Model-Based Diagnosis: Automating End-to-End Diagnosis of Network Failures

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***Abstract*—Fast diagnosis and repair of enterprise network failures is critically important since disruptions cause major business impacts. Prior works focused on diagnosis primitives or procedures limited to a subset of the problem, such as only data plane or only control plane faults. This paper proposes a new paradigm, *model-based network diagnosis*, that provides a *systematic* way to derive *automated* procedures for identifying the *root cause* of network failures, based on reports of end-to-end user-level symptoms. The diagnosis procedures are *systematically derived* from a model of packet forwarding and routing, covering hardware, firmware, and software faults in both the data plane and distributed control plane. These automated procedures replace and dramatically accelerate diagnosis by an experienced human operator. Model-based diagnosis is inspired by, leverages, and is complementary to recent work on network verification. We have built *NetDx*, a proof-of-concept implementation of model-based network diagnosis. We deployed *NetDx* on a new emulator of networks consisting of P4 switches with distributed routing software. We validated the robustness and coverage of *NetDx* with an automated fault injection campaign, in which 100% of faults were diagnosed correctly. Furthermore, on a data set of 33 faults from a large cloud provider that are within the domain targeted by *NetDx*, 30 are efficiently diagnosed in seconds instead of hours.**

I. Introduction

Failures in large operational enterprise networks and clouds are often subtle and can take hours to diagnose. This affects their ability to provide four nines availability, which allows only 52 minutes of down time in a year [9]. In practice, the diagnosis process often requires an expert human operator manually deploying multiple tools, such as traceroute and Wireshark; a process that is ad hoc, error prone, and can take multiple hours. In many cases, the complexity of the diagnosis task is due to a semantic (data plane vs. control plane) and physical distance between the observed symptom and the root cause of the failure.

Past relevant research focused on diagnosis primitives either for data plane faults (often in the context of SDN) [36], [60], [35], [37], [49], [50] or for control plane faults [40], [22], [16], [21], [34], without any way to automatically identify the root cause of the failure, taking into account interactions between the data and control planes. In contrast, this paper introduces a new top-down model-based paradigm that is completely different from past work (§XI). Crucially, this paradigm facilitates handling of complex data/control plane interactions, *automating* the procedures of an experienced network operator, improving failure response times **from hours to seconds** (§IX-C2).

Recent work in network verification [13], [28], [39], [27], [43], [57], [53] has exploited the fact that the correct network behavior is defined by network protocols, the network topology, and switch configurations. This allows the construction of a simple end-to-end model of packet forwarding and routing, and the use of this model to identify configuration faults.

In this paper, we apply this insight of the essential *simplicity* of networks for a different purpose. We propose *model-based network diagnosis*, in which network failures caused by switch or link faults can be diagnosed based on deviations from a formal end-to-end model of packet forwarding and routing (§IV). It should be noted that the term "model-based diagnosis" has been used in other contexts [25], [23], [24] with a different meaning.

Model-based network diagnosis is different from network verification since the goal is to identify faults in an operational network, not errors in configurations. Unlike model-based verification, that can be done proactively, switch or link failures happen in real-time and the resulting network failures must be responded to quickly in the field, using cues from the operational network. A global cloud provider with which we are working reports that, due to configuration verification tools, configuration errors have been greatly reduced and 66% of their current network failures are now due to switch hardware or software faults.

Switch or link failures may be caused by hardware faults. Switch failures may also be caused by software or firmware faults. We target diagnosis of permanent or high-frequency intermittent faults that ultimately result in excessive data packet drops or corruption. It should be noted that in the set of real world failures that we collected (§IX-A), the overwhelming majority of hardware or software faults were permanent and resulted in data packet drops or corruption.

We use model-based diagnosis to design and implement a system, called *NetDx*, that takes as input an end-to-end *failure report* and *automatically* identifies the root cause failed switch or link. A human user or an application generates the failure report that typically describes a loss of connection between two hosts or groups of hosts for all packets or some subset of packets. The goal of the diagnosis is to help network operators quickly resolve network disruptions. Thus, the diagnosis process only needs to identify the faulty *switch* or *link* rather than determine exactly which internal switch component has failed.

Based on a formal model of the *functionality* of network switches, we derive a fault model that describes how switch functionality can be disrupted. These models define the correct and faulty behaviors of the switch *at its interfaces* to the rest

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TABLE I
UNLIKE PRIOR WORK, MODEL-BASED DIAGNOSIS ALLOWS AUTOMATED DIAGNOSIS OF COMPLEX DATA PLANE/CONTROL PLANE FAULTS.

Category	Canonical Example(s)	Automated Diagnosis?	Overhead	Data Plane/Control Plane Interactions	Diagnosis Granularity	Performance Faults?
Monitoring	NetBouncer[51], Trumpet[45]	Yes	low	No	Switch/Link	Yes
New Switch Primitives	FlowRadar[42], NDB[35]	No	High	No	Switch/Link	Yes
HeaderMods + Primitives	INT[3], PathDump[49]	No	High	No	Switch/Link	Yes
Data Plane Log Analysis	Everflow[60]	No	High	No or limited	Switch/Link	Yes
Control Plane Log Analysis	BGP-Inspect[16], BGPlay[22]	No	High	No	Switch/ISP	No
Higher Level Abstractions	dShark[58], Marple[46], Everflow[60]	No but raises abstraction	High	No	Switch	Yes
Model-based Diagnosis	**NetDx** [this paper]	**Yes**	**Low**	**Yes**	**Switch/Link**	**No**

of the network and are *independent* of implementation details. Using these models and the specification of network protocols, we *systematically* derive *automated* diagnosis procedures by tracing the steps of packet forwarding and route propagation. At each step, the actions of switches in the operational network are compared to the correct actions derived from the model and the comparison results guide the diagnosis process. We leverage a configuration analysis tool [28] to provide a representation of the network model that is directly comparable to what is observable in the operational network.

A key challenge in the implementation of *NetDx* is efficient collection of information from the operational network in order to compare it to the model. Many proposed network diagnosis mechanisms rely on packet mirroring and logging to servers (e.g., [60], [58]), potentially requiring significant overhead in terms of network bandwidth and host resources. Some mechanisms piggyback diagnostic information on packets, potentially leading to packet fragmentation and resource usage at the hosts for processing the piggybacked information. In contrast, to minimize overhead, *NetDx*'s mechanisms are based on data collection primitives implemented in the switches that require minimal processing and storage resources on the switches and essentially no overhead in terms of network bandwidth and host resources (§V-A).

Table I compares *NetDx* to prior work. While the detailed explanation of the Table is left to §XI, the main takeaways are as follows. The current model is limited to IP/BGP networks and only deals with faults that manifest as packet drops or packet corruption. *NetDx* does not yet handle performance faults or some key features (e.g., overlays networks). However, the current *NetDx* implementation still accomplishes a task that has not been demonstrated previously: automatically identifying the root cause of complex failure scenarios that involve the interaction of the data and control planes, improving failure response times *from hours to seconds* (§IX-C2). We believe that our new model-based paradigm is extensible in a straightforward manner to, for example, other routing protocols and overlay networks. In contrast, for many real failure scenarios, the primitives introduced by prior work still need to be combined manually without a model to guide automation.

To evaluate *NetDx*, we built a network emulator that executes real routing software (FRR), injects realistic faults, and allows us to implement and test a *NetDx* implementation that is directly-transferable to a physical network. To enable modification of the data plane, the data plane of each emulated switch is an instance of the P4 [17] behavioral simulator [7]. Thus, the data plane is programmable.

We collected from a large cloud provider 33 real-world network failure scenarios (§IX-A) that are within the domain targeted by *NetDx* (§III) that occurred over several years. Their diagnosis was originally done manually and, in most cases, took multiple hours (median of 4.5 hours). We used these scenarios as a sanity check on our fault model and diagnosis procedures (§V) as well as to drive some of our experiments with *NetDx*. The evaluation of *NetDx* included an automated random fault injection campaign in which *NetDx* was able to correctly diagnose all injected faults.

Contributions: 1) Introduction of the novel, implementation-agnostic paradigm of *model-based network diagnosis* that enables *automated, end-to-end* diagnosis of operational enterprise networks, taking into account both data plane and control plane faults. 2) Derivation of a functional fault model of network switches that is completely independent of implementation details and can be used by others to evaluate network diagnosis mechanisms. 3) Design and implementation of a diagnosis system, *NetDx*, based on data collection at the switches, that is *systematically derived* from the network model, leverages the representation of the model by a configuration analysis tool (Batfish [28]), does not intrude on normal network operations, and only requires a small set of primitives and few resources. 4) Evaluation of *NetDx* using an automated fault injection campaign and a small user study comparing to manual diagnosis.

II. PRELIMINARY DISCUSSION

To dispel potential confusion, this section clarifies terminology and key concepts central to *model-based network diagnosis* (henceforth *MBND*) and *NetDx*.

***MBND* versus *NetDx*:** *NetDx* (§V, §VI) is a proof-of-concept implementation of *MBND* (§III, §IV). However, other implementations of *MBND* are possible. Starting from a report of end-to-end (host-to-host) user-level symptoms, *MBND* guides the derivation of *what* information needs to be collected and the order in which the information should be collected to identify the *root cause* of the particular network failure. *MBND* does not determine *how* to collect this information. *NetDx* shows one possible efficient implementation of how to collect the information and use it, following procedures derived using *MBND*, to reach diagnosis.

