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### Adaptive network threat detection in distributed automotive execution environments of connected vehicles

#### Abstract

An intrusion detection and prevention system (IDPS) has detection probes and detection hubs that are deployed onboard a connected vehicle and a detection correlation backend that is deployed on the cloud. A detection probe receives raw packets of network traffic of a communication network of the connected vehicle. The detection probe filters the raw packets in accordance with packet filter rule entries to generate packets of interest. The detection probe scans the packets of interest for data indicative of network threats and outputs corresponding unfiltered detection logs. The detection probe filters the unfiltered detection logs in accordance with detection filter rule entries to generate detection logs of interest. A detection hub aggregates detection logs of interest from one or more detection probes to generate aggregated detection logs. A detection correlation backend evaluates the aggregated detection logs to detect network threats.

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## Background/Summary

### TECHNICAL FIELD

(1) The present disclosure is directed to automotive cybersecurity.

### BACKGROUND

(2) A connected vehicle can communicate with devices or systems that are external to the vehicle. Most new vehicles on the market today are connected in that they have modules that can perform external communication by wireless or wired connection. A connected vehicle may also have sensors for receiving sensed data of its physical environment.

(3) Connected vehicles typically have a plurality of electronic control units (ECUs) that perform various functions. For example, a connected vehicle may have an ECU for the head unit, an ECU for engine management, an ECU for a telematic control unit, etc. ECUs are computers with software and hardware components. More particularly, an ECU has a processor that executes software components, such as an operating system, application programs, and/or firmware. Due to the complexity of ECUs, an original equipment manufacturer (OEM) of a connected vehicle sources one or more ECUs and/or software components thereof from third-party suppliers.

(4) A connected vehicle is susceptible to network threats, which are cyberattacks on a communication network of the connected vehicle. Intrusion detection and prevention systems (IDPSs) have been employed as a security measure against network threats in traditional

information technology (IT) networks. Generally, it is relatively easy to deploy an IDPS everywhere in an IT network including on personal computers, servers in the cloud, routers, proxies, virtual machines, etc., which typically run widely-used operating systems and have sufficient hardware (e.g., processor, storage) resources. In contrast, essential components of a connected vehicle, such as hardware resources, operating systems, and network topologies, can vary depending on the model and the OEM of the connected vehicle. Furthermore, it is relatively difficult to effectively operate and deploy a conventional IDPS in a connected vehicle due to limited hardware resources, restricted network accessibility, and highly customized operating systems of a typical connected vehicle.

#### BRIEF SUMMARY

(5) In one embodiment, an intrusion detection and prevention system (IDPS) has detection probes and detection hubs that are deployed onboard a connected vehicle and a detection correlation backend that is deployed on the cloud. A detection probe receives raw packets of network traffic of a communication network of the connected vehicle. The detection probe filters the raw packets in accordance with packet filter rule entries to generate packets of interest. The packet filter rule entries describe selected packets to be filtered out from the raw packets. The detection probe scans the packets of interest for data indicative of network threats and outputs corresponding unfiltered detection logs. The detection probe filters the unfiltered detection logs in accordance with detection filter rule entries to generate detection logs of interest. The detection filter rule entries describe detection logs to be filtered out from the unfiltered detection logs. A detection hub aggregates detection logs of interest from one or more detection probes to generate aggregated detection logs. A detection correlation backend evaluates the aggregated detection logs to detect network threats.

(6) These and other features of the present disclosure will be readily apparent to persons of ordinary skill in the art upon reading the entirety of this disclosure, which includes the accompanying drawings and claims.

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## Description

#### BRIEF DESCRIPTION OF THE DRAWINGS

(1) A more complete understanding of the subject matter may be derived by referring to the detailed description and claims when considered in conjunction with the following figures, wherein like reference numbers refer to similar elements throughout the figures.

(2) FIG. 1 shows a block diagram of a connected vehicle in accordance with an embodiment of the present invention.

(3) FIG. 2 shows a block diagram of a detection probe in accordance with an embodiment of the present invention.

(4) FIG. 3 shows a block diagram of a detection hub in accordance with an embodiment of the present invention.

(5) FIG. 4 shows a block diagram of a detection correlation backend in accordance with an embodiment of the present invention.

(6) FIG. 5 shows an example deployment of an IDPS with a single detection probe and a single detection correlation backend in accordance with an embodiment of the present invention.

(7) FIG. 6 shows an example deployment of an IDPS with multiple detection probes, a single detection hub, and a single detection correlation backend in accordance with an embodiment of the present invention.

(8) FIG. 7 shows an example deployment of an IDPS with detection probes and a detection hub that are running in virtual machines in accordance with an embodiment of the present invention.

(9) FIG. 8 shows an example deployment of an IDPS with detection probes and detection hubs that are running in separate ECUs of a connected vehicle in accordance with an embodiment of the

present invention.

(10) FIG. 9 shows a state diagram for time synchronization of detection probes, detection hubs, and detection correlation backend in accordance with an embodiment of the present invention.

(11) FIG. 10 shows a sequence diagram of a time synchronization phase state in the state diagram of FIG. 9, in accordance with an embodiment of the present invention.

(12) FIG. 11 shows a flow diagram of a method of detecting network threats in communication networks of a connected vehicle in accordance with an embodiment of the present invention.

#### DETAILED DESCRIPTION

(13) In the present disclosure, numerous specific details are provided, such as examples of systems, components, and methods, to provide a thorough understanding of embodiments of the invention. Persons of ordinary skill in the art will recognize, however, that the invention can be practiced without one or more of the specific details. In other instances, well-known details are not shown or described to avoid obscuring aspects of the invention.

(14) Connected vehicles provide very different execution environments compared to traditional IT networks. In a connected vehicle, an IDPS needs to run with minimal computing power and network bandwidth in various execution environments while processing a large number of packets, which may be normal or malicious. An IDPS in a connected vehicle thus greatly benefits from a customizable, scalable, and adaptive mechanism to throttle packet filtering and to aggregate detection logs, either locally or on demand.

(15) A conventional IDPS usually works independently without having to know sibling IDPS components. This is usually not an issue in IT networks because an IDPS can be deployed in multiple execution environments, with or without time synchronized with a common standard time, such as Coordinated Universal Time (UTC). In contrast, due to the topology of in-vehicle communication networks, multiple IDPS components in a connected vehicle can generate duplicate detections of the same events. Without synchronizing the clocks of different IDPS components, event detections in the connected vehicle cannot be sorted in temporal order, making it difficult to identify and aggregate duplicate event detections (e.g., those occurring within a short time range) to be identified. Unconditionally uploading duplicate event detections and event detections with arbitrary timestamp skews from the connected vehicle to a backend service on the cloud for network threat detection presents a huge burden on network bandwidth and the backend service.

(16) Referring now to FIG. 1, there is shown a block diagram of a connected vehicle **174** in accordance with an embodiment of the present invention. FIG. 1 shows a single connected vehicle **174**, a single third-party supplier **172**, and a single OEM **173** for illustration purposes only. As can be appreciated, there are many OEMs that manufacture connected vehicles that have modules sourced from many, different suppliers.

