Abstract—The Network Configuration (NETCONF) protocol and the associated YANG data modeling language are the foundations of contemporary network management frameworks evolving within the Internet Engineering Task Force (IETF). netopeer (a NETCONF server) and ncclient (a NETCONF client) are popular open-source projects that support the latest NETCONF v1.1 protocol using the mandatory Secure Shell (SSH) transport. We recently implemented and integrated NETCONF over Transport Layer Security (TLS) transport and NETCONF Call Home (CH) mechanisms using reverse TLS and SSH in both projects. The CH mechanism allows a managed device behind a Network Address Translation (NAT) running a NETCONF server (netopeer) to successfully establish a NETCONF session with a Network Management System (NMS) running a NETCONF client (ncclient). In this article, we describe how these standards allow home routers and NAT boxes (in particular) to be managed using these latest additions to the NETCONF protocol.

I. INTRODUCTION

The NETCONF protocol (RFC 6241) and the associated YANG data modeling language (RFC 6020) are the foundations of a new network management frameworks evolving within the IETF. NETCONF [1] is a network management protocol that provides a secure mechanism to install, manipulate and delete the configuration of network devices. NETCONF was standardized by the IETF in RFC 4741 and revised in RFC 6241. NETCONF is also tightly connected with another IETF activity – YANG modeling language (RFC 6020, RFC 7950). YANG data models are used to define not only the data accessible via NETCONF, but also NETCONF operations, notifications and various extensions.

There has been work on NETCONF interoperability testing in the past [2]. Meanwhile, implementations have matured significantly and the core NETCONF specifications have been revised in order to remove ambiguities and to address problems encountered with the first revision. For instance, Table I enlists basic NETCONF capabilities and protocol extensions supported by popular open-source and commercial server implementations. The standardized YANG data models supported by each server implementation are enlisted in Table II.

Recently, the IETF has standardized an optional underlying TLS transport (RFC 7589) and a NETCONF CH mechanism (RFC 8071). The optional TLS transport can be used to securely establish a NETCONF session in situations where the mandatory SSH transport (RFC 6242) mechanism is unavailable. The NETCONF CH on the other hand is used to allow NETCONF servers behind a NAT to successfully establish a session with a NMS running a NETCONF client. However, neither the TLS transport nor the CH mechanism is widely supported by NETCONF implementations because the YANG data model for configuring NETCONF clients and servers to configure TLS and CH have not been standardized yet.

We recently implemented the standardized TLS transport and CH mechanism in the netopeer and ncclient projects. netopeer ([II]) is a NETCONF client and server implementation based on libnetconf [3]. netopeer is the only

| Capability             | ConfD (v5.0) | YumaPro (v13.04) | Netopeer2 (v0.3) |
|------------------------|--------------|------------------|------------------|
| :base:1.0              | ✔            |                  |                  |
| :base:1.1              | ✔            |                  |                  |
| :writable-running:1.0 | ✔            |                  |                  |
| :candidate:1.0         | X            |                  |                  |
| :rollback-on-error:1.0 | X            |                  |                  |
| :startup:1.0           | X            |                  |                  |
| :url:1.0               | X            |                  |                  |
| :xpath:1.0             | X            |                  |                  |
| :confirmed-commit:1.0 | ✔            |                  |                  |
| :confirmed-commit:1.1 | ✔            |                  |                  |
| :validate:1.0          | X            |                  |                  |
| :validate:1.1          | X            |                  |                  |
| :notification:1.0      | X            |                  |                  |
| :interleave:1.0        | X            |                  |                  |
| :partial-lock:1.0      | X            |                  |                  |
| :with-defaults:1.0     | X            |                  |                  |

| Data Models             | ConfD (v5.0) | YumaPro (v13.04) | Netopeer2 (v0.3) |
|-------------------------|--------------|------------------|------------------|
| ietf-net-types          | ✔            |                  |                  |
| ietf-yang-types         | ✔            |                  |                  |
| ietf-netconf-monitoring | ✔            |                  |                  |
| ietf-netconf-notifications |        |                  |                  |
| ietf-netconf-acm        | ✔            |                  |                  |
| ietf-netconf-with-defaults |       |                  |                  |
actively developed and maintained open-source project implementing a NETCONF server-side functionality. ncclient [4] (§III) on the other hand is a Python library that facilitates client-side scripting and application development around the NETCONF protocol. In this paper, we introduce both projects. We then discuss approaches to integrate TLS transport (§IV) and CH mechanism (§V) into NETCONF tools and share our experiences with implementing these mechanisms in both projects. The implementations of the approaches described in this paper are available online at Github. We present how implementations of the TLS transport and CH mechanism allows management of home routers (§VI, VII) using these latest additions to the NETCONF protocol.

