Abstract

The stack in various forms has been widely used as an architectural template for networking systems. Recently the stack has been subject to criticism for a lack of flexibility. However, when it comes right down to it nobody has offered a truly compelling alternative. Various "cross-layer" optimizations have been proposed, but these optimizations are frequently hacks to achieve a particular goal and offer no direct insight into why the existing network stack is inadequate. We propose that a fundamental problem with the existing network stack is that it attempts to layer functionality that is not well-suited to layering. In this work we use a "bottom up" model of information computation, storage, and transfer and the "top down" goals of networking systems to formulate a modular decomposition of networking systems. Based on this modular decomposition we propose a semantic layered structure for networking systems that eliminates many awkward cross-layer interactions that arise in the canonical layered stack.

1 Introduction

As a starting point we will define what exactly networking and storage systems do. Stated simply, the goal of networking and storage is to move symbolic information to specified places and times without altering the meaning of that symbolic information, subject to some set of constraints on resources and operational parameters. In any real system moving a symbol entails moving the embodiment of that symbol. When a symbol is not embodied in a form suited for travel the symbol must first be transferred to some embodiment that is suited for travel, moved, and then transferred into whatever embodiment is required at the destination. We will explore what makes for a "suitable" embodiment for information in Section 2. Constraints may apply to concrete physical resources, e.g. energy and raw materials, subjective and abstract resources, e.g. social standing and opportunities when interacting with other entities, as well as on actions, e.g. a wireless system may only be allowed to operate on particular
frequencies at particular times. We will explore goals, actions, resources, and constraints in greater detail in Section 3. In Section 4 we will further break down the task of moving information in space and time into multiple sub-tasks, defining the functions that networking and storage systems must perform.

2 Networking, Storage, and Computation

In this section we will broadly categorize networking, storage, and computation. This categorization is based on fundamental tenets of modern physics, and was constructed under the influence of work by Feynman, Zuse, and Fredkin regarding fundamental notions of computation and physics. We do not claim that this is a novel categorization, and this work is not primarily about computation and storage. However, we feel that networking, storage, and computation are all fundamentally related tasks, and that having a firm notion of all three is critical for contextualizing and understanding networking. In the universe as we understand it computationally useful symbolic information must reside within some physical embodiment. This embodiment may be a wide range of things, e.g. DNA and RNA within cells, electrical potential, or a quantum superposition of spin states. Figure 1 shows diagrams of how symbols for analog, quantum, and digital computation system are formed from embodiments. In the digital system, glyphs are measured to create analog symbols, which are then further processed to generate digital symbols, and then mapped into bit symbol strings of machine word size. These machine words may be further mapped into operators of a microprocessor instruction set, Unicode characters of human language, or any number of other symbolic domains. The interpretation and semantics of symbols has been formally studied as denotational semantics, and semantics are central to computation, networking, and storage systems.

Of course, not all embodiments are alike, and some embodiments may be more suited to some purposes than others. We will broadly categorize “purposes” into three categories: networking, computation, and storage. Compu-
tion generally requires a low amount of travel in time and space, but an ability to rapidly change state when desired. Networking and storage must both be stable and able to survive over whatever lengths of time and space are required. Choosing an embodiment for networking, storage, or computation is fundamentally motivated by physical system characteristics. From a general system architecture design standpoint we propose four critical physical properties: stability, i.e. the difficulty/energy required to change a state, malleability, i.e. how quickly it may be changed, longevity, i.e. how easily it may be moved through time, and mobility, i.e. how easily it may be moved through space. These properties are illustrated in Figure 2. Expressing these properties quantitatively relies on an ability to handle physical space, time, and energy. Because networking and storage systems strive to preserve symbolic state we are also interested in distortion, i.e. unintended changes in physical and/or symbolic state, and fragmentation when symbols do not fit into a single embodiment. When treating an embodiment as a measured time-varying signal the bit may be used to quantify and analyze distortion as well as the natural size of an underlying symbol embodiment. The bit may also be used in conjunction with coding theory to design translation schemes that may be used to stave off symbol distortion. Unfortunately the term “bit” is overloaded: a “bit” not only refers to a specific way of converting a noisy signal into discrete symbols, but also the use of binary digits as a universal symbolic alphabet. When working with physically discretized systems it is convenient to use symbolic bits to represent states, but this is separate from performing bit-style signal filtering and discretizing.

3 Goals, Actions, Resources, and Constraints

Any practical system will have specific actions that it may take as part of its operation, resources that are required to take action, constraints placed on actions
and resources, and some fundamental set of goals that it should accomplish. In this section we will describe goals, resources, and constraints of networking systems in the context of both physical and symbolic computation (we will discuss actions later as part of our functional modularization of networking systems). In addition, we will also examine goals, resources, and constraints for communication systems in the human domain. The human domain is concerned with how humans build, operate, and use computational systems. Such a perspective is vital for building systems that are to be adopted by human society at large, and we will use this perspective as one of two top down perspectives. Our second top down perspective is a generic symbolic view of computation and communication. Our bottom up perspective is a physical view of computation and communication. The human and symbolic domains are connected through the physical world via human computer interaction (HCI) devices and applications, and different symbolic computation domains are connected through the physical world via networking devices and applications. In this work we will ignore specific details of HCI devices and applications, but still attempt to take the general demands of human users into account when determining what features a symbolic networking system should have.

We will broadly categorize goals, resources, and constraints into two major areas: physical and social. Physical elements include computation, but are more fundamentally concerned with the physical world, e.g. energy, space, time, and raw materials. Social elements are those which arise from interactions between multiple autonomous entities, and not obviously derived from physical or chemical first principles. Artificial social interactions may often be analyzed mathematically, e.g. carrier sense multiple-access systems[7]. Biological social systems are not generally amenable to precise quantification, though economists have made extensive efforts to create mathematical models capturing aspects of human commerce with varying degrees of success. Social and physical goals are often intertwined and interdependent. For example, people may cooperate socially in order to hunt, gather, and farm food (energy) more effectively, and conversely individuals may strive to hunt, gather, and farm more effectively in order to increase social standing. We will not engage in an extended discussion about the precise distinction between social and physical aspects of systems, but we will emphasize that social aspects will arise and have to be addressed in networking systems.

3.1 Goals

The physical goals of a networking system within the human domain generally concentrate on delivering media to some set of people (or other creatures capable of communication) with some specified acceptable amount of distortion and error within some specified amount of time. These physical goals are often driven by underlying social goals. For example, the social goals of security and privacy may dictate that some set of entities be unable to intercept and/or interpret the information during transit, potentially placing physical constraints on operation. For symbolic computation, the physical goal of a networking
system is to deliver specified sets of symbols to locations where further computation, storage, or transfer of those symbols may occur. Physical computation is tasked with moving some collection of physical embodiments to some specified locations in space and time with some limit on the allowed distortion of those embodiments.