(17) The vehicle **174** has a plurality of ECUs **180**. An ECU **180** may be for a safety system, body system, chassis system, power system, telematic control unit (TCU), Global Navigation Satellite System (GNSS), vehicle-to-everything (V2X) interfaces, remote keyless entry, etc. One or more of the ECUs **180** and associated software components may be provided by the supplier **172** to the OEM **173**, which is the manufacturer of the vehicle **174**. The supplier **172** may provide firmware, source code, and/or other software components by removable storage media (e.g., Universal Serial Bus (USB) flash storage) or over a communication network **175**, which includes the public Internet in this example. Each of the OEM **173** and the supplier **172** is depicted as a computer system to indicate that the OEM **173** and the supplier **172** may send and receive software components and/or communicate with the vehicle **174** over the communication network **175**.

(18) An ECU **180** is a computer comprising a processor **181**, a memory **184**, one or more network interfaces **182** for connecting to an in-vehicle (i.e., internal to the vehicle **174**) communication network and/or external communication network, and one or more input/output (I/O) circuits **183**. An I/O circuit **183** may be a data acquisition and control circuit, a sensor interface, or other circuit for receiving external data, such as communications from other connected vehicles, sensed data of

the environment outside the vehicle **174**, etc. The memory **184** may be non-volatile memory (e.g., non-volatile random access memory (NVRAM)) or volatile memory (e.g., dynamic random access memory (DRAM)). Instructions of one or more onboard (i.e., in the vehicle **174**) cybersecurity modules and other software components of the ECU **180** may be stored in the memory **184** for execution by the processor **181**. In one embodiment, the memory **184** stores one or more detection probes **101** and one or more detection hubs **201**.

(19) An ECU **180** may be connected to other ECUs **180** over an in-vehicle communication network, such as an Ethernet network, a Controller Area Network (CAN) bus, a Modbus network, etc. An ECU **180** may communicate with external devices outside of the vehicle **174** by way of a V2X network or a suitable vehicle ad-hoc network (VANET).

(20) A backend system **171** may comprise one or more computer systems for supporting cybersecurity operations in one or more connected vehicles. The backend system **171** is on the cloud in that it is external to the vehicle **174** and communicates with the vehicle **174** over the communication network **175**, which in this example includes the public Internet. The backend system **171** may serve as a vehicle security operations center for the vehicle **174**. In one embodiment, the backend system **171** hosts a detection correlation backend **301**. The detection correlation backend **301** comprises instructions stored in a memory of the backend system **171** that, when executed by at least one processor of the backend system **171**, cause the backend system **171** to operate as explained herein.

(21) As will be more apparent below, embodiments of the present invention provide an adaptive framework for deploying software components of an IDPS in heterogeneous multiple execution environments of a connected vehicle, with the framework allowing for ease of resource usage throttling, cooperative information exchange, and management. An “execution environment” indicates an operating system running in either a physical device or a virtual machine where software components can run with the required hardware components or software libraries.

(22) In one embodiment, the adaptive framework supports an IDPS comprising a plurality of distributed nodes, with a node being a detection probe **101**, a detection hub **201**, or a detection correlation backend **301**. The relationship between the detection probes **101**, detection hubs **201**, and correlation backend **301** may be defined as a hierarchy of nodes. A detection probe **101** has no child nodes and has only one parent node, which is either a detection hub **201** or a detection correlation backend **301**. A detection correlation backend **301** has no parent node and can have multiple child nodes, which are detection probes **101** and/or detection hubs **201**. A detection hub **201** can have multiple child nodes (which are detection probes **101** and/or detection hubs **201**) and has only one parent node (which is either a detection hub **201** or a detection correlation backend **301**).

(23) FIG. 2 shows a block diagram of a detection probe **101** in accordance with an embodiment of the present invention. The detection probe **101** receives raw packets **108-1** from a network interface **107-1**. The detection probe **101** receives time information from a wall clock **109-1** to generate a monotonic timestamp **110-1**.

(24) A “packet” may be an Open Systems Interconnection (OSI) layer 3 Internet Protocol (IP) packet, OSI layer 2 Frame, a Controller Area Network (CAN) bus frame, or other unit of network traffic data.

(25) A “network interface” may be a physical or virtual interface to an in-vehicle Ethernet network, CAN bus, Modbus network, etc. “Raw Packets” are packets captured by a network interface from a communication network being monitored. The format (i.e., the structures of sequential bitwise fields) of the raw packets may thus vary with different types of network interfaces. A “session” is the combination of key fields of the raw packets. Filtered with the key fields of a specified session, selected raw packets can be all attributed to a sequence of packets related to a specified connection. For example, an Ethernet session could contain the following key fields: Ether type (e.g., IPv4, Ipv6, . . . , etc.), source IP address, destination IP address, protocol type (e.g., TCP, UDP, ICMP, . . .

, etc.), source port, destination port, etc. The key fields may vary with different types of packets according to implementation details. The purpose of choosing the proper key fields is to make a unique key field combination for distinguishing and filtering different sessions effectively.

(26) “Wall clock” indicates a reference time source. In one embodiment, each node of the IDPS has its own wall clock. In one embodiment, the wall clock **109-1** provides UTC time that has been adjusted by best effort. In other words, a wall clock does not necessarily have to provide perfectly accurate time. System clocks of devices that cannot be synchronized with a standard time server can always be set to zero at every boot up, which will still provide time intervals or differences between detections. “Monotonic Timestamp” indicates strictly incremental values of timestamp, which may be used for time drift reduction as further explained with reference to FIGS. **9** and **10**. The packet filter **111**, detection engine **113**, and detection filter **115** use time information from the wall clock **109-1** for reference and to apply monotonic timestamps **110-1** on data they process.

(27) The detection probe **101** further includes a packet filter subscriber **105-1**, a detection filter subscriber **104-1**, a detection sender **102-1**, and a packet filter publisher **103-1**.

(28) “Sender” and “receiver” indicate a pair of endpoints for a unidirectional relationship, i.e., messaging from a sender to a receiver, that is required when connecting corresponding nodes of the IDPS. A receiver of a parent node can accept messages from multiple senders of child nodes, while a single sender of a child node can only connect to a single receiver of a parent node.

(29) “Publisher” and “subscriber” indicate a pair of endpoints for a unidirectional relationship, i.e., messaging from publisher to subscriber, that is optional when connecting to corresponding nodes. A publisher of a parent node can send messages to multiple subscribers of child nodes. A subscriber of a child node may receive messages from a single publisher of a parent node, instead of from multiple publishers, due to the defined hierarchical relationship between software components.

(30) In the example of FIG. **1**, the detection probe **101** receives raw packets **108-1** from the network interface **107-1** via the packet receiver interface **106**. The packet receiver interface **106** may be a user mode or kernel application programming interface (API), callback handler, packet capture interface, virtio-net device, etc. The packet filter **111** filters out selected packets from the raw packets **108-1** to generate packets of interest **112**. This advantageously allows the detection engine **113** to just scan the packets of interest **112**, instead of the entire raw packets **108-1**, for better performance and efficiency.

