Quantum Shortest Path Netsukuku

http://netsukuku.freaknet.org
AlpT (@freaknet.org)
February 3, 2008

Abstract

This document describes the QSPN, the routing discovery algorithm used by Netsukuku. Through a deductive analysis the main proprieties of the QSPN are shown. Moreover, a second version of the algorithm, is presented.
This document is part of Netsukuku.
Copyright ©2007 Andrea Lo Pumo aka AlpT <alpt@freaknet.org>. All rights re-
served.

This document is free; you can redistribute it and/or modify it under the terms of
the GNU General Public License as published by the Free Software Foundation; either
version 2 of the License, or (at your option) any later version.

This document is distributed in the hope that it will be useful, but WITHOUT
ANY WARRANTY; without even the implied warranty of MERCHANTABILITY or
FITNESS FOR A PARTICULAR PURPOSE. See the GNU General Public License
for more details.

You should have received a copy of the GNU General Public License along with
this document; if not, write to the Free Software Foundation, Inc., 675 Mass Ave,
Cambridge, MA 02139, USA.
## Contents

1 Preface 1

2 The general idea 1  
  2.1 The network model 1  
  2.2 The routing algorithm 1  
  2.3 The QSPN 2

3 Network topology 2  
  3.1 Fractal topology 2

4 Tracer Packet 2  
  4.1 Tracer Packet flood 2  
  4.2 Proprieties of the tracer packet 3

5 Routes of a graph 3

6 Acyclic Tracer Packet flood 5

7 Routes simplification 6  
  7.1 Simplification rules 6  
  7.2 General results 7  
  7.3 The question 8

8 Continuous Tracer Packet 9  
  8.1 Reflected CTP 9

9 QSPN v2 9  
  9.1 Interesting information 10  
  9.2 Live routes simplification 10  
  9.3 Cyclicity 11  
  9.3.1 Subcycles examples 11  
  9.4 Finiteness 11  
  9.5 Routes limit 11  
  9.6 Scalability 12  
  9.6.1 TP Classes 12  
  9.6.2 Subcycle filter 12  
  9.6.3 Efficiency order 14  
  9.7 Bandwidth issues 14  
  9.8 Worst case 14

10 QSPN v1 14  
  10.1 Q vs Q^2 15

11 Network dynamics 16  
  11.1 Extended Tracer Packet 16
12 QSPN optimisations  
  12.1 Rtt and bandwidth ................................................. 20  
    12.1.1 Rtt delay ....................................................... 20  
    12.1.2 Asymmetry in $Q^2$ ............................................. 20  
  12.2 Disjoint routes ..................................................... 21  
  12.3 Cryptographic QSPN ................................................. 21  

13 Simulating the QSPN v2 .............................................. 22  

14 TODO ................................................................. 25  

15 ChangeLog .......................................................... 25
1 Preface

The first part of the document describes the reasoning which led us to the construction of the current form of the QSPN v2. If you are just interested in the description of the QSPN v1 and v2 and you already know the concept of the Tracer Packet, you can directly skip to section 8.

2 The general idea

The aim of Netsukuku is to be a (physical) scalable mesh network, completely distributed and decentralised, anonymous and autonomous.

The software, which must be executed by every node of the net, has to be unobtrusive. It has to use very few CPU and memory resources, in this way it will be possible to run it inside low-performance computers, like Access Points, embedded devices and old computers.

If this requirements are met, Netsukuku can be easily used to build a worldwide distributed, anonymous and not controlled network, separated from the Internet, without the support of any servers, ISPs or control authorities.

2.1 The network model

Netsukuku prioritises the stability and the scalability of net: the network has to be able to grow to even $2^{27}$ nodes.

A completely dynamic network would requires rapid and frequent updates of the routes and this is in contrast with the stability and the scalability requirements of Netsukuku. For this reason, we restrict Netsukuku to the case where a node won’t change its physical location quickly or often.

This assumption is licit, because the location of a wifi node mounted on top of a building won’t change and its only dynamic actions would be the joining and the disconnection to and from the network and the changes of the quality of its wifi links. However, there are some consequences of this assumption:

1. Mobiles node aren’t supported by Netsukuku algorithms. ¹

2. The network isn’t updated quickly: several minutes may be required before all the nodes become aware of a change of the network (new nodes have joined, more efficient routes have become available, . . . ). However, when a node joins the network, it can reach all the other nodes from the first instant, using the routes of its neighbours.

2.2 The routing algorithm

One of the most important parts of Netsukuku, is the routing discovery algorithm, which is responsible to find all the most efficient routes of the network. These routes will permit to each node to reach any other node.

The routing algorithm must be capable to find the routes without overloading the network or the nodes’ CPU and memory resources.

¹It is possible to use other mesh network protocols designed for mobility in conjunction with Netsukuku, in the same way they are used in conjunction with the Internet (i.e. see olard).
2.3 The QSPN

Netsukuku implements its own algorithm, the QSPN (Quantum Shortest Path Netsukuku). The name derives from the way of working of its principal component: the TP (Tracer Packet), a packet which gains a “quantum” of information at each hop.

The QSPN is based on the assumptions described in section 2.1.

3 Network topology

The QSPN alone wouldn’t be capable of handling the whole network, because it would still require too much memory. For example, even if we store just one route to reach one node and even if this route costs one byte, we would need 1Gb of memory for a network composed by $10^9$ nodes (the current Internet).

For this reason, it’s necessary to structure the network in a convenient topology.

3.1 Fractal topology

Netsukuku, adopts a fractal like structure: 256 nodes are grouped inside a group node (gnode), 256 group nodes are grouped in a single group of group nodes (ggnode), 256 group of group nodes are grouped in a gggnode, and so on. (We won’t analyse the topology of Netsukuku. You can find more information about it in the proper document: [2]).

Since each gnode acts as a single real node, the QSPN is able to operate independently on each level of the fractal.

Since in each level there are a maximum of 256 (g)nodes, the QSPN will always operate on a maximum of 256 (g)nodes, therefore we would need just to be sure that it works as expected on every cases of a graph composed by $\leq 256$ nodes. By the way, we’ll directly analyse the general case.

For the sake of simplicity, in this paper, we will assume to operate on level 0 (the level formed by 256 single nodes).

4 Tracer Packet

A TP (Tracer Packet) is the fundamental concept on which the QSPN is based: it is a packet which stores in its body the IDs of the traversed hops.

4.1 Tracer Packet flood

A TP isn’t sent to a specific destination but instead, it is used to flood the network. By saying “the node A sends a TP” we mean that “the node A is starting a TP flood”.

A TP flood passes only once through each node of the net: a node which receives a TP will forward it to all its neighbours, except the one from which it received the TP. Once a node has forwarded a TP, it will not forward any other TPs of the same flood.
4.2 Proprieties of the tracer packet

1. A node $D$ which received a TP, can know the exact route covered by the TP. Therefore, $D$ can know the route to reach the source node $S$, which sent the TP, and the routes to reach the nodes standing in the middle of the route.

