SwitchWare: **Accelerating Network Evolution** (White Paper)

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ABSTRACT

We propose the development of a set of software technologies (“*SwitchWare*”) which will enable rapid development and deployment of new network services. The key insight is that by making the basic network service selectable on a per user (or even per packet) basis, the need for formal standardization is eliminated. Additionally, by making the basic network service programmable, the deployment times, today constrained by capital funding limitations, are tremendously reduced (to the order of software distribution times). Finally, by constructing an advanced, robust programming environment, even the service development time can be reduced.

A *SwitchWare* switch consists of input and output ports controlled by a software-programmable element; programs are contained in sequences of messages sent to the *SwitchWare* switch’s input ports, which interpret the messages as programs. We call these “*Switchlets*”. This accelerates the pace of network evolution, as evolving user needs can be immediately reflected in the network infrastructure. Immediate reconfigurability enhances the adaptability of the network infrastructure in the face of unexpected situations. We call a network built from *SwitchWare* switches an *active network.*

1. Introduction

The pace of network evolution (not switch evolution, *network* evolution) proceeds far too slowly. To a large degree this is a function of standardization. Standardization is a necessary step in network design to ensure interoperability, as a network’s utility increases with the number of interconnected nodes. Since today’s Internet architecture mandates the implementation of IP in all routers and hosts, and requires a 5-8 year standards→ development → deployment process (e.g., IETF → Cisco → Internet Service Providers), it is inflexible and evolves slowly.

The Internet Protocol (IP) forces interoperability by defining a standard packet format and addressing scheme which is overlaid on networks comprising the internetwork. Since it must operate on the least capable of networks, it is designed to offer a minimal set of functions; additional services are added by overlays on IP. Three undesirable consequences of this design are:

1. It must run everywhere (e.g., at hosts and switches). There are two subconsequences: changing IP means changing everything, and everyone must share the same service model.
2. Overlays (e.g., the reliable stream overlay of TCP, or multimedia multicast with MBONE.) are forced by people who don’t accept the communal service model, i.e., they want or need a different service.

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3. IP has no semantics for passing data-link layer information to the end-points.

Overlays are problems for two additional reasons. First, overlays may be inefficient because the underlying network does not take the functionality of the overlay into account; consider overlaying a packet-switching network on top of a circuit-switching network. Second, partitioning of resources becomes more difficult because we must split the partitioning of resources within an overlay from the partitioning of resources among overlays.

A second alternative, stemming from our overall goal of accelerating network evolution, is to create virtual switches, with important sub-goals.

This new set of goals, if realized, have profound consequences for the engineering of future networks. These are:

1. *Programmable services*, to accelerate network evolution.
2. *Extensibility*, so that *logical* overlays can be implemented within the switches rather than as true overlays at the endpoints. Programmability alone is not extensibility; for example, extensibility is missing in control software for telephone switches [25]. It seems most useful to provide user-extensibility, so that new applications not imagined by the designers can be easily added, and we can avoid the risks of a ‘‘narrow-gauge’’ infrastructure.
3. *Security*, as this is both an increasing concern as networks become more widely applied, and increasingly difficult as they become more complex. For us, *robustness* is an aspect of security.
4. *Partitioning*, to control resource allocation and scheduling under a programmable *policy*.
5. *Portability*, so that software switching performance can keep pace with component technology curves, such as processor performance, and carry software switched applications along the same upslope.

We propose a *SwitchWare* switch, which provides a programmable element, essentially a computer, to perform switching functions and address this list of goals. Extending the role of computing in the network is the key to accelerating the evolution of network infrastructure; a compelling example is the rate of evolution of the World-Wide Web with its simple HTML language and Common Gateway Interface scripts.

The approach suggested in this paper is an extension of that used to revolutionize telephony in the early 1990’s. Advanced Intelligent Networking [32], developed in part by Bellcore, separates the implementation of telephony services from basic switching by moving the service control to an adjunct processor from the switch. Since each call can now have a different service, the need for standardization of new services has been eliminated. Deployment times are greatly reduced, since a new service is essentially data entered into the database of the adjunct processor. Development times are even reduced by enabling service providers and users to define and develop new services, and by a graphical programming interface developed by Bellcore. The telephony industry has seen new production quality service creation times drop from over two years to as little as two weeks as a result of AIN. The *SwitchWare* switch will extend the approach used by AIN to greatly increase the level of programmability in the switch, by reducing the need for a call model which constrains AIN. We will also apply the technique to internetwork routers and ATM switches, which have not been attempted by AIN.

2. Switching and the Pace of Network Evolution

The pace of network evolution proceeds far too slowly, relative to the technological changes in the underlying transmission systems, where laboratory results have reached Terabit/second bandwidths, and relative to the applications deployed at the edges of the network, such as the World-Wide Web and its supporting technologies such as the Java [21] Programming language. The element interconnecting the links and end-nodes is a switch; logically (although atypically) it is possible to view routers, bridges, etc. as specialized switches.

Programmability of switching elements led to major progress in the evolution of our national network infrastructure. An excellent case study of telecommunications switching infrastructure [23] is the Western Electric 3B20D processor [38] and the associated Duplex Multiple Environment Real Time (DMERT) [15, 13] operating system. This system was employed in the Bell System's 5ESS switch systems which remain in widespread use. DMERT is based on the earlier MERT operating system [19], and provides both a real-time and timesharing environment. The 3B20D offered user-programmable microcode so that high-performance applications could in fact create a custom or emulated machine architecture within the context of the 3B20D processing unit; this was used to support code and devices from earlier switch fabrics such as the 1A attached processing unit. Up to four concurrent instruction sets were supported; an instruction set could be selected with a single native microcode instruction.