(31) Selected packets to be filtered out of the raw packets **108-1** may be described by one or more packet filter rule entries **117** (i.e., **117-1**, **117-2**). In the example of FIG. **2**, the packet filter **111** may receive packet filter rule entries **117-1** from the packet filter subscriber **105-1** and packet filter rule entries **117-2** from the detection engine **113**. The packet filter subscriber **105-1** may receive the packet filter rule entries **117-1** published by either a packet filter publisher **103** of a parent detection hub **201** (e.g., see FIG. **3**, **103-2**) or a packet filter publisher **103** of a parent detection correlation backend **301** (e.g., see FIG. **4**, **103-3**). The packet filter **111** may also receive packet filter rule entries **117-2** from the detection engine **113**. Packet filter rule entries **117-1** and **117-2** are stored in a local packet filter storage **118-1** with an explicit expiration time for each entry.

(32) The detection engine **113** scans the packets of interest **112** for data that match one or more detection patterns **119**. A detection pattern **119** describes data that are indicative of a network threat (e.g., data noted in a Common Vulnerabilities and Exposures (CVE) alert) or otherwise relevant to network threat detection. The detection engine **113** outputs an unfiltered detection log **114** in response to detecting data that match a detection pattern **119**. Unfiltered detection logs **114** may be unprioritized, very verbose, and not relevant for a given network condition.

(33) The detection filter **115** filters out selected detection logs from the unfiltered detection logs **114** to generate detection logs of interest **116-1**. Advantageously, the detection logs of interest **116-1**, instead of the entire unfiltered detection logs **114**, are sent by the detection sender **102-1** to a detection receiver **203** of a parent detection hub **201** (e.g., see FIG. **3**, **203-1**) or to a detection receiver **203** of a parent detection correlation backend **301** (e.g., see FIG. **4**, **203-2**). The detection

filter rule entries **121-1** describe the selected detection logs to be filtered out from the unfiltered detection logs **114**. The detection filter **115** may receive the detection filter rule entries **121-1** from the detection filter subscriber **104-1**. The detection filter subscriber **104-1** may receive the detection filter rule entries **121-1** published by either a detection filter publisher **202** of a parent detection hub **201** (e.g., see FIG. 3, **202-1**) or a detection filter publisher **202** of a parent detection correlation backend **301** (e.g., see FIG. 4, **202-2**). The detection filter rule entries **121-1** are stored in a local detection filter storage **120-1** with an explicit expiration time assigned to each entry.

(34) The detection engine **113** determines, from the detection patterns **119**, which sessions can be skipped rather than scanned thoroughly when there is no more possible matching with any further packets of the sessions. As a particular example, a detection pattern **119** may identify which packets of a session need to be scanned, and when those packets have been scanned and found to be normal, the other packets of the session may be skipped for scanning. The detection engine **113** can proactively notify the packet filter **111** with corresponding packet filter rule entries **117-2** in order to temporarily stop scanning of packets of certain sessions for a configurable duration of time. The packet filter rule entries **117-2** generated by the detection engine **113** may also be sent out by the packet filter publisher **103-1** to a packet filter subscriber **105** of a parent detection hub **201** (e.g., see FIG. 3, **105-2**) to allow the parent detection hub **201** to keep track of packet filter rule entries in the detection probe **101**.

(35) FIG. 3 shows a block diagram of a detection hub **201** in accordance with an embodiment of the present invention. The detection hub **201** is configured to dispatch detection logs of interest, aggregated detection logs, packet filter rule entries, and detection filter rule entries to nodes of the IDPS. The detection hub **201** comprises a detection log aggregator **204** and an advanced filter composer **207**. The detection log aggregator **204** and the advanced filter composer **207** use time information from a wall clock **109-2** for reference and to apply monotonic timestamps **110-2** on data they process.

(36) The detection hub **201** is configured to aggregate incoming detection logs, including incoming detection logs of interest **116-2** from child detection probes **101** and incoming aggregated detection logs **205-1** from child detection hubs **201**. The detection log aggregator **204** removes redundant (i.e., duplicate) detection logs from the detection logs of interest **116-2** and aggregated detection logs of interest **205-1** to generate the aggregated detection logs **205-2**. The detection log aggregator **204** may identify redundant detection logs based on their subjects and timestamps. The aggregated detection logs **205-2** are stored by the detection log aggregator **204** in a local detection log storage **206**, with limited count and duration.

(37) The detection log aggregator **204** sends the aggregated detection logs **205-2** to a parent detection hub **201** or a parent detection correlation backend **301** by way of a detection sender **102-2**. Aggregated detection logs **205-3** include the aggregated detection logs **205-2** and historical detection logs previously stored in the detection log storage **206**. The advanced filter composer **207** identifies redundant detection logs in the aggregated detection logs **205-3** to generate corresponding detection filter rule entries **121-3** that describe the redundant detection logs. The detection filter rule entries **121-3** allow redundant detection logs to be filtered out in child nodes.

(38) The detection hub **201** includes a packet filter subscriber **105-2** for receiving external packet filter rule entries **117-3** and a detection filter subscriber **104-2** for receiving external detection filter rule entries **121-2**. The advanced filter composer **207** generates packet filter rule entries **117-4**, which are packet filter rule entries from among the packet filter rule entries **117-3** that are not in child nodes of the detection hub **201**. Packet filter rule entries that are in child nodes of the detection hub **201** are stored in a local packet filter storage **118-2**.

(39) Similarly, the advanced filter composer **207** generates detection filter rule entries **121-3**, which are detection filter rule entries from among the detection filter rule entries **121-2** that are not in child nodes of the detection hub **201**. Detection filter rule entries that are in child nodes of the detection hub **201** are stored in a local detection filter storage **120-2**.

(40) The detection hub **201** includes a packet filter publisher **103-2** for sending out the packet filter rule entries **117-4** to its child nodes, which may be one or more detection probes **101** and/or one or more detection hubs **201**. This allows the packet filter rule entries **117-4** to be propagated through child nodes until the endpoint detection probes **101**. Similarly, the detection hub **201** includes a detection filter publisher **202-1** for sending out the detection filter rule entries **121-3** to attached child nodes, which may be one or more detection probes **101** and/or one or more detection hubs **201**. This allows the detection filter rule entries **121-3** to be propagated through all child nodes until the endpoint detection probes **101**.

(41) FIG. 4 shows a block diagram of a detection correlation backend **301** in accordance with an embodiment of the present invention. The detection correlation backend **301** may comprise a detection correlator **302**, an advanced filter composer **303**, and a machine learning discriminator **305**. The detection correlator **302** uses time information from a wall clock **109-3** for reference and to apply monotonic timestamps **110-3** on data it processes. In one embodiment, the detection correlation backend **301** is offboard, hosted by the backend system **171** (shown in FIG. 1) on the cloud.