The meaning of *root-cause diagnosis*: In this paper, *root-cause diagnosis* means identifying the switch or link that is actually faulty. This is different from the first location where a symptom of the fault is detected. For example, packets may be unexpectedly dropped by a fault-free switch, *SWA*, since another fault-free switch, *SWB*, forwards the packets in the wrong direction due to an incorrect route advertisement sent by a faulty switch, *SWC*. *Root-cause diagnosis* identifies the problem to be *SWC*, not *SWA* or *SWB*. Once the actual faulty switch is identified, it can be quickly replaced or configured out for separate offline detailed diagnosis by the switch manufacturer.

Diagnosis versus detection: Network failure *detection* mechanisms simply determine whether there is a fault somewhere in the network. On the other hand, the goal of a *diagnosis* mechanism (*MBND* and its implementation, such as *NetDx*) is to identify the faulty switch or link.

Interactions between the data plane and control plane must be accounted for: As stated earlier, the complexity of the diagnosis task is due to a semantic and physical distance between the observed symptom and the root cause of the failure. Consider the example described above. In such a scenario, existing techniques, such as ATPG [59], can identify the switch where packets are dropped (*SWA*), but not the actual faulty switch (*SWC*) that generates the incorrect route advertisement. A high-overhead mechanism that examines every FIB in the network may be able to identify *SWB*, but not *SWC*.

The meaning of *end-to-end diagnosis*: A network failure is manifested as a problem in the communication among hosts. *End-to-end diagnosis* is triggered by such a failure report and identifies the root-cause of the failure. Based on *MBND*, such diagnosis can be done *automatically*.

The meaning of *automated* diagnosis: *MBND* enables and guides systematic development of diagnosis procedures by human experts. These procedures are developed once and can then be used numerous times in multiple locations, without experts, to quickly and autonomously diagnose network failures.

III. A Model of Network Switches

This section presents a functional model of network switches which is then used to derive a switch fault model. These are the first and second steps in model-based diagnosis. The next section explains the third and fourth steps in which these two models are used to derive diagnosis primitives and automated diagnosis procedures.

Since the required resolution of diagnosis is a switch or link, diagnosis is only concerned with the *functionality* of these components at their interfaces to the rest of the network. While network switches are complex, their behavior *at their interfaces* is defined by their configurations and standard network protocols. This behavior forms the functional model of the switches that is *independent* of low-level implementation details. A fault in a switch is manifested as a deviation from the functionality defined by the switch model.

Model-based diagnosis can potentially deal with a wide variety of faults, including those that cause performance anomalies. However, since this work only deals with network failures that manifest as end-to-end (host-to-host) packet drops, the relevant switch model only needs to capture forwarding and routing. Thus, our model assumes that every switch includes structures, referred to as *data plane tables*, that are involved with the handling of every packet. The contents of the data plane tables are derived by the switch from other structures on the switch, referred to as *control plane table*. Examples of data plane tables are structures that permit or deny reception of packets (e.g., ACL tables) and guide the forwarding of packets (e.g., FIBs). Examples of control plane tables are structures that contains routing information (e.g., RIBs) as well as the configuration of packet permit/deny criteria.

Table II presents the high-level functional model of switches as well as the switch fault model *derived* from the functional model. The data plane portion is similar to functional models used in data plane verification, like Anteater [44] and HSA [39], while the combination of data and control plane models is most similar to Minesweeper [14] and ERA [27]. However, the work in network verification does not consider negations of the functional model to create a fault model.

The model consists of seven functionality categories. For each category there are four rows, where the top two rows contain informal and formal definitions of the functionality of a fault-free switch. The bottom two rows for each category contain the informal and formal definitions of the functionality of a faulty switch. The definition of the functionality of a faulty switch is derived by negating the functionality of a fault-free switch. The list of faulty functionalities forms the switch *fault model*. Table III is a key to the notation.

As an example, the top category in Table II defines the packet forwarding function of a switch. Specifically, a fault-free switch forwards a packet to one of a subset of the switch's interfaces. This forwarding is performed only if the packet header characteristics meet configured criteria ($C_{forward}$) as long as it does not encounter a full packet buffer due to congestion (the buffer state is $S_{uncongested}$). The packet is correctly dropped if the header characteristics are in $\overline{C_{forward}}$, i.e., they do not meet the configured forwarding criteria $C_{forward}$. Furthermore, the model covers the possibility that, in a fault-free switch, a packet may be correctly dropped if it encounters a full packet buffer ($S_{congested}$). A faulty switch may drop a packet that meets the header characteristics criteria ($C_{forward}$) despite the fact that the buffers are not full ($S_{uncongested}$). A faulty switch may also forward a packet to an incorrect egress interface or forward a packet that should be dropped.

The last category in Table II deals with the interactions of the switch with routing peers as well as with accesses from a remote host to a management port of the switch. A faulty switch may, for example, fail to establish a TCP connection with a BGP peer or fail to accept or respond to management messages from a remote host.

The high-level model presented in Table II must be instantiated for a particular network type. For *NetDx*, the model is instantiated for IPv4/BGP networks (Appendix D). For example, the forwarding characteristics and the header transformation function are, respectively:

$$C_{forward} = FIB(Header.IPv4.DstAddr) = Q \;\wedge\; Header.IPv4.TTL \neq 0 \;\wedge\; AccessControl(Header) \neq Deny \;\wedge\; CheckSum(Header.IPv4) = 0$$

$$Fhdrt(Pkt(C)) = Pkt(C), \text{with } SrcMacAddr \leftarrow EgressPortMac \;\wedge\; DstMacAddr \leftarrow NextHopMac \;\wedge TTL \leftarrow TTL_{in} - 1 \;\wedge\; Checksum \leftarrow ChecksumCompute(NewHeader.IPv4)$$

TABLE II
A FUNCTIONAL MODEL OF FAULT-FREE AND FAULTY SWITCHES.
FAULTY FUNCTIONALITY (THE FAULT MODEL) IS SYSTEMATICALLY DERIVED BY NEGATING THE FAULT-FREE FUNCTIONALITY.

Packet Forwarding	The switch forwards packets with characteristics $C_{forward}$ to a port in Q when the state of S meets condition $S_{uncongested}$ The switch drops packets with characteristics $C_{forward}$ when the state of S meets condition $S_{congested}$ The switch drops packets with characteristics $\overline{C_{forward}}$ regardless of the state	
	$EgressPort(C_{forward}, S_{uncongested}) = p, p \in Q, Q \subset P$ $EgressPort(C_{forward}, S_{congested})$ = Null $\quad EgressPort(\overline{C_{forward}}, *)$ = Null	
	Switch S drops packets with characteristics $C_{forward}$ when the state of the switch meets condition $S_{uncongested}$ ***or*** Switch S forwards packets with characteristics $\overline{C_{forward}}$ to a port $p, p \notin Q$ ***or*** Switch S forwards packets with characteristics $\overline{C_{forward}}$ to a port in the switch's port set P	**FAULTY**
	$EgressPort(C_{forward}, S_{uncongested}) = Null$ $EgressPort(C_{forward}, *) = p, p \notin Q \quad EgressPort(\overline{C_{forward}}, *) = p', p' \in P$	**FAULTY**
Packet Transformation	The switch transforms the header of packet Pkt(C) with characteristics C by function Fhdrt The switch should not change the payload of the packet	
	$NewPkt = Fhdrt(Pkt(C))$ $NewPkt.payload = Pkt(C).payload$	
	The switch transforms the header of packet Pkt(C) with characteristics C by function $Fbadt$, $Fbadt \neq Fhdrt$ The switch changes the payload of packet Pkt(C)	**FAULTY**
	$NewPkt = Fbadt(Pkt(C)) \neq Fhdrt(Pkt(C))$ $NewPkt.payload \neq Pkt(C).payload$	**FAULTY**
Data Plane Table Generation	The switch generates data plane tables according to their corresponding control plane tables	
	$\forall Entry \in ControlPlaneTable, \exists Entry' \in DataPlaneTable\ s.t.\ Entry \equiv Entry' \wedge$ $\forall Entry \in DataPlaneTable, \exists Entry' \in ControlPlaneTable\ s.t.\ Entry \equiv Entry'$	
	One of switch S's data plane tables is inconsistent with the corresponding control plane table	**FAULTY**
	$\exists Entry \in ControlPlaneTable, \forall Entry' \in DataPlaneTable, Entry' \not\equiv Entry \vee$ $\exists Entry \in DataPlaneTable, \forall Entry' \in ControlPlaneTable, Entry' \not\equiv Entry$	**FAULTY**
Route Table Generation	The switch computes Route Table using specified routing algorithms based on configuration and received routing information	
	$RouteTable = RouteCompute(Configuration, RecvRoutingInformation)$	
	The switch's Route Table is inconsistent with the result computed from the configuration and received routing information	**FLTY**
	$RouteTable \neq RouteCompute(Configuration, RecvRoutingInformation)$	**FLTY**
Route Advertisement Reception	The switch computes received routing information based on configuration and inbound route advertisements	
	$RecvRoutingInformation = RouteAdvReception(Configuration, InboundRouteAdv)$	
	Switch's received routing information is inconsistent with the result computed from configuration and inbound route advertisements	**FLTY**
	$RecvRoutingInformation \neq RouteAdvReception(Configuration, InboundRouteAdv)$	**FLTY**
Route Advertisement Generation	The switch generates outbound route advertisements based on configuration and Route Table	
	$OutboundRouteAdv = RouteAdvGeneration(Configuration, RouteTable)$	
	The switch's outbound route advertisements are inconsistent with the result computed from configuration and Route Table	**FLTY**
	$OutboundRouteAdv \neq RouteAdvGeneration(Configuration, RouteTable)$	**FLTY**
Interaction with External Entities	The switch responds to messages from external entities following protocols and configurations	
	$Response(InboundMessage, Configuration) = ProtocolMessage$	
	The switch responds to messages from external entities with Incorrect messages or it has no response to messages	**FAULTY**
	$Response(InboundMessage, Configuration) \neq ProtocolMessage \vee$ $Response(InboundMessage, Configuration) = Null$	**FAULTY**

TABLE III
THE NOTATION USED IN TABLE II.