For example, suppose that the TP received by $D$ is: $\{S, A, B, C, D\}$. By looking at the packet $D$ will know that the route to reach $B$ is $C \rightarrow B$, to reach $A$ is $C \rightarrow B \rightarrow A$, and finally to reach $S$ is $C \rightarrow B \rightarrow A \rightarrow S$. The same also applies for all the other nodes which received the TP, i.e., $B$ knows that its route to reach $S$ is $A \rightarrow S$.

2. The bouquet of $S$ is the set of all the TPs which will be forwarded or sent by the node $S$ during the flood. The first TP of this bouquet received by a generic node $D$, will be the TP which covered the fastest route which connects $S$ to $D$. The fastest $S \rightarrow D$ route is the route with the minimum $rtt$ (Round-Trip Time) between $S$ and $D$. This property is also valid if $S$ is the node which started the TP flood, i.e. the first node which sent the first bouquet of the TP flood.

Example

![A simple graph]

Figure 1: A simple graph

Suppose that $D$ sends a TP. The TP will cover this routes: $D \rightarrow E \rightarrow F$ and $D \rightarrow C \rightarrow B \rightarrow A$. When the TP reaches the node $F$ and the node $A$, the flood will stop, because either $A$ and $F$ won’t be able to forward the TP to any other node.

At the end, $A$ will know the route $A \rightarrow B \rightarrow C \rightarrow D$ and $F$ will know the route $F \rightarrow E \rightarrow D$.

5 Routes of a graph

Given a graph $G$ we want to find all the existing routes between a node and all the other nodes.

Let $N$ be a generic node. Starting from $N$ we explore the entire graph until we re-enter in a cycle already visited or we cannot proceed any further. This approach is similar to the Depth-First Search\[3\] algorithm, but instead of searching for a specific goal, we just traverse the entire graph. Note that a cycle is traversed only once, because we need non redundant routes. In other words, if we already know the $S \rightarrow A \rightarrow B \rightarrow C \rightarrow D$ route, it’s useless to known that we can reach $D$ with the $S \rightarrow A \rightarrow B \rightarrow C \rightarrow A \rightarrow B \rightarrow C \rightarrow D$ route.

This is the pseudo code of the algorithm:

```
generate_routes(G) {
    forall node in G
```
/* Starts the exploration of the graph from the ‘‘node’’ of the graph ‘‘G’’ and print all its routes */
walk(node, node)
}

/* Print all the routes which start from the node ‘N’ */
walk(N, branch) {
    deepened=0
    forall L in N.links
        /* L is a neighbour of N */
    if(L in branch)
        /* If ‘‘L’’ is already contained in the explored branch, we’ve found a cycle. Since we just need to traverse only once a cycle, we skip this ‘‘L’’ node and continue to consider the other neighbours of N */
        continue;
    newbranch=branch + L /* Append in the explored branch the ‘‘L’’ node */
    walk(L, newbranch) /* Recursively explore the new branch */
    /* Indicate that we’ve deepened in the graph at least once */
    deepened=1
    if(!deepened)
        /* We haven’t deepened in the above for, this means that the current branch can’t be explored anymore, therefore it is a valid route. Print it */
        print branch
}

A proof of concept of the above algorithm has been implemented in Awk [4].

Example
Consider this graph:
Given this graph as input the algorithm will output:

- $A \rightarrow B \rightarrow D \rightarrow C$
- $A \rightarrow B \rightarrow D \rightarrow E$
- $A \rightarrow C \rightarrow D \rightarrow B$
- $A \rightarrow C \rightarrow D \rightarrow E$
- $B \rightarrow A \rightarrow C \rightarrow D \rightarrow E$
- $B \rightarrow D \rightarrow C \rightarrow A$
- $B \rightarrow D \rightarrow E$
- $C \rightarrow A \rightarrow B \rightarrow D \rightarrow E$
- $C \rightarrow D \rightarrow B \rightarrow A$
- $C \rightarrow D \rightarrow E$
- $D \rightarrow B \rightarrow A \rightarrow C$
- $D \rightarrow C \rightarrow A \rightarrow B$
- $D \rightarrow E$

6 Acyclic Tracer Packet flood

We can consider each route given by the output of the above algorithm as a single Tracer Packet. In fact, it is possible to implement the same algorithm using a slightly modified version of the TP flood, called the Acyclic TP flood:

The flood is not restricted like in a normal TP flood: one or more ATP can pass from the same node. The end of the flood is given by this rule: a node will not forward to any of its neighbours the ATP if its node ID is already present in the route contained in the body of the packet. With this rule an ATP can walk in a cycle only once, hence the name. Finally, like in the normal TP, a node doesn’t forward the ATP to the neighbour from which it has received the packet itself.

If every node of the network sends an ATP flood, then every node will get all the possible routes to reach any other node.

As you can see, the ATP flood performs a “live” version of the algorithm described in section 5. Obviously this is far from an efficient routing discovery algorithm, but it represents a good start.
7 Routes simplification

Looking carefully at the example output (5) of the Generate Route algorithm, we can notice that many routes are highly redundant, in other words, some routes are almost the same. Consider for example the following four routes:

\[
\begin{align*}
A \rightarrow B \rightarrow D \rightarrow E & \quad (1) \\
D \rightarrow E & \quad (2) \\
A \rightarrow B \rightarrow D \rightarrow C & \quad (3) \\
D \rightarrow C \rightarrow A \rightarrow B & \quad (4)
\end{align*}
\]

As we’ve seen in the previous section 6, we can consider these routes as effective Tracer Packets. In this example, the TP (1) cover the same route of the TP (2). Therefore we can save one TP by just sending the TP (1), which will traverse the route (2) too.

The TP (3) covers part of the TP (4), thus we can simplify the two of them by just sending a TP which cover this route: \( A \rightarrow B \rightarrow D \rightarrow C \rightarrow A \rightarrow B \).

Continuing in this process we can further simplify the two TP:

\[
ABDCAB + ABDE \Rightarrow ABDCABDE
\]

Thus, from the initial four TPs we’ve found a unique TP which gives the same routes of the original ones.

7.1 Simplification rules

We can derive some rules to simplify routes.

Since we can represent a route as a string where each symbol is a node, we can also describe the routes simplification as a series of operations on strings.

In the following rules, each letter found in an expression represents a generic string, which may be also the NULL string, i.e. the “\( XX \)” string can be anything like “foofoo” or “1234512345”.

