The Remaining Improbable: 
Toward Verifiable Network Services

Pamela Zave, Jennifer Rexford, and John Sonchack 
Princeton University

ABSTRACT

The trustworthiness of modern networked services is too important to leave to chance. We need to design these services with specific properties in mind, and verify that the properties hold. In this paper, we argue that a compositional network architecture, based on a notion of layering where each layer is its own complete network customized for a specific purpose, is the only plausible approach to making network services verifiable. Realistic examples show how to use the architecture to reason about sophisticated network properties in a modular way. We also describe a prototype in which the basic structures of the architectural model are implemented in efficient P4 code for programmable data planes, then explain how this scaffolding fits into an integrated process of specification, code generation, implementation of additional network functions, and automated verification.

1. INTRODUCTION

Networks are an indispensable, mission-critical, and safety-critical part of global infrastructure. Network researchers and engineers now have a responsibility to work toward networks whose services and properties are verifiable. For this reason, the last decade has seen considerable research on network verification. Its success demonstrates that automated verification applies to real networks and scales well enough to be useful in practice [3].

The problems with current network verification are that it is low-level and lacks modularity [15], because it is focusing on packet delivery in physical networks, and on analysis of their routing and forwarding. We know that the Internet has many levels of virtual networks, and that these virtual networks are usually made of ad hoc tunnels, implemented by packet rewriting and encap/decapsulation [22]. Even if an existing network verifier can handle the packet transformations, neither the analysis nor the properties being checked reflect any awareness of the virtual networks. So the properties of virtual networks (with their own virtual names and topologies) cannot be verified, even though they are the networks that actually provide user services. And the strong natural modularity that comes from layering of virtual networks is unexploited during analysis.

Naturally there are efforts to raise the level of abstraction of network verification, but this is almost impossible when working from the bottom up. For example, researchers have suggested getting higher-level specifications by inferring them from existing artifacts. Existing artifacts, however, are full of defects accreted over time, as features were added and interwoven without the benefit of foreknowledge. If we had higher-level specifications we could clean up the defects, but no automated process is likely to extract pure intentions from messy artifacts.

We believe it is time to learn how to build network services that are modular and verifiable by construction. To do this, we begin with an architectural model that is precise, realistic, and formalizable, with layering and modularity as central concepts. §2 gives a brief overview of this model, explaining why its definition of layering is better than the familiar layers in the “classic” Internet architecture. In §3 we use an example to show how network services and their required properties can be specified with the model, even though they are built on virtual structures as much as physical ones. In §4, which is arguably the most important section in the paper, we discuss reasoning with the architectural model. The vast majority of properties can be verified by analyzing one separate module at a time, leading to major improvements in efficiency. Properties verified with completely different techniques can be composed to guarantee overall network behavior.

Having established that the architectural model meets our needs, our next task is to embody it directly in network components. This means that the modular structures of the architecture will be explicit in the implementation, so they can be exploited not just for enhanced and verified services, but also for measurement, management, and resource allocation. To reach this goal, programmable data planes are the key enabler. In §5 we describe our work in progress on a prototype implementation in the P4 language. We show how simple optimizations make it run efficiently, i.e., consuming about 3% of compute resources on the Barefoot Tofino. We also explain our plans to generate data- and control-plane code from templates and/or specifications.

There are two obvious objections to this research program. The first is that it is a clean-slate approach, and therefore too ambitious for credibility. This is not true, simply because the architectural model is drawn from close observation of
today’s networks [22]. For this reason modules and components in our architecture should interface easily with existing network hardware and software, and can interoperate with them in real deployments.

The second objection to this approach lies in the practical implications of such intensive use of explicit architectural structure and programmability in network implementations. Especially in the short term, it may not be efficient enough for real deployment. We have great hopes for optimizations and the march of chip technology, but no guarantees on them. Despite this objection, the research is worth doing, because model-based development is the only plausible approach to building networks whose services are verifiable in any meaningful sense. Even if our prototype is never complete or efficient enough to be used in production, all of the abstractions, properties, and implementation mechanisms we discover can be used directly by other researchers, and will find their way into practice. To quote Sherlock Holmes, “. . . when you have eliminated the impossible, whatever remains, however improbable, must be the truth.”

The paper concludes with related work (§6) and a summary of research plans (§7). §3 through §5 present new research, including a formal semantics for the architectural model, based on the original ideas in [22].