Social goals for symbolic and physical computation are built into a system by its designers, and often reflect the social goals of the designers, users, and builders in the human domain. Fairness is used as a metric for evaluating network protocols, and Dynamic Spectrum Access (DSA) techniques usually strive to be “good neighbors” by only utilizing unoccupied radio frequencies and obeying usage laws laid out by governmental agencies. The current debate over “network neutrality” and traffic shaping further illustrates how human social factors figure into protocol design.

3.2 Actions

The specific actions that a system may take vary depending on the system. In this section we will identify the broad actions that communication systems may take. Two key actions taken on information are to transmit information over some region of space and time, and to receive information from some region of space and time. Coordinating the transmit and receive operations such that they overlap in space, time, and physical embodiment is central to communication path establishment, or linking. Linking does not always operate directly on information, e.g. autonomous robotic systems may move in order to enhance communication or alter their configuration to facilitate communication, e.g. reconfigurable directional antennas. Advanced automated systems could even construct their own physical infrastructure for communication, e.g. deploying wire or fiber for fixed infrastructure, or even microscopic filaments for nanobots. Translation of information into another form, e.g. coding for distortion resistance and spatial/temporal footprint and buffering packets for flow control are information-centric actions that may be used for linking. Further information computation and storage operations are copying and erasing. Copying information may be very time and energy intensive in conventional systems, and expressly forbidden for quantum information. For reversible systems the act of erasing information is of fundamental significance, and may be expensive in conventional systems. We will discuss further details of these actions when we engage in a more detailed exploration of networking system architectural details.

3.3 Physical Resources and Constraints

Physical resources and constraints are, essentially, about time, space, energy, and entropy. As might be expected, physical computation is directly aware of physical constraints on space, time, and energy. The human domain must also account for physical space, time, and energy. Humans, in general, care
about where and when computation occurs, and may have to manage limited energy resources. Symbolic computation may subsume some physical constraints into more abstract constraints on network, storage, and computational capacity, though physically situated symbolic applications, such as sensor networks and autonomous robotic systems, may have extensive and detailed models of the physical environment. Furthermore, the symbolic computation domain should have some notion of space, time, and energy if it is to interact naturally with the human domain. Most conventional networking systems have striven to abstract away physical time and space through logical clocks and virtual coordinate systems. Such abstraction is useful in that it reduces reliance on clock synchronization and location knowledge. However, the complete removal of physical time, space, and energy constraints can make it awkward to connect the symbolic computation domain with both the physical computation domain and the human domain.

3.4 Social Resources and Constraints

Social constraints exist when multiple entities interact. In the realm of physical computation, MAC layers use various social strategies (protocols) to control access to shared communication media, such as carrier sense (transmit only after you can’t hear someone else transmitting), and dividing up a channel into frequency or time slices (frequency/time division multiple access). Traffic shaping, firewalls, and inter-AS forwarding are all examples of social strategies for symbolic computation systems. Social strategies for automated physical and symbolic systems are generally set within the context of some mathematical analysis of a system model, e.g. CSMA for wireless systems. The influence of the human domain is imprinted on the social structures of physical and symbolic computation systems. Protocol design usually involves extensive committee work, issues of “fairness” arise when designing new or modifying previously-deployed access schemes for networks, and game theory is periodically applied in attempts to design socially sustainable automated interacting systems. Furthermore, human laws may directly influence physical and symbolic systems directly, e.g. dynamic spectrum access systems that comply with government regulations on RF spectrum usage. Social resources and constraints within the human domain manifest directly within applications. The use of e-mail, Usenet, chat, peer-to-peer file distribution services, and social networking services all have developed social protocols. Spam is a primary example of what happens when voluntary social constraints are ignored, resulting in surrounding neighbors instituting other social constraints (blacklisting, filtering, etc.) as mitigating measures.

4 Network Functionality

Given the goals, constraints, and resources that we have enumerated for networking systems, how can we best partition functionality out into modules? In
Section 2 we identified three functions that arise from considering the physical embodiment used for symbols:  
fragmentation, distortion control, and symbol translation. Another core task is identification, i.e. naming and addressing. Networking systems need to have some way of identifying and locating symbols and endpoints if they are to manage the motion of symbols and endpoints. We will also break down the motion of symbols and endpoints into separate tasks: topology control for managing endpoints and symbol paths between endpoints and flow control for the managing the motion of symbols. The final function we will identify is multiplexing, i.e. allowing multiple clients to share a single underlying service, which has been empirically identified as useful for networking systems[13]. Naturally, this is not the only possible decomposition of networking into functions, though it is generally similar to other decompositions[13, 14] in many important respects. All of these functions may interact with each other, potentially in arbitrarily complex ways. A good architecture can help mitigate this complexity by making some core decisions about interactions in a way that balances abstraction, transparency, flexibility, and efficiency in a useful way. Of course, this task is much easier said than done, and has been a topic of practical and academic study for many years. In this section we will explore each of the seven functions we have identified as well as how those functions interact with each other and the constraints placed upon them.

4.1 Identification: Naming and Addressing

Earlier work[15] has stressed the fundamental nature of names, addresses, and routes. Before we define names and addresses we will first examine the broader problem of identification. Deep philosophical discussions aside, we propose that identification can be broadly split into two major components: location and appearance. Location is simple location in time and space, appearance is some set of observed properties of an entity. Appearance may involve aspects of location, but we will require that location-based elements of appearance be expressed within some local coordinate system of the entity being identified. For example, 3D polygonal models of objects are usually constructed in reference to some local object center and axes that may then be translated, rotated, and distorted as required to embed the model in larger scenes. Conversely, coordinate systems used for specifying location may rely on appearance to define critical points, e.g. the North and South Magnetic Poles of the Earth. Fortunately, human civilization has devised many useful coordinate systems, relieving most systems from the burden of deeming their own. With this in mind, we will not discuss the fundamental philosophical issues associated with defining coordinate systems, instead continuing on with practical aspects of identification. We will generically refer to an observed set of properties of an entity as a label. When a label specifies appearance we will call it a name and when a label specifies location we will call it an address. Identification is then achieved through some set of labels and/or constraints on labels.

Physical computation uses correspondingly physical names and addresses. For example, directional antenna systems use physical directions for addressing
and photon emission patterns for naming. The human domain utilizes both physical and symbolic schemes for naming and addressing, e.g. GPS coordinates and physical descriptions of size and color as well as names for abstract concepts, geographic regions, people, and other entities. Symbolic computation names and addresses can be very abstract as well. Existing network systems often take a very abstract “mathematical” view of naming and addressing. For example, DNS, IP, and Ethernet identifiers are static strings of symbols. IP addresses reflect network topology, and may be correlated only loosely and incidentally with geographic location. IP addresses are also widely used as names, causing quite a bit of extra complication when a network attachment point changes[10]. Such abstract symbolic systems may run into difficulty when attempting to mediate between the physical domain and the physically-oriented parts of the human domain. Attempting to eliminate physical considerations from the symbolic domain entirely can result in awkwardness when the human domain wants to utilize time and location information from the physical domain and vice versa.