This system reflected the importance of software in implementing the national telecommunications architecture, as it was designed from the start to be an effective execution platform for software. The programming model allowed programs to be loaded at run-time, but of course was not accessible to arbitrary users of the phone system.

What has changed in our modern environment is the need for a variety of programmed, customized *services*, and the model of updating central office switches using a van full of magnetic tapes is no longer appropriate.

2.1. A software approach: the Advanced Intelligent Network (AIN)

As we remarked earlier, the approach suggested in this paper is an extension of that used to revolutionize telephony in the early 1990's, Advanced Intelligent Networking [32], which was developed in part by Bellcore. The use of an independent control processor in the switching fabric gave service designers access to databases and other processors to provide call processing features. The response to a telephone call can then be represented as a state machine, which takes actions as information is input during a call. Examples of services that can be provided with this model would include routing of a call to the nearest shop in a chain of Pizza delivery services. The call processing would reference a Geographic Information System, and could be enhanced with vendor provided data such as availability of drivers.

The deep, and fundamental restriction on the applicability of this approach is its use of the call model, which is far too restrictive for the network infrastructure we have now, which is evolving from circuits to packets, and if the *SwitchWare* approach is taken, beyond to typed data objects.

2.2. Why not the Internet model?

As we argued in the Introduction, this slow evolutionary pace is a function of standardization. The Internet Protocol (IP) forces interoperability by defining a standard packet format and addressing scheme which is overlaid on networks comprising the internetwork. Since it must operate on the least capable of networks, it is designed to offer a minimal set of functions; additional services are added by overlays on IP.

The difficulty with this model is that it is extremely difficult to *interpose* new protocol functionality. This can be illustrated with the example of Domain Name Service (DNS). The pressures on DNS are tremendous and likely to increase. Many applications are dependent on it, and the World Wide Web's use of location-dependent naming places further pressure on DNS performance. The future will bring personal networks of perhaps hundreds of processors and intelligent sensors - such a network's elements will need names for management and function location. DNS will not scale to such an extent with caching, and yet the appropriate caching functionality cannot be built without interposed protocols for DNS cache management (including security features to prevent spoofing) and WWW proxies. These features require software embedded in the information network.

An excellent example of interposed functionality can be drawn from electronic mail systems, which can interpose tools like the ``vacation'' program to alter mail handling when people are on travel. Such systems have been extended with programming to provide priorities based on addressees and message sizes, which are transparent to the sender.

2.3. *SwitchWare* Programming

For any workable communication, there must be *some* agreement; standardization is essentially an agreement about what the agreement is. The IP protocol has been successful in standardizing packet formats, but because its standardization process operates at a political tempo rather than a technological tempo, the pace of evolution has been held back. We believe that a PostScript-like [35] concept, which raises the level of abstraction of the standard, to *SwitchWare* services rather than IP services, is the method for staying on the technology curve. Raising the level of abstraction also gives a much greater toehold for network management, specifically for automated self-diagnosis and repair. This is true because *(1)* behavioral assertions are simpler to state, *(2)* monitoring software is easier to write, and *(3)* the chain of assertions that lead to diagnosis and repair is less complex.

For most rapid evolution, networks must be user-customizable, and for users to drive deployment of new services, the network must be on-the-fly programmable. That is, it must be programmable by the packets that flow through it. While not all packets need contain code, packet sequences can contain modules of programming, as in the mobile agents prototyped by Knabe [17]. These code objects are used to provide customized services to the level of an individual user, or if predictions of hundreds of processors or intelligent sensors per person are true, perhaps composites of hundreds of such services.

3. *SwitchWare* Applications

We intend to implement one or more prototype services in a *SwitchWare* system in order to show feasibility. These services should have the properties of being useful to a subset, but not necessarily all users of the active network. Services which are useful to all or most users of the network, like simple unreliable datagram forwarding, or unreliable multicast are susceptible to being included in a traditional bearer service such as IP. Services which are highly speculative, too forward looking, or simply not well understood are good candidates for being implemented in an active network. Several example services which match these characteristics are described below.

3.1. Self-paying information transport

The idea of Self-paying information transport (we'll resist using the acronym) is to have an object which is to be transported through the network include some form of electronic payment information as part of the object. A simple analogy would be to the stamp on a letter today. A transportable object (such as a packet or a virtual circuit) would contain, as part of the control information (i.e. the packet header or VC setup messages) some sort of electronic payment information. This could be either e-cash, e-check, or an electronic credit card number. The payment information would then be examined by the *SwitchWare*, and if sufficient payment was offered, the object would be serviced by the *SwitchWare*. Note the service might be to provide computing by executing the object in the *SwitchWare*, or to provide communications by switching the object, to provide storage for state information the object may wish to leave in the *SwitchWare* switch, or some combination of these. The payment information may then be altered (some e-cash subtracted) as the object traverses the network.

This type of service is speculative enough that it would not be possible to consider standardizing it in a bearer service today. However, it is not hard to envision either commercial or military scenarios where it might be useful. In commercial situations, it provides the possibility of creating a dynamic market in network bandwidth, which may be more economically efficient than todays fairly static tariff structure where prices only change at fixed times of the day. A provider with an underutilized network might lower his prices, thus attracting objects into his network. A provider who was overloaded could raise prices until the demand subsided to match available capacity.

