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A Novel Reliable Routing Scheme for Tactile-oriented Internet Traffic

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***Abstract*—Over the past few years, many scientists have envisioned an Internet generation that will not only provide voice and data communications but can also support Haptic communications. This new Internet dimension can be beneficial for the society by facilitating the development of new technologies and applications that will improve our standards of living. In this study, we propose a novel traffic engineering policy that can satisfy the extremely strict requirements of the new traffic class associated with Haptic communications. Our proposed policy is based on Multi-Plane Routing (MPR) that consolidates various aspects in all-IP access infrastructures and enables network-wide path diversity. To this end, MPR has been remodeled and extended to facilitate Haptic communications. Our simulation results demonstrate that our proposed policy outperforms intra-domain routing protocols namely Open Shortest Path First (OSPF) and performs near-optimally. It will also become apparent that shortest-path solutions such as OSPF can not be used in order to handle Haptic communications in typical Internet network topologies. Finally, we formulate a binary optimization problem for the selection of the optimal Routing Plane (RP) in terms of the network effects such as delay, jitter and packet loss.**

I. Introduction

EACH Internet generation facilitates a better performance in terms of network characteristics (i.e. delay, packet loss, jitter etc.). Such improvements give rise to the opportunities to deploy new applications and technologies that help us improve our daily lives. Over the last years, many scientists and organizations have been considering an Internet generation that will enable a new dimension in our communications, i.e. the sense of touch. This new dimension is now widely known as the so-called Tactile Internet, a term that was first introduced by G. P. Fettweis in 2014 [1] [2]. The technical specifications of Tactile Internet have been proposed by ITU [3]. Accordingly, the main constrains of this new Internet dimension are extremely strict. Namely, ultra-low latency and a round trip time lower than 1ms. In the case where latency would exceed the threshold of 1ms, the Tactile application's user would not be able to control real and virtual objects without facing cyber-sickness. Another key challenge is to facilitate an extremely high reliability. Correspondingly, a packet loss even below 10^{-7} might be necessary in some cases. Finally, the variability over time of the packet's latency across a network (i.e. jitter) should not be greater than 20 μs.

Vendors have envisioned and proposed some potential benefits of this new Internet generation [1] [3] [4]. Tactile Internet will facilitate the development of new applications and opportunities that will have a significantly positive impact on society and business. The proposed applications can be applied in many different sectors and fields ranging across various industries. One example is the facilitation of dynamic activation and deactivation of local power generation and consumption in smart grids. Furthermore, as an effective tool in general remote control in robotics, this revolutionary concept can improve the health care sector by enabling remote surgeries. Tactile Internet will also gives rise to the possibility of improving the livelihood of people who reside in urban and remote areas. A market analysis has predicted that the potential market value for this new Internet generation could exceed 20 trillion dollars worldwide, which would account to approximately 20 percent of worldwide GDP [5].

Currently, Internet supports voice and data communications in addition to multimedia services such as audio and video. Nonetheless, the Tactile Internet must enable Haptic communications [6] as a major application and provide the medium for transporting Haptic information. Such information can be classified based on two different types of feedback [7]: kinaesthetic feedback (i.e. information that comes from proprioceptors within the body namely about position, force etc.) and Tactile feedback (i.e feedback that is related to the touch sense i.e. texture).

Tactile Internet communication is expected to be feasible in scoped and/or reasonable communication distances. This is due to the requirements being hard to control over the ranges of Internet networks that can be traversed by the packets with different traffic flow requirements. Therefore, the current study is focused on scoped network(s) or single administrative domains where a policy can be enforced.

A. *Related Work and Background*

There have been studies conducted on Tactile Internet that are not coherently developed and do not focus on a single Internet aspect, rather, a collection of proposals and thinking towards meeting some general requirements for Tactile Internet. Different techniques have been proposed for predicting motion and force information in Haptic media even for non-linear Haptic movements and force information [8]. Some studies have used the prediction techniques so as to reduce the network effects such as delay. Correspondingly, by predicting motion, force and compressing Haptic data, the stringent network effects such as delay, jitter and packet loss can be relaxed and alleviated [9].

Authors in [1] outline the importance of the physical packet length by stating that it should not exceed $33\mu s$ packet duration so as to achieve a round-trip latency lower than 1ms.