(42) The detection correlation backend **301** includes a detection receiver **203-2** for receiving external detection logs of interest **116-3** and external aggregated detection logs **205-4** from child nodes, which may be one or more detection probes **101** and/or one or more detection hubs **201**. The detection correlator **302** removes redundant detection logs from the detection logs of interest **116-3** and aggregated detection logs **205-4** to generate the aggregated detection logs **205-5**, which are stored in a detection log database **306**.

(43) Aggregated detection logs **205-6** include the aggregated detection logs **205-5** and historical detection logs previously stored in the detection log database **306**. The machine learning discriminator **305** employs one or more machine learning models **307** to assess the aggregated detection logs **205-6** to generate risk scores **304**, one for each detection log. A risk score **304** indicates a severity of a possible network threat identified in a detection log. The detection correlator **302** declares that a network threat is found when a risk score **304** is higher than a risk threshold. Detection log entries in the detection log database **306** combined with corresponding risk scores **304** can be correlated into behavior records **309**, which are stored in a behavior chronicles database **308**.

(44) A behavior record describes a security event indicated in a detection log. A behavior record may include: (a) an event ID that identifies the event, which can be encoded to describe distinct detection subjects; (b) start time (e.g., in UTC seconds) when the event started; (c) end time (e.g., in UTC seconds) when the event ended; (d) occurrences or count of the event occurring consecutively; and (e) source globally unique identifiers (GUIDs) that distinctly identify detection probes that detected the event in different execution environments.

(45) Behavior records may be supported by tables or data structures that add additional information in other dimensions, such as: (a) table of hierarchy of source GUIDs to describe the path through the detection probes; table of event IDs, event subjects, descriptions, risk scores, and other informative attributes; and table of external related events with specific periods, including campaigns, breaches, patch releases, CVEs, and so on.

(46) The severity of a security event indicated in a behavior record may be calculated in various ways. For example, for each behavior record, severity may be calculated based on frequency (i.e., occurrences/(end time–start time)) and the risk score of the corresponding detection log. Given normalized severity levels to be a floating number between 0.0 and 1.0, a severity level may be calculated as,

Severity Level=tanh(frequency\*risk score), where frequency>=0,risk score>=0

(47) By correlating the behavior records (with severity levels) and external related events in sequence found by a temporal ranges, patterns for distinguishing whether a series of security events is relevant or irrelevant may be identified.



(48) The advanced filter composer **303** identifies redundant detection logs from the aggregated detection logs **205-5** and generates corresponding detection filter rule entries **117-5** that its child nodes can use to remove redundant detection logs. The advanced filter composer **303** also generates packet filter rule entries **117-5** that describe packets that are not of interest (e.g., part of sessions that have been evaluated as normal) and thus should be filtered out by its child nodes. The packet filter rule entries **117-5** and detection filter rule entries **121-4** are stored in a packet filter storage **118-3** and a detection filter storage **120-3**, respectively.

(49) The detection correlation backend **301** includes a packet filter publisher **103-3** for sending the packet filter rule entries **117-5** to packet filter subscribers of child nodes, which may be one or more detection probes **101** and/or one or more detection hubs **201**. The detection correlation backend **301** further includes a detection filter publisher **202-2** for sending the detection filter rules entries **121-4** to detection filter subscribers of child nodes, which may be one or more detection probes **101** and/or one or more detection hubs **201**.

(50) Example deployments of nodes of an IDPS in accordance with embodiments of the present invention are now explained in FIGS. 5-8.

(51) FIG. 5 shows an example deployment of an IDPS with a single detection probe and a single detection correlation backend in accordance with an embodiment of the present invention. In the example of FIG. 5, a single detection probe **101-1** is running in a telematic control unit (TCU) **403** of the vehicle **174** and a detection correlation backend **301-1** is hosted on the cloud in the backend system **171** (shown in FIG. 1). The TCU **403** is implemented as an ECU of the vehicle **174**.

(52) In the example of FIG. 5, the detection probe **101-1** receives raw packets **108-2** from a network interface **107-2**, which is attached to a communication network (e.g., CAN bus) of the vehicle **174** being monitored for network threats. The raw packets **108-2** are from network traffic on the communication network. The detection probe **101-1** scans the raw packets **108-2** for data indicative of network threats and outputs corresponding detection logs of interest **116-4** to a parent node, which in this example is the detection correlation backend **301-1**. The detection probe **101-1** applies monotonic timestamps **110-4** on the detection logs of interest **116-4** using time information from a wall clock **109-4**.

(53) The detection correlation backend **301-1** evaluates the detection logs of interest **116-4** to detect network threats. The detection correlation backend **301-1** uses time information from a wall clock **109-5** for reference and to apply monotonic timestamps **110-5** on data it processes. The detection correlation backend **301-1** also outputs packet filter rule entries **117-6** and detection filter rule entries **121-5** to a child node, which in this example is the detection probe **101-1**. The detection probe **101-1** employs the packet filter rule entries **117-6** to selectively scan the raw packets **108-2**, by not scanning packets described by the packet filter rule entries **117-6**. The detection probe **101-1** generates the detection logs of interest **116-4** by filtering out detection logs described by the detection filter rule entries **121-5**.

(54) FIG. 6 shows an example deployment of an IDPS with multiple detection probes, a single detection hub, and a single detection correlation backend in accordance with an embodiment of the present invention.

(55) In the example of FIG. 6, a detection probe **101-2**, a detection probe **101-3**, and a detection hub **201-1** are running in the TCU **403**, and a detection correlation backend **301-2** is hosted on the cloud in the backend system **171**. The detection probe **101-2** receives raw packets **108-3** from a network interface **107-3**, and the detection probe **101-3** receives raw packets **108-4** from a network interface **107-4**. The network interfaces **107-3** and **107-4** are each connected to separate communication networks being monitored for network threats.

(56) The detection probes **101-2** and **101-3** use time information from wall clocks **109-6** and **109-7** for reference and to apply monotonic timestamps **110-6** and **110-7**, respectively, on data they process. The detection probes **101-2** and **101-3** scan the raw packets **108-3** and **108-4**, respectively, for data indicative of network threats and output corresponding detection logs of interest **116-5** to

the detection hub **201-1**. The detection hub **201** aggregates the detection logs of interest **116-5**, by removing redundant detection logs, into aggregated detection logs **205-8**.

(57) The detection correlation backend **301-2** uses time information from a wall clock **109-9** for reference and to apply monotonic timestamps **110-9** on data it processes. The detection correlation backend **301-2** receives and evaluates the aggregated detection logs **205-8** for network threats. The detection correlation backend **301-2** also outputs packet filter rule entries **117-7** and detection filter rule entries **121-6** to its child node, which in this example is the detection hub **201-1**.