Symbol	Semantics
S	A state of the switch's packet buffer
P	The set of all the switch's interfaces
Q	A set of switch interfaces, $Q \subset P$
C	A set of packet characteristics
Fhdrt	Packet header transformation function
DataPlaneTable	Forwarding & filtering data plane tables
ControlPlaneTable	Routing & filtering control plane tables

IV. PRIMITIVES AND PROCEDURES

This section describes, at a high level, the derivation of diagnosis primitives and procedures for model-based diagnosis. The next section presents the instantiation of these primitives and procedures in *NetDx*, our proof-of-concept implementation of a model-based network diagnosis tool.

Diagnosis is triggered by an end-to-end (host-to-host) failure report. A report is generated as a result of unexpected application behavior due to excessive rates of dropping or corruption of data packets by the network. Such reports are expected to contain information regarding the identity of source and destination hosts and possibly other packet characteristics, such as destination port number.

The diagnosis process must ultimately identify the switch or link whose behavior diverges from the expected correct behavior (§III) and is thus the *root cause* of the network failure. The following two requirements must be met in order to enable the detection of such divergences:

R1) *Primitives* (mechanisms) to collect from the operational network information that distinguishes faulty functionality from fault-free functionality, as defined in Table II.

R2) A way to derive from the *network model* information that is comparable to the information collected from the network and can thus be used to identify which parts of the collected information is incorrect.

R1 can be met by inspecting Table II. The first category in the table requires primitives for collection of information that indicates whether packets are dropped by a switch and what are the header characteristics of those packets. The second category requires primitives to retrieve packet headers at ingress and egress switch interfaces. Categories 3-6 require primitives to retrieve data from the switch's data and control plane tables. Category 7 requires primitives to capture packets exchanged between the switch and other entities.

The description of the required capabilities of the primitives is a starting point for the design and implementation of primitives for a diagnosis system. Implementation complexity, resource requirements, and impact on the normal operation of the network are key considerations for the choice of primitives. The next section describes the primitives used by *NetDx*.

Requirement **R2** can be met using configuration analysis tools, such as Batfish [28]. Based on switch configurations, network protocols, and network topology, such tools can answer queries regarding the correct network state as well as the possible ways in which packets are forwarded and routes are propagated.

The failure reports that trigger diagnosis contain information (packet characteristics) that is used to identify the location of data packet drops. However, the "path" from the root cause fault to this location may involve a multi-step chain of *symptoms*, where each symptom is a divergence from fault-free behavior. These divergences are not necessarily packet drops. For example, a symptom may be a switch that sends an incorrect route advertisement despite having a correct RIB and correct configuration. To locate the root cause fault, the diagnosis procedures must identify the packet drops and then trace back through the chain of symptoms.

Packets that, according to the *network* model, should not be dropped, may be dropped by a *fault-free* switch, *S*. This may occur if these packets are actually not supposed to reach *S*, or due to the failure of the rest of the network to provide to *S* routes required to handle the packets.

To cover the scenarios above, where a fault-free switch proactively drops packets, the diagnosis procedures must be able to obtain from a switch information indicating *why* packets are dropped. Thus, the system must include primitives for retrieving this information. Since the switch may, in fact, be faulty, this information cannot be trusted. Thus, every diagnosis step that uses information from one switch to transfer attention to another, must collect information from both switches and validate both using the network model.

If only a *single* switch in the network may be faulty at any time, potential diagnosis ambiguities can be resolved. Since the type of faults we consider (hardware faults and firmware or software Heisenbugs [31]) are rare, simultaneous multiple faults are highly unlikely. Furthermore, §IX shows that the diagnosis procedures are robust and are highly likely to correctly handle two simultaneous faults.

In summary, the diagnosis procedure is a recursive process that begins by locating a switch or link where packets with the characteristics identified in the failure report are dropped. Next, the procedure determines whether the drops were the correct local action. If not, the switch is identified as faulty. Otherwise, the focus shifts to the switch that forwarded the packets to the current switch, or to a switch that provided an incorrect route or failed to provide a required route.

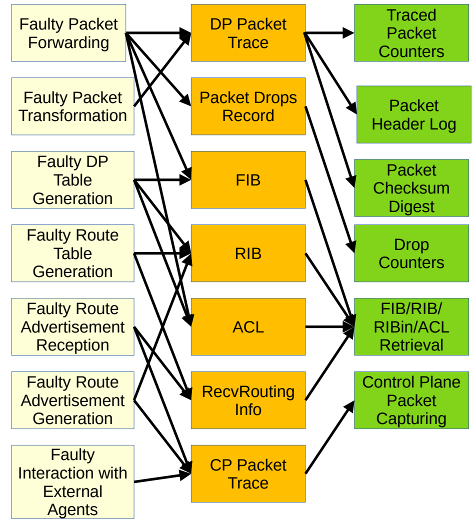

Fig. 1. Derivation of *NetDx*'s diagnosis primitives. DP: data plane. CP: control plane.

V. *NetDx's* PRIMITIVES & PROCEDURES

NetDx is a proof-of-concept implementation of model-based diagnosis instantiated for IPv4/BGP networks. This section describes the instantiation of efficient diagnosis primitives and procedures for this network type. Implementation details are provided in §VI.

A. *NetDx's Diagnosis Primitives*

Since packet forwarding and the processing of routing information is done by the switches, the data that indicates what is happening in the network is either stored on the switches (e.g., tables) or passes through the switches (e.g., data packets and route advertisements). Thus, overhead is minimized by basing diagnosis on data normally maintained by switches (FIB, RIB, ACL) as well as data collected by specialized mechanisms regarding packets that pass through the switch. As described below, this is the basis for the primitives used by *NetDx*.

Figure 1 shows the derivation of the diagnosis primitives. The left column entries are the seven fault categories in Table II. The middle column entries are the sources of information needed to diagnose particular faults. The right column entries are the *NetDx* primitives used to collect the different categories of diagnosis information.

The first step of the diagnosis process is to identify the switch or link where packets are dropped. This can be done by comparing counts of outgoing and incoming packets. Since a low rate of packet loss is generally acceptable, simply identifying some packet loss is not sufficient. The failure report typically specifies some specific flow characteristics (header 5-tuple) and those flows may account for only a small fraction of the total network traffic. Thus, the task is to identify the switch or link where the rate of packet loss from the flows of interest (*FoIs*) exceeds a given threshold. Hence, there is a need to collect incoming and outgoing counts of packets from the FoIs.

NetDx requires that switches include counters at ingress and egress interfaces that count only FoIs packets. Hence, edge switches must be configurable to set a *trace bit* (similar

TABLE IV
NetDx's DIAGNOSIS PRIMITIVES.

Mark packets of interest at network edge as *traced packets*	
Traced Packet Counters	Drops: no forwarding,ACL,IP header corruption, 0-TTL,congestion
	Link silent drop detector
	Switch silent drop detector
Log of recent traced packet headers	
Log of recent dropped traced packet headers	
Table lookup/retrieval: ACL, FIB, RIB, RIB-in, RIB-out	
Packet injection	
Capture of control plane packets	
Alerts for high-frequency switch state changes: FIB, RIB, connections	
Alerts for resource exhaustion: ACL/FIB/RIB entries, CPU load	

to Everflow's *debug bit* [60]) in packet headers matching a given pattern. The counters in every network switch count only packets, henceforth *traced packets*, where the *trace bit* is set. For meaningful count comparisons, the ingress and egress counts of every switch or link must be from a consistent snapshot [18], [56]. However, consistency is needed only for one switch or one link, not the entire network (see §VI-A).

Since packets may be dropped by a fault-free switch (§IV), once a drop location is identified, additional information is needed to determine whether the fault is local. This is done based on the fact that a fault-free switch may drop packets for several reasons: (1) ACL deny, (2) no matching forwarding entry, (3) the packet's TTL is 0, (4) incorrect IP header checksum, and (5) congestion. In all of these cases, there is an explicit decision by a fault-free switch to drop a packet. Hence, *NetDx* requires the switch to maintain *drop counters* that count the traced packets dropped for each of these reasons.

Table IV presents *NetDx*'s diagnosis primitives. In addition to the facilities described above, they include primitives to retrieve FIB, RIB, and ACL information. Diagnosis of some faults, such as incorrect TTL modification, require examination of packet headers. Hence, switches maintain locally and provide access to short logs of headers of recently-forwarded and recently-dropped traced packets. Arbitrary incorrect modifications of packets performed by a link are detectable by the Layer 2 CRC code. To facilitate diagnosis of arbitrary incorrect payload modifications by switches, switches compute and provide access to payload checksums of specially-marked packets. To facilitate diagnosis of incorrect route advertisements, switches can capture and provide access to routing packets sent to or from the control plane. There are additional details regarding the use of these facilities in §VI-B.

B. NetDx's Diagnosis Procedures

NetDx's diagnosis procedures are derived systematically, tracing the steps of network operation in reverse order. The multi-step incremental diagnosis procedure begins with configuring switches at the network edge or the source of the FoIs specified in the failure report to set the trace bit for the FoIs. It proceeds with identifying the location of FoIs packet drops and ends with the location of the root cause failed switch or link.