Furthermore, it is mentioned that the modulation technique that is used by LTE is not a feasible solution because of OFDM symbol alone being in the order of 70 μs. Consequently, a new cellular system has to be designed in order to support Tactile Internet. Also, a candidate solution for Tactile packets over wireless networks would be the TCP/IP packets bypassing the MAC layer and being forwarded directly to the physical layer. Emphasis is placed on the fact that current systems have little provisioning for defining the minimum latency of protocol handing. Another interesting article on Tactile Internet [10] shows that latency and packet re-transmission can be reduced significantly by combining network coding and Software Defined Networks (SDN). However, for simplicity, this study is based on a simple multi-hop network topology and does not explore the case of large and realistic topologies of Internet networks with the possibility of path diversity and exploring the multi-path routing for expediting routing characteristics for certain types of traffic.

Multi-Plane Routing (MPR) was initially proposed in [11]. A study has recently emerged containing the detailed analysis of MPR [12]. MPR is based on Multi-Topology Open Shortest Path First (MT-OSPF) principle that unites various aspects in the all-IP network infrastructure. MPR maximises path diversity in access network topologies (campus and metropolitan area networks) by applying a purely IP-based Traffic Engineering (TE) approach where multiple logical Routing Planes (RPs) that represent instances of OSPF are built. Hence, the availability of multiple routing paths for each *source-destination* (i.e. *Ingress-Egress*) pair in the network is ensured. MPR is being investigated in our university to include more diversity and cover various network routing scenarios, including all options for *Ingress-Egress* pairs and downlink/uplink traffic flows. MPR with extensions in routers' queues (i.e. resembling a coupling with DiffServ approaches) is an attractive routing solution for Haptic communications in scoped access networks as it allows a network wide efficient differentiation of routing resources. MPR is already proven to achieve performance gains against Multi-Protocol Label Switching (MPLS) and OSPF considering the overall network and a significant number of key performance criteria [13]. Furthermore, the offline and online separation of algorithms in MPR allows for pre-planned and extremely responsive adaptations to various traffic requirements making it a more adaptable and faster solution than conventional IntServ schemes and native SDN approaches that are seen as incurring route configuration delays that are intolerable in the Tactile Internet.

We note that a relevant Internet protocol called Efficient Transport Protocol (ETP) was proposed in [14]. ETP is a protocol focused on real-time applications and its main objective is to reduce Round-Trip Time (RTT) and Inter-Packet Gap (IPG). Therefore, ETP is optimized for interactive applications that makes it a candidate transport protocol for Haptic communications. Nevertheless, we will not consider ETP as it has not been deployed yet.

B. Contributions

The main contribution of this study is to design a reliable routing policy to accommodate for Haptic communication using delay, jitter and packet loss, alongside capacity, as combined path selection criteria. To the best of our knowledge, such a policy that is designed in order to handle Tactile packets subject to the strict and multiple limitations is absent in literature where most of the solutions for expedited routing (either best-effort or multi-path) reduce the objective to a convoluted cost or apply reductions to one or a few criterion that are chosen as being pertinent. As we are at the stage of validating the possibility of supporting Tactile traffic in scoped Internet networks with three specific criteria (i.e. delay, jitter and packet loss), keeping all three with equal bearing is considered a practical necessity (presuming bandwidth is available). Our policy is based on the application of MPR as a routing solution for access networks (i.e. Intra-domain routing in single administrative domains) which has been remodelled to allow for a reliable communication for Tactile packets by allowing two types of queues to be installed in routers, for priority and non-priority traffic. To this end, a new mathematical model has been proposed.

The rest of this paper is organized as follows: Section II sets out our system model. The problem formulation and its associated notations are presented in section III. Section IV presents the experimental demonstrations. Finally, section V concludes the paper.

II. System Model

A. Concept

Network is partitioned by MPR into several logical planes enabling routers to maintain multiple independent logical RPs. Each RP can overlap with another RP and share any sub strain of the network topology. Moreover, every RP represents an OSPF instance that is correlated with a particular link weight setting. The different OSPF instances converge to maximise path diversity and can be used to increase reliability of the communication.