Since payment is really a complex form of priority, it's possible that in a military application, the payment may instead be interpreted as an authorization and priority. Requests that carried insufficient priority in times of high demand would be either offered a lower grade of service, delayed, or possibly even dropped. Far more dynamic schemes might be constructed as required. This scheme could be used, for example, to control QoS-based scheduling inside the *SwitchWare* run-time system.

3.2. Network management

Many network management tasks consist of collecting and collating data, such as event counts. To provide the most useful network management data, such as exception indications, intelligence must be used to filter out uninteresting (unexceptional) events. An easy way to write a network management system, assuming that appropriate authentication and protection can be devised, is to write a network management program using modules constructed from sequences of ‘‘program’’ packets.

Fault management is a very important and difficult task, particularly so for large networks and for correlated failures. Correlated failures may be caused by both environmental factors, such as earthquakes or explosions, or by malicious intruders. We believe that active networking can be used to significantly improve fault detection and management capabilities in the network.

Existing network monitoring for fault detection consists of gathering a known set of measurements. The fault management system filters and correlates these measurements. A problem with this approach is that it's difficult to integrate network elements that operate with different fault management systems. Network elements are designed to operate with one specific fault management system. Also, differing design philosophies may prevent the integration of several fault management systems. These incompatibility issues also make it difficult to evolve the fault management system, because it is difficult to add a network element that does not conform with all existing elements.

Active networks can provide the desired flexibility, because the fault management system can be changed as necessary without the need to worry about backward compatibility. Existing systems can be reconfigured as necessary simply by changing the code used for fault management. Active networking also may allow for hierarchical fault management. As faults are being isolated and identified, the fault management system can be refocused to examine in more detail those network elements that may be operating incorrectly. Different versions of fault detection code can be loaded into selected network elements for each level of the hierarchical fault management process.

3.3. Active Network Striping for Software Scalable Bandwidth

One of the major challenges to the vision of Active Network technology and virtual infrastructures is providing compelling examples of the usefulness of the on-they-fly programmable infrastructure. *SwitchWare* provides the opportunity for *software scalable bandwidth* to be derived from the virtual infrastructure. Variations on the same technique can address delay jitter (by resynching typed packets with *SwitchWare*) and reliability.

Two interconnected *SwitchWare* switches and attached host computers are shown in **Figure 1**.

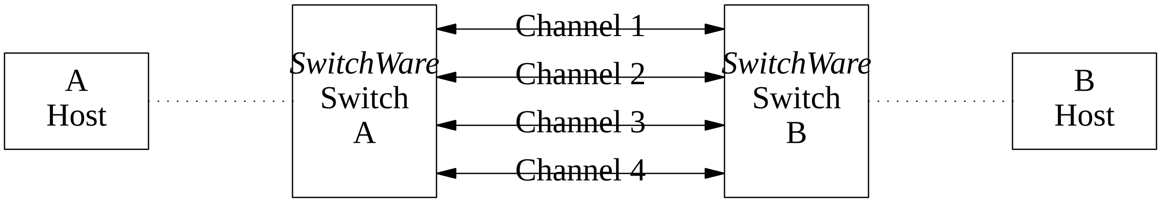


Figure 1: Interconnected *SwitchWare* Switches

While adding striping *hardware* to all switches in a network is unlikely to be cost-effective [39, 40], the *SwitchWare* infrastructure can be programmed to provide striped services. A software-implemented solution would stripe most effectively by using multiple interfaces to send multiple concurrent packets. Thus, simple pseudocode of a *Switchlet* for sender striping (asynchronous `Send()`), would be:

```
When Arrives(Packet,InPort)
{
      Send((SequenceNumber,Packet),OutPort);
      OutPort := (OutPort + 1) Mod Channels;
}
```

and the receiver would execute:

```
When Arrives((SequenceNumber,Packet),InPort)
{
      If (InOrder(SequenceNumber,Expected))
      {
            Send(Packet,OutPort);
            Expected := Expected +1;
      }
      else
            Queue((SequenceNumber,Packet),QueueName);

      if(CheckQueue(QueueName,Expected))
      {
            DeQueue((Expected,Packet));
            Send(Packet,OutPort);
            Expected := Expected + 1;
      }
}
```

The key observation to make about packet striping is that it offers the possibility of multiplying the throughput available between processors in proportion to the number of stripes.