The diagnosis process is controlled by a *diagnosis manager* running on a host in the network. It is able to retrieve the collected information from any switch. The drop counters

```
configure network entry points to mark packets of interest
identify location of packet drops
if (CAT(packets not supposed to be forwarded through location))
  recurse -- change focus to sending neighbor switch
switch(classification packet drops cause)
  case (ACL deny):   diag ← current switch is faulty
  case (IP checksum error):   diag ← link or its end points
  case (zero TTL):
    back trace packet path from drop location
    if (loop caused by incorrect forwarding)
      recurse -- change focus to mis-forwarding switch
    else
      diag ← switch incorrectly decrementing TTL
  case (silent drops):
    diag ← dropping switch OR link or its end points
  case (no forwarding):
    if (there is a forwarding entry for packet)
      diag ← current switch is faulty
    if (there is a routing entry for packet)
      diag ← current switch is faulty
    if (routing entry for packet received (filtered RIB-in))
      diag ← current switch is faulty
    diagnose(CAT(for providers of relevant routes)) AND
      routes to/from them and current switch
```

Fig. 2. *NetDx*'s diagnosis procedure. CAT: Configuration Analysis Tool.

guide how diagnosis proceeds. For example, *ACL deny drops* in switch S1 of packets forwarded by switch S2 cause the diagnosis manager to *query* Batfish whether the traced packets should ever be forwarded by S2 to S1. A positive answer indicates that the problem (fault or configuration error) is on S1. A negative answer shifts the diagnosis focus to switch S2, to determine why packets were forwarded incorrectly. Thus, once the location of packet drops is identified, at every point in the diagnosis process a particular switch is the current *switch under test* (SUT). The identity of the SUT shifts to different switches as diagnosis proceeds.

The most complex diagnosis tasks involve both the data plane and control plane. In these cases, the switch where the packets are dropped has a high value of the *no matching forwarding entry* drop counter. This triggers a sequence of steps that include a query of whether the switch is supposed to handle the FoIs, followed by examination of the FIB, RIB, and RIB-in. These steps may indicate routing information that had been received by the switch was not processed correctly, pointing to a fault in the switch. However, these steps may also indicate that the expected routing information has not been received. In this case, this triggers steps that involve routing peers (neighbors) that are supposed to provide the expected routing information.

The high-level flow of the diagnosis procedure of *NetDx* is shown in pseudocode in Figure 2.

A key feature of *NetDx* is that the diagnosis process is *automated*. This is enabled by scripts executed by the diagnosis manager. The scripts are triggered based on failure reports from users, such as excessive packet drops for a particular flow. The scripts then use the primitives iteratively to localize the root cause to a switch or a link. The scripts require information regarding the topology and configuration of the network. This information is obtained for the scripts on demand by the

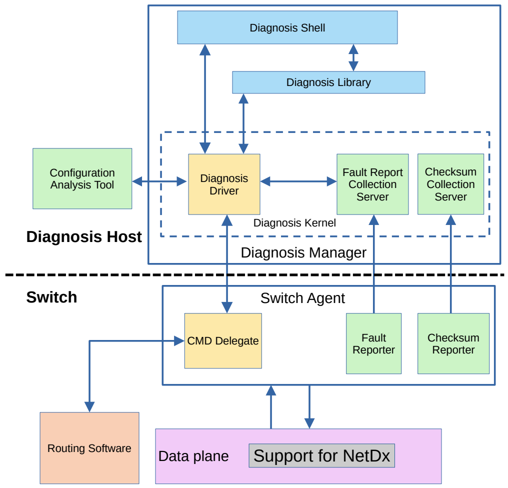

Fig. 3. *NetDx* architecture.

diagnosis manager from the configuration analysis tool.

The diagnosis scripts are written manually, requiring an understanding of switch functionality, network protocols, and *NetDx*'s diagnosis primitives, Hence, the development of scripts involves significant human effort. However, this is a one-time cost; once the scripts are written, diagnosis of network failures is automated. For example, Appendix A shows the workflow of the diagnosis procedure for the case, mentioned above, where packets are dropped due to *no matching forwarding entry*. This entire diagnosis procedure is performed automatically by *NetDx*, starting with only a failure report indicating that there are dropped packet on some FoIs.

VI. Implementation of *NetDx*

The diagnosis procedure described in §V-B requires a system that collects data on the switches and then processes it in a coordinated manner. This section describes an implementation of such a system. The architecture of the system is shown in Figure 3. It includes data plane primitives implemented on the switches, described in §VI-A; a *NetDx switch agent* and related software executed by the CPU on each switch, described in §VI-B; and a *diagnosis manager* executed on a host in the network, described in §VI-C. There is a special challenge with *NetDx* to handle a failure of the diagnosis manager to communicate with a switch during diagnosis; §VI-D presents our solution to this problem.

Based on real world network faults (§IX-A), we concluded that, within the framework of *NetDx*, there is a need for specialized detectors of anomalous switch behavior that is otherwise difficult to detect. These detectors operate *locally* on the switches, generating fault reports to the diagnosis manager as needed. As described in Appendix B, they include detectors for high rate route oscillations and for resource exhaustion. They are part of our implementation, but we have so far not implemented diagnosis scripts that use their results.

A. Data Plane Support for Diagnosis

NetDx requires special features of the switch data plane that facilitate the collection of diagnosis information. These features can be implemented in hardware. Our prototype is designed for programmable switches and the required functionality is implemented using the P4[17], [8] programming language. Our implementation consists of 1432 lines of P4. It should be noted that, if the required data plane functionality is implemented in some other way, switch programmability is not necessary for *NetDx*.

Packet Drop Counters: Switches are designed to deliberately drop packets when specific conditions related to the packet and the switch state are met. The switches can record such events. Specifically, *NetDx* requires every switch to maintain, at each ingress port, four counters that count the *traced packets* that are dropped due to the following four reasons: no matching forwarding (FIB) entry, ACL deny, zero TTL, and incorrect IP header checksum. A sliding window mechanism is used to restrict the counts to recent packet drops.

Fault Report Triggers: The first step of the diagnosis process is to identify the location where *affected data packets* (henceforth, ADPs) are dropped. To minimize the latency of this step, when *traced packets* are deliberately dropped by a switch, as described above, the switch sends a *fault report* (§VI-B) to the diagnosis manager. This operation is triggered by the data plane. To avoid frequent false positives, this trigger is generated only if, during a time window, the ratio of dropped *traced packets* to all arriving *traced packets* exceeds a given threshold. An additional condition for the trigger is that the number of *traced packets* received by the ingress port during the time window must exceed another threshold. The latter condition avoids the situation where, for example, a fault report is triggered as a result of a time window during which only one *traced packets* is received and it is dropped.

After a deliberate packet drop, if the conditions for a fault report are met, the switch control plane is notified (triggered). This is done by forwarding a modified version of the packet to the switch CPU. The CPU (§VI-B) sends the fault report to the diagnosis manager.

Traced Packet Counters: Counters of *traced packets* are maintained at every switch ingress and egress port. A sliding window mechanism is used to restrict the counts to only recent packets. These counters are used for silent packet drop detection as well as for tracing the routes of FoIs.

Silent Drop Detection: Packets may be silently dropped by a switch or link. The use of the *traced packet counters* to detect silent drops is complicated by the fact that packets are buffered within a switch. Thus, even if there are no packet drops, the sum of ingress counter values is likely to be larger than the sum of egress counter values. Furthermore, it is not possible to read the values of multiple counters on a switch or the counters on two adjacent switches at exactly the same time.

For drop detection within switches, the problem of inconsistent counters is solved by relying on the ability of the switch to attach to packets meta data that is maintained only within the switch. Specifically, at each ingress port, the current switch time stamp is attached to each packet. When the packet exits the switch, this time stamp is used to update the *virtual* clock at the egress port through which the packet is transmitted. Traced packet counts during two time windows are maintained at each port. These time windows are based on the switch clock at the ingress ports and the virtual clocks at the egress ports, This allows sums of consistent counts to be computed and used to detect silent drops within switches.

Detection of silent drops on a link is based on special *marker packets* that are sent by the switch agent and processed by the data planes of adjacent switches. Specifically, the diagnosis manager initiates the process by sending a command to the switch agent of one of the switches. That switch agent sends the *marker packet* to the adjacent switch. At the egress port of the first switch, the current *traced packet* count is recorded in the *marker packet*. The adjacent switch ingress port intercepts the *marker packet*, records its *traced packet* count on the packet, and sends it back to the switch agent of the first switch. Packet drops on the link are detected based on the two counts on the marker packet.

Local Packet Header Logs: Each switch maintains short logs of packet headers at its ports. At each ingress port there is a header log of the most recent *traced packets* received at that port. There is also a header log of the most recent dropped *traced packets* received and deliberately dropped at that port. For each egress port, there is a header log of the most recent *traced packets* transmitted from that port. Each log entry contains, in addition to the packet header, meta data such as the header length and the reason for the packet drop.

Local Packet Mirroring to the Control Plane: To allow switch control plane software to process select packets forwarded by the switch, the data plane mirrors to the control plane packets in which the DSCP field of the IP header is set to $0x14$. As described in §VI-B, this enables fast diagnosis of packet corruption.

It should be noted that the local logging of packet headers and the very limited mirroring of packets described above are *local* to the switch. The packet header logs are small (on the order of ten) and are only used in rare cases during diagnosis (diagnose drops due to TTL=0). Local packet mirroring is used only for very few packets (less than ten) injected only during rare diagnosis procedures (currently only used for diagnosing packet corruption).

B. The Switch Agent

The switch agent is executed by the switch CPU and provides the interface between the diagnosis manager and the switch. It interacts with both the switch data plane and control plane. As shown in Figure 3, it consists of three modules: the command delegate, the fault reporter, and the checksum reporter. The switch agent is implemented in 978 lines of Python code.