The \( c \ldots c \) expression represents a cycle, where the \( c \) character refers to just one node, and not to an entire string.

\[XY + YZ \Rightarrow XYZ\] If two routes share respectively the ending and the starting part, they can be merged into a unique route. Example:

\[
ABCD + CDKRE \Rightarrow ABCKRE
\]

\[YXZ \Rightarrow YXZ\] Example:

\[
123ABCXYZ + ABC \Rightarrow 123ABCXYZ
\]

\[Xc \ldots c + XcY \Rightarrow Xc \ldots cY\] Example:

\[
123ABCDA + 123A987 \Rightarrow 123ABCDA987
\]

\[c \ldots cZ + YcZ \Rightarrow Yc \ldots cZ\] Example:

\[
ABCD + 123 + 987 \Rightarrow 987ABCD
\]

\[ABCD + 123 + 987 \Rightarrow 987ABCD
\]
c\ldots c + YcZ \Rightarrow Yc\ldots cZ \quad \text{Example:}

\[ ABCDA + 987A123 \Rightarrow 987ABCDA123 \]

**Invalid route** A route must not be in the form of:

\[ Xa\ldots aY \]

where \( a \) and \( c \) are two nodes. A simplification, which gives a route of this form, is not considered valid. This is because a TP must not change its verse while traversing a network.

All these rules can be applied recursively to the routes of a graph, until they cannot be simplified anymore.

A proof of concept of the above algorithm has been implemented in Awk [5].

**Example**

Simplifying all the routes of the example 5, we obtain just these two TPs:

\[ A \rightarrow B \rightarrow D \rightarrow C \rightarrow A \rightarrow B \rightarrow D \rightarrow E \quad (5) \]
\[ A \rightarrow C \rightarrow D \rightarrow B \rightarrow A \rightarrow C \rightarrow D \rightarrow E \quad (6) \]

You can verify that all the routes listed in 5 are contained in these two simplified TPs.

**7.2 General results**

By looking at many different simplifications, we can recognize some general rules:

1. For each TP there has to be its inverse. For example, if there’s a TP which covered the route 12345, then there has to be at least the TP which covers the inverse route 54321.

2. In a segment, to give all the routes to all the nodes, it is sufficient that the two extremes sends a TP. Example: in this case, if \( A \) and \( F \) send a TP,

\[ \begin{array}{c}
A \quad B \quad C \quad D \quad E \quad F
\end{array} \]

all the routes will be generated, since the two TP would be: \( ABCDEF \) and \( FEDCBA \). You can verify that in these two TP, there are contained all the routes of the segment.

3. In a cycle, just two TP are needed, and one is the reverse of the other. The first can be constructed in this way:

\[ \begin{array}{c}
A \quad B \\
C \quad D \\
E \quad F
\end{array} \]

Figure 3: A segment

all the routes will be generated, since the two TP would be: \( ABCDEF \) and \( FEDCBA \). You can verify that in these two TP, there are contained all the routes of the segment.

3. In a cycle, just two TP are needed, and one is the reverse of the other. The first can be constructed in this way:

- Choose a node of the cycle, this will be the pivot node.
• Start from one neighbour of the pivot and write sequentially all the other nodes until you return to the pivot (but do not include it). Call this string $C$.
• The TP will be: $C_pC$

where $p$ is the pivot node.

Example: if we choose the node $D$ as the pivot, we can write the TP as:

\[
\begin{align*}
\text{Figure 4: A cycle} \\
EFABCDEFABC \\
\text{and its reverse:} \\
CBAFEDCBAFE
\end{align*}
\]

These two TPs will give all the routes to all the nodes of the cycle.

### 7.3 The question

Can we implement a “live” version of the Simplify Route algorithm like we did with the Generate Route one?

The reply is ahead.
8 Continuous Tracer Packet

A Continuous Tracer Packet (CTP) is an extension of the TP flood: a node will always forward a TP to all its neighbours, excepting the one from which it has received the TP. If a node is an extreme of a segment, i.e. a node with just one link, it will erase the route stored in the body of the TP and will forward back the TP.

In short, a CTP is a TP flood which will never end, thus it will continue to explore all the infinite combination of routes.

Example

Consider this graph. If $A$ sends a CTP flood, there will be two CTPs that will explore respectively these routes:

$$A \rightarrow B \rightarrow C \rightarrow A \rightarrow B \rightarrow C \rightarrow A \rightarrow B \rightarrow C \rightarrow \ldots$$

$$A \rightarrow C \rightarrow B \rightarrow A \rightarrow C \rightarrow B \rightarrow A \rightarrow C \rightarrow B \rightarrow A \rightarrow C \rightarrow \ldots$$

8.1 Reflected CTP

Suppose that the node $N$ has just one link. $N$, before back forwarding the received CTP, erases the route contained in the body, because the nodes preceding it, already know this same route.

For example, consider this segment:

$$\ldots \leftrightarrow A \leftrightarrow B \leftrightarrow C \leftrightarrow N$$

If $N$ hadn’t erased the route received in the CTP, $A$ would have received the following CTP:

$$\ldots \rightarrow A \rightarrow B \rightarrow C \rightarrow N \rightarrow C \rightarrow B \rightarrow A$$

This packet contains the route $C \rightarrow N \rightarrow C$, which is invalid, as explained in section 7.1. The valid parts of the packet are: $\ldots \rightarrow A \rightarrow B \rightarrow C \rightarrow N$ and $N \rightarrow C \rightarrow B \rightarrow A$. For this reason, when $N$ receives the first part, it will send a new, empty CTP.

9 QSPN v2

The second version of the QSPN\(^2\) can be described in a single phrase:

A Continuous Tracer Packet will continue to roam inside the network until it carries interesting information.

\(^2\)The short name of the QSPN v2 is $Q^2$
9.1 Interesting information

A node considers a received CTP interesting when its body contains at least a new route, i.e. a route that the node didn’t previously know. In other words, if a CTP contains routes already known by the node, it is considered uninteresting.

When a node receives an interesting CTP, it forwards the packet to all its neighbours, excepting the one from which it has received the CTP. If, instead, the CTP is uninteresting, it will drop the packet.

Note that if a CTP is uninteresting for the node $N$, then it is also uninteresting for all the other nodes. This is because an uninteresting CTP contains routes which has been previously received, memorised and forwarded by the node $N$. Therefore all the other nodes already know the same routes too.

Example

Consider this graph. Suppose that $A$ sends a CTP. The two CTPs, after having covered the following two paths will stop:

$A \rightarrow B \rightarrow C \rightarrow A \rightarrow B \rightarrow C$

$A \rightarrow C \rightarrow B \rightarrow A \rightarrow C \rightarrow B$

Let’s analyze the first CTP step by step, considering that before $A$ sent the CTP, none knew any route.

$A \rightarrow B$ At this point $B$ doesn’t know any route to reach $A$, therefore it considers this CTP as interesting and forwards it to $C$.

$A \rightarrow B \rightarrow C$ By looking at this packet $C$ learns a route to reach $B$ and $A$.