(58) The detection hub **201-1** uses time information from a wall clock **109-8** for reference and to apply monotonic timestamps **110-8** on data that it processes. The detection hub **201-1** keeps track of filter rule entries that are locally stored in the detection probes **101-2** and **101-3**. When the detection hub **201-1** receives the packet filter rule entries **117-7** and detection filter rule entries **121-6** from the detection correlation backend **301-2**, the detection hub **201-1** will deliver to its child detection probes **101-2** and **101-3** only filter rule entries that are not in the detection probes **101-2** and **101-3**. In FIG. 6, the lines for packet filter rule entries **117-8** and detection filter rule entries **121-7** are bolded to indicate multiple unidirectional callbacks between packet filter publisher-subscriber pairs and detection filter publisher-subscriber pairs. The detection probes **101-2** and **10-3** employ the filter rule entries to selectively scan raw packets and to generate detection logs of interest.

(59) FIG. 7 shows an example deployment of an IDPS with detection probes and a detection hub that are running in virtual machines in accordance with an embodiment of the present invention. In the example of FIG. 7, a detection probe **101-4**, a detection probe **101-5**, a detection probe **101-6**, a detection probe **101-7**, and a detection hub **201-2** are running in the TCU **403** of the vehicle **174**. A detection correlation backend **301-3** is hosted on the cloud in the backend system **171**. A hypervisor **404** is running in the TCU **403**. A first virtual machine **405-1**, a second virtual machine **405-2**, and a third virtual machine **405-3** are running under the hypervisor **404**. The virtual machines **405** provide separate execution environments for the nodes of the IDPS.

(60) The detection probes **101-4** and **101-5** are running in the virtual machine **405-1**. The detection probe **101-4** receives raw packets **108-5** from a network interface **107-5**, and the detection probe **101-5** receives raw packets **108-6** from a network interface **107-6**. The network interfaces **107-5** and **107-6** are virtual network interfaces that are each connected to separate virtual communication networks being monitored for network threats. The detection probes **101-4** and **101-5** use time information from wall clocks **109-10** and **109-11** for reference and to apply monotonic timestamps **110-10** and **110-11**, respectively, to data that they process.

(61) The detection probes **101-6** and **101-7** are running in the virtual machine **405-2**. The detection probe **101-6** receives raw packets **108-7** from a network interface **107-7**, and the detection probe **101-7** receives raw packets **108-8** from a network interface **107-8**. The network interfaces **107-7** and **107-8** are virtual network interfaces that are each connected to separate virtual communication networks being monitored for network threats. The detection probes **101-6** and **101-7** use time information from wall clocks **109-12** and **109-13** for reference and to apply monotonic timestamps **110-12** and **110-13**, respectively, to data that they process.

(62) The detection probes **101-4**, **101-5**, **101-6**, and **101-7** scan raw packets for data indicative of network threats and output corresponding detection logs of interest **116-6**. The detection hub **201-2** receives the detection logs of interest **116-6** by way of the hypervisor **404**. The detection hub **201-2** uses time information from a wall clock **109-14** for reference and to apply monotonic timestamps **110-14** to data that it processes. The detection hub **201-2** removes redundant detection logs from the detection logs of interest **116-6** to generate the aggregated detection logs **205-9**, which the detection hub **201-2** sends to the detection correlation backend **301-3**.

(63) The detection correlation backend **301-3** is on the cloud hosted by the backend system **171**. The detection correlation backend **301-3** receives and evaluates the aggregated detection logs **205-9** for network threats. The detection correlation backend **301-1** also outputs packet filter rule entries

**117-9** and detection filter rule entries **121-8** to one or more child nodes, which in this example is the detection hub **201-2**. The detection correlation backend **301-3** uses time information from a wall clock **109-15** for reference and to apply monotonic timestamps **110-15** on data that it processes.

(64) The detection hub **201-2** keeps track of detection filter rule entries and packet filter rule entries that are locally stored in its child detection probes **101-4**, **101-5**, **101-6**, and **101-7**. When the detection hub **201-2** receives the packet filter rule entries **117-9** and detection filter rule entries **121-8** from the detection correlation backend **301-3**, the detection hub **201-2** will deliver to its child detection probes only filter rule entries that are not in its child detection probes. In FIG. 7, the lines for packet filter rule entries **117-10** and detection filter rule entries **121-9** are bolded to indicate multiple unidirectional callbacks between packet filter publisher-subscriber pairs and detection filter publisher-subscriber pairs. The child detection probes of the detection hub **201-2** employ the filter rule entries to selectively scan raw packets and to generate detection logs of interest.

(65) FIG. 8 shows an example deployment of an IDPS with detection probes and detection hubs that are running in separate ECUs of a connected vehicle in accordance with an embodiment of the present invention.

(66) In the example of FIG. 8, a detection probe **101-8**, a detection probe **101-9**, and a detection hub **201-3** are running in an ECU **406-1**. The detection probe **101-8** receives raw packets **108-9** from a network interface **107-9**, and the detection probe **101-9** receives raw packets **108-10** from a network interface **107-10**. The network interfaces **107-9** and **107-10** are each connected to separate communication networks being monitored for network threats. The detection probes **101-8** and **101-9** use time information from wall clocks **109-16** and **109-17** for reference and to apply monotonic timestamps **110-16** and **110-17**, respectively, to data that they process.

(67) The detection probes **101-8** and **101-9** scan raw packets for data indicative of network threats and output corresponding detection logs of interest **116-7**, which are sent to the detection hub **201-3**. The detection hub **201-3** uses time information from a wall clock **109-18** for reference and to apply monotonic timestamps **110-18** to data that it processes. The detection hub **201-3** removes redundant detection logs from the detection logs of interest **116-7** to generate aggregated detection logs **205-10**, which the detection hub **201-3** sends to the detection hub **201-5** running in the TCU **403**.

(68) A detection probe **101-10**, a detection probe **101-11**, and a detection hub **201-4** are running in an ECU **406-2**. The detection probe **101-10** receives raw packets **108-11** from a network interface **107-11**, and the detection probe **101-11** receives raw packets **108-12** from a network interface **107-12**. The network interfaces **107-11** and **107-12** are each connected to separate communication networks being monitored for network threats. The detection probes **101-10** and **101-11** use time information from wall clocks **109-19** and **109-20** for reference and to apply monotonic timestamps **110-19** and **110-20**, respectively, to data that they process.

(69) The detection probes **101-10** and **101-11** scan raw packets for data indicative of network threats and output corresponding detection logs of interest **116-8**, which are sent to the detection hub **201-4**. The detection hub **201-4** uses time information from a wall clock **109-21** for reference and to apply monotonic timestamps **110-21** to data that it processes. The detection hub **201-4** removes redundant detection logs from the detection logs of interest **116-8** to generate aggregated detection logs **205-10**, which the detection hub **201-4** sends to the detection hub **201-5** in the TCU **403**.

(70) The detection hub **201-5** receives the aggregated detection logs **205-10** from its child detection hubs **201-3** and **201-4**. The detection hub **201-5** uses time information from a wall clock **109-22** for reference and to apply monotonic timestamps **110-22** to data that it processes. The detection hub **201-5** removes redundant detection logs from the aggregated detection logs **205-10** to generate aggregated detection logs **205-11**, which the detection hub **201-5** sends to the detection correlation backend **301-4**.

