

Original software publication



QKNetSim+: Improvement of the quantum network simulator for NS-3

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ABSTRACT

The first Quantum Key Distribution (QKD) networks are currently being deployed, but the implementation cost is still prohibitive for most researchers. As such, there is a need for realistic QKD network simulators. The *QKNetSim* module for the network simulator NS-3 focuses on the representation of packets and the management of key material in a QKD network at the application layer. Although QKNetSim's representation of a QKD network is insightful, some its components lack the depth that would allow the simulator to faithfully represent the behaviour of a real quantum network. In this work, we analyse QKNetSim's architecture to identify its limitations, and we present an enhanced version of QKNetSim in which some of its components have been modified to provide a more realistic simulation environment.

Code metadata

Current code version
Permanent link to code/repository used for this code version
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Legal Code License
Code versioning system used
Software code languages, tools, and services used
Compilation requirements, operating environments & dependencies
If available Link to developer documentation/manual
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1.0
<https://github.com/ElsevierSoftwareX/SOFTX-D-23-00830>
–
GNU General Public License (GPL)
git
C++, Python, NS-3
See GitHub repository
See GitHub Repository
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1. Motivation and significance

Quantum technologies have experienced a significant advance in recent years [1–3]. In specific, Quantum Key Distribution (QKD) protocols allow two nodes to agree on a key through a quantum channel, in such a way that it would be impossible for an eavesdropper to obtain the key without being detected [4]. This key can then be used to encrypt communications between the two nodes.

The number of implemented QKD networks is currently very small due to the high cost of the required material and the lack of maturity in the technology. Thus, researchers must employ simulators that imitate the behaviour of a quantum network. There are multiple alternatives depending on the scope of the research [5]: some simulators focus on representing the physical layer of the quantum channel, while others

allow users to define entire networks in which nodes can execute QKD between them.

The network simulator NS-3 is widely used in the scientific and educational communities due to its level of detail and its customising capabilities. There exists a module implemented for NS-3 for the simulation of quantum networks, named QKNetSim [6]. The advantages of QKNetSim over other simulators come from the granularity of NS-3: this simulator allows for in-depth configuration of every component, and packets sent over the simulated network are fully defined, including headers for all protocols involved. Unlike other quantum network simulators, QKNetSim focuses on a network perspective and the managing of the key material generated through QKD. The layered structure of NS-3 also allows QKNetSim to represent QKD networks

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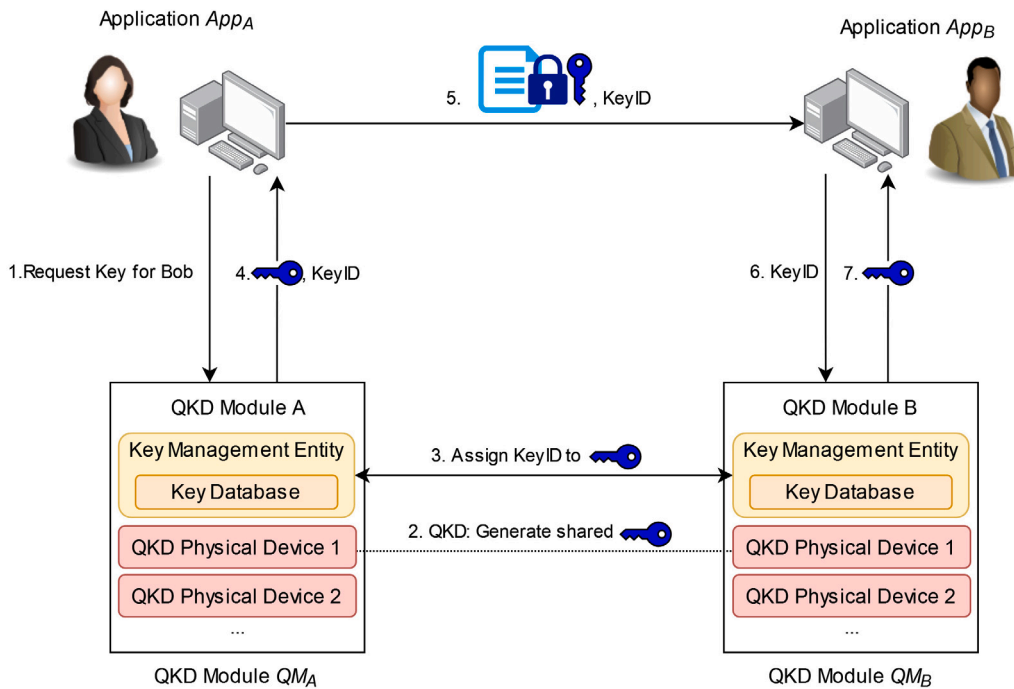