$A \rightarrow B \rightarrow C \rightarrow A$ The node $A$ learns a route to reach $C$.

$A \rightarrow B \rightarrow C \rightarrow A \rightarrow B \rightarrow C$ Finally, $C$ drops the packet, because it already knows all the routes contained in it.

From this example we can derive a general result: a CTP will always terminate in a cycle.

9.2 Live routes simplification

The QSPN v2 is the “live” version of the Simplify Route algorithm (section 7).

The CTP flood of the QSPN v2 explores the entire graph, but unlike the ATP (section 6), it drops the TPs which contains redundant routes, thus only the simplified, non redundant routes survives and continue to explore the graph.
9.3 Cyclicity

When a CTP reaches the extremity of a segment, it is back forwarded, thus it’s as if the extreme nodes had a link with themselves.

![Figure 7: A segment as viewed from a CTP](image)

From the point of view of a CTP, even a segment is a cycle, therefore, for a CTP, any connected graph is formed just by cycles.

For this reason, a CTP will explore any combination of cycles of the graph.

9.3.1 Subcycles examples

These examples highlights some subcycles of a simple graph.

![A CTP would explore all these cycles.](image)

9.4 Finiteness

$Q^2$ will finish the exploration of the graph in a finite amount of time, i.e. the flood will terminate.

As we’ve seen in the example 9.1, a CTP flood of a cycle will always terminate. Moreover in section 9.3 we’ve noticed that, from the point of view of a CTP, any connected graph is formed by a combination of cycles. Therefore, a CTP flood of a graph will always terminate in a finite amount of time.

9.5 Routes limit

Even if $Q^2$ is finite, it still generates too many routes and packets. Therefore we need to limit the exploration of the graph.

An efficient and elegant solution is to further define what the “interesting information” is:

Let each node of the network keep a maximum of $MaxRoutes$ routes in its memory. A node considers a received CTP interesting when its body contains at least a route which is more efficient than the previously memorised routes. The efficiency of a route can be quantified with a convenient parameter, i.e. the
rtt or the bandwidth capacity. If the node has reached the MaxRoutes limit, it will substitute the old route with the more efficient one.

Note that this definition is more general than the previous. Indeed, if the node $S$ doesn’t know the route to reach $D$, the efficiency of the route $S \rightarrow D$ is equal to 0.

A node can also keep in memory more than MaxRoutes routes, because this limit applies only to the number of routes which will be used to evaluate the received CTP.

9.6 Scalability

We will now exploit the bouquet property of the Tracer Packets, which has been described in section 4.2.

Suppose that in our network every link has the same bandwidth capacity and that the generic node $D$ doesn’t know any route to reach the node $T$. If a TP, received by the node $D$, contains a new route $t$ that connects $D \rightarrow T$, then we can deduce, by the bouquet property, that $t$ is the fastest route between $D$ and $T$.

The immediate consequence is that $D$ will receive all the other $D \rightarrow T$ routes in order of efficiency: the first is, as we’ve seen, the best route, the second one will be slower than the first but surely better than any other, and so on.

9.6.1 TP Classes

Two different routes can be very similar, because they can differ only in a small part. Two routes which differs of just one hop, are almost identical. For this reason, other than the best $D \rightarrow T$ route, the CTP will also explore all the other routes which are almost identical to it.

We can thus order all the TPs which $D$ will receive into classes. The first class, denoted with $[1]$, contains the TP which have covered the best route and all the others similar to it, i.e. all the other routes with the same number of hop and a similar trtt (total round trip time). The second class $[2]$, contains the TP which have covered routes which are less efficient than those contained in $[1]$ but are more efficient than those of class $[3]$. More generally we can say that the $[n]$ class contains the routes that, if included in a list of all the routes of the graph, ordered in decrescent order of efficiency, will be listed starting from the position $(n - 1)\alpha + 1$. Where $\alpha$ is the numbers of routes contained in each class.

In the classes we are including routes and not tracer packets, because a TP may contain more than one route.

9.6.2 Subcycle filter

Each node of the graph acts as a filter for all the subcycles containing it.

Suppose the node $D$ is contained in the subcycle $\sigma$ and that a CTP $t$ enters in it (through another node). If the node $D$ has the MaxRoutes limit set, it will memorise, for each node of the network, only the first MaxRoutes received routes, while the rest will be disregarded, and not forwarded. The CTP $t$ won’t be forwarded by the node $D$, if it contains routes which exceed the MaxRoutes limit, but this is true for all the nodes of $\sigma$, therefore $t$ won’t even
be able to escape from the subcycle $\sigma$. However, this also means that all the CTPs, which are in a higher class than that of $t$, won’t be allowed to pass from $\sigma$.

Since this happens for all the subcycles of the graph, we can conclude that at worst, the number of CTPs increases in polynomial time with the increase of subcycles.

**Example**

Consider this graph. Let’s analyse the difference between a CTP without limits and the same CTP with MaxRoutes set.

![Graph](image-url)

**Figure 8: Sequential composition of cycles**

**Unlimited CTP**  
A sends a CTP. Suppose for simplicity that this CTP won’t loop inside a cycle.

- $D$ receives 2 packets from $A$, $G$ 2 * 2 from $D$ and finally $L$ 2 * 2 * 2 from $D$.
- $L$ sends back all the received CTPs, thus $G$ gets $2^4$ CTPs from $L$, $D$ gets $2^5$ and finally $A$ receives $2^6 = 64$ packets. Obviously this is too much for this simple graph.

**Limited CTP**  
Let’s use $\text{MaxRoutes} = 1$ and suppose that the CTP won’t loop inside a cycle. We’ll write $D_A(n, z)$ to indicate that $D$ received $n$ CTPs from the node $A$ but has kept and forwarded only $z$ packets.

$A$ sends a CTP.

\[
A_0(0, 2) \rightarrow D_A(2, 2) \rightarrow G_D(4, 3) \rightarrow L_G(6, 4) \rightarrow G_L(8, 5) \rightarrow D_G(10, 6) \rightarrow A_D(12, 0)
\]

At the end, $A$ gets 12 packets.

Each node forwards $p/2 + 1$ packets, where $p$ is the number of received CTPs. This is because the first two packets give to the node a new route, while the other two, and the successive ones, cover a superfluous route. For example, consider

\[
A \rightarrow C \rightarrow D \rightarrow E \rightarrow G \quad (7)
\]

\[
A \rightarrow C \rightarrow D \rightarrow E \rightarrow G \quad (8)
\]

\[
A \rightarrow B \rightarrow D \rightarrow E \rightarrow G \quad (9)
\]

\[
A \rightarrow B \rightarrow D \rightarrow F \rightarrow G! \quad (10)
\]
The underlined routes are the new route for $G$. As you can see, in the CTP (10) $G$ doesn’t find any new route, so it drops the packet and doesn’t forward it.