II. NETCONF SERVER (NETOPEER)

The netopeer project provides a NETCONF server implementation that allows application developers to integrate remote configuration functionality using the NETCONF protocol within their products. The project has evolved over the years and there are multiple building blocks that can be used independently as shown in Fig. 1. While each building block is written in C, there are bindings available for various languages to allow applications written in different programming languages to use the offered functionality. We next describe each building block of the netopeer project.

A. libyang

libyang is YANG data modeling language parser and toolkit. A need for better handling of the YANG 1.0 (RFC 6020) and YANG 1.1 (RFC 7950) schemas and manipulation of instance data in the netopeer server was felt which led to the creation of the libyang toolkit. While the main functionality is to provide access and allow manipulation with the data modeled by YANG, libyang also has the capability to parse and validate YANG (and YIN) schemas. It can also parse, validate and print instance data in XML and JSON (RFC 7951) format. libyang includes yanglint, which is a feature rich tool for validation and conversion of the schemas and YANG modeled data. libyang supports default values in the instance data (RFC 6243) and YANG metadata (RFC 7952) and extensions.

B. libnetconf

libnetconf is a library that implements the NETCONF protocol. It can be used by NETCONF clients as well as servers to create, send, receive, process and respond to NETCONF requests as well as asynchronous event notifications. libnetconf is NETCONF v1.0 (RFC 4741) and v1.1 (RFC 6241) compliant thereby providing support for several basic NETCONF capabilities such as writable-running, candidate configuration, validate capability, distinct startup and URL capability as defined in RFC 6241. libnetconf supports the mandatory underlying SSH (RFC 4242) transport mechanism and support for DNSSEC SSH key fingerprints (RFC 4255). Further features include support for NETCONF Event Notifications (RFC 5277, RFC 6470), with-defaults capability (RFC 6243) and NETCONF access control (RFC 6536). libnetconf also provides bindings for applications written in the Python programming language. We further added to this feature set, by implementing the optional NETCONF over TLS (RFC 7589) transport mechanism and NETCONF CH mechanism using reverse TLS and SSH (RFC 8071).

Based on experiences with libnetconf, the next generation of this library (libnetconf2) based on libyang is currently under development. Originally, libnetconf used libxml2 to represent NETCONF data. Although the NETCONF (YANG modeled) data can be represented as XML data, it is limited when compared with a generic XML data format where mixed content is not allowed. As such, it is inefficient to parse and store this data in generic XML structures. The way of storing and manipulating the data has been changed in libnetconf2 which uses the libyang toolkit. With libnetconf2, the implementation of the NETCONF datastores as well as the mechanism used to connect the datastore with applications (TransAPI) have been moved out of the library into the sysrepo project described below.
C. sysrepo

sysrepo is a YANG-based configuration and operational state data store for GNU/Linux applications. The main purpose is to support applications with simple and unified access to their configuration data. As such, applications (instead of using flat configuration files) can use sysrepo to store their configuration modeled by the provided YANG model. sysrepo provides access to administrators to manipulate with the configuration data of the connected applications. Using YANG schemas, sysrepo validates configuration data and all the performed changes. In this way, it ensures consistency of the data stored in the datastore and enforce data constraints defined by the YANG models. It interconnects administrators (including automated control systems) with the applications by announcing configuration changes to the applications and providing event notifications and status data from applications to administrators.

sysrepo implements the NETCONF datastore previously present in libnetconf. In contrast to previous implementation, it is based on libyang and able to run as a standalone local daemon. However, such a local sysrepo instance can be extended by netopeer-server providing remote access to the datastore via NETCONF protocol.

D. netopeer-server

netopeer-server is the NETCONF server implementation. It integrates the sysrepo datastore and covers libnetconf functionality to interconnect datastores with NETCONF clients. Using libnetconf functions, netopeer-server integrates SSH and TLS servers listening for incoming NETCONF connections. The server behavior is controlled through implementation of several standard IETF YANG schemas covering NETCONF server configuration. As such, the netopeer-server behaves as controlling as well as a controlled application when communicating with sysrepo. The schemas cover even the CH mechanism. It enables netopeer-server not only listen for incoming connections but also actively open and maintain connections to NMS according to the specified configuration.