Fig. 1. Diagram of a QKD communication.

at the application level, in which multiple users and programs share common QKD resources such as quantum channels and key buffers. This level of detail, when applied to QKDNetSim's simulation of quantum networks, could help newcomers to understand the fundamentals of quantum communications.

However, QKDNetSim contains some limitations that affect its ability to faithfully represent the behaviour of a real quantum network. The main shortcomings of QKDNetSim are in key management: the nodes do not adequately process the key material that they receive and the cryptography handler does not function properly. These aspects are crucial to the architecture of QKD networks, so QKDNetSim's inability to simulate them imposes a significant limitation on its usefulness.

For this work we present an enhanced version of the quantum network simulation module QKDNetSim. To this end, we will start with an analysis of QKDNetSim: of which elements it is composed and to which degree it imitates the behaviour of a real quantum network, including the limitations and errors that prevent QKDNetSim from achieving its purposed objectives. Our implementation will provide enhancements to overcome the mentioned limitations while maintaining the architecture of the simulation module. The enhanced version of QKDNetSim can be employed by researchers to study the behaviour of QKD networks, with a focus on key synchronisation and management. It can also be used as a first approach to the design of complex QKD networks and to analyse their performance.

1.1. QKD network architecture

In experimental settings, the execution of QKD protocols is very slow and thus it would be very inefficient to block the generation of a packet to obtain key material through QKD [7]. For that reason, it is common to asynchronously execute the QKD protocol at a previous time, and store the resulting key material in a buffer to be consumed when needed [8]. As a result, the processes of generating and consuming key material are decoupled, at the cost of managing the synchronisation of buffers of adjacent nodes.

Due to the high cost of deploying quantum communications infrastructure, these devices are usually shared between multiple Applications. There have been efforts to standardise the communication

between Applications and QKD devices. In the ETSI GS QKD standards 004 [9] and 014 [10], a QKD Module is composed of multiple QKD Physical Devices (possibly belonging to different manufacturers) and a Key Management Entity, or *KME*. The KME contains a Key Database and is tasked with managing the key material that is shared through the QKD Physical Devices. An example communication flow between Applications is shown in Fig. 1: their respective QKD Modules are tasked with generating the shared key material through a QKD protocol (such as BB84 [11]) and assigning it a KeyID, which the Applications can then use to retrieve the cryptographic key.

1.2. QKD simulators

Due to the experimental state of QKD, most researchers rely on simulators to study the behaviour and structure of quantum networks. There are a variety of available simulators [5] that focus on different aspects of quantum networks, whether it be the network structure, the representation of quantum states or the execution of QKD protocols.

Qunetsim [12] is a simulator written in Python that allows users to represent quantum networks. The nodes can exchange not only classical messages, but also qubits that are simulated through different backends such as *SimulaQron*. *Qunetsim* mainly focus on simulating the quantum channels that connect nodes and implementing different QKD protocols and methods of transmitting information through qubits, including the use of entangled states. Because of this low-level approach, *Qunetsim* does not provide functionalities for key management or buffer synchronisation between QKD nodes. The network is functional, but not completely simulated as packets do not contain protocol headers as in real networks.

NetSquid [13] is another alternative written in Python. It also focuses on the representation of qubits and the simulation of quantum channels, including the possibility of adding delay, noise and loss to imitate real conditions. Unlike *Qunetsim*, *NetSquid* does formally represent the behaviour of a real network by employing a discrete-event simulation engine. However, it also leaves the management of key material to be implemented by users.