An important question for any system is what kinds of entities require identification. For networking systems we will identify three major entity types: endpoints, information, and paths. The precise definitions of endpoint, information and path depend on the particular system in use and the level of abstraction at which the system operates. In the human domain, people are quite often the intended endpoints, generally interacting with some computational application as a proxy. Information may be any content used by humans (text, video, audio, still pictures, etc.), and paths typically consist of the people and places through which and to which the information flows. In the traditional “operating system” view of symbolic computation, applications are the endpoints, information resides within files, and paths are “symbol pipes” between applications with some (possibly time-varying) capacity and latency. For physical computation the endpoints may be any physical entities that interact with the information embodiment, information consists of some collection of physical embodiments, and paths are defined in terms of physical space and time as well as the physical entities (endpoints) that interact with the embodiments as they travel.

4.2 Topology Control

Topology Control tracks and manages endpoints and the paths between endpoints where information may travel. For physical computation topology management is tightly tied to the physical world: endpoints and paths are physically identified regions in time and space, though they may also have names associated with them that directly relate to physical properties. Controlling topology in this context means directly controlling aspects of the physical environment as well as coordinating control of the physical environment with other entities. Topology control in the human domain often explicitly involves physical time and space, but also has a significant component related to named entities. Paths are likely to be defined in terms of who can receive the information at what times as well as physically where the information goes at what times. Symbolic com-
putation has the option of ignoring space and time completely, *e.g.* viewing endpoints and paths as abstract graphs. However, as we briefly discussed in Section 4.1 it is generally sensible for the symbolic domain to maintain some models of physical time and location in order to mediate more effectively between the physical and human domains.

### 4.3 Flow Control

*Flow Control* moves and tracks information through time and space via the paths determined by Topology Control. As such, Flow Control is the “prime mover” of a networking system. Without Flow Control, Topology Control would not know where best its paths should go. Distortion Control and Fragmentation/Reassembly would have no moving information on which to operate. The primacy of Flow Control is obscured in many systems by the complexity of Topology Control. Many traditional routing systems attempt to preemptively discover and track all possible destinations and paths in a network, allowing Flow Control to select any destination within the network as desired. Furthermore, Flow Control is not usually given any choice of routes taken by an individual packet. Multihoming may be exploited to encourage multipath routing\[17\], but such schemes could clearly benefit from having a more direct and overt way to exploit multipath diversity. An important feature of our semantic stack is that it does not mandate *layering* as the primary modularization of Flow Control and Topology Control, as in a stack based on functional layers.

### 4.4 Distortion Control

*Distortion Control* ensures the integrity of information by controlling unwanted changes to information. For physical computation distortion is tied directly to physical attributes of embodiments, *e.g.* the frequency and polarization of a photon. As such it is important to characterize the physical environment (*i.e.* the channel) and its effect on the physical embodiment. For example, radio waves in a highly reflective environment often experience multipath distortion at the receiver. One way of mitigating multipath distortion at the physical level would be to embed symbols in the frequency of the photons and not the phase so that the symbols directly measured from the information embodiment experienced less distortion in the channel. Another option would be to encode the information in such a way that the low-level physical symbol distortions did not result in higher-level information symbol distortions, or even *exploit* the multipath reflections (as with MIMO systems). Such *channel coding* techniques are a fundamental part of information theory. Symbolic computation has a more abstract notion of distortion than physical computation. Physical distortion and its immediate effect on symbolic interpretation is not modelled in detail. Instead, distortion occurs as alterations to symbols or the loss of symbols entirely, *e.g.* bit errors and loss in binary symmetric channels and binary erasure channels.
Moving into the human domain the notion of distortion becomes even more abstract. For example, a sequence of numbers may be interpreted as a sequence of characters used in human languages, such as EBCDIC, ASCII, and Unicode. These strings may be further interpreted as words in human languages. In isolation it may not be clear which language is intended. For example, the word “die” on its own could be a word in German or English, meaning entirely different things to speakers of those languages. Even within a single language words and sentences may be semantically ambiguous and heavily context-dependent, e.g. “die” in English could be a polyhedral random number generator or a transition into death. Such abstract distortion is not traditionally tackled by networking systems (at least not above the relatively simple problem of bit order and the choice of little or big endian numeric encodings), though the semantic web and some content-based networking schemes\cite{15, 16} have attempted to address such issues.

4.5 Fragmentation and Reassembly

Fragmentation and reassembly arise whenever there is a mismatch in the desired size of information embodiment and the actual physical embodiments available. Application-Level Framing (ALF)\cite{13} refers to desired application information embodiments as an Application Data Units: network devices have corresponding Transportation Data Units. Matching ADUs and TDUs may require significant computation and storage resources and introduce additional jitter and latency.

4.6 Multiplexing

Multiplexing is resource sharing. Broadly speaking, resources may be shared in two ways: full access to resources on a part-time basis or full-time access to reduced resources. A realistic multiplexing scheme may employ either or both of these techniques depending on the nature of the available resources and the demands of multiplexed clients. When client demands exceed the available resources then clients will experience delays (jitter) or even complete outages. As a further complication, predicting the resource demands of even one application may be very difficult, let alone the cumulative demands of multiple non-cooperating applications, making it hard to give client applications any realistic guarantees on service. Multiplexing appears throughout communication systems. TDMA and CSMA schemes provide part-time access to communication channels, CDMA and OFDM provide full-time access to reduced communication channels. Circuit-based systems provide full-time access to a subset of available communication links, and packet-switched systems provide part-time access to potentially any communication link in a network. Multiplexing resources is where social constraints and resources manifest most obviously, though physical constraints and resources are clearly of great importance as well.
Figure 3: Interactions between basic network functions. Ovals are used to indicate functions, lines denote potential interactions, and a box indicates a logical grouping of modules. A line connected to a box implies potential interactions with ALL of the individual modules contained within the box.

4.7 Translation

Translation is required at semantic boundaries, i.e. where there is a change in the meaning of symbols as interpreted by some computational entity. One such example is the Shannon bit boundary: an analog signal is transformed into a stream of discrete symbols. A rarely-used example in the canonical network stack is the Presentation layer, though it could be argued that the semantic web functions as a Presentation layer writ large.