III. NETCONF CLIENT (NCCLIENT)

ncclient [4] is a Python library that facilitates client-side scripting and application development around the NETCONF protocol. ncclient is an open-source project hosted on github with an Apache 2.0 licence. Bhushan et al. in [4] describe the design and first prototype implementation of ncclient. The project has significantly evolved over several years of development effort and adoption in the industry. For instance, initially, ncclient provided support for NETCONF v1.0 (RFC 4741). As network equipment vendors adopted and implemented the NETCONF protocol, ncclient started to gain visibility and attract interest. However, minor deviations in the implementation of NETCONF v1.0 on behalf of the vendors made each of them fork the project and implement their own flavor of ncclient. A major release merged the vendors’ changes and the idea of modular device handlers was introduced. Each vendor can define their individual handling for ssh connection parameters, devices operation, reply parsing, and proprietary server capabilities. Later releases added compatibility with Python 3 and NETCONF event notifications (RFC 5277). A milestone in the development history of ncclient is our implementation of NETCONF v1.1 (RFC 6241) which adds support for handling chunked frames (RFC 6242). As ncclient was already established, we made sure that backwards compatibility is maintained to allow clients to fallback to NETCONF v1.0 end of message framing scheme (RFC 4742) so as to provide support for server implementations that have not yet adopted and advertise the NETCONF v1.1 capability.

ncclient device handler provides customized solutions for Alcatel-Lucent/Nokia 7x50, Cisco CSR, Cisco IOS-XE, Cisco IOS-XR, Cisco Nexus, Huawei, HP Comware and Juniper devices. ncclient is the core component of Juniper’s network automation framework Junos PyEZ, the core component of Openstack’s networking as a service project Neutron, the core component of the open-source network virtualization platform OpenContrail, the core component of GEANT’s Firewall on Demand flowspec-based Distributed Denial-of-Service (DDoS) mitigation services [5] and the core component of Ansible’s NETCONF role. It is also used in several academic and corporate network management projects.

ncclient is currently one of the most comprehensive NETCONF client implementations not only in the open source community but also in the industry. From a development standpoint, it is actively developed and maintained with new features and performance improvements. What makes the case of ncclient unique is the combined contribution of industry, academia and private individuals.

IV. NETCONF OVER TLS TRANSPORT

We describe the integration of TLS transport mechanism in both netopeer and ncclient projects. There are two general approaches to integrate TLS support within a NETCONF server. The first approach is to use a standalone TLS proxy prepped before the NETCONF server as shown in Fig. 2. We use stunnel since the NETCONF over TLS transport specification (RFC 7589) mandates the use of at least TLS v1.2 with mutual-authentication to secure the session. The TLS server (stunnel) works as a proxy, which encrypts
NETCONF server
NETCONF client
a) TLS 6513
TLS server
b), c)
a) establish a TLS session
b) map CERT to NETCONF username
c) establish NETCONF session.
NETCONF over TLS [RFC 7589]

Figure 3. nccclient establishing a NETCONF over TLS session with a NETCONF server using an integrated TLS server.

(and decrypts) the communication between the NETCONF client and the server. However, client-authentication depends on the content of the NETCONF configuration. As such, it is necessary to either implement the NETCONF server configuration data directly inside the TLS proxy (stunnel) or pass the client certificate back to the NETCONF server (netopeer) during the TLS handshake. The former approach requires larger modifications of the TLS proxy, which is the reason we initially implemented the latter approach within netopeer. In this way, when nccclient initiates a TLS session (see Fig. 2), the client certificate is checked within stunnel and then passed into the netopeer server to map the certificate to a specific user and authorise the client for further communication.

The second approach is to integrate TLS support on the server-side by implementing a TLS server directly within the NETCONF server process by using a TLS library as shown in Fig. 3. This approach significantly simplifies the NETCONF server-side but requires additional effort to correctly implement a TLS server. It is still necessary to authorize the connecting client according to the current NETCONF server configuration. However, the certificate processing is done directly in the NETCONF server process. This makes it simpler to access the server configuration data to map the certificate to the user and authenticate the client. In the netopeer server, we first implemented TLS server support using the stunnel standalone TLS proxy server. However, to simplify the server design and the deployment process, TLS server was later moved directly into the netopeer server by using openssl toolkit.

The client-side (nccclient) update was simpler with an additional TLS transport mechanism that largely offloaded the TLS support to the Python openssl library with strict authentication support. In this way, nccclient can now establish a secure NETCONF session with netopeer over TLS.