9.6.3 Efficiency order
We’ve noted in section 9.6 that any node will receive the CTPs in order of efficiency, thus we are sure that only the first $MaxRoutes$ received routes (which point to a specific node) are meaningful, while all the successive ones are uninteresting and should be dropped. This is important, because each node will first receive $MaxRoutes$ interesting routes and then the uninteresting ones, that will be dropped. Doing so, an uninteresting route won’t be forwarded before its interesting correspondent, and as soon it is recognised it will be dropped.

To clarify this concept suppose that the routes aren’t received in order of efficiency and that $MaxRoutes = 2$. Then suppose that node $D$ doesn’t have any route yet and receives a CTP of class [7]. $D$ will consider this CTP as interesting and forward it, because it’s the first one it receives.

In conclusion, the CTP of class [7] would be allowed to be propagated among the network even if the $MaxRoutes$ has been set to 2 routes. Instead, if $D$ receives the packet in an ordered manner, it will first get the CTPs of class [1], then those of class [2] and so on. For this reason the CTP of class [7] and all the other which exceed the $MaxRoutes$ limit, won’t be allowed to pass from $D$.

9.7 Bandwidth issues
Until now we’ve supposed that every link of the network has the same bandwidth capacity. However, we’ll see in section 12.1 that the QSPN can be used in the general case.

9.8 Worst case
The graph, formed by $n$ nodes, which has the maximum number of cycles is the worst case for $Q^2$, because, if not limited, it will have to explore any combination of cycles.

Such graph is the complete graph [7], and the total number of its subcycles is:

$$\sum_{k=3}^{n} \frac{1}{2} \binom{n}{k} (k - 1)!$$

10 QSPN v1
It isn’t necessary to read this paragraph in order to understand the rest of the paper. If you aren’t interested in the QSPN v1, just skip over.

The QSPN v1 is a restricted case of $Q^2$. It is divided in two phases. The first one is called qspn_close: a node sends a QTP (QSPN Tracer Packet) called qclose, this node becomes a qspn starter. A qclose is a modified form of tracer packet. A node $N$, which receives a qclose from the link $l$, marks as “closed” the same link $l$ and forwards the packet to all its other neighbours. All the following qclose packets received by the same node $N$, will be forwarded only to the links which have not been already closed. During the graph exploration, some nodes will close all their links. These nodes are
called extreme nodes. When a node becomes an extreme node, it will send another type of tracer packet, called $q_{spn}$-open (which is also the name of the second phase) to all its neighbours, except the one from which it received the last qclose packet (let’s call this neighbour $L$). The qopen packet sent to $L$ is empty, while those sent to the other neighbours contains the body of the last received qclose packet.

The qopen behaves as the qclose: it "opens" the links, however the nodes which have all their links opened won’t forward any other packets.

**Example:** Consider figure 9.

![Figure 9: Example of a QSPN v1 graph exploration](image)

- The node $E$ sends a qclose. It is now a $q_{spn}$ starter.
- Suppose that the node $A$ receives the qclose before $C$. $A$ closes the link $E \rightarrow A$ and forwards the qclose to $B$, $C$ and $D$.
- $C$ receives the qclose from $E$, closes the link $E \rightarrow C$ and forwards it to $A$ and $D$.
- $C$ receives the qclose from $A$ and closes the link.
- $B$ and $D$ have received from $A$ the qclose and close the respective links.
- Suppose that $B$ is the first to forwards the qclose to $F$.
- $D$ forwards the qclose to $F$, but at the same time $F$ forwards it to $D$.
- $D$ receives the qclose from $B$, too.
- $D$ and $F$ have all the links closed. They send a qopen.
- The qopen propagates itself in the opposite sense.
- The qopen ends. Each node has the routes to reach all the other nodes.

The $q_{spn}$-close phase can be seen as a CTP with the added rule that when two CTPs collide, they will be converted to two normal TPs (the qopen phase).

### 10.1 Q vs $Q^2$

These are the substantial differences between $Q$ (QSPN v1) and $Q^2$ (QSPN v2):

1. $Q$ generates less packets than $Q^2$, because in the qopen phase it uses normal TPs which expires quickly. The side effect of this behaviour is that $Q$ may not discover all the best routes. However $Q$ gives at least one route to reach each node of the graph.

2. $Q$ uses less memory than $Q^2$, because it just keeps a forwarding table, instead, $Q^2$ needs to memorize $MaxRoutes$ complete routes to evaluate the successive CTPs. By the way, this difference is minimal.
3. $Q^2$ doesn’t need synchronization. The CTPs doesn’t need to have an ID, thus many nodes can send simultaneously or asynchronously a CTP without creating any problem.

This isn’t the same in Q, which requires a strict synchronization between the nodes: two nodes can send a qclose only at the same time.

4. This is a consequence of the propriety described above: every time a node joins the net or dies or its rtt/bw capacity changes, it is possible to immediately send a CTP. Indeed, if the changes in the local gnode regard that node only, the CTP will be like a normal Tracer Packet (see 4.1).

5. $Q^2$ is easier and simpler than Q to be implemented. In general this means that the code of $Q^2$ will have less bugs.

From this comparison we can conclude that $Q^2$ is preferable over Q.

11 Network dynamics

The QSPN v2 defined until now is not suitable for dynamic networks. As example, consider this problem:

suppose that the whole graph has been already explored, and thus every node has at least one route to reach all the other nodes. Consider the case when the efficiency of a link, f.e. $N \rightarrow P$, worsens. $N$, in order to update the maps of the other nodes, sends a CTP to its neighbour $P$, and $P$ forwards it to its neighbours. However this CTP will be immediately dropped! Indeed, the nodes will consider this CTP not interesting, because the contained \( \cdots \rightarrow P \rightarrow N \) route is less efficient than the old one, which has been saved during the last graph exploration.

11.1 Extended Tracer Packet

The ETP solves the problem of how the graph should be re-explored to update the maps of the nodes interested to a network change. Its way of working is based on a simple observation:

The first QSPN exploration distributes, among the nodes, information describing the network topology. When a change in the network occurs, only the information stored in the nodes affected by the change must be updated. The unaffected nodes will still have up to date information that they can simply redistribute with the use of the Extended Tracer Packets.

An ETP is an Acyclic Tracer Packet,\(^3\) which contains a portion of a map. Since a map is a set of routes and a route can be described by a TP, the ETP can be considered as different TPs packed together. Each TP of the ETP is then subjected to the rules of the QSPN v2.

In order to give an exact definition of an ETP, we must examine each case of network change.

Worsened link Suppose that the link $A \rightarrow B$ worsens.

Let’s analyse what $B$ will do (the situation is symmetric for $A$).