2. COMPOSITIONAL NETWORK ARCHITECTURE

Compositional network architecture is based on the ideas that a network is a module, and that network services today are provided by rich, flexible compositions of heterogeneous network modules. Each network/module is a microcosm of networking, with all the basic mechanisms including a namespace, members, links, routing, forwarding, session protocols, and directories. Networks are composed by bridging, with the obvious meaning. They are also composed by layering, which means something new and very specific. In any network, a session is an instance of one of the services provided by that network. One network is layered on another network if a (virtual) link in the overlay network is implemented by a session in the underlay network.

As a consequence, layers in the new model are bigger than layers in the “classic” Internet architecture of [4] and [7] (see Figure 1). The advantage is that a bigger network/layer is more complete, so its interface to an overlay network is the same as the interface of an underlay network to it. In other words, we have made networks composable like Lego blocks.

As demonstrated in [22], the compositional architecture provides precise and comprehensive descriptions of how the Internet works today. For example, we see multiple layered IP networks, each with its own purpose and geographical or logical span. Each has its own namespace and routing, appropriate to its own level of abstraction. If the purpose of a network is narrow, one or more of its parts might be vestigial, which causes no problems.

3. NETWORK SERVICES AND PROPERTIES

In this section, we use a security-oriented example to illustrate the compositional model and sketch out how higher-level service properties can be specified. Figure 2 shows an enterprise IP network with security features. The employee’s laptop has an IP address E in the block reserved for the personnel department. The filter F allows only machines belonging to the personnel department to access the personnel database. It also does anti-virus scanning. Because access from E is allowed, there is now a TCP session between E and D. Network security is intended to enforce two properties: P1: All accesses to the personnel database are TCP sessions initiated by user machines belonging to the personnel department, and are free of known viruses. P2: Packet streams traveling on the network paths cannot be read or tampered with by any untrusted machine.

Even though this example is simple so far, and the enforcement of P2 is not yet shown, a rigorous argument for P1 requires these lemmas: L1a: Every network path with the personnel database as destination has a filter in it. L1b: All packets of a TCP session go through the same filter instance, so the filter can reconstruct the TCP byte stream to look for viruses. L1c: Addresses in the personnel block are only put into the source fields of packets by machines belonging to the personnel department. L1d: Forwarders in network paths do not alter the source or destination fields of packets (necessary because L1a and L1c depend on these fields).

In today’s environment, employees expect to be able to work on their laptops wherever they happen to be. So a more complete version of the enterprise network and its implementation is shown in Figure 3. This figure shows that the enterprise network uses virtual private network (VPN)
technology to allow secure employee access from remote locations. The laptop is connected to two IP networks, one of which is layered on top of the other. The leftmost pink bar represents the laptop, and the ovals represent its members of (interfaces to) the two IP networks. In the enterprise network it has IP address $E$, while in the IP network of the coffee shop where the employee is working, it has the short-term IP address $X$. Network members $E$ and $X$ communicate through the operating system of the laptop.

In this scenario, $E$ has created a virtual link, in the enterprise network, directly to a VPN server. This overlay link is implemented by an IPsec/ESP session in the underlay, consisting of bridged public and private IP networks. TCP packets sent virtually on the enterprise link are actually encrypted (headers included), encapsulated in packets of the IPsec session, and transmitted through the underlay IP networks. The VPN server also authenticates the employee laptop, checking that it has the private key of enterprise identity $E$.

Throughout this example, for simplicity, we assume that all middleboxes such as $V$, $F$, and $W$ are correct and trustworthy in essential respects. This will enable us to focus on the networks themselves. So authentication in $V$ satisfies $L1c$, as the VPN server is only one hop away from the laptop.

Now we consider security property $P2$ of the enterprise network. Because the trustworthiness of middleboxes is assumed and the necessary properties of forwarders are covered by $L1a$, $L1b$, and $L1d$, there is only one new lemma.

$L2$: All links of the enterprise network are secure, in the sense that no untrusted machine can read the packets on a secure link (neither header nor data), and no machine can insert or alter packets on a secure link. In the figure, links to the right of $V$ are located in enterprise buildings and secured physically. The virtual link between $E$ and $V$ is secure if every packet received by either endpoint is the data part of a packet received in the IPsec session between $X$ and $S$. The NAT/router alters the headers of IPsec packets, but not the headers of encapsulated enterprise packets.