The communications' reliability is further enhanced by forwarding duplicate packets of the same nature (i.e. Tactile) on two of the best available RPs having been ranked in terms of cost. MPR is able to support up to 8 RPs by using the IPV4-header integrated Type of Service (ToS) field (as put forward by IETF in [15]), [1] therefore bearing no extra overhead on IP packets. It has been proven that a performance close to optimum in terms of link utilization can be achieved by using 3-5 RPs for similar cases of topologies [11].

B. Experimental Setup

The network in Fig. 1 represents an Autonomous System (AS) which constitutes a metropolitan or campus access network with a single gateway towards the big Internet. All Aggregation Routers (ARs) and the Gateway (GW) can act as Ingress or Egress points for traffic in the network. Traffic can be to/from external Internet networks or internal between ARs. This reference fat-tree model is based on [16]. The network is comprised of 6 base stations acting as ARs. Nodes are considered to be interconnected by wired Ethernet links.

[1]MPR is expected to be attractive in future Internet implementations using IPv6 suite, where additions of plane information bits in IP packet's header is more extensive

Two $M/M/1$ queuing models are considered for every node, one for priority class packets and one for non-priority class packets. The priority class is dedicated to Tactile related traffic whereas the other traffic types would use the non-priority class. Link capacities are set depending on the level they belong to in our reference network following a uniform distribution. [360, 400], [200, 240], [140, 180] and [60, 100] are used respectively for the four different levels in the network studied as marked in Fig. 1.

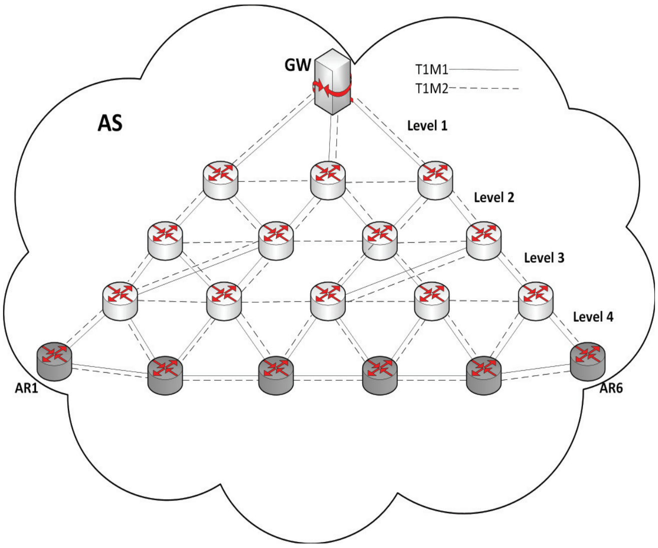


Fig. 1: Autonomous system comprised of 19 nodes and 32/41 links. Average node degree: 3.36/4.32. Total capacity: 11.94/15.34 (Gb). 4 and 5 RPs respectively.

III. MPR's Traffic Engineering Mechanism

A. Graph Theoretical Representation

Topology of a given communication access network is represented by a connected directed graph $G = (\mathcal{V}, \mathcal{E})$. The network is comprised of a set $\mathcal{E}$={$e : e = 1, ..., E$} of edges with finite capacities C_e, and a set $\mathcal{V}$={$v : v = 1, ..., V$} of vertices. Let the set of Routing Planes (RPs) be represented as $\mathcal{N} : n = 1, ..., N$. Every $e \in \mathcal{E}$ is assigned with N distinct link weights denoted by $w(n, e); \forall n \in \mathcal{N}$. The network supports a set of demands for every *Ingress - Egress* pair denoted by $\mathcal{D}$={$d : d = 1, ..., D$}. An $N \times E$ matrix X^d represents the link usage. $x^d_{eP^d_n} = 1$ if path P_n of pair d uses link e and $x^d_{eP^d_n} = 0$ otherwise. Matrix X^d for demand d is:

$$X^d = \begin{bmatrix} x^d_{1P^d_1} & x^d_{2P^d_1} & \cdots & x^d_{EP^d_1} \\ x^d_{1P^d_2} & x^d_{2P^d_2} & \cdots & x^d_{EP^d_2} \\ \vdots & & & \\ x^d_{1P^d_N} & x^d_{2P^d_N} & \cdots & x^d_{EP^d_N} \end{bmatrix} \tag{1}$$