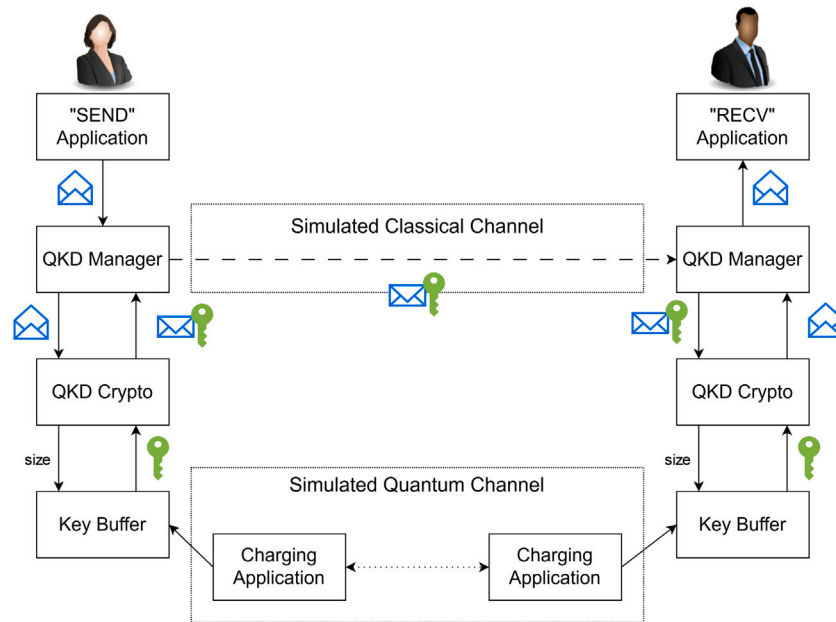


Fig. 2. Architecture of QKDNetSim.

2. Software description

2.1. Original QKDNetSim's architecture

The module QKDNetSim adds to NS-3 the possibility of creating quantum channels between pairs of nodes. To this end, the following components are added to each pair of nodes:

- **Send/Receive Applications:** they simulate programs that create packets to be encrypted by the rest of QKDNetSim's components. When they are generated or received, they are sent to the Manager to perform the pertinent cryptographic operations.
- **QKD Manager:** the central component of the module, which serves as connection between the others. The Manager processes incoming and outgoing packets, identifies which operations need to be performed and calls the pertinent component to execute them.
- **Cryptography Handler:** receives petitions from the Manager to encrypt or decrypt packets. It implements multiple cryptographic algorithms, and has access to the Key Buffer. Corresponds with the Object *QKDCrypto*
- **Simulated Quantum Channel:** imitates the behaviour of a quantum channel. Each of the nodes possesses a *Charging Application*, which constantly generate new shared key material.
- **Key Buffer:** Stores key material transmitted through the quantum channel for future use.

The interaction between elements is shown in Fig. 2.

Unlike the simulators mentioned in Section 1.2, QKDNetSim focuses on the structure of QKD nodes and the components that manage the key material that is generated through QKD protocols. The structure of QKD nodes, with the inclusion of Key Buffers as a fundamental component, is compatible with ETSI's definition of a QKD Module, as represented in Fig. 1.

As mentioned, the quantum channel is simulated through the *Charging Applications* that are installed for each pair of connected nodes. Fig. 3 shows the contents of a packet exchanged between the Charging Applications of two adjacent nodes, which includes (after the label *ADDKEY*) the key material that will be added to the buffers.

QKDNetSim uses buffers to store key material, as introduced in Section 1.1. the Charging Applications are constantly generating new

key material and storing it into their respective Key Buffers. Whenever the Send Application generates a new packet, some of the previously generated key material is consumed to encrypt it.

Fig. 4 shows the amount of key material stored inside a Key Buffer during a simulation. It increases periodically when the Charging Applications creates new key material, and it decreases when new packets are encrypted. It is possible to manually define the maximum and minimum amounts of key material that the Key Buffer can hold, as well as the initial amount. As shown in Fig. 4, the Simulated Quantum Channel only generates new key material when the current amount is below a "Threshold" value.

2.2. QKDNetSim's shortcomings

QKDNetSim correctly identifies the components that take part in a QKD network. However, the implementation of these components lacks realism in some aspects, which prevent QKDNetSim from providing a faithful simulation. We highlight the following shortcomings of QKDNetSim:

The messages sent through the Simulated Quantum Channel are all identical. The Simulated Quantum Channel is tasked with the creation of new key material between two nodes. However, all messages exchanged between the Charging Applications of adjacent nodes contain only a string of '0's, as can be seen in Fig. 3. Since all the key material that is created is the same, all packets are encrypted with the same key. The receiver's Charging Application does not process *ADDKEY* messages, since it already knows that the key is a string of '0's. This defeats the purpose of QKD and makes QKDNetSim a less realistic simulator.