V. NETCONF CALL HOME

The CH mechanism (RFC 8071) allows a managed device deployed behind a NAT running a NETCONF server to successfully establish a session with a NMS running a NETCONF client. The CH mechanism can be secured either over SSH or TLS transport. The CH mechanism requires implementation of a CH daemon on the server-side (netopeer) and a TCP listen mode on the client-side (nccclient). In this way, the underlying TCP connection is initiated by the server thereby punching a hole in the NAT gateway. Once the TCP connection is established, the roles are reversed and the control is delegated to the NETCONF client which initiates a TLS (or a SSH) secure session and eventually the NETCONF session on top of the established secure transport. The NETCONF server also needs to support the server configuration YANG data model (work in progress) that specifies how the CH connections are maintained. This allows the NETCONF server to monitor call home sessions and re-establish the connection in a standardized way. As in case of the TLS transport implementation, CH can be implemented as a standalone process or it can be fully integrated into the NETCONF server process. The standalone CH daemon on receiving the request forks a transport server process (sshd or stunnel) depending on the type of the incoming connection as shown in Fig. 4. Alternatively, the integrated CH daemon can pass the connection data directly into the NETCONF server with the integrated transport server as shown in Fig. 5. The pros and cons of both approaches are similar to the case of integrating the TLS transport.

On the client-side, a -callhome switch is implemented to start nccclient in TCP listen mode. nccclient listens on TCP port 4334 (SSH transport) and on TCP port 4335 (TLS transport) simultaneously. A CH from netopeer establishes the TCP connection. The roles are reversed at this stage whereby nccclient passes on the connected socket and depending on the port used, nccclient initiates a TLS (or SSH) session and a NETCONF session on top of the secure transport.
VI. DEPLOYMENT ON A HOME ROUTER

NETCONF (RFC 6241) can function as a control protocol to manage home gateways. In order to understand the memory impact and possibility of using NETCONF on these low-end consumer devices, we deployed a NETCONF server on an TP-Link device running OpenWrt. We describe a number of technical challenges we faced during this process. These real-world issues led to improvements of both ncclient, netopeer and related OpenWrt packages.

A. Optimizations

The libnetconf library (part of the netopeer project) uses GNU extensions and some other features (such as utmpx) that are not available in uClibc, the C library available on the OpenWrt platform. Therefore, libnetconf was modified to detect availability of such extensions. In case of missing C library features, libnetconf was enhanced with alternative ways to achieve the requested functionality.

There is a misconfiguration in the libssh2 OpenWrt package. The package is built with static and dynamic library support by default. However, the package although does export dynamic libraries, it does not export static libraries into staging directories. This makes the static library unusable by default. We updated the package sources and informed the OpenWrt package maintainers to get this resolved upstream.

libnetconf supports NETCONF event notifications (RFC 5277). It uses dbus to share information about these events between libnetconf instances. However, not all versions of OpenWrt support dbus. Besides modifying the libnetconf build process to switch off support for NETCONF notifications, the libnetconf event notifications codebase was also simplified and dbus is no more required.

The NETCONF server binary before being deployed was 2.6Mib in size. A considerable part of this size was occupied by the statically linked code not necessary for the server side applications. By optimizing the building process and providing alternative implementation of several features in libnetconf, we were able to reduce the server binary to 1.5MiB in size.

When the NETCONF server uses standalone transport servers instead of their integration, it is necessary to hook it as a subsystem in the ssh server implementation. However, OpenWrt deploys dropbear as an ssh server implementation. dropbear is a tiny ssh server implementation that is mostly suited for embedded Linux, such as wireless routers, but they do not have any support to hook subsystems. OpenWrt provides packages for alternative OpenSSH server implementation, however there is not enough flash memory space available to run a OpenSSH server on home routers. In order to circumvent the issue, we deployed a separate dropbear instance to handle NETCONF specific calls on port 830. Anyway, the issue was later overcome by integrating the transport servers directly into the netopeer-server.

VII. HOME ROUTER MANAGEMENT

We use the core system data model (RFC 7317) standardized by the IETF to configure such home gateways. This YANG data model specifies configuration and state data used to set and retrieve information about the system identification, time and users management as well as a DNS resolver. Furthermore, the model defines new NETCONF operations for a device restart and shutdown. We prepared a libnetconf core system transAPI module for our NETCONF server. The module is a set of calls employed when specific parts of a configuration data are changed. For example, when a user changes timezone settings in the running datastore, a specific callback function applying this parameter to the home gateway is automatically called. Similarly for NETCONF RPC operations, for example, when the system-restart operation is requested by a client, libnetconf passes the program control to the appropriate transAPI module function that performs a reboot of the home gateway.

The latest Netopeer works very similar way but the datastore and the interaction with applications (core system module) is moved into sysrepo. It was rapidly improved to e.g. provide access to the configuration data even if the NETCONF server or even sysrepo daemon are not running. The API is richer and more granular to cover more use cases.