The actions of the command delegate are initiated by commands from the diagnosis manager. It performs the following functions: retrieve data plane counter values, FIB entries, and ACL entries; retrieve control plane RIB, RIBin, and RIBout entries; capture routing packets sent to and from the control plane; send information it retrieves to the diagnosis manager; command the data plane to perform functions such as marking packets as *traced packets* as well as performing a test for silent packet drops on a switch or link (§VI-A). The command delegate can also relay commands from the diagnosis manager to another switch. As discussed in §VI-D, this is used for handling situations where network failure prevents the diagnosis manager from connecting to some switches.

The fault reporter receives packet drop notifications from the data plane (§VI-A) and relays them to the diagnosis manager. To avoid fault report storms, after sending a fault report, the fault reporter sets a flag in the data plane that disables further drop notifications. The diagnosis manager eventually unsets this flag via the command delegate.

The checksum reporter is used for diagnosing corruption of packet payloads. This diagnosis involves injecting packets with the DSCP field set to $0x14$, which are then mirrored at every switch to the control plane (§VI-A). The checksum reporter receives these packets and sends a limited number of checksums to the diagnosis manager. The diagnosis manager uses these checksums to identify the corruption location.

Once a failure report is received, diagnosis requires packets matching the FoIs' characteristics (5-tuple) to be continuously transmitted. However, the packets' source may be remote and under different administrative control. Hence, there is need to be able to inject at a data center edge switch packets that match the ADPs. This injection is performed by the switch agent, triggered by a command from the diagnosis manager.

C. The Diagnosis Manager

The diagnosis manager is executed on a *diagnosis host*, where it coordinates the diagnosis process and interacts with the human network operator. The diagnosis manager also interacts with the Batfish [28] configuration analysis tool, from which it obtains responses to queries about what the switches should be doing. The diagnosis manager is implemented in 1688 lines of Python code, while the diagnosis scripts (see below) consist of 1036 lines of Python code.

The diagnosis manager provides an API that allows sending commands to switch agents, receiving information retrieved by switch agents, and interaction with Batfish. Diagnosis is generally performed by scripts that use this API. A command line interface (CLI) allows direct invocations of primitives and scripts as well as the instantiation and invocation of new scripts. Multiple scripts can be stored as a *script library*. Scripts can invoke other scripts. All the diagnoses reported in this paper were performed by such a *diagnosis library*. This library includes a top-level script that is invoked with a description of the failure report and returns a diagnosis.

The fault injection campaign (§IX-C) showed that, in a few outlier cases, *NetDx* failed to produce a diagnosis if the network routing state was in the process of changing. With the *NetDx* scripting mechanism this was easy to fix. Specifically, we modified the top level script to run each diagnosis at least twice with a short delay between runs. The diagnosis process completes only when two consecutive runs yield the same result. Since a diagnosis run typically completes in seconds, the additional latency is not significant. After this modification, all the outlier cases resulted in correct diagnosis results.

D. Handling Disconnected Switches

During diagnosis, the diagnosis manager (**DM**) typically connects to the switch agents on multiple switches. However, network failure may prevent the connection to some of the switches, thus potentially blocking the diagnosis from proceeding normally. To avoid such blocking, the original diagnosis is transformed to a diagnosis of the connection failure between the diagnosis host (**DH**) and the disconnected switch (**DS**). This failure may indicate that **DS** is faulty but may also be a result of faults on other switches. Thus, as described below, *NetDx* includes a special procedure to handle this scenario.

DH is assigned two IP addresses: the *primary* (*PIP*), that is used normally, and the *secondary* (*SIP*), that is used as described below. Throughout the network, the configuration of routing to these two IP addresses is normally identical. The procedure is based on forming a *statically-routed path* (henceforth, *SRP*), composed of a sequence of static routes, between **DH** and **DS**. This is done using **DH**'s *SIP* and *SIP*s assigned to the switches as needed by **DM**.

Upon failure of **DM** to connect to a switch, it initiates diagnosis of this failure. This is done hop-by-hop, starting from the switch closest to **DH**, along a path acquired by querying Batfish, using *PIP*s. At each hop, static routes are added between **DH**'s SIP and the SIP that is to be assigned to **DS**. This phase of the procedure identifies the disconnected switch closest to **DH** along this route. If this switch is not the original **DS**, the procedure is recursively invoked with the switch closer to **DH** now being the focus. We denote by **N** the physical neighbor switch of **DS**, which is closer to **DH** on the route from **DH** to **DS**.

Since **DS** and **N** are physical neighbors, they can communicate regardless of routing, unless one of them or the link between them is faulty. Based on the procedure described above, **DM** can connect to **N** using their *PIP*s. The command delegate on **N** is used to relay commands from **DM** to **DS**. If **N** is unable to connect to **DS**, this locates the fault to **DS**, **N**, or the link between them. Otherwise, using this mechanism, **DM** attempts to cause **DS** to install a static route from itself to **DH**'s *SIP* via **N**. This ensures that packets from **DS** to **DH** are not routed on a path that may include a faulty switch. As a result, **DH**, using its *SIP*, is able to communicate with **DS**.

After the steps above, **DM** initiates the diagnosis of a connection failure from **DH** to **DS**'s *PIP* and then from **DS** to **DH**'s *PIP*. For this diagnosis, **DM** uses **DH**'s *SIP* to communicate with the switch agent on **DS**.

VII. The *Podnet* Emulation Platform

The implementation of *NetDx* required a network with data and control planes that are as close as possible to those of a real network. It also required the ability to easily modify the data and control planes as well as to later be able to test the operation of *NetDx* under a variety of faults. These requirements mandated the use of a simulated or emulated network. To facilitate data plane modifications, switches with programmable data planes [17] were the obvious choice. For a realistic control plane, it was desirable to use routing software that is also used in real networks. As in real networks, an independent instance of this software must run on each switch.

Based on the above considerations, available existing tools [41], [6], [26], [12] were not suitable for our purpose.

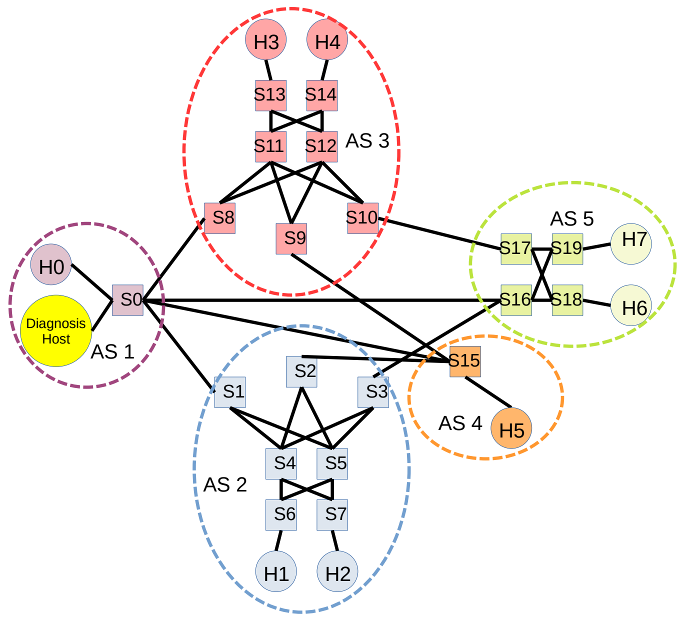

Fig. 4. Topology of the network used in §VIII and §IX.

This led to the development of *Podnet*, an emulator of a network of switches with data planes that are programmable using P4 [17] and a control plane based on FRR [2]. Since both P4 and FRR are used in real networks and *NetDx* is operational on *Podnet*, it is expected that our *NetDx* implementation can be ported to a real network with limited effort. Appendix C presents additional details regarding *Podnet*.

VIII. *NetDx* Diagnosis Example

To further explain the operation of *NetDx*, this section describes the diagnosis by *NetDx* of an example fault. We use a network whose topology is shown in Figure 4, emulated on *Podnet* (§VII).

The fault is that the IGP and BGP routing daemons of switch S10 (AS-3) crash (fault class 7 in Table V). As a result, switch S17 (AS-5) withdraws the routes to AS-3 and AS-4 from the switches in AS-5. AS-3 and AS-4 switches still have routes to AS-5 through AS-2. However, due to policy configurations, S0 (AS-1) and S3 (AS-2) do not advertise to AS-5 routes to ASes other than themselves. Hence, AS-5 switches do not have any routes to AS-3 and AS-4. Thus, communication between hosts H7/H6 (AS-5) and hosts H3/H4/H5 is disrupted.

We injected the fault above by killing the routing daemons on switch S10. As a result, a user-level failure report indicated that host H7 cannot reach host H3. In response, *NetDx*'s top-level diagnosis script was invoked, specifying the source and destination hosts. The diagnosis script configured switch S19 (AS-5) to set the trace bit of packets from H7 to H3. On switch S19, the *no forwarding entry drop counter* value exceeded the threshold and the switch sent a fault report to the diagnosis manager (**DM**). As a result, the script on **DM** invoked the *diagnose no forwarding drop* script, targeting switch S19. The script retrieved routing information from switch S19 and determined that the required route was missing. The script then queried Batfish for the switches that were supposed to propagate the route to S19 and the response pointed to switch S17 (AS-3).

Based on the above, the script invoked the *diagnose bgp route adv missing* script, targeting switch S17. This script retrieved routing information from S17 and found that S17 did not have the route. By querying Batfish, the script found that S10 (AS-3) should provide the route to S17. The script retrieved status information regarding S10 from S17 and found that the BGP connection between S17 and S10 was down. This caused the invocation of the *diagnose bgp routing neighbor down* script targeting S17 and S10. The script attempted to establish a TCP connection with S10. Since the routing daemon on S10 had crashed, the rest of the network lost routes to S10 and this attempt failed.