The Key Buffers do not store keys. The key material generated through the Simulated Quantum Channel is not stored anywhere. This should be the function of the Key Buffer: instead, it only stores a number which represents the *amount* of key material it should have.

Whenever the Simulated Quantum Channel tries to insert new key material in the Key Buffer, it is discarded and the *amount* is increased. A similar process occurs when the Manager requests key material from the Buffer: a new string of '0's is returned and the *amount* is decreased by its length. The plot shown in Fig. 4 represents this *amount*, since it is the only metric the Buffer can provide.

Since there is no real key material inside the Buffers, there is also no mechanism for ensuring, maintaining or recovering synchronicity

```

> Frame 1964: 462 bytes on wire (3696 bits), 462 bytes captured (3696 bits)
Raw packet data
> Internet Protocol Version 4, Src: 10.1.1.1, Dst: 10.1.1.2
> Transmission Control Protocol, Src Port: 49153, Dst Port: 8000, Seq: 261000, Ack: 1, Len: 410
> Data (410 bytes)
0000 45 00 01 ce 03 c2 00 00 40 06 00 00 0a 01 01 01  E.....@.....
0010 0a 01 01 02 c0 01 1f 40 00 03 fb 88 00 00 00 01  .....@.....
0020 80 10 80 00 00 00 00 00 08 0a 00 00 3c 3c 00 00  .....<<.....
0030 3c 1e 00 00 41 44 44 4b 45 59 3a 33 30 30 30 30  <...ADDK EY:30000
0040 30 30 3b 30 30 30 30 30 30 30 30 30 30 30 30  00;00000 00000000
0050 30 30 30 30 30 30 30 30 30 30 30 30 30 30 30  00000000 00000000
0060 30 30 30 30 30 30 30 30 30 30 30 30 30 30 30  00000000 00000000

```

Fig. 3. Packet containing key material sent by Charging Application.

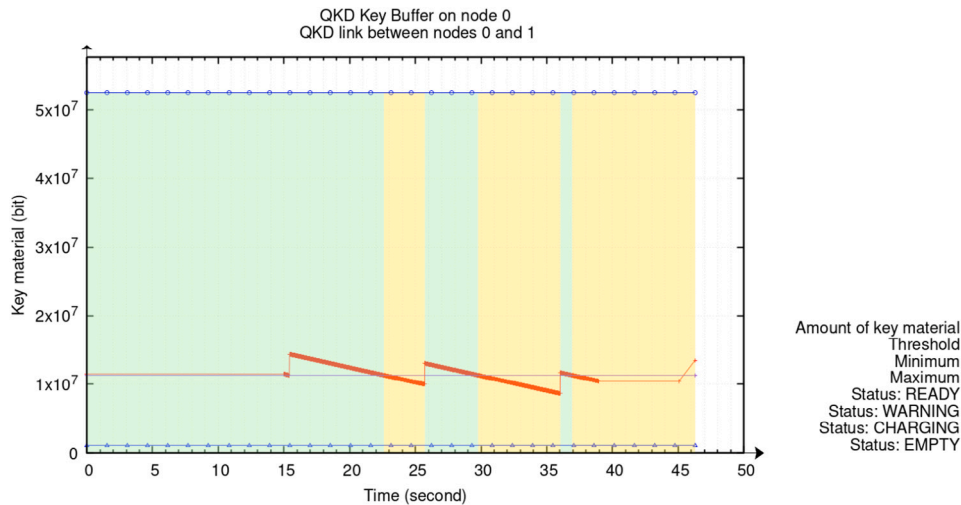


Fig. 4. Amount of available key material inside the Key Buffer throughout the simulation.

between Key Buffers of connected nodes. This makes QKDNetSim less realistic, as it does not represent a problem that needs to be addressed in real quantum networks.

Encryption is disabled and does not work. The Cryptography Handler provides implementations for the encryption algorithms AES and One-Time Pad (OTP). However, these implementations contain errors: they incorrectly assume keys are represented as an array of bytes, when they are an array of bits. Thus, whenever the simulator tries to encrypt a packet, it crashes.