5 Network System Architecture

In Figure 3, we illustrate general interactions between the seven core network functions we have defined. For clarity we have grouped Flow Control, Distortion Control, and Fragmentation/Reassembly together into a single entity called Information Control. One of our primary architectural goals is to make and ex-
pose the easy decisions upfront in such a way that specific implementations may hide the details of the hard decisions from external clients [20, 21], hopefully resulting in cleaner and more extensible systems. Fortunately, Figure 3 offers at least two functions that stand out as potential “easy” targets: multiplexing and translation.

We can highlight the core nature of multiplexing and translation to network structure by artificially simplifying network requirements and functions until only the bare bones of a system remain. We will make no effort to explicitly identify anything, neither will we attempt to control or learn about the topology or flow of information. Our best effort guarantee for the sender will be that information will travel wherever it can in whatever embodiment is convenient, arriving at whomever might be listening with an arbitrary and unknown amount of distortion. Information may sometimes be fragmented, but never reassembled. At the receiver we will have a similar guarantee: whatever information arrives will be passed up to the application for processing as it arrives. Even this minimalist system would have to perform at least one task: translation of information between embodiments suitable for transport and embodiments suitable for computation. If we permit multiple applications and/or multiple communication links our minimalist system would also have to perform some multiplexing between those applications and links. We will continue by exploring Translation, Multiplexing, and the interaction between Topology and Information Control in greater detail.

6 Translation and Semantic Boundaries

Translation is more obviously layer-friendly than other network functionality. Information must be translated into a form that the application can understand before the application can utilize the information in a meaningful way, and conversely information from the application must be translated into a form suitable for transit before the information can be moved. In this section we will describe how semantic boundaries may be used to define semantic layers. The bottom semantic layer hides embodiment-specific details, providing generic symbol physical transportation services. The top semantic layer also hides embodiment-specific details, providing generic symbolic computation services where the semantics of the symbols are determined by individual applications. Strictly speaking, these two layers are sufficient for system construction. However, it has proven convenient to consolidate generic symbol transport services into a third network layer between computation and transportation layers. For storage systems one could imagine a similar stack, with a physical storage layer replacing the physical transportation layer and an intermediate repository layer replacing the network layer. A Delay-Tolerant Network (DTN) [22] system presents a combined network/repository layer, perhaps by aggregating separate network/transport and repository/storage layers underneath. Figure 4 shows our proposed semantic layer and sublayer boundaries and how these semantic layers line up with the layers of the OSI network stack. We will now describe
each of these semantic layers.

6.1 Physical Transportation Layer

The Physical Transportation layer directly manages the motion of symbol embodiments through space and time and the transfer of symbols to and from embodiments suitable for transport. The conversion between transport and computation embodiments is often (though not always) performed in two main stages. The Transducer sublayer transforms the transportation embodiment into a more computation-friendly embodiment (and vice-versa). This computation-friendly embodiment is then further processed by the Signal layer to transform it into the primary computation embodiment used by the Network layer. The Signal layer may itself use multiple computational embodiments as required. For example, radio communication systems typically use analog circuits for high-frequency signal processing tasks such as modulating and demodulating to and from a carrier, but often opt for more flexible digital systems for processing at baseband.

Practical Transducer and Signal layers may be very tightly tied together: a particular Signal layer entity may have to make assumptions about aspects of its attached Transducer that limit combinations. For example, the sampling rate used to produce a signal is tightly tied to the physical phenomenon measured or manipulated by a transducer: attempting to send a signal with a gigahertz of bandwidth through an acoustic transducer and channel may not produce the desired result. Different systems may have to have vastly different views of
the physical universe. Classical waves are sufficient to describe a great many communication systems. However, quantum mechanical models of the universe are required for quantum systems, and relativity for others. The physical model of the universe in use and the physical units of captured signals are important when determining how best to utilize communication channels. Different systems that must share a physical channel usually have some shared models of the channel in order to facilitate joint operation. This specialized physical knowledge enables the Physical layer to most effectively negotiate single or multihop paths through shared physical media. Most existing systems limit themselves to single hop paths to avoid duplicating the effort of multihop routing at multiple layers, but we will not apply a single hop limit at the Physical layer in our semantic stack. If the Physical layer must utilize detailed medium-specific knowledge to negotiate multihop paths, then the task it performs may be different than the task performed by multihop routing at higher abstraction layers and does not constitute duplicated effort. This constraint relaxation should not be taken as an advocacy of rampant and opaque multihop routing at the Physical layer. In our semantic stack the Physical layer is not in a position to directly know enough about global traffic demands to make detailed and autonomous decisions about multihop paths and routing. Such knowledge is concentrated at the Network layer, and a key job of the Physical layer is to present the Network layer with transportation options while attempting to meet the goals and constraints requested by the Network layer. We will discuss more details of the interactions between the Physical and Network layers when we discuss the Network layer in Section 6.3.

Concentrating physical concerns down in the Physical layer frees higher layers from knowledge of specific physical embodiments. However, there may be some cases where some knowledge of physical embodiments by higher layers is unavoidable or even desirable. For example, sensor/actuator applications are inherently physical in nature, operating “below the bit” as analog systems. Even purely digital systems may also have some coupling to physical embodiments. A radio communication application might want to know if a particular segment of a voice transmission was received on a designated emergency channel in order to alert the operator. Conversely, if the operator hears a vocal distress call the operator may want to clear usage of that channel for emergency traffic, requiring higher layer semantic information to be pushed back down into the Physical layer. This potential coupling of higher layer semantics to embodiment-specific characteristics is a primary place where cross-layer interactions may enter into our architecture, and we will discuss this issue in greater detail in Section 7.1.

6.2 Computation Layer

The central networking tasks for the Computation layer are to package application symbols into meaningful quanta (i.e. Application Data Units), and

---

1We include electromagnetic waves in the “classical” category, even though relativistic and quantum mechanical effects appear.
to negotiate constraints on distortion, delivery times and locations for those quanta with the Network layer. Feedback about available resources from the Network layer may result in changes to Application Data Unit packaging, e.g. a streaming video application might opt to use a lower quality but more compact encoding scheme if a high bitrate link is not available. We will discuss more details of interactions between the Computation and Network layers in the context of the Network layer in Section 6.3. Multiple applications may opt to consolidate and share information, and information about application information semantics may be exploited to shape the flow of information. Tracking all possible application symbol semantics is likely not feasible for a generic networking or storage system. However, splitting the Computation into two sublayers: the Application and Content layers can facilitate consolidation.

The Application sublayer is equivalent to the Application layer in common usage today. The Content sublayer may manage the flow of shared Application layer information through network and storage systems. The Content layer could be limited to simple tasks, e.g. Presentation layer style conversion of small atomic symbol strings. The Content layer is not required to have a deep understanding of data semantics. Traditional network flow control (such as TCP) operates at least partially within the Content layer: even though the application data is not being semantically “understood” application data is summarized and uniquely identified by application type (port number) and a sequence number. The content-oriented nature of flow control is emphasized by schemes (e.g. Structured Streams [26] and SCTP [27]) that permit applications to specify variable packet delivery requirements than it is with “single purpose” schemes such as TCP and UDP. A Content layer could also perform complicated wrangling of storage resources, identification of large aggregate data objects, multiplexing application usage of underlying communication links, and even encoding content to better fit available communication resources. Content-Based Routing systems [18, 28] and content-oriented overlay networks [29] illustrate the utility of having a dedicated Content layer.