Due to the failure to connect to S10, the diagnosis script invoked *diagnose connectivity loss of switch* script (§VI-D), with S10 as the "disconnected switch" (**DS**). As described in §VI-D, this ended up with the invocation of the script to diagnose packet drops between the diagnosis host (**DH**) and S10. This involved configuring S0 (AS-1) to set the trace bit packets destined to S10. After a short delay, **DM** received from S0 a *no forwarding entry* packet drop fault report. This led to a new invocation of the *diagnose no forwarding drop* script, targeting S0. This script ultimately determined that S10 should provide a route for itself to its neighbors while it does not. This led to the script attempting and failing to retrieve routing information from S10, identifying S10 as the root cause.

IX. Evaluation

This section presents preliminary evaluation and validation of *NetDx*. It involved injection of faults using *Podnet* and the execution of the diagnosis script by *NetDx*. The experiments used an emulated network, whose topology is shown in Figure 4, consisting of five autonomous systems, twenty switches, and nine hosts. We collected a set of faults that were detected in a production network of a major cloud service provider. The fault set and the a summary of the diagnosis coverage of *NetDx* is presented in §IX-A. The fault used as an example in §VIII is based on one of the faults in this fault set. In practice, network diagnosis is often done manually by network operators, using tools such as ping and traceroute. A comparison of the diagnosis of the fault in §VIII with *NetDx* vs. manual diagnosis is presented in §IX-B. An automated fault injection campaign and its results are presented in §IX-C.

A. Collected Fault Set

Table V presents a set of 52 faults that were detected and diagnosed in the enterprise network of a major cloud service provider over multiple years. These faults are grouped into 15 equivalence classes. The collected data included 16 faults, excluded from Table V, that were automatically detected and corrected by built-in mechanisms on the switches and thus did not require external diagnosis. The faults in classes 1, 2, 3, and 11 involved only the data plane. The diagnosis of the faults in classes 4-10 and 13-15 also involved the control plane.

Out of the 52 faults in Table V, 19 faults are currently not within the scope of *NetDx*, as defined in §I. These include faults in classes 10, 11, 12, which, respectively, involve overlay networks, cause packet delays rather than packet drops, or are transient faults. In addition, the six faults in class 9 are also not within the current scope of *NetDx*, since *NetDx* does not have the mechanisms for diagnosing the root causes of congestion. The eight faults in class 13, 14, 15 were configuration errors, which are handled by network verification tools [13], [28], [39], [27], [43], [57], [53] and are thus not targets for a tool focused on diagnosing hardware and software faults in operational networks.

TABLE V
A FAULT SET COLLECTED FROM A MAJOR CLOUD SERVICE PROVIDER.

Fault Class	# of Faults	Description
1	18	A switch failed and dropped packets.
2	2	A link failed and droped packets.
3	6	A switch or a link corrupted packets.
4	1	Software fault caused installation of ACL rules to fail.
5	1	Routing software crash caused routes missing.
6	1	BGP route table was inconsistent because of software fault.
7	1	FIB entry corrupted by data race of software.
8	3	Route oscillation caused intermittent route missing.
9	6	Faults that require primitives for diagnosing congestion.
10	3	Faults that need emulation for overlay network.
11	1	A hardware fault that caused extremely high delay on a switch rather than packet drops.
12	1	The effect of the fault was transient.
13	3	Route filter configuration errors caused routes missing.
14	1	An incorrect configuration change caused BGP connections down.
15	4	Packets were denied by ACL due to ACL configuration errors.

There are 33 faults that are potentially within *NetDx*'s domain in equivalence classes 1-8. For each class, we injected a fault in our emulated network that reproduces the effect of the fault on the switches and links. In each case, the input to *NetDx* corresponded to the failure report that a user would provide to the network operators. Specifically, this input identifies the affected flows by providing source, destination, and possibly other packet characteristics. In all eight cases, the diagnosis script executed by *NetDx* identified the fault that was root cause of the failure. However, three out of the 33 faults were intermittent and there were no records regarding their frequency. Hence, we could not determine whether they could be diagnosed by *NetDx*. To be conservative in our reporting, we count them (3 out of 33) as diagnosis failures.

B. Comparison with Manual Diagnosis

We used the example described in §VIII to compare *NetDx* with manual diagnosis. We asked three Computer Science Ph.D. students whose research focuses on computer networks and are unaffiliated with our group to act as three independent operators to perform the manual diagnosis. We informed them of the end-to-end failure report above. They were allowed to use ping and traceroute on any host or switch to probe any destination and they also had access to all switches. We also ran *NetDx*'s diagnosis script that produced the diagnosis automatically.

For comparison, we measured the time to reach diagnosis and the number of commands invoked: Person 1: 33:48 minutes, 38 commands; Person 2: 26:32 minutes, 32 commands; Person 3: 14:44 minutes, 18 commands; *NetDx*: 1:38 minutes, 77 commands (primitives).

As expected, manual diagnosis was much longer. Moreover, this experimental setup artificially increases *NetDx*'s diagnosis time since *Podnet*, where every switch is a complex simulator, is extremely slow. In a real enterprise network, where packet latency is, at most, a few milliseconds, *NetDx*'s diagnosis time would certainly be less than five seconds. There are also many factors that impact the manual side of the experiment. For example, while our testers are knowledgeable regarding networks, they are not experienced network operators. However, it should be noted that the fault used in this experiment is based on a real fault that happened in the global WAN of a major cloud service provider. It took them more than 30 minutes to identify the faulty switch.

C. Fault Injection Campaign

To test the coverage and robustness of *NetDx*, we developed an automated fault injection campaign as described below. In the first part of the campign, only a single fault at a time was injected. While it may appear that nothing can be gained by injecting faults from the fault model used to derive the diagnosis procedures, this was invaluable for enhancing some of the diagnosis procedures (§VI-C), identifying and correcting bugs in our implementation, and estimating the latency of diagnosis (§IX-C2). In the second part of the campign two simultaneous faults were injected. Since *NetDx* was developed to handle only a single fault at a time, the goal was to check its ability to handle more complex scenarios.

1) Experimental Setup: We built a test harness on *Podnet* (§VII) that injects faults in a network and evaluates the *NetDx* diagnosis outcomes for these faults. The harness is based on a setup similar to Pingmesh[32] consisting of processes executing on all the hosts, sending ICMP probes to all other hosts. If one of these processes detects multiple consecutive dropped probes, it sends a failure report to an *injection campaign controller* running on the diagnosis host. Each pingmesh process is limited to sending at most one failure report until it is reset. The communication between the pingmesh processes and the campaign controller is out of band, so that it is not affected by the fault injection. The campaign controller can cause the injection of ten different fault types on any of the switches.

It is important to note that Pingmesh and the *injection campaign controller* are not part of the diagnosis process and are **not part of *NetDx***. In this setup Pingmesh is used to represent a user who reports an end-to-end (host-to-host) network failure.

An injection run begins with the campaign controller using the facilities of *Podnet* to inject one or two faults in switches. The controller then waits a specified amount of time to receive failure reports from the pingmesh processes. If multiple failure reports are received, one of them is selected at random to invoke the top-level *NetDx* diagnosis script. When a diagnosis result is produced by *NetDx*, it is compared to the known fault injection locations to determine whether the diagnosis is correct. The fault is then reversed (undone) and the pingmesh is reset. If two faults were injected, a new diagnosis run is initiated to diagnose the second fault. Otherwise, a new injection run is started.

TABLE VI
FAULT INJECTION CAMPAIGN RESULTS.

Fault Type	#primitives	#fault reports
SilentDropInSwitch	27	0
SilentDropOnLink	22.3	0
CorruptionOnLink IP	142.0	10
IncorrectDecrementTTL	27.6	10
PacketPayloadCorruptionInSwitch	22.3	0
IncorrectForwardingDrop	33.2	10
FIBDiscrepancy	24.1	8
IngressBgpUpdateModification	90.5	10
BgpNeighborMissing	131.5	8
EgressBgpUpdateModification	108.1	10

2) Fault Injection Campaign Results: Table VI shows ten fault types that cover all the categories in the fault model. In the single fault injection campaign, faults from each fault type were injected in a random location until there were ten injections that resulted in failure reports from pingmesh. In the double fault injection campaign, there are 100 injection runs, with two faults injected per run. The types and locations of the two faults are picked at random. In both campaigns all the faults were correctly diagnosed by *NetDx*.

Single fault campaign. Table VI shows the results from the single fault injection campaign. The table shows, for each fault type, the average number of primitives that the diagnosis manager invoked in switch agents to diagnose the fault, as well as the number of diagnoses in which the switch where ADPs were dropped was identified by a fault report from that switch.

The results show that in most cases the switch where ADPs were dropped was identified by a fault report from that switch. This shows the value of the proactive fault reporting mechanism that eliminates the need for the diagnosis manager to retrieve information from many switches just to find the switch dropping the ADPs. Out of the 100 diagnoses, 6 involved dealing with a disconnected switch (§VI-D), demonstrating the need for this mechanism. The "#primitives" column provides information regarding the expected diagnosis latency on a real network. Specifically, each primitive translates to a latency of a network round trip plus the processing time for the primitive on the switch. *Thus, diagnosis latency with a real network will be on the order of,* ***at most, seconds***.

Double fault campaign. In the double fault injection campaign, the diagnosis of each fault pair involved two invocations of *NetDx*. The first invocation identifies one of the faulty switches, that switch is then "repaired," and a second invocation identifies the second faulty switch. A key point is that in first invocation the existence of two faults did not prevent a correct diagnosis result. However, the average number of primitives required for the first invocation was 98.01, while it was only 36.26 for the second. This indicates that the diagnosis of the first fault was a more complex process than that of the second. For example, 11% of the first fault diagnoses required dealing with a disconnected switch, but this was required for only 1.8% of the second fault diagnoses. The proactive fault report mechanism was utilized in 71 out of the 100 double fault injection runs.