$B$, if interested in the change, will create an ETP containing all its old routes, affected by the change, and all the backup routes used as substitute for the old ones. The ETP will be sent to all its neighbours, except $A$. In detail, $B$ will use the following algorithm:

\(^3\) An ATP (see paragraph 6) is a normal TP with the following rule: a node drops the received ATP if its node ID is already present in the route contained in the body of the packet. Note also, that since it is a normal TP, it is not reflected back, when it reaches the end of a segment.
1. If at least one of the primary routes\(^4\) saved in the map of \(B\) and different from the route \(B \rightarrow A\), uses the link \(l\), then \(B\) creates an empty ETP, otherwise the algorithm halts, i.e. \(B\) won’t do anything.

2. If the empty ETP has been created, \(B\) updates its maps: suppose that the route \(r\), passing through the link \(l\), had a total rtt \(t_0(r)\). If the rtt of the link \(l\) before the change was \(t_0(l)\) and now is \(t_1(l)\), then \(t_1(r) := t_0(r) - t_0(l) + t_1(l)\).

   For the bandwidth we have:

   \[
   \begin{align*}
   b_0(r) & \quad \text{the total bandwidth of the route } r, \text{ before the change} \\
   b_0(l) > b_1(l) & \quad \text{the bw of } l \text{ has worsend during the change} \\
   b_1(r) & := \min\{b_0(r), b_1(l)\}
   \end{align*}
   \]

   The routes are then sorted.

3. \(B\) creates the temporary set \(Q\), containing all the primary routes passing through the link \(l\). From \(Q\) it creates the set \(R\), where

   \[
   R = \{ r \in M \mid \exists q \in Q : \text{dst}(r) = \text{dst}(q) \}
   \]

   where \(M\) is the set of all the primary routes of the map, and \(\text{dst}(r)\) is the destination of the route \(r\). In other words, \(R\) is the set of primary routes having the same destination of at least one route of \(Q\). Note that \(Q \subseteq R\).

   Each route \(r \in R\) is saved as \((\text{dst}(r), \text{rem}(r), \text{tpmask}(r))\), where \(\text{rem}(r)\) is the Route Efficiency Measure, and \(\text{tpmask}(r)\) is a bitmask of 256 bits, where the bit at the i-th position indicates if the node i is an hop of the route \(r\).

4. \(B\) fills the ETP:

   (a) it adds in it the set \(R\)

   (b) it appends the ID of \(A\), along with the efficiency value of the link \(l\), and, as usual, its ID.

   (c) it sets to 1 the flag of interest.

5. Finally, \(B\) sends the ETP to all its neighbours, except \(A\).

Suppose that the neighbor \(C\) of \(B\) has received the ETP. \(C\) will examine the ETP and, if considered interesting, it will update its map and forward the ETP to the other neighbours, as follow:

1. If the ID of the node \(C\) is already present in the received ETP, then \(C\) immediately drops the ETP, and skips all the following steps\(^5\).

2. Let \(R\) be the set of routes contained in the ETP received by \(C\).

   Let \(M\) be the set of all primary routes contained in the map of \(C\).

   For each route \(r \in R\), the node \(C\) looks for a route \(m \in M\) such that

   \[
   \text{dst}(m) = \text{dst}(r), \quad \text{tpmask}(m) = \text{tpmask}(r)
   \]

   If \(m\) exists, then \(C\) sets \(\text{rem}(m) := \text{rem}(r)\) \(^6\). Otherwise, \(r\) is copied in the temporary set \(R'\).

   \(M\) is sorted, i.e. the routes of the map of \(C\) are sorted in order of efficiency.

3. For all \(r' \in R'\),

\(^4\) a route \(src \rightarrow dst\) is called primary if it is among the first MaxRoutes routes of type \(src \rightarrow dst\)

\(^5\)This is the acyclic rule

\(^6\)with this operation we are actually replacing \(m\) with \(r\), in the map \(M\)
(a) if \( r' \) is a better alternative to at least one primary route \( m' \in M \) such that \( \text{dst}(r') = \text{dst}(m') \), then \( r' \) is saved in the map of \( C \) (note 7).
(b) otherwise, \( r' \) is removed from \( R \).

Note 8

4. If \( R \) is now empty, i.e. all its routes have been removed, then \( C \) considers the ETP as uninteresting. Let’s suppose for now that it is interesting: the flag of interest remains set to 1.

5. \( C \) packs the ETP with the previously modified set \( R \), and adds its ID. The ETP is sent to all its neighbors, except \( B \).

The nodes of \( C \) will use this same procedure. In this way, the ETP will continue to be propagated until it is considered interesting.

Let’s suppose now that a node \( N \) receives the ETP and considers it uninteresting. \( N \) won’t just drop the ETP, but will also send back another ETP containing its own routes. The reason is simple: \( N \) considers the received ETP uninteresting, this means that \( N \) isn’t affected by the change of the link \( l \), i.e. all its primary routes don’t pass through \( l \) and thus are still optimal. Therefore, \( N \) will send back its routes, hoping that they will be useful to the nodes affected by the change. In detail, this is what will happen when \( N \) receives the ETP:

1. \( N \) receives the ETP from the node \( L \), and considers it uninteresting.
2. Let \( R \) be the set of routes contained in the ETP.
   Let \( M \) be the set of all primary routes contained in the map of \( N \).
   \( N \) creates the following set:
   \[
   S = \{ m \in M \mid \exists r \in R : \text{dst}(m) = \text{dst}(r) \}
   \]
3. \( N \) creates the new ETP, appending in it the set \( S \) and its ID. The flag of interest of this ETP is set to 0.
4. The ETP is sent to \( L \).

At this point, the new ETP created by \( N \), will propagate back in the same fashion of the previous ETP (see page 17), i.e. until considered interesting. The only difference is that when a node considers it uninteresting, it is just dropped9.

A node dies Suppose the node \( A \) dies. Each neighbour \( B \) of \( A \) will send an ETP. The ETPs are generated and propagated with the algorithms described in the worsened link case (page 16), the differences are:

1. Instead of considering the routes passing through the worsened link we consider the routes passing from the dead node.
2. Suppose that the node \( N \) receives the ETP from its neighbour \( L \) and considers it uninteresting. \( N \) sends back to \( L \) the new ETP to share its routes among the interested node. However, unlike the case for the worsened link, \( N \) creates also a new simple TP, where it writes only the information of the death of \( A \). \( N \) sends this TP to all its neighbours, except \( L \).

7When saving a route \( r \) of the ETP in the map, we must consider the hops covered by the ETP, so the real saved route is \( r \leftarrow \text{hop}_1 \leftarrow \text{hop}_2 \leftarrow \cdots \leftarrow \text{hop}_n \). In this case we’ll have \( r \leftarrow B \leftarrow A \).
8this step implements the QSPN v2 rules: only good routes are kept, the other are discarded. Notice the extension: if the ETP had only one route, it would be almost equal to a CTP (the CTP doesn’t have the acyclic rule)
9the node will drop the ETP if the flag of interest is set to 0 and if it is uninteresting.
This simple TP will be propagated with the rules of the QSPN v2. For this reason and since it carries only one useful information (the death of A), each node will receive it just once (the second time it will be dropped). This simple TP serves to inform the nodes, unaffected by the network change, of the death of A.