6.3 Network Layer

The Network layer is the “center of mass” in our proposed architecture. The Network layer must multiplex applications and physical network devices, all of which may be competing for limited shared resources. The Network layer also integrates paths provided by multiple Physical layer devices and multiple communication endpoints at the ends of those paths to perform multihop routing. An important aspect of our semantic stack is that this multiplexing and routing is all performed within a single layer, instead of three as with the canonical stack. This unification permits greater flexibility in how these functions are modularized, rather than forcing layered functionality for all systems. We would like to emphasize that the layers of the canonical stack could be implemented within the context of the semantic stack; such a system could provide an “in place” means for transitioning between the canonical stack and the semantic stack. We will not delve into more detail about the Network layer in this section; many
important issues for the Network layer will be discussed at greater length in Section 7.

7 Architectural Implications

In this section we will highlight some implications of our framework for system architecture. We will also assess the canonical network stack and propose techniques for retrofitting existing layered systems to support “cross layer” interactions in a systematic way.

7.1 Cross-Layer Semantic Interactions

In Section 6.1 we briefly discussed the potential for cross-layer semantic interactions between the Physical layer and the Computation layer when application-level semantics relate directly to physical characteristics of an information embodiment. Sensor/actuator systems are a prime example of such systems, but are by no means the only one, e.g. our earlier example of emergency radio frequency usage. Broadly speaking, we imagine two ways of approaching this problem: either application-level semantic information must be pushed into the Physical layer or physical information must be pushed into the Computation layer. Both of these approaches couple the Physical and Computation layers, albeit in different ways. As a general guideline we believe that when the semantics may be directly tied to the control plane (we will further discuss data and control planes in Section 7.4) the semantics are suitable for pushing into the Physical and Network layers. Our “emergency channel” example could fall into this category: an emergency channel is a social construct that may have meaning for the control plane at all layers of the stack. If the Network layer also has such a social construct then the “shortcut” cross-layer interaction may be eliminated by propagating information through the stack in an orderly fashion. A role-based approach to metadata could provide a reasonably flexible mechanism for this task.

On the other hand, if the information is purely part of the data plane then it is suited for pushing up into the Application layer. The data plane version of our “emergency channel” example would tag received packets with metadata describing physical properties and units of the embodiment that contained the packet. In this example the key pieces of information are the type of embodiment (radio waves), and the range of frequencies (center and bandwidth) that contained the information. Further physical information about the radio waves could include intensity and polarization, and information-theoretic metrics such as the signal-to-noise ratio could also be of interest. Such data plane cross layer applications veer strongly into the realm of generic sensor/actuator systems. In many ways, sensor/actuator applications reside alongside the Physical layer in our semantic stack: we could even imagine sensor applications sharing a common Transducer layer with the networking system. These “parallel” system structures could become very confusing, particularly if a sensor/actuator application
wishes to use generic network services. This confusion could be compounded if the same device used for sensing and actuating were also used as a network communication device (our emergency channel example is a very basic instance of a sensor application). We will discuss the flow of data within the stack (and the potential for circular flows) in greater detail in Section 7.3. In general, we will draw a line between sensor systems and network systems by their intent. In essence, a networking system is a very specialized type of sensor/actuator system. If a sensor/actuator system intends to provide a generic symbolic communication service on top of some physical embodiment, then architecturally it should reside within the Physical layer and not the Application layer. However, it is important to stress that residing at the Physical layer of a semantic stack does not require implementation directly in hardware or as a kernel module. A time and memory intensive task might be better placed well outside the kernel in user space, but that placement does not alter its semantic stack layer. We will discuss such issues in greater detail in Section 7.5.

A further potential semantic cross-layer interaction occurs due to the fact that many computer systems interact with humans, and humans (by and large) are resident in the physical world and are concerned about location, time, and energy. One way of thinking about this is that user interface systems may be viewed in terms of semantic layers, connecting the Application layer with users in yet another Physical layer (e.g. mice, keyboards, printers, and monitors). Usually the HCI Physical and Network Physical layers are non-overlapping, but this shared grounding in the physical world implies that there may be some utility in placing some physical awareness into the Network layer. We will discuss this issue in greater detail in Section 7.6.

7.2 Routing

In this section we will highlight some key points about routing in our semantic stack. We will discuss where and how multihop paths are determined, how multihop path information can propagate between layers, and some of the tradeoffs available when attempting to scalably handle topology information.

7.2.1 Multihop Routing and Paths

Networking systems usually perform the bulk of routing within the Network layer (e.g. IP routing) and the Application layer (e.g. overlay networks). Routing is also performed at the Physical layer, but is usually limited to single hop paths (spanning tree bridges are a common exception). An argument made against multihop routing at lower layers is that it leads to excessive duplication of effort and needless overhead. However, multihop routing using a particular embodiment within a particular region of space and time is not necessarily the same thing as multihop routing using an abstract graph-theoretic model [31].

Acoustic telephone modems are one rapidly vanishing point at which human and network Physical layers intersect.
detrimental to overall scalability and abstraction, and creating a good abstract model of all physical embodiments is not a trivial task. It is not sufficient to simply capture basic information-theoretic characteristics of an embodiment, e.g., in terms of Shannon channel characteristics and interference: operational characteristics and social norms that apply to each physical embodiment must be accounted for as well. The potential complexity of such a task is illustrated by the extensive efforts made by the Software Defined/Cognitive Radio community\textsuperscript{[32]} to codify knowledge about the RF domain.

It is important to stress that we are not advocating a model where lower layers perform isolated, opaque multihop routing and simply present all reachable endpoints as single-hop neighbors. Such an approach would hide too much information and control from higher layers. Instead, we propose that full path information be made available to higher layers if requested, and that higher layers be able to specify requests for desired paths in a way that shapes how the lower layers establish paths. We will discuss paths and their representations in greater detail in the next section.