X. Discussion

This section summarizes some of the key results and limitations of this work.

Scalability of *NetDx*: Scalability is a key requirement for a network diagnosis mechanism. *MBND* enables scalability by guiding targeted collection of relevant data, avoiding the need to collect information from the entire network. Two key mechanisms of *NetDx* further enhance scalability. (I) The *trace bit* mechanism (§V-A, based on Everflow's *debug bit* [60]) eliminates the need to configure every switch to target the flows of interest. (II) The fault reporting mechanisms in the switches (§VI-A, §VI-B) allow switches with relevant information to proactively send it to the diagnosis manager, eliminating the need for the diagnosis manager to collect information from every switch that *potentially* has relevant information.

Overhead of *NetDx*: A key to the low overhead of *NetDx* is that it avoids packet mirroring and logging to servers as well as piggybacking diagnostic information on normal packets. Only a small amount of data is collected locally on each switch. During diagnosis, only minimal interactions are required between the diagnosis manager and switch agents, involving negligible network throughput.

The cost of developing diagnosis scripts: A limitation of this work is that human experts are required to develop diagnosis scripts. However, as explained earlier (§II), *MBND* enables and guides this development, thus greatly reducing the required human effort. Furthermore, these scripts are developed once and can then be used numerous times in multiple locations, without experts. Importantly, the diagnosis procedures depend only on network protocols, network topology, and switch configurations. They do not depend on the detailed switch implementation. Thus, human experts are required only to support additional protocols, not for every new switch implementation.

Switch hardware requirements: A limitation of *NetDx* is that it requires switches capable of operations (§V-A, §VI-A) that are not all available on many current switches. However, as explained earlier, while *NetDx* is an efficient low overhead implementation of *MBND*, *MBND* can be implemented using different mechanisms for data collection. Furthermore, the data collection requirements of *MBND* can guide future switch developments, suggesting primitives that should be added to ASICs used to implement these switches. Finally, as demonstrated by our prototype, the ability to support a new generation of network diagnosis mechanisms may be a motivation to consider programmable switches.

Evaluation: A limitation of this work is that we were not able to deploy and validate *NetDx* on a real network. However, our prototype implementation does show that an efficient implementation of *MBND* is feasible on existing hardware (P4 switches). The extensive fault injection campaign (§IX-C) demonstrates the robustness of the implementation. While the comparison with manual diagnosis (§IX-B) did not match up *NetDx* with highly-experienced network operator, such operators are often not immediately available in real-world deployments. A key advantage of *MBND* and *NetDx* is that they enable automated diagnosis without such experts.

XI. Related Work

New Data-plane Diagnostic Primitives: Some prior works [42], [46], [33] propose data plane primitives implemented on the switches that enable new queries that allow network operators to inspect subtle network behaviors. Compared to *NetDx*, they can collect finer-grained information at the cost of higher overhead on the switches. They are usually used to analyze network performance issues rather than network failures. Other mechanisms [3], [15], [4], [37], [49], [50] piggyback diagnostic information on packets and require the destination hosts to send the information to collection servers. This involves overhead on the hosts and collection servers, increased network bandwidth use, and potentially require packet fragmentation. None of these mechanism can diagnose control plane faults and the interaction between data and control planes.

Data Plane Log Analysis and Monitoring: Similarly to Cisco's NetFlow [1], these mechanisms log data plane information from switches to collection servers for later diagnosis. In some cases, switches send packet-level information to the collection servers [60], [36], [35], [29]. Spidermon[55] optimizes the collection of logs using wait-for relations for specific performance faults. dShark [58] proposes a data processing engine that facilitates the log analysis. In general, these mechanisms incur high overhead on the switches, networks, and collection servers. Monitoring systems, such as Pingmesh[32] and NetBouncer [51], use servers to send probes across the network to triangulate the location of data plane faults. Dapper [30] and Trumpet [45] also use host-based monitoring but leverage inference algorithms to reconstruct the network state. They are helpful for detecting the symptoms of faults but do not provide root cause diagnosis. Most log analysis and monitoring systems do not focus on control plane faults or the interaction between the data and control planes.

Route Log Analysis: Some works propose tools that analyze routing dynamics in the internet by processing and visualizing logs of BGP updates [40], [22], [16]. These are particularly useful for diagnosing the global WAN, where no single entity can access all parts of the network. They incur high overhead and do not cover data plane faults or the interaction between data and control plane faults.

LLM-based Diagnosis: Some recent works propose the use of Large Language Models to automate diagnosis for cloud systems. NetAssistant[54] uses LLM to automate the interaction between users and the diagnosis system. Since the actual diagnosis is done by proprietary in-house workflows, we cannot compare it with *NetDx*. RCAcopilot[20] only shows the compound F-1 score for diagnosing multi-class distributed systems. It is unclear how effective it is in diagnosing computer networks.

Summary: *NetDx* is advantageous over prior work in providing automation, low overhead, and coverage of data plane and distributed control plane interactions. Further, *NetDx* represents a new top-down model-based paradigm that is completely different from past work which mostly consists of bottom up debugging primitives that must be combined manually by experts to do end to end root cause diagnosis.

XII. Conclusion

This paper introduces *model-based network diagnosis*, a foundation for tools that ***automatically*** identify the root cause of disruptions in operational networks due to switch hardware and software faults. Diagnosis is based on identifying deviations from a formal end-to-end model of packet forwarding and routing. This model is based on network protocols, network topology, and switch configurations. The model is used to derive a functional fault model for switches that describes how switch functionality can be disrupted. This approach is enabled by *leveraging configuration analysis tools* (e.g., Batfish) that provide a representation of the network model that is directly comparable to what is observable on the operational network.

As an example of *model-based network diagnosis*, we implemented *NetDx*, a system that takes a high-level symptom of a network failure as input and automatically pinpoints the root cause failed switch or link. *NetDx*'s diagnosis primitives and procedures are derived systematically from the network model. The novel basis of *NetDx* allows it to diagnose networks with distributed control planes, tracing through interactions between the data and control planes, to identify the root cause of network failures. *NetDx*'s choice of mechanisms show a way to *instantiate* model-based network diagnosis with essentially no performance overhead.

Unlike earlier approaches that use ideas from streaming databases [58] or probabilistic inference [51], *NetDx* uses ideas from the dependability community, such as explicit fault models, minimizing intrusion, and fault injection campaigns [19], [52], [47], [38], [11]. Unlike classical work in the dependability community, however, *NetDx* uses the fact that networks are simple enough computing artifacts to derive what their correct behavior should be.

The evaluation of *NetDx* on a real world fault dataset shows that it is able to diagnose most network failures. An automated fault injection campaign was invaluable in the development of *NetDx* and demonstrates the robustness and coverage of *NetDx*. It also shows that, on a real network, diagnosis can be performed ***in seconds instead of hours***. Future work on *NetDx* includes extending the model-based paradigm to overlay networks, other IP features, and other networks.

Appendix A
No Forwarding Diagnosis Example

Figure 5 shows the workflow of the diagnosis procedure for the *no forwarding* case. *NetDx*'s general diagnosis procedure is applicable to all routing protocols. However, diagnosis of the control plane involves capturing and decoding routing messages. The procedure shown in Figure 5 is specialized to BGP. In one outcome of the procedure in Figure 5, the conclusion is that there is a broken connection with a routing neighbor. This is not the end of the diagnosis procedure. Rather, this triggers an invocation of a procedure to diagnose connectivity between the two routing neighbors. This is a recursive invocation of the same procedure that is initially triggered by the original failure report.

Appendix B
Specialized Anomaly Detectors

As mentioned in §VI, there is a need to implement specialized detectors of anomalous switch behavior that is otherwise difficult to detect. These detectors operate locally on the switches, generating fault reports to the diagnosis manager as needed. Adding such specialized anomaly detectors fits within the framework of *NetDx* and demonstrates the extensibility of the approach. They are part of our implementation (§VI). However, we have so far not implemented diagnosis scripts that use the results of these detectors.

Some faults result in a high rate of route oscillations or oscillations of the connections between routing daemons on the switches. It is relatively simple to modify routing software to count the number of changes of the RIB within a given time window. When the count exceeds a threshold, a potential fault report is sent to the diagnosis manager. Excluding periods when significant network changes are initiated, such reports can help with diagnosis. Similarly, it is useful to identify a high rate of connections and disconnections of, for example, BGP peers.

The second group of detectors monitor resource usage on the switches and report resource exhaustion. We have implemented such detectors of CPU utilization (load average), memory use, and use of FIB entries.

Appendix C
Podnet Details

The Podnet emulation platform is briefly introduced in §VII. This appendix presents additional details regarding its implementation and fault injection capabilities.

A. Network Emulation

To implement the functionality of a P4 switch, we use an existing P4 behavioral simulator [7]. Each *Podnet* emulated switch consists of a P4 simulator instance and an FRR instance. All the processes that make up an emulated switch run in a Linux container (managed by Podman [10]). Parts of *Podnet* are based on Containernet [48], which, in turn, is based on Mininet [41]. However, neither of these two emulators isolates each switch in a container. The architecture of the emulated switch is shown in Figure 6.