**Improved link** Suppose that the link \( A \xleftarrow{l} B \) improves.

Let’s examine the events, starting from A, keeping in mind that the situation is symmetric for B.

Since the link \( l \) improved, it may be possible for B to use it to improve some of its routes. For this reason, A will send to it an ETP with all the routes of its map, except those of the form \( A \rightarrow B \rightarrow \ldots \). If B finds something of interest, it will forwards the ETP. In detail:

1. Let \( M \) be the set of all primary routes contained in the map of A.
   
   \( A \) creates the following set:
   
   \[
   R = \{ m \in M \mid gw(m) \neq B \}
   \]
   
   where \( gw(m) \) is the first hop of the route \( m \). Each route \( r \in R \) is saved as \((\text{dst}(r), \text{rem}(r), \text{tpmask}(r))\).

2. \( A \) creates the ETP:
   
   (a) it writes in it the set \( R \)
   
   (b) it appends the its node ID, along with the efficiency value of the link \( l \),
   
   (c) it sets to 1 the flag of interest.

3. It sends the ETP to B

   At this point, the ETP is propagated exactly in the same way of the worsened link case (see page 16).

**A new node joins** Suppose the node A is joining the network. Its neighbours are \( B_1, B_2, \ldots, B_n \), which are all already hooked, i.e. they aren’t joining. Then,

1. Each neighbour \( B_i \) sends its whole map to A

2. \( A \) waits until the maps of all its neighbours are received.

3. The maps are “merged” into a single map, which becomes the map of A. In simple words, the merge of two maps result in a map having only the best routes of the two.

4. If the neighbours of A are more than one, i.e. \( n > 1 \), then A sends, to each of them, an ETP containing all the primary routes of its map.

5. The ETPs are propagated exactly in the same way of the worsened link case (see page 16).

   Note that this case extends the hooking procedure.

**Broken link** The case where the link \( A \xrightarrow{l} B \) becomes invalid, is handled in the same way of the worsened link case (see page 16), because we can consider \( l \) as infinitely worsened.

**New link** The case where a new link \( A \xleftarrow{l} B \) is established between, is handled in the same way of the improved link case (see page 19), because we can consider \( l \) as infinitely improved.
12 QSPN optimisations

12.1 Rtt and bandwidth

The bandwidth capacity of a route can be used as a parameter of its efficiency. In this section we’ll analyse the implications for the QSPN. For more information about the bandwidth management in Netsukuku you can read the NTK RFC 002 [9].

12.1.1 Rtt delay

Each node of the network will delay the forwarding of a received CTP by a time inversely proportional to its upload bandwidth. In this way the CTPs will continue to be received in order of efficiency (see section 9.6.3). The side effect of this rule is that the extreme cases will be ignored, i.e. a route with a very low rtt but with a very poor bw, or a route with an optimal bw but with a very high rtt. However, in the “real world” these extreme cases are rare, because the rtt and the bw are often related.

12.1.2 Asymmetry in Q$^2$

The QSPN v2 is a very flexible algorithm that can be adapted to a large range of cases. Indeed, with a minimal added overhead, it is possible to achieve asymmetric routing discovery, i.e. a discovery that discerns the upload bandwidth of a route from its download one.

We call this extension the asymmetric QSPN v2, while we refer to the old one as symmetric Q$^2$.

1. First of all, it is necessary to define further the “interesting information”. A CTP will be considered interesting, not only when it contains interesting (see 9.1) download routes, but also upload ones. In other words, we consider the upload sense of a route too.

   For example, suppose that the node A received the CTP $ABCDAERTA$. In this case A will know two distinct upload routes: $A \rightarrow B \rightarrow C \rightarrow D$ and $A \rightarrow E \rightarrow R \rightarrow T$. Instead, in the classic CTP, A would have known only $A \rightarrow T \rightarrow R \rightarrow E$ and $A \rightarrow D \rightarrow C \rightarrow B$.

2. Secondly, since we are considering the reverse (upload) routes too, we have to remove the restriction imposed on the CTP, which has been described in section 8.1. The body of the CTP reflected from the extreme of a segment won’t be erased, thus it will contain the old routes too. This is because the old routes can contain interesting information about upload routes. For example, consider this segment:

   \[ \cdots \leftrightarrow A \leftrightarrow B \leftrightarrow C \leftrightarrow N \]

   If N doesn’t erase the route received in the CTP, A will receive the following CTP:

   \[ \cdots \rightarrow A \rightarrow B \rightarrow C \rightarrow N \rightarrow C \rightarrow B \rightarrow A \]

   In this case A will know the following upload route:

   \[ A \rightarrow B \rightarrow C \rightarrow N \]

   When parsing a CTP, a node will recognize the part of the routes which are in the form of $XacaY$, where a, c are two nodes and X and Y are two generic routes. The packet will then be split in $Xac$ and $caY$.

At this point we’ve finished. In fact, we are sure to receive at least one upload route per node because a CTP traverses each path first in one sense and then in the opposite. The CTP information filter, will allow us to receive only the best routes. However,
since the Rtt Delay (12.1.1) is tuned for download routes only, it is possible that some upload paths will be ignored.

It is interesting to note that in the majority of cases, the number of CTPs will remain equal to that of the symmetric $Q^2$.

12.2 Disjoint routes

The routing table of each node should be differentiated, i.e. it should not contain redundant routes.

For example, consider these $S \rightarrow D$ routes:

- $SBCFG_1G_2G_3G_4G_5G_6G_7 \ldots G_{19}D$ (11)
- $SRTEG_1G_2G_3G_4G_5G_6G_7 \ldots G_{19}D$ (12)
- $SZXMNO_1O_2O_3O_4O_5D$ (13)
- $SQPVY_1Y_2Y_3Y_4D$ (14)

The first two are almost identical, indeed they differ only in the first three hops. The last two are, instead, totally different from all the others. Since the first two routes are redundant, the node $S$ should keep in memory only one of them, saving up space for the others non-redundant routes.

Keeping redundant routes in the routing table isn’t optimal, because if one of the routes fails, then there’s a high probability that all the other redundant routes will fail too. Moreover when implementing the multipath routing to load balance the traffic there won’t be any significative improvements.

$Q^2$ itself should avoid to spread redundant routes. In order to achieve this result, we refine the efficiency value associated to a route. Suppose we want to affect the efficiency value $R_e$ assigned to the route $R$:

1. let $0 \leq s(R, S) \leq 1$ be the similarity level of the route $R$ with $S$.
2. for each memorised route $S$ we compute $s(R, S)$ and if we find a route $S$ such that $s(R, S) > 0.5$ we go to step 3.
3. we set $R_e = R_e - \frac{1 - s(R, S)}{k}$

where $k$ is an appropriate coefficient.