(71) The detection correlation backend **301-4** is on the cloud hosted by the backend system **171**. The detection correlation backend **301-4** receives and evaluates the aggregated detection logs **205-10** for network threats. The detection correlation backend **301-4** also outputs packet filter rule entries **117-11** and detection filter rule entries **121-10** to one or more child nodes, which in this example is the detection hub **201-5**. The detection correlation backend **301-4** uses time information from a wall clock **109-23** for reference and to apply monotonic timestamps **110-23** on data that it processes.

(72) The ECU **406-1**, ECU **406-2**, TCU **403**, and backend system **171** provide different execution environments, each having its own operating system. The ECU **406-1** and the ECU **406-2** are not connected to the public Internet; Internet connectivity to the backend system **171** is provided by the TCU **403**. To collect and upload detection logs through restricted networks and between different execution environments, the detection hubs on respective ECUs are configured to connect to child detection probes and child detection hubs. In general, a detection hub should only operate on messages to or from its direct child nodes and direct parent node. In the example of FIG. 8, this is implemented with the detection probes **101-8** and **101-9** being connected to a parent detection hub **201-3**, the detection probes **101-10** and **101-11** being connected to a parent detection hub **201-4**, the detection hubs **201-3** and **201-4** being connected to a parent detection hub **201-5**, and the detection hub **201-5** being connected to a parent detection correlation backend **301-4**.

(73) The detection hub **201-5** keeps track of detection filter rule entries and packet filter rule entries that are locally stored in its child detection hubs **201-3** and **201-4**. When the detection hub **201-5** receives the packet filter rule entries **117-11** and detection filter rule entries **121-10** from the detection correlation backend **301-4**, the detection hub **201-5** will deliver to its child detection hubs only filter rule entries that are not in its child detection hubs.

(74) The detection hubs **201-3** and **201-4** keep track of detection filter rule entries and packet filter rule entries that are locally stored in their respective child detection probes (i.e., detection probes **101-8** and **101-9** for the detection hub **201-3**; detection probes **101-10** and **101-11** for the detection hub **201-4**).

(75) When the detection hubs **201-3** and **201-4** receive packet filter rule entries and detection filter rule entries from the detection hub **201-5**, the detection hubs **201-3** and **201-4** will deliver to their respective child detection probes only filter rule entries that are not in their respective child detection probes. The child detection probes employ the filter rule entries to selectively scan raw packets and to generate detection logs of interest. In FIG. 8, the lines for packet filter rule entries **117-12** and detection filter rule entries **121-11** are bolded to indicate multiple unidirectional callbacks between packet filter publisher-subscriber pairs and detection filter publisher-subscriber pairs.

(76) Time between IDPS nodes (i.e., detection probes, detection hubs, and detection correlation backend) are synchronized for proper operation. Accordingly, each node has its own wall clock for providing time information, which may be a local system time or adjusted global time. Wall clocks in different deployment scenarios may vary depending on their precision. Nodes with Internet connectivity, such as nodes in the TCU **403** and backend system **171**, can frequently synchronize their wall clocks via Network Time Protocol (NTP), described in RFC 5905, or any updated time standard.

(77) Virtual machine environments have a certain amount of time delay due to the latency of sharing and context switching executed by the hypervisor. The hypervisor can adjust the virtual wall clock for each virtual machine when the time differences between virtual machines exceed predefined limits. This may result in time drifts in virtual machine environments.

(78) Some ECUs have restricted network access and thus cannot synchronize their wall clocks with NTP. To keep the correct timing between such ECUs, some standard timing algorithm or mechanism may be applied, such as Precision Time Protocol (PTP) compliant with IEEE 1588 and Time-Sensitive Networking (TSN).

- (79) To prevent or minimize time drifts, nodes of the present invention employ monotonic timestamps that are defined to have strictly incremental values. The monotonic timestamps may be in Unix epoch time (also referred to as Posix time, the total seconds since Jan. 1, 1970, in UTC) or a counter of uptime (i.e., total elapsed seconds since last successful boot).
- (80) FIG. 9 shows a state diagram for time synchronization of detection probes, detection hubs, and detection correlation backend in accordance with an embodiment of the present invention. The detection probes, detection hubs, and detection correlation backend are also referred to as “nodes”. Two nodes can be connected by connecting the sender/publisher of a node to a receiver/subscriber of the other node.
- (81) In the example of FIG. 9, a node starts in a disconnected state **512**. A node returns to the disconnected state **512** from any of the other states when a connection to the node is stopped, as indicated by transitions **515** (i.e., **515-1**, **515-2**, **515-3**, **515-4**).
- (82) From the disconnected state **512**, a node starts to connect or tries to reconnect to another node by entering the connecting state **513** through the transition **516**. The node re-enters the disconnected state **512** through the transition **523** when a connection cannot be established to the other node.
- (83) The sender/publisher of a node can connect to a receiver/subscriber of another node by way of an underlying channel, such as Data Distribution Service (DDS), Scalable service-Oriented MiddlewarE over IP (SOME/IP), User Datagram Protocol (UDP), Transmission Control Protocol (TCP), etc. If the receiver/subscriber is reachable, the channel between sender/publisher and the receiver/subscriber is established, and the sender/publisher and receiver/subscriber enter the time synchronization phase state **503** through the transition **517**. The receiver/subscriber and sender/publisher re-enter the connecting state **513** through the transition **522** when they cannot successfully handshake to perform time synchronization.
- (84) FIG. 10 shows a sequence diagram of the time synchronization phase state **503** in accordance with an embodiment of the present invention. As shown in FIG. 10, when a sender/publisher **501** starts to negotiate with a receiver/subscriber **502**, the sender/publisher **501** initiates a handshaking protocol where the messages A (FIG. 10, **508**), B (FIG. 10, **509**) and C (FIG. 10, **510**) carry required information, including the source timestamps and the transit delays. The number of time synchronization steps can be greater than or equal to 3 (i.e., Messages A, B, and C). For some execution environments with transit delays that fluctuate a lot, the number of time synchronization steps may be increased to obtain a better estimation.
- (85) Assuming the timestamp in the receiver/subscriber **502** side is from a base wall clock for reference, there should be a nearly constant time offset (i.e., A in FIG. 10) between the sender/publisher **501** and receiver/subscriber **502** sides regarding the coincident timestamp values that they possess.
- (86) The average transit delay ( $d$ ) is defined by the below EQ. 1 and the average constant time offset ( $\Delta$ ) is defined in the below EQ. 2, wherein the definitions of the transit delays, including  $d_1$  (FIG. 10, **504**),  $d_2$  (FIG. 10, **507**), and  $d_3$  (FIG. 10, **505**), are illustrated in FIG. 10.
- (87) 
$$\bar{d} = \frac{\frac{d_1 + d_2}{2} + \frac{d_2 - d_3}{2} + \dots + \frac{d_{n-1} + d_n}{2} + \frac{d_n - d_{n+1}}{2}}{n} = \frac{\sum_{i=1}^n (d_i - d_{i+1})}{2n}, \quad (\text{EQ. 1})$$
- where  $n = \{x \mid x \in N, x \neq 0\}$
- $$\bar{\Delta} = \frac{d_2 + d_1}{2} + \frac{d_2 - d_3}{2} + \dots + \frac{d_{n-1} - d_{n-1}}{2} + \frac{d_n + d_{n+1}}{2} = \frac{\sum_{i=1}^n (2d_{2i} - d_{2i-1} - d_{2i+1})}{2n}, \quad (\text{EQ. 2})$$
- where  $n = \{2x \mid x \in N, x \neq 0\}$
- (88) The receiver/subscriber **502** tracks the average transit delay ( $d$ ) and the average constant time offset ( $\Delta$ ) periodically.
- (89) Referring to FIG. 10, after the time synchronization phase state **503** has successfully completed (see also FIG. 9, transition **518**), both the sender/publisher **501** and the receiver/subscriber **502** will enter the data transmission phase state **506**. At the data transmission