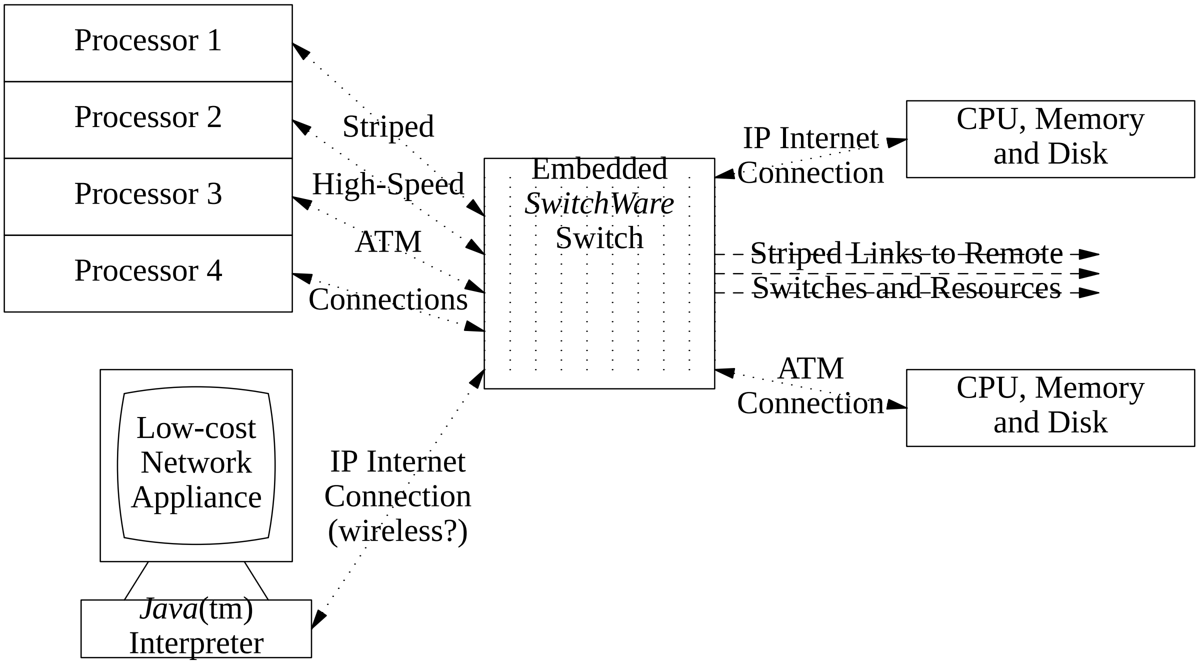


Figure 2: An embedded *SwitchWare* switch

This multiplication can be accomplished with no change in the hardware; rather, assuming that the interfaces are attached to processors able to support their memory bandwidth demands, the focus is on algorithms for deciding which interface(s) to use, and when to stripe, versus simply using a single connection. **Figure 2** illustrates striping in an embedded switch.

3.4. Other applications

Another application of the multiple channel approach is for reliability. Consider the two interconnected *SwitchWare* switches shown in **Figure 1**. If three channels worth of capacity are required, we can implement the striping algorithm on the three channels, and utilize the fourth as an error/loss correction channel, as in RAID systems [16]. So, for example, we could (using *SwitchWare*'s capacity for processing), for each three packets sent on the three stripes, compute a fourth packet consisting of the Exclusive-OR of the three packets comprising the stripe. Then, if any 3 of the four packets arrive in time, the data can be recovered and forwarded.

Such modules can carry out many tasks. For example, consider the sensor fusion required to detect an automobile on the other side of a bend; a CCD camera, IR camera (at night) or other sensor could be feeding a broadcast network. An application injected into the network by your automobile could run a motion detection algorithm on the real-time video feed and signal a monitor in the automobile with an approach speed indication or warning tone. An actuator for a rear window defroster in a car-area network might fuse information from a smart thermometer with light diffusion measures to automatically turn on; directional remote motion detection could dim the high beams, etc. Another example is personal multicast topologies; it is easy to write a small program which moves itself from *SwitchWare* switch to switch [33], replicating itself selectively to output ports to create a per-packet multicast.

Still more applications include:

- Speech coding conversion for interoperation of national telecommunications infrastructures; this would be accomplished with *SwitchWare* libraries or DSPs if higher performance is needed.

- Self-adaptation of packets to network dynamics such as failure and congestion, as they could carry algorithmic code specifying appropriate responses to failures.
- Subnet-specific compression, as bandwidth and latency characteristics dictate how much effort should be spent compressing.
- Data type-specific routing and stream synchronization. As an example video frames might choose a higher bandwidth link with a greater loss rate, while motion control streams for interactive telerobotics [2] would select a path with low bandwidth but high reliability and low delay jitter.

4. Security and *SwitchWare*

Security of information means that the right information gets to the right people at the right place at the right time, meaning that security failures occur when these conditions are not met, i.e., wrong people, wrong place, wrong information, wrong time. Security failures can include unauthorized viewing of information, denial of service [27], and insertion of false information. These sorts of failures [6] will become more common unless security is *designed* into a system.