Even if these errors are corrected and packets are adequately encrypted, the PCAP still shows them in plaintext. The fact that contents of the PCAP do not correspond to the real messages that were exchanged makes the simulation harder to understand.

2.3. Description of enhancements to QKDNetSim

As we have shown, QKDNetSim is limited in its representation of QKD networks since it does not adequately represent tasks related to key management, which are fundamental operations in real scenarios. In our improved version of QKDNetSim we provide the following enhancements to the aforementioned shortcomings:

Key generation and transmission. The Charging Applications now adequately process incoming *ADDKEY* messages. As in the original module, one of the nodes is designated as “Primary” and the other as “Secondary”: the Primary node is tasked with generating the key material and sending the *ADDKEY* messages, while the Secondary receives and processes them.

As mentioned, in the original QKDNetSim all keys are generated by the Charging Applications as a string of ‘0’s. In our implementation we provide a new component named “QKD Random Generator” for the generation of key material. We use NS-3’s PRNG as the default source

of randomness, but we also provide the option of using a real Quantum Random Number Generator (QRNG) [14–16], which are commonly used as a source of entropy in quantum networks.

We have employed IDQuantique’s *Quantis* QRNG, which is accessible through a USB interface and has a key generation rate of about 4 Mb/s. Our QKD Random Generator component performs calls to Quantis’ C++ API to generate the key material that is to be transmitted through the Simulated Quantum Channel.

Key storage. The Key Buffers are now composed of two different structures:

1. *Raw key material storage:* Key material generated by the Simulated Quantum Channel that has not been assigned a KeyID yet. Its capacity is regulated by the “MAX”, “MIN” and “THRESHOLD” parameters shown in Fig. 4
2. *Key Database:* Set of indexed keys with information about their KeyID and length.

The process of obtaining key material from the raw storage and inserting it into the Key Database with a KeyID is called *reserving*. In our implementation, this is performed by the Cryptography Handler whenever it requires a key of any length for either encryption or authentication of Application packets. The reservation of key material is done in the sender and receiver at the same time, so that both nodes can access the same key with a specific KeyID. The keys are used only once and then are removed from the Key Database.

Encryption. Whenever a packet generated by an Application reaches the Cryptography Handler, it is encrypted and authenticated, including any TCP/IP headers that it contains. Then, a *QKDHeader* is added, which includes the length of the packet, the MessageID, and the KeyIDs for the encryption and authentication keys. The QKDHeader was also present in the original QKDNetSim, but since the Key Buffers did not

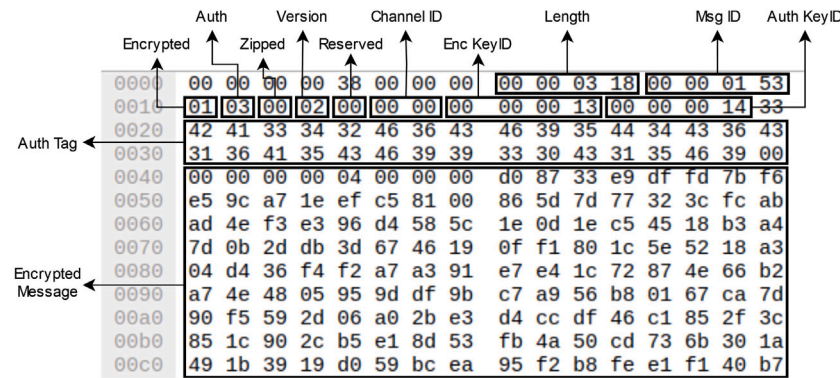


Fig. 5. Contents of an encrypted message sent by the Send Application.

contain a Key Database, the KeyIDs had no meaning. Therefore, the values of the QKDHeader were mostly ignored.

The original QKDNetSim omits the logging of encrypted messages into a PCAP file, as it only includes their unencrypted version in packet captures. Of particular interest are the values inside the QKDHeader. Fig. 5 shows an example packet as logged by the simulator. The values for “Encrypted” and “Auth” represent the employed algorithms, which for this packet are OTP and VMAC, respectively.