Finally, we add security property $P3$: machines at the edge of the enterprise network are protected against flooding attacks. This property is enforced by the access network in Figure 3 where firewalls usually allow incoming packets to public IP address $S$, but begin to filter out suspicious ones when there is a sudden surge in traffic. Lemma $L3$ states: All paths through the access network to machines of the enterprise network pass through a firewall.

4. MODULAR REASONING WITHIN THE ARCHITECTURE

This section, while informal, is based on our formal semantics of the compositional network architecture. It is written in Alloy [8], which is a blend of first-order predicate logic and relational algebra. The Alloy Analyzer verifies properties automatically for models of bounded size, making it an excellent tool for experimentation with formal models.

4.1 Verification of Forwarding

Existing tools for data-plane verification [3] take the forwarding rules in network elements and compute from them reachability, non-reachability, middlebox insertion, and other important path properties. We propose to do exactly the same thing, except that in our implementation each network in a layered architecture has separate forwarding rules and other tables (see §5), and each layer can be analyzed independently. This kind of modularity is not exploited in any current verification tools [13].

The first advantage of this approach is that a layer/network has not only properties we need to prove, but the structure and constraints we need to prove it. Analysis of the enterprise network in [3] can use the fixed naming scheme that allocates a block of names for machines of the personnel department, regardless of the fact that the employee’s laptop will have a different IP address in each coffee shop, and that the source name in its packets changes from $X$ to $N$ as the packets pass through the coffee shop’s NAT. Analysis of the enterprise network can identify TCP packets and check that they go through a filter that reconstructs TCP byte streams, regardless of the fact that on some physical hops they look like IPsec packets and the TCP headers are encrypted. Anal-
ysis can use as an axiom that forwarding through the enterprise network does not modify the user-chosen fields of packet headers, which satisfies lemma \( L1d \).

The second advantage of this approach is that modularization makes verification more efficient. Lemmas \( L1a \) and \( L3 \) are essentially the same property—all packets with certain destinations must pass through a security middlebox—but they are verified in different (and simpler) networks. To quantify the potential benefits, consider the example of [15], in which layered separation of a policy-driven network (forwarding to middlebox instances) from a destination-driven network is found necessary to prevent combinatorial explosion in the number of rules. With no layering, the forwarding rules would not fit in the TCAM of forwarders. This suggests that, in comparison to the number \( n \) of forwarding rules in a non-modularized network, the number of rules in one layer of a two-layer architecture might be \( \sqrt{n} \) rather than \( n/2 \).

We studied a variety of network services and properties, and found that all of the necessary lemmas could be verified in a single layer. About half of the properties apply directly to the layer in which they are implemented, such as the \( L1 \) lemmas and \( L3 \) in this example. The other half apply to compositions of networks (next subsection).

## 4.2 Hierarchical reasoning over forwarding and session properties

A one-to-one correspondence between implementing sessions and implemented links allows bottom-up propagation of properties verified within individual networks: any property known to be true of an implementing session is also true of the implemented link. For this reasoning to be credible, there must be a “tight seam” between the two that does not allow any leakage of packets in or out. This “seam” is built into our architecture and implementation, rather than being constantly and casually re-invented—it can be scrutinized once with great care.

This hierarchical reasoning has an important advantage that we have not seen in other verification work—it can prove theorems that rely on properties of routing/forwarding and on properties of session protocols. It can also prove theorems that rely on the composition of completely different forms of automated reasoning. For example, property \( P2 \) of [3] is a property on paths through the enterprise network, including forwarders, middleboxes, and links. We have already discussed properties of paths, forwarders, and middleboxes, but what about the links (\( L2 \))? Links outside the walls of the enterprise are secure only because they are implemented by a cryptographic session protocol, which can be verified using pure mathematics and temporal-logic model checkers.

Note that TCP sessions in the enterprise network cannot be encrypted because \( F \) works on plaintext. Packets on enterprise links are always plaintext, even if the implementing sessions are encrypting them. This works because the session protocol at the lower level decrypts the data before delivering it upward to be received on the virtual link.

In our study of a variety of network services and properties, the other half of the properties are verified in a single underlay network, but they are verified for the benefit of overlays. In reasoning about the overlay networks, the properties become assumptions about the behavior of their links.

### 4.3 Packet traceability

Our final example is based on a “service network” that underlies multiple private customer networks, as in [24]. The service network offers wide-area connectivity along with enhanced performance, reliability, security, and customized communication services. Consider a customer network that must abide by HIPAA regulations on medical-patient privacy. Even if the service network normally examines customer packet contents for optimization or security filtering, it cannot examine the contents of packets carrying patient records.