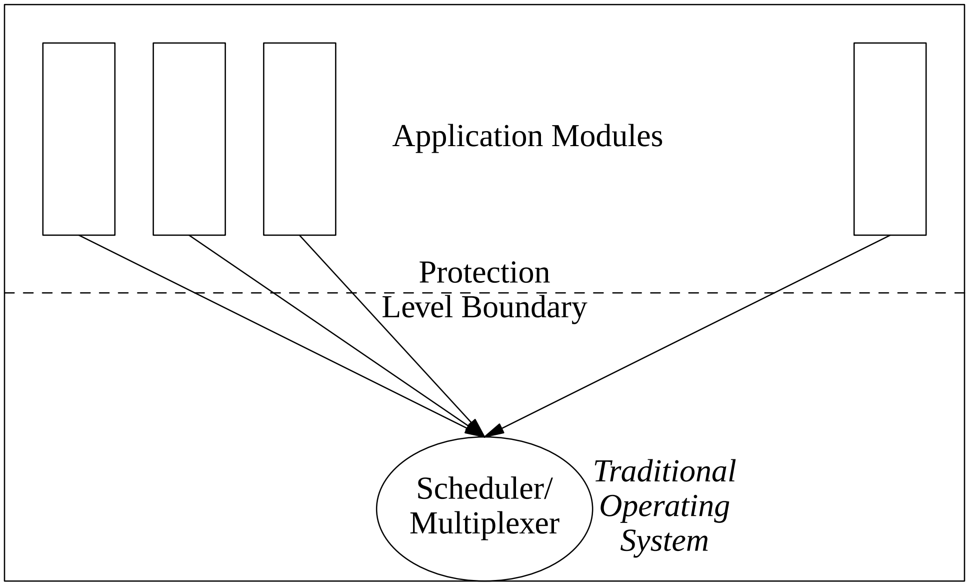


Figure 3: A multi-application’s elements share a processor

While cryptography provides potential end-to-end privacy, it has no effect on denial-of-service attacks, which can prevent correct and timely delivery of important information; such attacks must be precluded. Consider for example the difficulty of preventing traffic analysis when packet switching is used. Typically, messages or packets must have headers in the clear, even if the data portion is protected by a cryptographic privacy transformation. It is easy to imagine a sequence of packets where the first packet contains a program capable of obtaining a key from a trusted authority, used by the *SwitchWare* to decode the headers of subsequent packets in the train.

Active networks offer the network users a powerful tool for improving network performance and flexibility. However, the powerful capabilities of the system provide powerful tools to malicious intruders. Consequently, network security and authentication become correspondingly more important. Network elements must assure that any code they execute was produced by an authorized source. Also, any fault detection and management systems must be able to verify the validity of any network monitoring data that are received from network elements.

Although security and authentication mechanisms are being proposed in many networking forums, active networking may allow us to design a single integrated security mechanism for *all* network resources. This eliminates the need for multiple security/authentication systems that operate independently at each communication protocol layer. It would also allow us to address the traditional need for separation of the transport and management planes, which have been separate for reasons of security, performance and modularity. The difficulty is the resource management. Any switching system, no matter how simple or complex, represents a *multi-application*, consisting of a number of tasks, which may be concurrent or provided with the illusion of being so via time-division multiplexing of a shared element. **Figure 3** illustrates a multiapplication mapped onto a single shared processor.

The dashed line of **Figure 3** illustrates a crucial design decision; to control multiplexing of the machine resources, e.g., to associate code activations with interrupts, to operate on network adapters and persistent state resident on secondary storage, an *operating system* is used to create a resource protection boundary between applications, which have access to a ‘‘virtual machine’’, and the multiplexing mechanism, which has access to all system resources and provides the virtual machine.

4.1. Access Control by O.S. or Compiler? — Multiplexing Implications

Unfortunately, this multiplexing architecture has severe performance limitations, in particular for the boundary crossing operation between the application and the operating system (the ‘‘kernel’’). Multiplexing performance is crucial in switching. A great deal of recent research has tried to alleviate these costs while preserving the protection semantics of the operating system [9, 10]. To obtain an order of magnitude estimate of the penalty for this boundary crossing, we compared system calls with an ideal scheduling method, i.e., co-routine scheduling. The method used was the facilities `setjmp()` and `longjmp()` provided by the C library. They provide the ability to achieve a non-local goto, that is, one which crosses routine boundaries. `setjmp()` saves the current "state" of the program (i.e., a minimal set of registers, floating registers, frame pointers, etc) into a `jmp_buf` structure (described in `/usr/include/setjmp.h`) and `longjmp()`, given a `jmp_buf`, restores the specified state, including the program counter.

On an SGI Challenge L, when the program is run on a 3,334,216 octet file (`/unix`), it requires 2.43 seconds of execution time; a version of the program which merely reads and writes takes 0.69 seconds. Counting two context switches per character, we get (2*3334216)/(2.43-0.69) or 3,832,432 contexts per second, or 260 nanoseconds per context switch. Measurements of a microbenchmark which reads 0 bytes from `/dev/null` repeatedly show that each `read()` requires 17 microseconds, with 14.7 microseconds consumed by the operating system. This suggests that we can context-switch between threads *at least 60 times faster* if we get the programming language model right, and further optimizations should be able to reduce costs to approximately a procedure call.

Allowing the user to program and extend the basic network fabric provides great flexibility and power, but as with any power tool it also creates a safety hazard. It is possible (likely) that programs down-loaded into a switch or router, could interfere with, corrupt, or subvert the traffic of other users. Thus a key question in the design of *SwitchWare* is how this power can be provided safely.

4.2. Systems Security and Programming Environments

Familiarity with the Internet Worm [34] or recent security problems [8] found in systems such as Netscape's Web browser and the Java [21] highlight the importance of security in distributed computing. Although these problems manifested themselves as security breaches, many of them were a result of the lack of safety features in the programming language, notably C. Languages like SML and Java avoid these problems by supporting *pointer safety*. In pointer safe languages, pointers *cannot* point to invalid locations in memory, thus avoiding "core dumps" and array overruns. The key features needed for pointer safety are strong (though not necessarily static) type checking, array bounds checking and automatic storage management or *garbage collection*.

4.3. Formal Semantics of Programming Languages

‘‘Formal Methods’’ is a rubric used to refer to a collection of techniques which seek to apply ideas from formal mathematical logic to computational problems arising from hardware or software. Such techniques have been an active area of investigation for at least two decades. Although not a panacea, the techniques do have the potential of being quite useful, especially in areas of program specification, hardware verification, and language design.