phase state **506**, the sender/publisher **501** can then send consecutive messages (see FIG. **10**, **511**) to the receiver/subscriber **502**. During the data transmission phase state **506**, the receiver/subscriber **502** is responsible for periodically checking the average transit delay ( $d$ ) and average constant time offset ( $\Delta$ ) to ensure that they don't drift beyond predefined tolerance ranges.

(90) In certain abnormal circumstances, for example, if the receiver/subscriber **502** finds that the timestamps of consecutive messages are not ascending, the receiver/subscriber **502** assumes that time drift is occurring in the sender/publisher **501**. In that case, the receiver/subscriber **502** can immediately check for time drift, which in FIG. **9** is by entering the time drifting state **514** through the transition **520**.

(91) Continuing in FIG. **9**, when checking for time drift has been triggered either periodically (through the transition **519**) or by abnormal circumstances (through the transition **521**), the receiver/subscriber will notify the sender/publisher to enter the time synchronization phase state **503** to re-establish the connection and underlying channel between the receiver/subscriber and the sender/publisher.

(92) While receiving messages, the nodes should normalize the timestamps of the messages with the corresponding constant time offsets regarding different message senders/publishers. After the proper timestamp normalization, each node can thus correctly sort the messages of various sources in temporal order.

(93) FIG. **11** shows a flow diagram of a method **600** of detecting network threats in communication networks of a connected vehicle in accordance with an embodiment of the present invention. The method **600** may be implemented using components disclosed herein. As can be appreciated, other components may also be employed without detracting from the merits of the present invention.

(94) In step **601**, a first set of raw packets of network traffic of a first communication network of the connected vehicle being monitored for network threats is received.

(95) In step **602**, the first set of raw packets is filtered in accordance with one or more packet filter rule entries to generate a first set of packets of interest. The packet filter rule entries describe selected packets to be filtered out from the first set of raw packets.

(96) In step **603**, the first set of packets of interest is scanned for data indicative of network threats.

(97) In step **604**, a first set of unfiltered detection logs is generated in response to detecting data indicative of network threats in the first set of packets of interest.

(98) In step **605**, the first set of unfiltered detection logs is filtered in accordance with one or more detection filter rule entries to generate a first set of detection logs of interest. The detection filter rule entries describe selected detection logs to be filtered out from the first set of unfiltered detection logs.

(99) In step **606**, a second set of raw packets of network traffic of a second communication network of the connected vehicle being monitored for network threats is received.

(100) In step **607**, the second set of raw packets is filtered in accordance with one or more packet filter rule entries to generate a second set of packets of interest. The packet filter rule entries describe selected packets to be filtered out from the second set of raw packets.

(101) In step **608**, the second set of packets of interest is scanned for data indicative of network threats.

(102) In step **609**, a second set of unfiltered detection logs is generated in response to detecting data indicative of network threats in the second set of packets of interest.

(103) In step **610**, the second set of unfiltered detection logs is filtered in accordance with one or more detection filter rule entries to generate a second set of detection logs of interest. The detection filter rule entries describe selected detection logs to be filtered out from the second set of unfiltered detection logs.

(104) In step **611**, the first and second sets of detection logs of interest are aggregated to generate aggregated detection logs.

(105) In step **612**, the aggregated detection logs are evaluated to detect network threats. Remedial

actions to be performed in response to detecting a network threat may include raising an alert (e.g., sending a text or email to a network administrator; displaying a warning message on a display screen), blocking the source of the network traffic, putting the packets in quarantine for additional investigation, etc.

(106) In step **613**, the packet filter rule entries and the detection filter rule entries are updated based on the evaluation of the aggregated detection logs. The packet filter rule entries are updated based on scanning of packets of interest for data indicative of network threats.

(107) The method **600** may be performed a variety of ways depending on the deployment scenario of an IDPS. For example, the steps **601-611** may be performed on a single ECU of a plurality of ECUs of a connected vehicle. As another example, one or more steps of the method **600** may be performed in virtual machine environments. Yet another example, the steps of the method **600** may be distributed across several ECUs of the connected vehicle. The step **612** of evaluating the aggregated detection logs to detect network threats may be performed on the cloud, in a backend system that is external to the connected vehicle. Performing evaluation of the aggregated detection logs on the cloud addresses hardware limitations of the connected vehicle to effectively detect network threats onboard.

(108) While specific embodiments of the present invention have been provided, it is to be understood that these embodiments are for illustration purposes and not limiting. Many additional embodiments will be apparent to persons of ordinary skill in the art reading this disclosure.

## Claims

1. A method of detecting network threats in a connected vehicle, the method comprising: in a first electronic control unit (ECU) of a plurality of ECUs of a connected vehicle: receiving raw packets of network traffic of a first communication network of the connected vehicle, filtering out selected packets from the raw packets of network traffic of the first communication network to generate a first set of packets of interest, scanning the first set of packets of interest for data indicative of network threats, generating a first set of unfiltered detection logs in response to detecting data indicative of network threats in the first set of packets of interest, and filtering out selected detection logs from the first set of unfiltered detection logs to generate a first set of detection logs of interest; in a second ECU of the plurality of ECUs of the connected vehicle: receiving raw packets of network traffic of a second communication network of the connected vehicle, filtering out selected packets from the raw packets of network traffic of the second communication network to generate a second set of packets of interest, scanning the second set of packets of interest for data indicative of network threats, generating a second set of unfiltered detection logs in response to detecting data indicative of network threats in the second set of packets of interest, and filtering out selected detection logs from the second set of unfiltered detection logs to generate a second set of detection logs of interest; in a third ECU of the plurality of ECUs of the connected vehicle: aggregating the first and second sets of detection logs of interest to generate aggregated detection logs; and in a backend system that is external to the connected vehicle: evaluating one or more detection logs of the aggregated detection logs to detect network threats in the first and second communication networks of the connected vehicle.