As explained in section 9.5 the efficiency of a route is used as a parameter to evaluate its interest, therefore the more a route is similar to a memorised route the more its efficiency will decrease. Hence it will be considered less interesting.

Note that this is a generalization of concept of interesting route defined in section 9.5, in fact, when $R$ and $S$ are equal, we’ll have

$$s(R, S) = 1$$

so the $R_e$ value will be equal to 0.

12.3 Cryptographic QSPN

A node could easily forge a TP, injecting in the network false routes and links information. The attack would just create a temporary local damage, thanks to the distributed nature of the QSPN. However the optimal solution is to prevent these attacks.

A node, whenever joins Netsukuku, generates a new RSA key pair. The continuous generation of keys prevents the leakage of the node’s anonymity. The node shares its
public key to all the other nodes of its group node. Each entry appended in a TP is then signed with its private key, doing so the other nodes will be able to prove its authenticity and validate the path covered by the TP. The size required to store the signatures in the TP can be kept constant using the aggregate signature system [10] [11].

13 Simulating the QSPN v2

As a proof of concept, we’ve written the q2sim.py[6], a simulator implementing the core of the QSPN v2. The q2sim is an event-oriented Discrete Event Simulator. Each (event, time) pair is pushed in a priority queue. The main loop of the program retrieves from the queue the event having the lowest ‘time’ value. This “popped” event is executed. In this case, the events are the packets sent on the network.

In this paragraph we’ll analyze the results of various simulations.

TP flux The TP flux of a node \( n \), is the number of distinct\(^{10} \) TP packets which have been forwarded by \( n \) during the entire QSPN exploration. it is indicated with \( \Phi(n) \).

Mean TP flux Given \( k \) nodes \( n_1, \ldots, n_k \), their mean TP flux is:

\[
\Phi_m(n_1, \ldots, n_k) = \frac{\sum_{i=1}^k \Phi(n_i)}{k}
\]

Starter node A starter node is a node which sends the first TP in a graph, not yet explored by the \( Q^2 \). There can be more than one simultaneous starter node.

In all the following tests the MaxRoutes limit has been set to 1.

As a general result, the mean TP flux is proportional to the number of subcycles present in the graph. Thus the maximum mean TP flux is reached in a complete graph, where each node is connected to all the others. In a complete graph of \( k \) nodes the mean TP flux is approximately:

\[
\Phi_m \approx k - 1, \quad \Phi_m \leq k
\]

The figure below shows this result. In the \( x \) axis, an integer point corresponds to the number of nodes of the complete graph. The adjacent points of the graph have been connected with straight line segments.

\(^{10}\)To clarify what we mean with “distinct TPs”: suppose \( n \) has 6 neighbours, it receives only two TPs and sends only a new one, then \( \Phi(n) \neq 5 + 5 + 6 \), but \( \Phi(n) = 3 \).
By increasing the number of starter nodes the mean TP flux increases slightly until it reaches $\Phi_m = k$. Indeed, if all the nodes of the graph are starters, then each of them will send a TP to all the other nodes. The increasing of the number of starter nodes decreases the time required to complete the exploration of the graph. The figure below shows this result. In the $x$ axis, an integer point corresponds to the number of starter nodes. Each plotted line corresponds to a complete graph with different number of nodes. The first bisector has been plotted to facilitate the reading of the graph.

The complete graph is the worst case for the $Q^2$, therefore in the general case the mean TP flux will be:

$$\Phi_m \leq n$$

where $n$ is the number of nodes of the graph. For example, in random graphs with increasing number of nodes, the mean TP flux will assume the distribution shown in the figure below:

---

23
The same happens for a mesh graph. The mesh graph used in the simulations is a square grid where every intersection represents a node. If the graph is uniformly connected, as in the case of a mesh graph, then the distribution of single TP fluxes is uniform too. The majority of single TP fluxes are near to the mean TP flux, while the highest TP fluxes are shared between different nodes, i.e. there aren’t few unlucky nodes which have to bear a high TP flux. In the following figure, we can observe the TP flux distribution of two different QSPN exploration of a mesh graph with 11 × 11 nodes. In the x axis, an integer point corresponds to a single node of the graph. Adjacent points are connected by a straight line.

In the first exploration, plotted in red, the starter node (node 40) and the eight nodes surrounding him (node 50, 51, 52, 28, 29, 30, 39, 41) have the highest TP flux. The TP flux decreases with the increase of the distance from the starter node. Since the graph
is a $11 \times 11$ grid, there are 11 classes where the TP flux falls and for this reason in
the graph there are exactly 11 slopes. The nodes with lower TP fluxes are those with
the least number of links, i.e. the nodes on the edge of the mesh, which have only
3 links (and not 4). The four nodes at the vertices of the grid (node 0,10,110,120),
which have just 2 links, register the lowest TP flux.
The second exploration, plotted in blue, simulates the scenario where 32 links of the
graph change and consequently the interested nodes send a new CTP to inform the
other nodes and update their maps. As supposed, the mean TP flux (26.80) is heavily
lower than that of the initial exploration (82.90), because the majority of routes are
already known by the nodes. Even the execution time is lower (2.6s vs 3.5s). Note
that this scenario is the most common in real world, because in general, the nodes
won’t join or die at once, but progressively.

14 TODO

1. The $Q^2$ must be implemented in the ntkd daemon.
2. Improve, test and implement the Caustic Routing: RFC 0013
3. Research a “mobile QSPN”

15 ChangeLog

- April 2007
  - New section: “Network dynamics” (11)
  - Description of the ETP (sec. 11.1)
  - Link ID section remove. With the ETP they are no more necessary.
  - More detailed description of the QSPN v1 (sec. 10)
  - Subsection “QSPN v2 - High levels” removed. It was redundant with the
topology document[2]

- October 2006
  Initial release.

References

[1] Netsukuku website: http://netsukuku.freaknet.org/
[2] Netsukuku topology document: topology.pdf
[3] Depth-First Search: http://en.wikipedia.org/wiki/Depth-first_search
[4] Generate Routes in Awk: generate_routes.awk
[5] Simplify Routes in Awk: simplify_routes.awk
[6] QSPN v2 simulator: q2sim.py
[7] Complete graph: http://mathworld.wolfram.com/
[8] Network simulator: http://www-mash.cs.berkeley.edu/ns/
[9] NTK RFC 002: Bandwidth measurement
[10] A Survey of Two Signature Aggregation Techniques:
    http://crypto.stanford.edu/dabo/abstracts/aggsurvey.html
[11] Aggregate and Verifiably Encrypted Signatures from Bilinear Maps:
    http://crypto.stanford.edu/dabo/abstracts/aggreg.html