In the area of language design, research in *programming language theory* has developed a collection of tools appropriate to the mathematical specification of programming languages. The value of such a specification is that it makes properties of the language, the programs written in it, and its compilers amenable to rigorous or (in limited cases) automated proof. Formal treatments have been provided for most widely-used languages. For instance: DoD commissioned the completion of such a semantics for a substantial portion of its Ada language while, more recently, C++ and other object-oriented languages have been the subject of focused attention.

It has been less common for a programming language to be *developed* in the context of considerations from programming language theory—language designs are usually more influenced by programming and compilation issues. However, accounting for theoretical considerations as part of a design has significant advantages if ensuring certain properties of (programs written in) the language is of paramount concern. In particular, this is the case when there is a strong need to guarantee various safety or security constraints. As a motivating example, the programming language Standard ML (SML) is descended from a Meta-Language (ML) used to guide a goal-directed theorem-proving system [12]. The standard [22] was completed in 1987 and is described via a set of mathematical rules. Since the soundness of the language as a theorem-proving vehicle was a paramount early concern, the semantics of the language was constructed with great rigor and attention to detail. Consequently, it is one of the most rigorously designed languages being used in significant programming projects. It has, for instance, been of interest to DARPA, which has funded research on its potential use in systems and network programming [14].

We would like to apply techniques similar to the ones used to design and specify SML to similar goals for the *SwitchWare* language. This will make it possible to apply a collection of techniques developed by the programming language theory community to the language. In particular, it will be possible to formulate and prove various safety and security properties based on the language definition. This will ensure that programs written in the language and evaluated with a correct interpreter will respect such properties. Proofs of this kind cannot be viewed as a ‘silver bullet’—they will be limited in scope and difficult if the *SwitchWare* language is large—but researchers have had success with the development of appropriate mathematical techniques and marshalling of automated tools to attack such problems for various languages. In particular, work at Penn under the supervision of Carl Gunter has had significant success with SML, which should form a solid starting-point for work on the *SwitchWare* language, which will be implemented as part of the experimental effort in this project.

4.4. Authenticated Type-checked modules

When we apply mathematical methods to the context of a highly-available distributed switching fabric, which depends on type-checking, we must face the challenge of making the formal guarantees in the face of threats in the network [26]. Several authors have addressed the need for secure object storage [11] in such an environment, and new cryptographic technologies [7] for digital signatures are applicable to this environment; in particular a type-checked module can be stored in a machine-independent form, which is then either signed directly or supported by a secure hashing algorithm. New technologies are becoming available for message-hashing, such as MD5, which can be very helpful in distributed type-checking. A trusted authority is referenced as part of loading a new module into the system. This work can easily build on existing work for distributing loadable modules [17]. A rogue loadable module can be looked at as a particularly harmful form of virus, one introduced directly into the network infrastructure, so we can draw on the considerable work [31] focused on this topic.

5. Concurrency and garbage collection

Garbage collection is crucial because it avoids the possibility that storage will be returned to the memory allocator while it is still in use. Using garbage collection also avoids the possibility that unused storage will not be returned to the allocator, avoiding the problem of "memory leaks". Even slow leaks can cause long-lived servers to crash and they also cause systems to use resources unnecessarily.

Users of `emacs` know that garbage collectors typically stop the client program while reclaiming storage, creating a *garbage collection pause*. These pauses can be of arbitrary length and several second pauses are not uncommon. While annoying to the users of interactive programs, they can be catastrophic to real-time control programs. Consider, for example, a computer-augmented jet fighter occasionally losing control for a few seconds at Mach 2! And yet, such applications are also ones in which freedom from crashes related to pointer errors is highly desirable. The basic technique for eliminating pauses is to allow the collector to run concurrently with the client, as discussed next.

Threads are provided in Java, thus providing low-level support for parallelism; it seems likely that this will be one of the low-level mechanisms used by parallel applications. Unfortunately, the degree of concurrency offered by such an implementation is limited by the need to garbage collect the store sequentially. Nettles, *et al.*, have developed a new concurrent GC technique, *replicating collection* [29]. Based on ideas from distributed systems, replicating collection is a simple and and elegant solution to the difficult problem of making copying collection concurrent. It has been implemented in the runtime of SML/NJ on both DEC uniprocessors running Mach and on SGI multiprocessors using IRIX. The results of the implementation show that GC can make good advantage of parallel machines, thus eliminating the concurrency bottleneck caused by garbage collection. More importantly, the results show that replicating collection is very successful at eliminating the long pauses often associated with garbage collection. These pauses are a substantial reason for high-level languages not being used for performance critical applications. [28] These techniques are applicable to other garbage-collected languages like Java and should greatly improve the performance of garbage-collected languages, and allow significant speedups on multiprocessors.

6. Run-time support for the Bellcore Programmable Output Port Controller — OPCv2

Switches require buffers to handle the case in which multiple input packets are destined for single output port simultaneously. If we desire a switch that provides Quality of Service, then a scheduling mechanism determines the order in which packets are processed by the output port. Although many different scheduling algorithms are possible, a single programmable packet scheduler can be built that is capable of implementing a variety of algorithms. Any packet scheduling algorithm can be split into two parts. The first part of the algorithm is the computation of a label for each packet. The second part of the algorithm is the sorting of packets based on their label to establish their transmission order. By allowing programmability of the label generation algorithm, the QoS mechanism of the switch can be changed easily to implement various packet scheduling policies.

