. In the former, actions occur when these boundaries are exceeded, as in Timed Petri Nets, temporal logic, or time-out timers [MeFa76, Sc82]. In Mirage, time is a fully parametric and continuous value, over which other entities vary. Similarly, time as an aging variable [Sh82] is not as general, since time markers age, but other entities do not vary with time. In the Mirage model, time transforms the volumes arbitrarily. Incorporating time as a valid interval for each state of a protocol machine is akin to denoting the interval in which the expansion of the volumes is well-defined [Ag83]. The extension in which hold times of protocol states are cumulative distribution functions is similar to a temporal projection of this state space.

There are also other state space models of communication protocols [Bo78, Da80]. These models are based on determinism, modelling a point in the state space, while Mirage is aimed at the a constrained nondeterministic version of this, where a volume of the state space is modelled.

5.3. Models of distributed systems / databases

The notion of restricting a machine to operate only within the valid volume is an extension of distributed/replicated database techniques, most notably read/write quorum strategies [He86]. In addition, there are designs for external entities which maintain the operation of a system to within some desired constraints [Fa76]. The use of these environments or supplemental programs to warn of dead-ends, maintain locality, and restrict other programs to within some valid region of state space, is similar to the methods used here. Mirage differs in that these notions are central to the operation of the protocol, rather than external, supplemental constraining devices.

5.4. Physics analogies

Finally, as noted earlier, Mirage exploits some analogies between latent communication and quantum interactions. The splitting of a point in state space into a volume is similar to the interactions described by Feynman diagrams, and the denotation of the aggregate characteristics of a system based on the distribution of possible occurrences in its state space volume is similar to that described by a path integral. In addition, there are
analogues in thermodynamics and its relationship to quantum mechanics, beyond the existing analogue of information as negative entropy [ToFa89, ToFa90].

6. PLAN OF ACTION

This part of the overall Mirage research focuses on the development of the underlying model, so that the remainder of the Mirage effort rests on a sufficiently formal basis. While such a formal model can be developed without external reference, we note that a concrete example of the instantiation of a model is often necessary for its correct development and understanding. The dissertation we propose will consist of a three phase development of formal model, providing for its synthesis and examples of its use. The first phase uses the description of a simple, existing protocol to assist in the development of the formal model. The model thus developed will be used in the analysis of an existing protocol problem (phase 2), an finally to predict a new type of protocol (phase 3).

The first phase involves the initial instantiation of the formal methods with respect to a simple, existing protocol. We have chosen the Network Time Protocol (NTP) [Mi89] for this purpose. NTP is a sufficiently simple protocol for such a task, and has aspects of synchronization which will adequately exhibit some of the salient features of the Mirage model. Included in this analysis will be an investigation of the aspects of the model relating to probabilistic clock synchronization techniques [Cr89].

In addition to developing the Mirage model to describe NTP, we will also consider the application of the Mirage model principles towards the analysis of a new protocol, specifically a flow protocol [Zh89]. In these protocols, the designers often incorporate mechanisms for accumulating unused bandwidth, and occasionally removing this accumulation. It is hoped Mirage will explain the need for such resetting mechanisms, and provide a method with a less arbitrary justification.

The development of the Mirage model with respect to these two protocols will provide a basis for determining the validity and utility of the model, as it is being constructed. Beyond simply describing existing protocols and analyzing emerging protocols, we will show how Mirage can be useful in the design of new protocols. In particular, we can apply this model toward the design of new distributed cache management protocols. Mirage suggests interesting tradeoffs and optimizations in the protocols used to maintain caches in a distributed shared memory.
7. Dissertation Outline

The following is a preliminary outline for the proposed dissertation, based on our existing understanding of the research components. The outline is representative of the expected organization and emphasis of the dissertation. Note that the description of earlier sections is more complete as work in these areas has already commenced; the final sections, comprising the core of the dissertation, will be outlined in more detail as the research progresses.

I. Introduction

II. What has changed (justification)
   A. Amount of information in transit - network characteristics
   B. Need to account for latency - omission in theory
   C. No longer just file transfers - change in use

III. Description of model goals (goal statements)
   A. Express tradeoff - latency / imprecision
   B. Exhibit constrained imprecision - (i.e. from quantum mechanics)
   C. Show uses of additional bandwidth - compensate for latency

IV. Existing theory / models (prior work)
   A. Shannon
   B. Petri Nets
   C. State transitions
   D. Partitions
   E. Physics analogues

V. Mirage model (description of features)
   A. State space transformations
   B. Stability criteria
   C. Guarded messages

VI. Description of a simple, existing protocol (phase 1)
   - Network Time Protocol

VII. Analysis of an existing protocol (phase 2)
   - flow / virtual clock protocol

VIII. Development of a new protocol (phase 3)
   - distributed shared memory caches

IX. Evaluation of the Mirage model (evaluation)
   A. For protocol description
   B. For protocol analysis
   C. For protocol prediction

A good organization of these topics is provided by the following intermediate papers and goal dates. Not all papers are intended for external publication.

1. Gigabit protocols ARE really necessary. October 1990
2. A Mirage description of NTP. (phase 1) November 1990
References