So the service network must distinguish normal packets from patient records—without looking into them—and treat the patient records differently. Our architectural model makes this easy. In the customer network, there can be a separate topology of virtual links used for patient records only. In the service network, each virtual link is implemented by a uniquely identifiable session. Session identifiers then give the service network a reliable indicator of how each packet should be treated.

This example illustrates how the architectural model provides perfect traceability of packets across all layers of a network hierarchy. Traceability supports reasoning about many security properties involving packet provenance. It also has other uses; for example, it provides accountability for dynamic, measurable properties such as performance metrics.

## 5. PROTOTYPE IMPLEMENTATION

The first goal for our prototype was to implement the architectural model’s basic structures, especially layering—which must form a “tight seam” at the interface between networks. We can now show that this scaffolding is comprehensible, reusable, and efficient. Our next goal, in progress, is to gain insight from the prototype on how the scaffolding could work with control functions, management functions, session protocols, and verification in an integrated approach to network development.

### 5.1 Implementation of the model

In this subsection we describe the P4 code needed to implement the data plane, specifically making the following three points: (i) The implementation is completely general, and works for any set of layered networks. (ii) The P4 code is so regular that most of it can be generated automatically, greatly reducing costs and risks of error. (iii) The general-purpose code is easy to optimize, so that specific networks can be implemented efficiently.

Figure 4 shows an example in which a service network (from §4.3) is implementing the customer link from \( d \) to \( e \) with a session from \( p2 \) to \( p4 \), routed through service for-
In the Send table is the `sessIdent`, and the action is an encoding of the session’s header. The program encapsulates the packet in this header, adds the metadata `inLink = Self` to the packet, and applies Forward for `p2` in the service network.

Step 3 applies the Forward table, with keys `inLink` and header fields. The result of a match is either the action `Drop` or an `outLink` on which the packet should be transmitted. The `outLink` is 5, and next (Step 4) the Transmit table is applied with this key. Step 4 in the service network is analogous to Step 1 in the customer network. Currently links in the service network are simulated as physical (Primitite), and the packet is sent out the machine’s egress port 5.

In Step 5, as the packet is received on the other end of the link, it gets the metadata `inLink = 3`. The keys into the Acquire table are the `inLink` and the packet header, which is matched against header predicates in the table. The possible actions in the table are Receive and Forward. Because `p3` is not the destination of the packet, the next step will be to apply the Forward table. Steps 6, 7, and 8 of the example are similar to Steps 3, 4, and 5.

In Step 8 the Acquire table says the packet will be received, and in Step 9 the key in the Receive table is the session identifier in the packet header. The action in the table might be Primitite, meaning that this session is being used by its machine for the machine’s own purposes, so the packet should simply be delivered to the operating system. In this case the action is an external link, which is a (network, `linkIdent`) pair. This means that the session is implementing the identified virtual link in the external network, so the next step is to apply the Acquire table for `e` in the customer network, after stripping off its service-network header.

With these five functions and suitable match-action tables, any set of composed networks, no matter how complex their layering relationships, can be implemented. The P4 functions for a particular network depend chiefly on its header format, so for known network types, most of the P4 code for a set of composed networks can be generated automatically.

At the same time, with knowledge of a specific network, it is easy to make optimizations (which can be factored into code generation). For example, we know that in this example all customer links are implemented by sessions in the service network (as opposed to being physical links), and all service links are simulated physical links. With this simplifying knowledge alone, a packet can be processed and forwarded at a machine, through two layered networks, in a total of 4 match-action stages. In an unoptimized program, there would be 8 stages. On the Barefoot Tofino, our optimized prototype consumes about 3% of the compute resources, e.g., ALUs, metadata, action buses, and gateways.

The P4 functions for a network can have additional code for network management, and this code is easy to place. In the service network, e.g., code for monitoring the performance of a customer link would be plugged into Send and Receive for the service session implementing the link.

\section{5.2 Integrated network development}
We have shown that each network is a module with its own separate set of match-action tables and its own partition of the total set of properties to be proved. We have also shown that properties of different networks often take a similar form. This means that cumulative experience will make it much easier to identify the goals, constraints, and properties of specialized networks. This is especially important for security goals, because it is the modeling gaps that are exploited by adversaries.