Bellcore has already built such a device into the output port controller of the Sunshine ATM switch [20]. An Intel 80960 processor is used to compute packet labels for each cell, and a custom VLSI sorting chip is used to order the cells by packet label for transmission. The existing Bellcore design can be used to determine the primitive operations necessary to allow specification of a packet scheduling algorithm. The existing packet scheduler also could be used as a stepping-stone to a more sophisticated design.

7. Other research in this area

Borenstein's ATOMICMAIL [5] system used LISP functions embedded in electronic mail messages, to support overlay functions such as automatically generated mailing lists and software distribution via e-mail. Considerable value stemmed from combining message transport with programs applied to interpreting the messages, especially for widely heterogeneous user environments.

The SOFTNET [41] system was a packet radio network where packets of multithreaded M-FORTH code were interpreted by network elements consisting of two-processor nodes; one serviced network events, and the other ran user programs. The nodes were supported by a small operating system, which protected the network elements, e.g., to prevent buggy programs from destroying the packet-switching fabric. The focus was proof-of-concept rather than a wholesale change in network infrastructure, models and run-time support.

Erlang [1] is a concurrent functional programming language for large industrial real-time systems, providing transparent cross-platform distribution, primitives for detecting run-time errors, real-time GC, and dynamic code replacement. Erlang has been deployed in switches built by Ericsson. It does not provide the strong static type checking we propose in our approach.

A previous Bellcore project, the Touring Machine, is a distributed multimedia communication system which supported 150 users in both point-to-point communications and broadcast meetings and lectures. The architecture has many similarities to an active network. Network elements, such as the end nodes, switches, and audio/video bridges, all have associated processors. All communication functions, such as connection setup/tear-down, were performed by sending blocks of executable LISP code to various processor platforms in the network. There was no formal model and no abstraction useful for security and interoperability validation developed.

We intend to work with other researchers on Active Networks, contribute software and methods, utilize research prototypes, and to host nodes for experimental efforts, which may communicate over existing transmission facilities (such as the Internet). *Table I* relates our research activities and Tennenhouse's [37] proposed framework.

Activity	Enabling Tech.	Platform Develop.	Pgm’ing Models	Middleware Svcs./Apps.	Active Ctls./Algs.	Netw. Ops.
1.Formal Model		***	*		*	***
2.Runtime Env.		**	**	**		
3.Router				**	**	**
4.Security		*	**	**	***	**
5.OPCv2	***				**	

Table I: SwitchWare Contributions to overall effort, *s for relative importance

We have had informal discussions with other research groups interested in *Active Networks* and are aware of their work and contributions. We will borrow technology as appropriate in an attempt to produce an integrated effort in Active Network research.

The SPIN [3] Project is an effort to build extensible operating systems kernels, with the idea that type-safe Modula-3 code could be loaded into an operating system for reasons of performance or access to resources. This work reinforces our belief that type-safe modern programming languages are a fertile ground for systems programming in even the most performance-sensitive environment. While it is unlikely we can directly employ any of the code produced by the SPIN Project in our efforts, we expect that interactions with like-minded researchers will be valuable. The setting of a switch infrastructure has different challenges, including the need for resource partitioning algorithms, distributed loading of type-checked modules, security and a high degree of multiplexing/ parallel processing, that are less pressing for workstations.

The Scout Project [24] at the University of Arizona uses an algorithm, pathfinding, to optimize the paths through protocol executions in a realization. This is a valuable technology that could be employed in the building of *SwitchWare*, but does not directly address the algorithmic, security and management issues we face in the design of an on-the-fly upgradable network infrastructure. We believe that while Scout itself may be able to operate across many environments, it is providing a level of abstraction that is too low to gain the interoperability advantages of our extensions to SML/NJ.

The Exokernel [10] project at MIT has been focusing on an operating system restructuring, where much of the operating system functionality is carried out in libraries. There is still, for security, a need for a small kernel. We believe, as we discussed in **Section 4**, that the protection kernel approach has some fundamental performance limitations, especially as regards the high degree of multiplexing found in a network switch. We believe that as the Exokernel architects attempt to re-virtualize the O.S. functions, for example by providing multiplexing of an adapter with a processor embedded in the adapter, that they will run into problems either with the level of abstraction (and therefore interoperability) or with performance barriers that are unavoidable on today’s hardware. What it seems likely they will contribute is a great deal of knowledge on how to craft systems which provide dedicated application access to adaptors, a model which the *SwitchWare* run-time may employ.

The FOX Project at CMU [14] is likely to be an essential supplier of technology. To somewhat oversimply, the research group at CMU has been focused on evangelizing SML to the systems community, and they have been doing this by focusing on interesting problems such as writing a TCP/IP in Standard ML [4]. We look at the CMU work as providing tools. Their implementation ideas for compilers [36] and run-time environments [18] can be viewed as aids and assists to providing a high-performance implementation of our *SwitchWare* language system; in essence, our SML/NJ extensions for *SwitchWare* ride the compiler technology curve as well. Our run-time research compliments their research, and our setting, a high-performance switch as part of an active network infrastructure, draws on the demonstrated strengths of our team and its organizations. Our focus in programming language semantics allows us to attack the theoretical problems in a restricted context, that of an Active Network Switch, that increases our chances of success.