3. Illustrative example

We have prepared an example execution to demonstrate the behaviour of the enhanced QKDNetSim module. The simulation consists of two different nodes, with IPs in the 10.1.1.0/24 network: a sender and a receiver. The sender will generate 5 packets and send them to the receiver, encrypted with key material generated through the Simulated Quantum Channel. Listing 1 shows the output of an example execution of QKDNetSim.

```
Source IP address: 10.1.1.1
Destination IP address: 10.1.1.2

+0.000000000s -1 QKDRandomGenerator:printCardsInfo(0x5573d19b9c80, "Displaying cards info:")
+0.000000000s -1 QKDRandomGenerator:printCardsInfo(0x5573d19b9c80, "* Searching for USB devices
...")
+0.000000000s -1 QKDRandomGenerator:printCardsInfo(0x5573d19b9c80, " Found ", 1, " card(s)")
+0.000000000s -1 QKDRandomGenerator:printCardsInfo(0x5573d19b9c80, " - Details for device #", 0)
+0.000000000s -1 QKDRandomGenerator:printCardsInfo(0x5573d19b9c80, " driver version: ", 0, "", 1)
+0.000000000s -1 QKDRandomGenerator:printCardsInfo(0x5573d19b9c80, " core version: ", 60b1c01)
+0.000000000s -1 QKDRandomGenerator:printCardsInfo(0x5573d19b9c80, " serial number: ", "206361
A410")
+0.000000000s -1 QKDRandomGenerator:printCardsInfo(0x5573d19b9c80, " manufacturer: ", "id
Quantique")
+0.000000000s -1 QKDRandomGenerator:printCardsInfo(0x5573d19b9c80, " module ", 0, ":", "found", "
", "(enabled)")
QKDCrypto:QKDCrypto(0x558a0f5a4d60)
+0.000000000s -1 QKDBuffer:QKDBuffer(0x558a0f5a8460, 0, 1)
+0.000000000s -1 QKDBuffer:Init(0x558a0f5a8460)
+0.000000000s -1 QKDBuffer:QKDBuffer(0x558a0f5a8770, 0, 1)
+0.000000000s -1 QKDBuffer:Init(0x558a0f5a8770)
+0.000000000s -1 QKDRandomGenerator:generateStream(0x7ff0becb050, "Requesting ", 51000, " bytes:")
+0.000000000s -1 QKDRandomGenerator:generateStream(0x7ff0becb050, "Single call")
+0.000000000s -1 QKDBuffer:AddKeyMaterial(0x558a0f5a8460, "m_McCurrent", 0, "size": 51000, "key
material[0-30]"; 82, 228, 78, 97, 249, 182, 105, 0, [...], "key material[(end - 30) - end]";
[...], 149, 189, 196, 234, 197, 154, 69, 235)
+0.000000000s -1 QKDBuffer:AddKeyMaterial(0x558a0f5a8460, "m_McCurrent", 51000, "buffer final
material"; [...], 149, 189, 196, 234, 197, 154, 69, 235)
+0.000000000s -1 QKDBuffer:AddKeyMaterial(0x558a0f5a8460, " Adding new Key Material: ", 51000, "
bytes")
+0.000000000s -1 QKDBuffer:AddKeyMaterial(0x558a0f5a8770, "m_McCurrent", 0, "size": 51000, "key
material[0-30]"; 82, 228, 78, 97, 249, 182, 105, 0, [...], "key material[(end - 30) - end]";
[...], 149, 189, 196, 234, 197, 154, 69, 235)
+0.000000000s -1 QKDBuffer:AddKeyMaterial(0x558a0f5a8770, "m_McCurrent", 51000, "buffer final
material"; [...], 149, 189, 196, 234, 197, 154, 69, 235)
+0.000000000s -1 QKDBuffer:AddKeyMaterial(0x558a0f5a8770, " Adding new Key Material: ", 51000, "
bytes")
+0.000000000s -1 QKDBuffer:InitTotalGraph(0x558a0f5a8460)
+0.000000000s -1 QKDBuffer:InitTotalGraph(0x558a0f5a8770)

[...]

QKDCrypto:ProcessOutgoingPacket(0x558a0f5a4d60, "***** ENCRYPTION MODE *****", 1)
QKDCrypto:ProcessOutgoingPacket(0x558a0f5a4d60, "SrcBuffer")
+20.256000000s 0 QKDBuffer:ReserveKeyMaterial(0x558a0f5a8460, " Reserved Key with ID ", 19, "of size
", 720)
+20.256000000s 0 QKDBuffer:FetchKeyByID(0x558a0f5a8460, " Fetching Key with ID: ", 19, " Value: ", "
D08733E9CFBDF7BF6[...]")
QKDCrypto:ProcessOutgoingPacket(0x558a0f5a4d60, "DstBuffer")
+20.256000000s 0 QKDBuffer:ReserveKeyMaterial(0x558a0f5a8770, " Reserved Key with ID ", 19, "of size
", 720)
+20.256000000s 0 QKDBuffer:FetchKeyByID(0x558a0f5a8770, " Fetching Key with ID: ", 19, " Value: ", "
D08733E9CFBDF7BF6[...]")
+20.256000000s 0 QKDBuffer:DeleteKeyID(0x558a0f5a8460, "KeyID is deleted from 'm_keys", 19)
```