7.2.2 Generic Path and Routing Metrics

An important question for layered routing systems is how to specify route characteristics across layers. This question is even more important for our semantic stack because of our emphasis on paths at multiple layers. Metrics based on fundamental information and physical characteristics such as symbol capacity, time, space, and energy seem promising for making abstract routing decisions at the network/internetwork layers and higher because they relate to human concerns handled by the Computation layer as well as embodiment properties handled by the Physical layer. Such physical metrics are also amenable to graceful adaptation. For example, instead of forcing a wireless MAC layer to declare a link “up” or “down” based on some internal quality metric, the MAC layer could estimate how much time, energy, and space it would require to move symbols along various paths and let higher layers determine which paths to use.\textit{Expected Transmission Time} (ETT)\textsuperscript{[33]} is an example of a time-based metric which could be extended to include energy and space, particularly when using \textit{Expected Transmission Count} (ETX)\textsuperscript{[34]} as a foundation. Space in this context could be expressed directly in terms of physical space and/or more abstractly in terms of known endpoints that could receive a transmission. How the expected values for time, space, and energy are calculated should be determined by specific Physical layer entities. For example, if a channel is well-characterized in terms of its information-theoretic properties then observed SNR and model predictions of SNR could be used to predict expected values for path metrics instead of direct feedback-driven observation of the time, energy, and space required to send packets.

A further critical property of paths is the degree of \textit{entanglement} between different paths. For example, wireless networks may have apparently “independent” paths that share no endpoints in common but are mutually interfering. Such entanglement information is critical for systems that wish to perform mul-
tipath routing. The exact means by which entanglement may be expressed abstractly and succinctly but with sufficient detail for effective operation is an open issue. Simple aspects of mutual interference may be expressed through degradation of individual path performance when multiple paths are used. However, actual path independence may also require taking physical and social channel characteristics into account. For example, two directional free-space optical links might not interfere with each other at all, but both suffer significant degradation simultaneously when fog or mist is present. Two optical links running through the same bundle of fiber would be impervious to fog, but suffer simultaneous catastrophic failure if the fiber cable were accidentally cut by construction workers. Such concerns may be difficult to succinctly and dynamically express. For example, Cognitive Radio systems utilize detailed models and reasoning in an attempt to capture such physical and social details about RF systems.

7.2.3 Scalable Topology Management

The choices made when designing Information Control and Topology Control can have a large effect on system capabilities and resource requirements. In realistic systems Information Control, Topology Control, and Identification may be tightly tied together and quite complex. However, there are some basic tradeoffs that shape these three primary functions. Systems may opt to place greater emphasis on either Topology Control or Information Control, and such a decision can have a significant effect on the demands made on Identification. For example, generic networking systems are designed to support large quantities and varieties of potentially private information traversing relatively fewer endpoints. As such it is more practical to track the endpoints in a network via Topology Control than to attempt to track all of the information via Information Control. Conversely, a very dense, specialized sensor network or special-purpose “swarm” system could have an overwhelming number of endpoints yet only a few types of content, making it more practical to track content instead of worrying about the locations of particular endpoints. Figure 5 illustrates some basic tradeoffs that may be made when constructing network routing systems and makes a rough assessment of the tradeoffs made by some existing systems. Systems that require both large numbers of endpoints and large numbers of pieces of information simultaneously may have to combine scalable aspects of Information Control and Topology Control.

7.3 Flow Control

In our semantic stack we define a more prominent and distinct role for Flow Control than is typical. Instead of limiting Flow Control to specifying when packets are sent, we also have Flow Control manage where packets are sent based on options provided by Topology Control. This does not entail having Flow Control calculate shortest-hop paths through the network, but rather having Flow Control specify topological priorities to Topology Control and choosing between paths made available by Topology Control. Because Flow Control
Routing information may be embedded alongside payload at the source or computed along the way in a distributed fashion. Routing decisions may be based within Information Control and/or Topology Control, and routing information may be preemptively discovered and maintained or discovered and maintained as required by Flow Control.

has primary ownership of packets it would seem to be the entity best suited for multiplexing usage of limited information pathways provided by Topology Control. Approaches like Structured Streams seem very promising for letting Flow Control direct Topology Control. Any number of existing routing protocols are useful for Topology Control to provide Flow Control with paths.

### 7.4 Data Plane and Control Plane

Networking systems often utilize separate paths for data and control information, commonly referred to as the data plane and control plane respectively. The control plane conveys goals, constraints, actions, and state for topology and information, and the data plane moves information and associated metadata through the system for processing. Strictly speaking, the data plane must always carry some control information. Even if a packet is handed off with ostensibly no action requested, there is an implicit request to store the packet pending some future action request, and many systems treat the packet handoff as an implicit request to transmit the packet.

The underlying transport and storage resources for control and data information may be unified, completely separate, or some combination of the two. The exact split depends greatly on the resources available to a system and its requirements. Unified data and control plane paths are simpler when data and control plane operations are inherently synchronized, e.g. a packet handoff contains an implicit transmit operation and the receipt of a control packet results in corresponding control plane information. However, split control/data
plane resources could arise in some situations. A data plane communication path could be optimized for unidirectional flow of large data packets alongside a matching control plane optimized for bidirectional communication of small amounts of control information. This situation arises for optical networks that use non-optical IP networks to negotiate the setup and teardown of high-speed all-optical communication paths.

An interesting property of such optical systems is that they operate both at the Physical layer by controlling paths through the optical fabric as well as clients of generic networking services by using wired IP networks as a control plane. This apparent cross-layer interaction raises questions of how data and control information flows within a communication stack. Typical networking stacks maintain straightforward packet flows: received packets move up the stack until they are consumed or forwarded back down the stack, and transmitted packets move down the stack until they are sent or discarded. However, our optical system example could benefit from relaxation of such flow restrictions. Instead of creating a cross-layer system (as outlined in Section 7.1) to permit operation both at the Physical and Application layers an alternative would be to permit the Physical layer to send packets up the stack to the adjacent Network layer which would then deliver the packets as required, sending them back down the stack. Care would have to be taken in order to avoid loops, but with the benefit of averting some potential cross-layer interactions.

7.5 Flexible Multiplexing and Temporal Boundaries

Temporal and computational resource constraints have strongly shaped the canonical network stack. Figure 6 illustrates the computational flexibility/speed tradeoff implicit in canonical stack implementations, as well as other functional and semantic boundaries in the stack. In our semantic stack we attempt to decouple such temporal and computational resource constraint tradeoffs from “height” in the stack. Each layer is no longer necessarily monolithically implemented within a single computational domain, e.g. as hardware, within the kernel, or in user space, but instead may be split across different computational domains. Such splits occur in explicitly in the canonical stack: the results of routing are memoized within forwarding. The routing/forwarding split also has benefits for modularity, but modularity on its own does not require splitting functionality into different layers. A further example is that of 802.11 MAC layer acknowledgement packets. Practical implementations may opt to generate MAC layer ACK packets down alongside the implementation of the PHY layer in order to meet latency requirements\textsuperscript{36}. Dynamically managing computational and temporal constraints, especially across multiple network hops\textsuperscript{37}, is a tricky proposition in general, and semantic layering on its own does not address such problems. However, semantic layering does complement systems that manage such resources by providing larger context and structure. For example, dynamic flow-based systems such as Click\textsuperscript{38} and Scout\textsuperscript{39} could very easily fit into our semantic layers, as could XORP\textsuperscript{40} and Switchlets\textsuperscript{41}. Such systems seem well-suited for constructing the “internal organs” required for a semantic
Figure 6: The OSI stack and its relationship to functional, semantic, and temporal system boundaries. Computational resources are often (though not always) most flexible and slowest at the top of the stack and least flexible and fastest at the bottom of the stack. Multiplexing may also be performed by each OSI layer, though the TCP stack does not multiplex to such a large degree.
layer “exoskeleton” to come to life.