The implementation of the emulated data plane requires packets arriving on a virtual network interface of the container to be directed to the P4 simulator. To this end, the P4 simulator captures packets at the interface using libpcap, while those packets are blocked from entering the Linux network stack using iptables. After packets are processed by the P4 simulator, they are forwarded to either the local control plane (data-plane egress interface in Figure 6) or the interface to the next hop. Packets from the switch control plane are redirected to the P4 simulator (control-plane egress interface in Figure 6) using

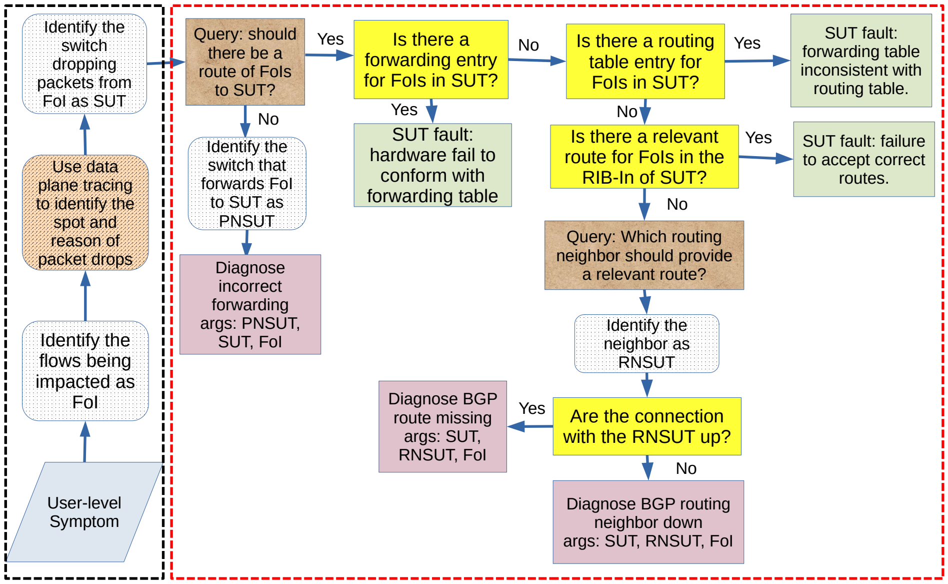

Fig. 5. Diagnosis of packet drops due to no matching forwarding entry. SUT: Switch Under Test; FoI: Flow of Interest; PNSUT: Physical Neighbor of the SUT; RNSUT: Routing Neighbor of the SUT.

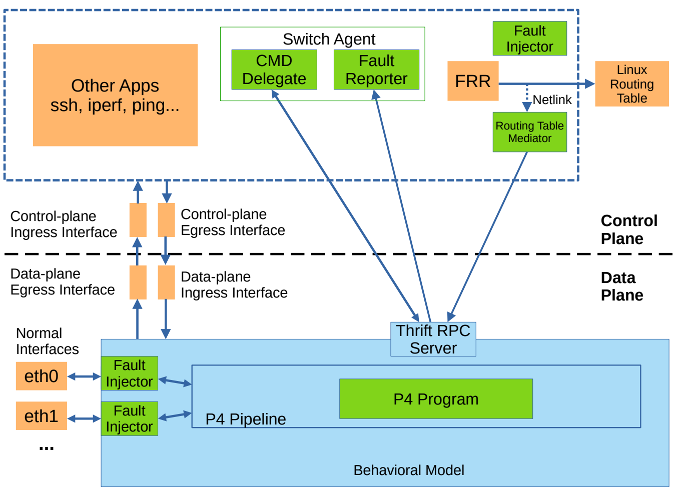

Fig. 6. The architecture of an emulated switch.

iptables. Thus, these packets are forwarded by the P4 simulator to the next hop.

The FRR routing software running on the switch container installs routes into the routing table of the Linux kernel. FRR does this by sending a Netlink [5] route change message to the Linux kernel. *Podnet* includes a *routing table mediator* that monitors route changes in the Linux routing table via a Netlink socket and installs the changes to the forwarding table of the P4 simulator via an RPC interface (Figure 6).

B. Fault Injection

To test and evaluate *NetDx*, *Podnet* includes a fault injector that is able to inject the faults in our functional fault model. Below are examples of how specific faults are injected:

- Silent drop in a switch: activate a special P4 stage that drops packets.
- Silent drop on a link: activate a modification of the packet capturing module in the P4 simulator so that it drops packets.
- No-forwarding drop caused by inconsistency between FIB and RIB: activate a special feature of the routing table mediator that removes an entry in the FIB.
- ACL deny drop caused by incorrect ACL rule: add an ACL rule that denies the particular packets.
- BGP neighbor missing caused by a software bug: use iptables to block BGP packets.
- Incorrect BGP advertisement caused by a software bug: configure iptables to direct packets to an nf-queue monitored by a code that uses libnetfilter_queue. This code captures and modifies BGP advertisements that contain specified routes.

APPENDIX D
MODEL INSTANTIATION FOR IPV4/BGP

A high-level functional model of fault-free and faulty switches is presented in §III. Table VII is an instantiation of this model for IPv4/BGP networks. As in Table II, the instantiation consists of seven functionality categories. For each category there are three rows, where the top row contains the instantiation of the abstract objects, characteristics, or functions for IPv4/BGP. The middle row is a definition of the functionality of a fault-free switch. The bottom row is a definition of the functionality of a faulty switch. The definition of the functionality of a faulty switch is derived by negating the functionality of a fault-free switch. The list of faulty functionalities forms the switch *fault model*.

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TABLE VII

AN INSTANTIATED FUNCTIONAL MODEL OF FAULT-FREE AND FAULTY SWITCHES IMPLEMENTING IPV4 AND BGP PROTOCOLS.

Packet Forwarding	$C_{forward} = FIB(Header.IPv4.DstAddr) = Q \wedge Header.IPv4.TTL \neq 0 \wedge$ $AccessControl(Header) \neq$ Deny $\wedge$ $CheckSum(Header.IPv4) = 0$ $\overline{C_{forward}} = FIB(Header.IPv4.DstAddr) = Null \vee Header.IPv4.TTL = 0 \vee$ $AccessControl(Header) =$ Deny $\vee$ $CheckSum(Header.IPv4) \neq 0$
	$EgressPort(C_{forward}, S_{uncongested}) = p, p \in Q, Q \subset P$ $EgressPort(C_{forward}, S_{congested}) =$ Null $EgressPort(\overline{C_{forward}}, *) =$ Null
	$EgressPort(C_{forward}, S_{uncongested}) = Null$ $EgressPort(C_{forward}, *) = p, p \notin Q$ $EgressPort(\overline{C_{forward}}, *) = p', p' \in P$
Packet Transformation	$C = *$ $Fhdrt(Pkt(C)) = Pkt(C)$, with $SrcMacAddr \leftarrow EgressPortMac \wedge DstMacAddr \leftarrow NextHopMac \wedge$ $TTL \leftarrow TTL_{in} - 1 \wedge Checksum \leftarrow ChecksumCompute(NewHeader.IPv4)$ $Fbadt(Pkt(C)) = Pkt(C)$, with $SrcMacAddr \leftarrow Mac' \vee DstMacAddr \leftarrow Mac'' \vee$ $TTL \leftarrow TTL' \vee Checksum \leftarrow ChecksumCompute'(NewHeader.IPv4)$ where $Mac' \neq EgressPortMac$, $Mac'' \neq NextHopMac$, $TTL' \neq TTL_{in} - 1.5$, $ChecksumCompute' \neq ChecksumCompute$
	$NewPkt = Fhdrt(Pkt(C)) \wedge$ $NewPkt.payload = Pkt(C).payload$
	$NewPkt = Fbadt(Pkt(C)) \neq Fhdrt(Pkt(C)) \vee$ $NewPkt.payload \neq Pkt(C).payload$
Data Plane Table Generation	$ControlPlaneTable \leftarrow RIB_{IPv4}$ & $ACLConfig$ $DataPlaneTable \leftarrow FIB_{IPv4}$ & ACL
	$\forall Entry \in ControlPlaneTable, \exists Entry' \in DataPlaneTable\ s.t.\ Entry \equiv Entry' \wedge$ $\forall Entry \in DataPlaneTable, \exists Entry' \in ControlPlaneTable\ s.t.\ Entry \equiv Entry'$
	$\exists Entry \in ControlPlaneTable, \forall Entry' \in DataPlaneTable, Entry' \not\equiv Entry \vee$ $\exists Entry \in DataPlaneTable, \forall Entry' \in ControlPlaneTable, Entry' \not\equiv Entry$
Route Table Generation	$RouteTable = RIB_{BGP}$ $RecvRoutingInformation = RIBin_{BGP}$ $RouteCompute = BGPRouteCompute$
	$RouteTable = RouteCompute(Configuration, RecvRoutingInformation)$
	$RouteTable \neq RouteCompute(Configuration, RecvRoutingInformation)$
Route Advertisement Reception	$RecvRoutingInformation = RIBin_{BGP}$ $RouteAdvReception = BGPInboundRouteAdvFiltering$ $InboundRouteAdv = InboundBGPUpdateMsg$
	$RecvRoutingInformation = RouteAdvReception(Configuration, InboundRouteAdv)$
	$RecvRoutingInformation \neq RouteAdvReception(Configuration, InboundRouteAdv)$
Route Advertisement Generation	$RouteTable = RIB_{BGP}$ $RouteAdvGeneration = BGPInboundRouteAdvFiltering$ $OutboundRouteAdv = OutboundBGPUpdateMsg$
	$OutboundRouteAdv = RouteAdvGeneration(Configuration, RouteTable)$
	$OutboundRouteAdv \neq RouteAdvGeneration(Configuration, RouteTable)$
Interaction with External Entities	$Response \leftarrow TCPResponse/BGPResponse$ $ProtocolMessage \leftarrow TCPMsg_{SYN-ACK} or BGPOpenMsg/BGPNotificationMsg/BGPRefreshMsg$
	$Response(InboundMessage, Configuration) = ProtocolMessage$
	$Response(InboundMessage, Configuration) \neq ProtocolMessage \vee$ $Response(InboundMessage, Configuration) = Null$

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