Table 1
Comparison between other QKD network simulators and our implementation.

Ref.	Name	Network simulation	QKD headers & packets	Key management	Classical encryption
[12]	QuNetSim	Ad-hoc	No	No	No
[13]	NetSquid	Discrete-event	No	No	No
[6]	QKDNetSim	Discrete-event	Yes	Yes (limited)	Non-functional
This work	–	Discrete-event	Yes	Yes	Yes

of bytes from the Key Buffer and assigning them a KeyID. Once the Key Buffers are notified, the sender encrypts and authenticates the message (including IPv4 and TCP headers) and adds a QKDHeader which includes the KeyIDs of the employed keys. The receiver then processes this packet, labelled with PacketID 340, and obtains the required keys from its Key Buffer using the KeyIDs to complete the decryption process. The encrypted message that appears in this execution trace is also shown in Fig. 5, where all QKDHeader values are identified.

The last section shows an exchange between the Charging Applications to add new key material to both nodes' Key Buffers. The sender's Charging Application generates a random string of 500 bytes through the QKDRandomGenerator and adds it to its buffer. The key material is then encapsulated in an ADDKEY message and sent to the receiver's Charging Application, which processes the message and inserts the same random string in its Key Buffer. The trace shows the trailing bytes of both Key Buffers, which correspond to the key material that was inserted.

4. Impact

Our implementation of an enhanced QKDNetSim provides a faithful representation of QKD networks, which allows users to better understand the operations involved in them, specially those related to key management at the application layer.

Table 1 highlights the difference between existing QKD network simulators, including QKDNetSim in its original state, and our implementation. As shown, QKD network simulators usually place its focus on representing a quantum channel in order to simulate QKD algorithms or entanglement of qubit states. While they are undoubtedly very useful simulators, they leave out significant components of QKD networks like key management. In contrast, in our simulator the shared key material generated through QKD protocols is put to use: we allow for different Applications to employ this cryptographic keys without needing to interact with the physical layer of QKD. This also requires the use of different structures like Key Buffers to decouple the processes of obtaining the key material and using it, and to perform synchronisation with buffers of adjacent nodes.

Our enhancements over the original QKDNetSim provide a more realistic simulation of QKD networks. We maintain QKDNetSim's overall architecture while improving each component separately. In our enhanced version of QKDNetSim, the simulator uses randomly-generated key material (with the option of employing a real QRNG) instead of dummy packets filled with zeros. The inclusion of real key material also implies that the Simulated Quantum Channel must be able to process incoming QKD packets and that Key Buffers need to be actively synchronised.

5. Conclusions

In this work, we have analysed NS-3's quantum network simulation module QKDNetSim, describing its main components and identifying its shortcomings and their impact in the quality of the simulation of a QKD network. The shortcomings that we analyse in this document are related to key management and encryption which, as we have identified, are the elements that mainly differentiate QKDNetSim from other quantum network simulators. Our implementation of an enhanced QKDNetSim maintains the module's overall structure while overcoming the limitations of the Key Buffer, Cryptography Handler and Simulated Quantum Channel. We also provide the option of employing a real QRNG as a source of randomness for the Simulated Quantum Channel.

CRediT authorship contribution statement

David Soler: Conceptualization, Investigation, Supervision, Writing – original draft. **Iván Cillero:** Investigation, Software. **Carlos Dafonte:** Supervision, Writing – review & editing. **Manuel Fernández-Veiga:** Supervision, Writing – review & editing. **Ana Fernández Vilas:** Supervision, Writing – review & editing. **Francisco J. Nóvoa:** Conceptualization, Project administration, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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