Turner’s group [30] at Washington University propose an approach of interconnectin powerful general purpose processors with an ATM switching system. Thus, the hardware has the ability, in principle, to execute *SwitchWare*-like software. They make two important assumptions which we believe are unproven, and which the *SwitchWare* architecture is not fundamentally subject to. First, they believe that by detecting opportunities to set up ATM circuits, they can avoid most per-packet processing once a ‘‘flow’’ is detected through their system. This means that software participation in packet processing is an exception rather than the rule. *SwitchWare* technology attempts to make packet processing fast enough that *all* packets could be processed; hardware assists are assists and not essential. Second, they presume that a stripped-down UNIX operating system can in fact process the ‘‘non-flowed’’ packets fast enough to provide gigabit range performance. Based on our measurements of UNIX context-switching performance on extremely fast processors, we believe that this approach is wrong. The protection overhead of a conventional operating system architecture is too large to sustain high degrees of IP multiplexing, and is likely to induce considerable jitter. Additionally, we believe that the security of this approach (both for access control and resource denial, such as bandwidth starvation) is dependent on the security of UNIX rather than provable statements about security enforced at compile time, as in our approach. If you can do it once in the compiler, why do it repeatedly at run time?

8. Plan of Work

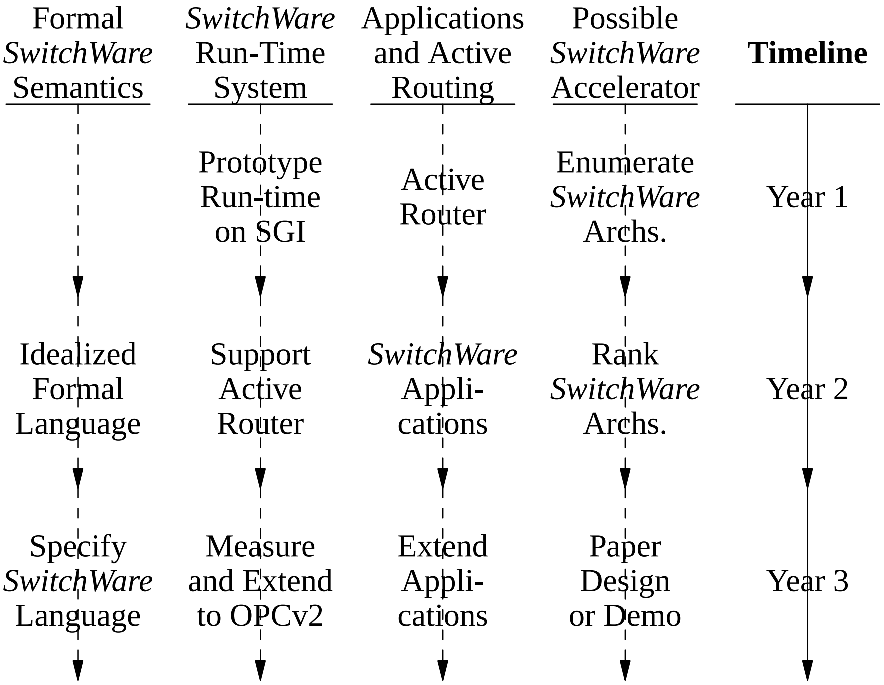
Project tracking is shown in **Figure 4**. Our networking priorities are, in order, *(1)* flexibility, *(2)* robustness, *(3)* security, *(4)* link performance and *(5)* processor performance. Our approach addresses the first four, to the detriment of the fifth.

Although *SwitchWare* will depend critically on formal and mathematical techniques, we plan to pursue an experimental approach for the project as a whole. The programming language implementation challenge in *SwitchWare* will be providing good performance for SML when it is used as a systems programming language. A recent implementation of SML, the TIL compiler at CMU by Morrisett and Tarditi [36], strongly suggests that SML implementations with performance similar to C are feasible.

8.1. Experimental Methodology - Highlights

A first-order experiment will be performed by attaching a number of network adaptors (perhaps several ATM adaptors, and one or more varieties of Ethernet) to a small scale shared-memory multiprocessor. The processors would then act simultaneously as port controllers and execution engines for the language. The loadable language modules would be transported between *SwitchWare* switches, forming trains of active packets, which we call *Switchlets*. To preserve the power of the semantic model, type-checked modules are digitally checksummed with a Secure Hash Algorithm provided by a trusted authority. This takes advantage of the fact that it is easier to verify the proof than to do the proof.

This approach provides the concurrent execution model necessary in any realistic switching environment, while providing an attractive environment in which to develop software and algorithms. This would provide initial insights into the programming model, and demonstrate that packet interpretation can be usefully applied. The same environment will be used for SML runtime system and active router experiments. Additional experience will be gained from the Bellcore Programmable Output Port Controller — OPCv2.



Formal *SwitchWare* Semantics	*SwitchWare* Run-Time System	Applications and Active Routing	Possible *SwitchWare* Accelerator	**Timeline**
	Prototype Run-time on SGI	Active Router	Enumerate *SwitchWare* Archs.	Year 1
Idealized Formal Language	Support Active Router	*SwitchWare* Appli-cations	Rank *SwitchWare* Archs.	Year 2
Specify *SwitchWare* Language	Measure and Extend to OPCv2	Extend Appli-cations	Paper Design or Demo	Year 3

Figure 4: Project Tracks and Timeline

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