7.6 The Physical World

Some aspects of the physical world are present at all layers of our semantic stack. We view this as unavoidable because humans are resident in the physical world and have physical concerns that must be considered at the Application layer. Combined with the fact that the Physical layer is concerned with the physical world, and a potential cross-layer interaction arises, as discussed in Section 7.4. To help moderate this cross-layer interaction, we propose that the Network layer have some basic awareness of the physical world. We do not desire extensive physical knowledge at the Network layer because such knowledge can erode abstraction. However, we do feel that knowledge of time, space, and energy are sufficiently fundamental that the benefit of adding awareness of them outweighs potential loss of abstraction.

Time, space, and energy are by no means new to computation and networking. In fact, their significance is highlighted by concerted attempts to create suitable abstractions for them. For example, Lamport clocks[12], timers in network protocols such as TCP, geographic routing[33, 44], and more recently in energy-aware systems and programming languages[45]. We propose that time, space, and energy should all be treated as first-class entities at all layers of the network stack. It may be difficult (or even impossible) for all systems to agree on a single shared common notions of space, time, and energy, but such universal agreement is not required so long as it is possible to translate between different schemes. Physical knowledge may sometimes benefit abstraction by placing absolute bounds on system performance requirements and parameters. For example, the light cone (shown in Figure 7) of an entity shows the largest possible regions of time and space that could possibly interact with that entity. At the other end of the scale, the Planck time and Planck length give theoretical limits on the minimum amounts of space and time that quantum mechanics may describe, providing bounds on the absolute resolution required when measuring physical quantities. Thermodynamics sets basic limits on computational density and speed[46]. Such bounds may be used to create “future-proof” sizes for protocol elements that rely directly or indirectly on such limits. For example, a software system that needed to operate over the next 1,000 years could use a clock value with sufficient bits to track the number of Planck intervals that occur over 1,000 years if it wanted to be certain of avoiding clock rollover and/or insufficient precision during that period of time. Using 365.25 days per year and $5.39 \times 10^{-44}$ seconds for the Planck time, 179 bits would be required for a clock in such a system. Certainly not a small number of bits, but not unreasonable given that 64 bit microprocessors are commonly found in consumer-grade systems. Such concerns are of fundamental interest to Delay Tolerant Networking (DTN)[22] systems intended for interplanetary and other slow-moving communication paths.

23
7.7 Social Resources and Constraints

Social concerns arise throughout networking systems and require first-class design consideration. For example, dynamic spectrum access systems [8] are subject to governmental regulation and oversight. However, even systems not directly subject to government regulation and rules are still replete with social norms, albeit usually norms driven by mathematical models and analysis instead of emerging from autonomous behavior. An important practical consequence of this pervasive social interaction is that systems should not simply assume that an “optimal” route in one context is an “optimal” route in another context. For example, a minimum hop path that traverses an untrusted or unfriendly node may be deemed vastly inferior to a longer path that only traverses trusted and friendly nodes. Furthermore, different applications on the same system may adhere to different social norms, potentially resulting in very different “optimal” paths for different applications. In fact, it is not unreasonable for a single application to have different social requirements for different pieces of information, resulting in even more dynamic behavior. Such operational flexibility clearly has some computational and architectural complexity cost, but this tradeoff should be made explicitly. We do not advocate having a single, unified “social context” for all layers of the stack unless such a context truly exists. One great benefit of layering, abstraction, and delegation is that local details may be kept local.
8 Summary and Future Work

In this work we have presented a layered network architecture based on semantics. We have justified this structure using reasoning based on physics, information theory, software engineering principles, and aspects of human/computer interaction. Naturally, there are many details of such a system to explore. We plan to move forward by designing and constructing practical systems based on our architecture, utilizing well-established and compatible platforms, e.g. the Click Modular Router [38] and XORP [40], to fill out the framework laid out by our semantic stack. As an initial primary point of exploration we are looking at paths and path representations. Paths and path properties are a central part of interactions between layers in our architecture, and as such we feel they warrant detailed exploration.

References

[1] Hubert Zimmerman. OSI reference model - the ISO model of architecture for open systems interconnection. IEEE Transactions on Communications, 28(4):425–432, April 1980.

[2] Richard Phillips Feynman. Feynman Lectures on Computation. Perseus Books, Cambridge, MA, USA, 2000.

[3] Konrad Zuse. Rechnender raum. In Physik und Informatik - Informatik und Physik, Arbeitsgespräch, pages 16–23, London, UK, 1992. Springer-Verlag.

[4] E. Fredkin. Digital mechanics: an informational process based on reversible universal cellular automata. Phys. D, 45(1-3):254–270, 1990.

[5] Joseph E. Stoy. Denotational Semantics: The Scott-Strachey Approach to Programming Language Theory. MIT Press, Cambridge, MA, USA, 1981.

[6] C. E. Shannon. A mathematical theory of communication. Bell System Technical Journal, 27:379–423,623–656, July/October 1948.

[7] L. Kleinrock and F. Tobagi. Packet switching in radio channels: Part i-carrier sense multiple-access modes and their throughput-delay characteristics. Communications, IEEE Transactions on [legacy, pre - 1988], 23(12):1400–1416, Dec 1975.

[8] Qing Zhao and Brian M. Sadler. Dynamic spectrum access: Signal processing, networking, and regulatory policy, 2006.

[9] P. Basu and J. Redi. Movement control algorithms for realization of fault-tolerant ad hoc robot networks. Network, IEEE, 18(4):36–44, July-Aug, 2004.
[10] M. Moore, A. Enomoto, T. Nakano, R. Egashira, T. Suda, A. Kayasuga, H. Kojima, H. Sakakibara, and K. Oiwa. A design of a molecular communication system for nanomachines using molecular motors. In Proceedings of the Fourth Annual IEEE Conference on Pervasive Computing and Communications and Workshops, March 2006.

[11] F. Tobagi and L. Kleinrock. Packet switching in radio channels: Part ii—the hidden terminal problem in carrier sense multiple-access and the busy-tone solution. Communications, IEEE Transactions on [legacy, pre - 1988], 23(12):1417–1433, Dec 1975.

[12] Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Spec, IEEE 802.11 Standard. Technical report, Institute of Electrical and Electronics Engineers, Inc.