2. The method of claim 1, wherein the selected packets filtered out from the raw packets of network traffic of the first communication network are described by filter rule entries that are updated based at least on the scanning of the first set of packets of interest for data indicative of network threats in the first ECU.

3. The method of claim 1, wherein the selected packets filtered out from the raw packets of network traffic of the first communication network are described by filter rule entries that are updated based at least on the evaluation of the one or more detection logs of the aggregated detection logs in the backend system.

4. The method of claim 1, wherein the selected detection logs filtered out from the first set of unfiltered detection logs are described by detection filter rule entries.
5. The method of claim 4, wherein the detection filter rule entries are updated based at least on evaluation of the one or more detection logs of the aggregated detection logs in the backend system.
6. A system comprising: a first electronic control unit (ECU) of a plurality of ECUs of a connected vehicle, the first ECU comprising a memory and at least one processor, the memory of the first ECU storing instructions that when executed by the at least one processor of the first ECU cause the first ECU to: receive raw packets of network traffic of a first communication network of the connected vehicle; filter out selected packets from the raw packets of network traffic of the first communication network to generate a first set of packets of interest; scan the first set of packets of interest for data indicative of network threats; generate a first set of unfiltered detection logs in response to detecting data indicative of network threats in the first set of packets of interest; filter out selected detection logs from the first set of unfiltered detection logs to generate a first set of detection logs of interest; receive raw packets of network traffic of a second communication network of the connected vehicle; filter out selected packets from the raw packets of network traffic of the second communication network to generate a second set of packets of interest; scan the second set of packets of interest for data indicative of network threats; generate a second set of unfiltered detection logs in response to detecting data indicative of network threats in the second set of packets of interest; filter out selected detection logs from the second set of unfiltered detection logs to generate a second set of detection logs of interest; and aggregate the first and second sets of detection logs of interest to generate a first set of aggregated detection logs; and a backend system comprising a memory and at least one processor, the memory of the backend system storing instructions that when executed by the at least one processor of the backend system cause the backend system to evaluate one or more detection logs of the first set of aggregated detection logs to detect network threats in the first and second communication networks of the connected vehicle.
7. The system of claim 6, further comprising: a second ECU of the plurality of ECUs of the connected vehicle, the second ECU comprising a memory and at least one processor, the memory of the second ECU storing instructions that when executed by the at least one processor of the second ECU cause the second ECU to: receive raw packets of network traffic of a third communication network of the connected vehicle; filter out selected packets from the raw packets of network traffic of the third communication network to generate a third set of packets of interest; scan the third set of packets of interest for data indicative of network threats; generate a third set of unfiltered detection logs in response to detecting data indicative of network threats in the third set of packets of interest; filter out selected detection logs from the third set of unfiltered detection logs to generate a third set of detection logs of interest; receive raw packets of network traffic of a fourth communication network of the connected vehicle; filter out selected packets from the raw packets of network traffic of the fourth communication network to generate a fourth set of packets of interest; scan the fourth set of packets of interest for data indicative of network threats; generate a fourth set of unfiltered detection logs in response to detecting data indicative of network threats in the fourth set of packets of interest; filter out selected detection logs from the fourth set of unfiltered detection logs to generate a fourth set of detection logs of interest; and aggregate the third and fourth sets of detection logs of interest to generate a second set of aggregated detection logs, wherein the instructions stored in the memory of the backend system when executed by the at least one processor of the backend system cause the backend system to evaluate one or more detection logs of the second set of aggregated detection logs to detect network threats in the third and fourth communication networks of the connected vehicle.
8. The system of claim 6, wherein the instructions stored in the memory of the first ECU when executed by the at least one processor of the first ECU cause the first ECU to filter out selected



packets from the raw packets of network traffic of the first communication network in accordance with a first set of packet filter rule entries that are updated based at least on a result of the scan of the first set of packets of interest for data indicative of network threats.

9. The system of claim 6, wherein the instructions stored in the memory of the first ECU when executed by the at least one processor of the first ECU cause the first ECU to filter out selected packets from the raw packets of network traffic of the first communication network in accordance with a first set of packet filter rule entries that are provided by the backend system.

10. A method of detecting network threats in a connected vehicle, the method comprising: receiving raw packets of network traffic of a first communication network of a connected vehicle; filtering out selected packets from the raw packets of network traffic of the first communication network to generate a first set of packets of interest; scanning the first set of packets of interest for data indicative of network threats; generating a first set of unfiltered detection logs in response to detecting data indicative of network threats in the first set of packets of interest; filtering out selected detection logs from the first set of unfiltered detection logs to generate a first set of detection logs of interest; receiving raw packets of network traffic of a second communication network of the connected vehicle; filtering out selected packets from the raw packets of network traffic of the second communication network to generate a second set of packets of interest; scanning the second set of packets of interest for data indicative of network threats; generating a second set of unfiltered detection logs in response to detecting data indicative of network threats in the second set of packets of interest; filtering out selected detection logs from the second set of unfiltered detection logs to generate a second set of detection logs of interest; aggregating the first and second sets of detection logs of interest to generate aggregated detection logs; and evaluating one or more detection logs of the aggregated detection logs to detect network threats in the first and second communication networks of the connected vehicle.

11. The method of claim 10, wherein the selected packets filtered out from the raw packets of network traffic of the first communication network are described by filter rule entries that are updated based at least on the scanning of the first set of packets of interest for data indicative of network threats.

12. The method of claim 10, wherein the selected packets filtered out from the raw packets of network traffic of the first communication network are described by filter rule entries that are updated based at least on the evaluation of the one or more detection logs of the aggregated detection logs to detect network threats.

13. The method of claim 10, wherein the selected detection logs filtered out from the first set of unfiltered detection logs are described by detection filter rule entries.

14. The method of claim 13, wherein the detection filter rule entries are updated based at least on the evaluation of the one or more detection logs of the aggregated detection logs to detect network threats.

15. The method of claim 10, wherein the raw packets of network traffic of the first communication network are received in a first electronic control unit (ECU) of a plurality of ECUs of the connected vehicle, the first set of detection logs of interest is generated in the first ECU, the raw packets of network traffic of the second communication network are received in a second ECU of a plurality of ECUs of the connected vehicle, the second set of detection logs of interest is generated in the second ECU, and the aggregated detection logs are generated in a third ECU of the plurality of ECUs of the connected vehicle.

16. The method of claim 15, wherein the aggregated detection logs are evaluated in a backend system that is external to the connected vehicle.

17. The method of claim 10, wherein the raw packets of network traffic of the first communication network are received in a first virtual machine running in a first electronic control unit (ECU) of a plurality of ECUs of the connected vehicle, the first set of detection logs of interest is generated in the first virtual machine, the raw packets of network traffic of the second communication network

are received in a second virtual machine running in the first ECU, the second set of detection logs of interest is generated in the second virtual machine, the first and second set of detection logs are aggregated in a third virtual machine running in the first ECU, and the aggregated detection logs are evaluated in a backend system that is external to the connected vehicle.

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