The purpose of our formal semantics is to translate match-action tables into network-wide behavioral properties. So the formal semantics enables us to look at a network’s tables and say, e.g., “all paths to destination d pass through a firewall” or “consist of secure links.”

For small, static networks we can use the Alloy Analyzer to check or generate match-action tables. For real networks, in which tables are large and dynamic, there must be control functions to generate and update them. For our prototype we plan to experiment with a centralized controller. With a specification of network topology and properties, it may even be possible to generate controller code that is verified correct, so that the tables it produces need not be verified. This is already conceivable with tools such as Rosette [17], and the modularity of networks may make it feasible. Without network properties introduced as design principles, not only would controller generation be impossible, but the properties necessary for data-plane verification would be missing.

6. RELATED WORK

Research on “future Internet architectures” has produced plans for a number of clean-slate architectures, e.g., [1,19] [20] [23]. Each has its own special emphasis—so it is doubtful that any one of them could meet all of the Internet’s future needs, and they are not compatible enough to merge into one unified design. Compositional network architecture is not a clean-slate approach, but rather a structured and modular way of describing networks as they already are. It easily covers special-purpose networks such as Named Data Networks [23], showing how they can be composed with other networks in a flexible architecture.

The remaining related work concerns network verification. Tools for verification of routing and forwarding, e.g., [9][10][11][14], were mentioned in §4.1. These tools have the advantage of applying to existing networks. They are equally applicable to networks with our architecture, however, and modularity should make them even more scalable. The Tiros verification tool [2] already benefits from incorporating some customer-level abstractions, albeit without the unifying compositional model.

There has been much recent research activity on automated verification of P4 programs, such as ASSERT-P4 [5], the p4v tool [13], and Vera [18]. Generally speaking, these verification efforts focus on low-level, service-independent properties of P4 programs, e.g., is a referenced header field valid? Are array accesses in bounds? Are there recirculation loops? These should be very useful for making our P4 code robust.

Not surprisingly, the most significant issue for these verifiers is how to check higher-level, network-wide properties without knowing the match-action tables that will be driving the programs. Sample tables can be given to a verifier, although this makes analysis a hybrid of verification and testing. ASSERT-P4 and Vera are both based on symbolic execution, and use symbolic (partial) representations of table contents. The p4v tool, on the other hand, comes with a language for specifying the properties of match-action tables, so that verification can rely on these properties if they are known. This is the best solution, but useless without the table properties. The value of our approach is that the properties of tables will be readily available, as well as the specification of network-wide requirements.

7. RESEARCH PLANS

Due to the breadth and novelty of our approach, our current work is exploratory in nature. Completing the prototype will answer remaining feasibility questions, including: (i) How much changes when networks are dynamic rather than static? (ii) How do we incorporate session protocols, especially those that may require non-P4 custom code to perform encryption and decryption? Then, we can proceed to further research projects, with evaluation, to answer more interesting questions such as these: (iii) Will easily-automated optimizations be sufficient to produce acceptably efficient P4 code? (iv) How much of the service design space can be covered by model-based development? (v) How much code generation and automated verification can actually be achieved? (vi) Can we evaluate architectural trade-offs in two dimensions—both for implementation efficiency and for effectiveness of specification and verification?

Inevitably, there will always be a need for custom code, in both control and data planes. One promising approach to making it trustworthy is the development of verifiable programming languages such as Dafny, which is general enough for systems programming yet restricted enough for automated verification [6][12]. Another promising approach is the development of reusable, customizable, and verified middleboxes, for example on the Vigor platform [21], greatly reducing the need for writing unverified code. Even middleboxes benefit from layering, because their functions within separate networks can become separate modules.

In summary, this paper presents a constructive approach toward verifiable network services. Of course it will not be sufficient, but there is ample evidence to show that it is at least a necessary step forward. It also has the potential to coalesce and magnify the benefits of many other research projects on network programming, verification, and security. Although it may seem improbable, it is better than the impossible of continuing forever to connect the world with untrustworthy network services, or the impossible of working bottom-up from unprincipled to principled networks.
8. REFERENCES

[1] D. G. Andersen, H. Balakrishnan, N. Feamster, T. Koponen, D. Moon, and S. Shenker. Accountable Internet Protocol (AIP). In Proceedings of ACM SIGCOMM, 2008.

[2] J. Backes et al. Reachability analysis for AWS-based networks. In Proceedings of the International Conference on Computer-Aided Verification, pages 231–241. Springer LNCS 11562, 2019.