VIII. CONCLUSION AND FUTURE PERSPECTIVES

In this article, we presented an overview of the NETCONF and YANG feature support in popular commercial and open-source implementations. We showed that netopeer (a NETCONF server) and ncclient (a NETCONF client) open-source projects have evolved over several years of development effort. We captured the significant developments made within these projects. We further described how we implemented the recently standardized NETCONF TLS transport [6] and CH mechanisms [7] within both these projects. Towards the end, we demonstrated how these features allow home routers to be managed using the NETCONF protocol.

We envision a future where it would be possible to implement measurement capabilities directly inside home routers circumventing the need to deploy separate measurement devices [8], [9]. The management of such home routers will thus involve configuration and scheduling of measurements using a control protocol. The IETF has standardized a YANG data model [10] that can be used to configure and schedule measurements on home routers. RESTCONF [11] could be the control protocol that can be used with the YANG data model to configure home routers and report measurement results using event notifications. RESTCONF uses HTTP methods to provide operations and capabilities (similar to NETCONF) on a datastore specified by the YANG schema. We expect our implementation effort and demonstration of possibility of using such protocols to manage home routers serves as input towards progressing standards development within the IETF.

ACKNOWLEDGEMENTS

We like to thank Jürgen Schönwälder for his feedback. Martin Björklund (Tail-f) and Andy Bierman (YumaWorks) for providing us with licensed copies of their commercial NETCONF implementations.
REFERENCES

[1] J. Schönwälder, M. Björklund, and P. Shafer, “Network configuration management using NETCONF and YANG,” ser. IEEE Communications Magazine, vol. 48, no. 9, 2010, pp. 166–173. [Online]. Available: http://dx.doi.org/10.1109/MCOM.2010.5560601

[2] H. M. Tran, I. Tumar, and J. Schönwälder, “NETCONF Interoperability Testing,” ser. Conference on Autonomous Infrastructure, Management and Security, AIMS, 2009, pp. 83–94. [Online]. Available: https://doi.org/10.1007/978-3-642-02627-0_7

[3] R. Krejci, “Building NETCONF-enabled network management systems with libnetconf,” ser. IFIP/IEEE International Symposium on Integrated Network Management (IM 2013), 2013, pp. 756–759. [Online]. Available: http://ieeexplore.ieee.org/xpl/freeabs_all.jsp?arnumber=6573071

[4] S. Bhushan, H. M. Tran, and J. Schönwälder, “ncclient: A Python Library for NETCONF Client Applications,” ser. IP Operations and Management, IPOM 2009, 2009, pp. 143–154. [Online]. Available: http://dx.doi.org/10.1007/978-3-642-04968-2_12

[5] L. Poulopoulos, M. Mamalis, and A. Polyrakis, “FireCircle: GRNET’s approach to advanced network security services’ management via bgp flow-spec and NETCONF,” ser. The Trans European Research and Education Networking Conference. TERENA, October 2012. [Online]. Available: http://www.terena.org/publications/nc2012-proceedings/

[6] M. Badra, A. Luchuk, and J. Schönwälder, “Using the NETCONF Protocol over Transport Layer Security (TLS) with Mutual X.509 Authentication,” RFC 7589 (Proposed Standard), RFC Editor, Jun. 2015. [Online]. Available: https://www.rfc-editor.org/rfc/rfc7589.txt

[7] K. Watsen, “NETCONF Call Home and RESTCONF Call Home,” RFC 8071 (Proposed Standard), RFC Editor, pp. 1–13, Feb. 2017. [Online]. Available: https://www.rfc-editor.org/rfc/rfc8071.txt

[8] V. Bajpai and J. Schönwälder, “A survey on internet performance measurement platforms and related standardization efforts,” IEEE Commun. Surv. Tutorials, vol. 17, no. 3, pp. 1313–1341, 2015. [Online]. Available: https://doi.org/10.1109/COMST.2015.2418435

[9] V. Bajpai, S. J. Eravuchira, and J. Schönwälder, “Lessons learned from using the RIPE atlas platform for measurement research,” Comput. Commun. Rev., vol. 45, no. 3, pp. 35–42, 2015. [Online]. Available: https://doi.org/10.1145/2805789.2805796

[10] J. Schoenwaelder and V. Bajpai, “A YANG Data Model for LMAP Measurement Agents,” RFC 8194 (Proposed Standard), RFC Editor, Fremont, CA, USA, Aug. 2017. [Online]. Available: https://www.rfc-editor.org/rfc/rfc8194.txt

[11] A. Bierman, M. Björklund, and K. Watsen, “RESTCONF Protocol,” RFC 8040 (Proposed Standard), RFC Editor, Fremont, CA, USA, Jan. 2017, updated by RFC 8527. [Online]. Available: https://www.rfc-editor.org/rfc/rfc8040.txt