[13] D. D. Clark and D. L. Tennenhouse. Architectural considerations for a new generation of protocols. In SIGCOMM '90: Proceedings of the ACM symposium on Communications architectures & protocols, pages 200–208, New York, NY, USA, 1990. ACM Press.

[14] R. Bush and D. Meyer. Some Internet Architectural Guidelines and Philosophy. IETF RFC 3439, IETF, December 2002.

[15] Bernard M. Hauzer. A model for naming, addressing and routing. ACM Trans. Inf. Syst., 4(4):293–311, 1986.

[16] Charlie Perkins. IP Mobility Support. IETF RFC 2002, IETF, October 1996.

[17] Janardhan R. Iyengar, Paul D. Amer, and Randall Stewart. Concurrent multipath transfer using sctp multihoming over independent end-to-end paths. IEEE/ACM Trans. Netw., 14(5):951–964, 2006.

[18] Antonio Carzaniga, Matthew J. Rutherford, and Alexander L. Wolf. A routing scheme for content-based networking. In Proceedings of IEEE INFOCOM 2004, Hong Kong, China, March 2004.

[19] Antonio Carzaniga and Alexander L. Wolf. Forwarding in a content-based network. In Proceedings of ACM SIGCOMM 2003, pages 163–174, Karlsruhe, Germany, August 2003.

[20] D. L. Parnas and D. P. Siewiorek. Use of the concept of transparency in the design of hierarchically structured systems. Commun. ACM, 18(7):401–408, 1975.

[21] D. L. Parnas. On the criteria to be used in decomposing systems into modules. pages 139–150, 1979.

[22] V. Cerf, S. Burleigh, A. Hooke, L. Torgerson, R. Durst, K. Scott, K. Fall, and H. Weiss. Delay-Tolerant Networking Architecture. IETF RFC 4838, IETF, April 2007.
[23] Chip Elliott, David Pearson, and Gregory Troxel. Quantum cryptography in practice. In SIGCOMM ’03: Proceedings of the 2003 conference on Applications, technologies, architectures, and protocols for computer communications, pages 227–238, New York, NY, USA, 2003. ACM Press.

[24] Lov K. Grover. A fast quantum mechanical algorithm for database search. In STOC ’96: Proceedings of the twenty-eighth annual ACM symposium on Theory of computing, pages 212–219, New York, NY, USA, 1996. ACM.

[25] Neil Ashby. Relativity in the global positioning system. Living Reviews in Relativity, 6(1), 2003.

[26] Bryan Ford. Structured streams: a new transport abstraction. SIGCOMM Comput. Commun. Rev., 37(4):361–372, 2007.

[27] R. Stewart, Q. Xie, K. Morneault, C. Sharp, H. Schwarzbauer, T. Taylor, I. Rytina, M. Kalla, L. Zhang, and V. Paxson. Stream Control Transmission Protocol. IETF RFC 2960, IETF, October 2000.

[28] Ion Stoica, Robert Morris, David Karger, M. Frans Kaashoek, and Hari Balakrishnan. Chord: A scalable peer-to-peer lookup service for internet applications. In SIGCOMM ’01: Proceedings of the 2001 conference on Applications, technologies, architectures, and protocols for computer communications, pages 149–160, New York, NY, USA, 2001. ACM.

[29] Akamai, Inc. Akamai. http://www.akamai.com.

[30] Robert Braden, Ted Faber, and Mark Handley. From protocol stack to protocol heap: role-based architecture. SIGCOMM Comput. Commun. Rev., 33(4):17–22, 2003.

[31] Yan Gao, J.C. Hou, and Hoang Nguyen. Topology control for maintaining network connectivity and maximizing network capacity under the physical model. INFOCOM 2008. The 27th Conference on Computer Communications. IEEE, pages 1013–1021, April 2008.

[32] Joe Mitola. The software radio architecture. IEEE Communications Magazine, 33(5):26–38, May 1995.

[33] Richard Draves, Jitendra Padhye, and Brian Zill. Routing in multi-radio, multi-hop wireless mesh networks. In MobiCom ‘04: Proceedings of the 10th annual international conference on Mobile computing and networking, pages 114–128, New York, NY, USA, 2004. ACM.

[34] Douglas S. J. De Couto, Daniel Aguayo, John Bicket, and Robert Morris. A high-throughput path metric for multi-hop wireless routing. Wirel. Netw., 11(4):419–434, 2005.

[35] III Mitola, J. and Jr. Maguire, G.Q. Cognitive radio: making software radios more personal. Personal Communications, IEEE, 6(4):13–18, Aug 1999.
[36] Michael Neufeld, Jeff Fifield, Christian Doerr, Anmol Sheth, and Dirk Grunwald. Softmac - flexible wireless research platform. In *Fourth Workshop on Hot Topics in Networks (HotNets-IV)*, November 2005.

[37] David D. Clark, Scott Shenker, and Lixia Zhang. Supporting real-time applications in an integrated services packet network: architecture and mechanism. *SIGCOMM Comput. Commun. Rev.*, 22(4):14–26, 1992.

[38] Eddie Kohler, Robert Morris, Benjie Chen, John Jannotti, and M. Frans Kaashoek. The click modular router. *ACM Transactions on Computer Systems*, 18(3):263–297, August 2000.

[39] David Mosberger and Larry L. Peterson. Making paths explicit in the scout operating system. pages 153–167, 1996.

[40] Mark Handley, Orion Hodson, and Eddie Kohler. Xorp: an open platform for network research. *SIGCOMM Comput. Commun. Rev.*, 33(1):53–57, 2003.

[41] J. E. Van Der Merwe and I. M. Leslie. Switchlets and dynamic virtual atm networks. In *Proc Integrated Network Management V*, pages 355–368. Chapman and Hall, 1997.

[42] Leslie Lamport. Time, clocks, and the ordering of events in a distributed system. *Commun. ACM*, 21(7):558–565, 1978.

[43] J. Li, J. Jannotti, D. De Couto, D. Karger, and R. Morris. A scalable location service for geographic ad-hoc routing. In *Proceedings of the 6th ACM International Conference on Mobile Computing and Networking (MobiCom ’00)*, pages 120–130, August 2000.

[44] Young-Bae Ko and Nitin H. Vaidya. Location-aided routing (lar) in mobile ad hoc networks. *Wireless Networks*, 6(4):307–321, 2000.

[45] Jacob Sorber, Alexander Kostadinov, Matthew Garber, Matthew Brennan, Mark D. Corner, and Emery D. Berger. Eon: a language and runtime system for perpetual systems. In *SenSys ’07: Proceedings of the 5th international conference on Embedded networked sensor systems*, pages 161–174, New York, NY, USA, 2007. ACM.

[46] Seth Lloyd. Ultimate physical limits to computation, 1999.