[3] R. Beckett and R. Mahajan. Capturing the state of research on network verification. https://netverify.fun/2-current-state-of-research accessed 5 June 2020.

[4] D. D. Clark. The design philosophy of the DARPA Internet protocols. In Proceedings of SIGCOMM. ACM, August 1988.

[5] L. Freire, M. Neves, L. Leal, K. Levchenko, A. Schaeffer-Filho, and M. Barcellos. Uncovering bugs in P4 programs with assertion-based verification. In Proceedings of the Symposium on SDN Research. ACM, 2018.

[6] C. Hawblitzel, J. Howell, M. Kapritsos, J. R. Lorch, B. Parno, M. L. Roberts, S. Setty, and B. Zill. IronFleet: Proving practical distributed systems correct. In Proceedings of the Symposium on Operating Systems Principles. ACM, 2015.

[7] ITU. Information Technology—Open Systems Interconnection—Basic Reference Model: The basic model. ITU-T Recommendation X.200, 1994.

[8] D. Jackson. Software Abstractions: Logic, Language, and Analysis. MIT Press, 2006, 2012.

[9] P. Kazemian, M. Chang, H. Zeng, G. Varghese, N. McKeown, and S. Whyte. Real time network policy checking using Header Space Analysis. In Proceedings of the 10th USENIX Conference on Networked Systems Design and Implementation, 2013.

[10] P. Kazemian, G. Varghese, and N. McKeown. Header space analysis: Static checking for networks. In Proceedings of the 9th USENIX Conference on Networked Systems Design and Implementation, 2012.

[11] A. Khurshid, X. Zou, W. Zhou, M. Caesar, and P. B. Godfrey. VeriFlow: Verifying network-wide invariants in real time. In Proceedings of the 10th USENIX Conference on Networked Systems Design and Implementation, 2013.

[12] K. R. M. Leino. Accessible software verification with Dafny. IEEE Software, 34(6):94–97, 2017.

[13] J. Liu, W. Hallahan, C. Schlesinger, M. Sharif, J. Lee, R. Soulé, H. Wang, C. Caçavale, N. McKeown, and N. Foster. p4v: Practical verification for programmable data planes. In Proceedings of ACM SIGCOMM, 2018.

[14] H. Mai, A. Khurshid, R. Agarwal, M. Caesar, P. B. Godfrey, and S. T. King. Debugging the data plane with Anteater. In Proceedings of SIGCOMM. ACM, 2011.

[15] T. Millstein. Toward modular network verification. https://netverify.fun/toward-modular-network-verification accessed 5 June 2020.

[16] Z. A. Qazi, C.-C. Tu, L. Chiang, R. Miao, V. Sekar, and M. Yu. SIMPLE-fying middlebox policy enforcement using SDN. In Proceedings of ACM SIGCOMM, 2013.

[17] The Rosette language. https://emina.github.io/rosette/ accessed 12 June 2020.

[18] R. Stoenescu, D. Dumitrescu, M. Popovici, L. Negreanu, and C. Raiciu. Debugging P4 programs with Vera. In Proceedings of SIGCOMM. ACM, 2018.

[19] A. Venkataramani, J. F. Kurose, D. Raychaudhuri, K. Nagaraja, S. Banerjee, and Z. M. Mao. MobilityFirst: A mobility-centric and trustworthy Internet architecture. ACM SIGCOMM Computer Communication Review, 44(3):74–80, July 2014.

[20] Y. Wang, I. Matta, F. Esposito, and J. Day. Introducing protoRNA: A prototype for programming recursive-networking policies. ACM SIGCOMM Computer Communications Review, 44(3), July 2014.

[21] A. Zaostrovnykh, S. Pirelli, R. Iyer, M. Rizzo, L. Pedrosa, K. Argyraki, and G. Candea. Verifying software network functions with no verification expertise. In Proceedings of the Symposium on Operating Systems Principles. ACM, 2019.

[22] P. Zave and J. Rexford. The compositional architecture of the Internet. Communications of the ACM, 62(3):78–87, March 2019.

[23] L. Zhang, A. Afnanasyev, J. Burke, and V. Jacobson. Named data networking. ACM SIGCOMM Computer Communication Review, 44(3):66–73, July 2014.

[24] Y. Zhe, R. Zhang-Shen, S. Rangarajan, and J. Rexford. Cabernet: Connectivity architecture for better network services. In Proceedings of the ACM Workshop on Re-Architecting the Internet. ACM, 2008.