Every plane is a subset of the physical topology of the underlying network. A separate RIB/FIB is maintained for every subset being an instance of OSPF. For graph G, the subgraph induced on a vertex subset $\rho^{\mathcal{K}}_n \in G$ of V_G is denoted as $G(\rho^{\mathcal{K}}_n)$ where:

$$\begin{cases} V_{G(\rho^{\mathcal{K}}_n)} = \{i, j \in V_G | \exists e \in E_G\} \\ E_{G(\rho^{\mathcal{K}}_n)} = \{e \in E_G | e = \langle i, j\rangle \;\; i, j \in V_G\} \end{cases} \tag{2}$$

B. MPR Offline RP Construction

MPR's offline algorithm has been designed in order to improve path diversity and facilitate an improved load balancing. The potential benefits of path diversity in access networks was investigated and ratified in [17]. To this end, MPR's offline approach was initially put forward in [11] and it was shown in [18] that by increasing path diversity, the performance of the network can be improved significantly. This algorithm is of offline nature as it does not require the real time state of the network in order to build the planes. Three principles are enforced in this algorithm which are listed below:

1) Each link must not be used in at least one RP.
2) In addition to *Ingress-Egress* router pairs in the network between which a route is ensured in every RP, the network contains transient routers that only route traffic without generating or absorbing it.
3) Each link is used in at least one plane.

We apply MPR's offline TE approach to build the RPs ahead of the traffic flow into the network.

C. RP selection optimization problem

MPR's online packet routing renders the best possible path (i.e. RP for packets belonging to a session). We assume that the information on the status of network's link usage is known by the Ingress points where the plane/path selection is performed. As the paths/planes overlap for all the *Ingress-Egress* pairs in the network, the online algorithm can be represented as an optimisation problem of choosing the best possible path, subject to the cumulative use of network's routing resources.

We introduce a binary optimisation problem for RP selection in the online TE. The main aim of this formulation is to select the appropriate RP (i.e. path) for each session based on the class that the session's packets belong to. For instance, if the packets belong to the priority class, the optimisation problem finds the RP that is optimal in terms of delay, jitter and packet loss in line with the strict Tactile requirements. Herein, we consider three requirements to be of equal importance; therefore, they are normalized in the objective function. In the case in which the packets of the session belong to the non-priority class, the optimization problem finds a RP that solely satisfies the bandwidth constraint.

We denote the network effects by i ($i = 1$ represents delay, $i = 2$ represents jitter and $i = 3$ represents packet loss), the Tactile class constraint for session j by $\mathcal{L}_{i,j}$, the examined RP by n, the examined session by j, the network effects for RP n and session j by $l_{n,j,i}$, the required capacity for the priority class for the RP n by $c_{1,n}$, the required capacity for the non-priority class for the RP n by $c_{2,n}$ and the binary variable that enables us to select a specific RP n for a specific session j by $x_{n,j}$. C_n represents the bottleneck capacity of RP n.

$$
\begin{aligned}
\min \quad & \sum_{n\in\mathcal{N}}\sum_{j\in\mathcal{J}}\sum_{i=1}^{3} x_{n,j} e^{(o+\frac{l_{n,j,i}}{\mathcal{L}_i})} \\
\text{s.t.} \quad & \sum_{j\in\mathcal{J}} x_{n,j} c_{2,n} \le \mathcal{C}_n, \forall n \in \mathcal{N} \qquad (a) \\
& \sum_{j\in\mathcal{J}} x_{n,j} c_{1,n} \le \mathcal{C}_n, \forall n \in \mathcal{N} \qquad (b) \\
& \sum_{j\in\mathcal{J}} x_{n,j} l_{n,i,j} \le \mathcal{L}_{i,j}, \forall n \in \mathcal{N} \ \ and \ \ \forall l \in \mathcal{L} \ \ (c) \\
& \sum_{j\in\mathcal{J}} x_{n,j} = 1, \forall n \in \mathcal{N} \qquad (d) \\
& x_{n,j} = 0 \ \ or \ \ 1, \forall n \in \mathcal{N} \ \ and \ \ \forall l \in \mathcal{L} \qquad (e)
\end{aligned}
\tag{3}
$$

In order to normalize the weight of each network effect we chose to use $e^{(o+\frac{l_{n,j}}{\mathcal{L}_i})}$ function. o is a constant that enables us to operate in different regions of the e^x function. Furthermore, as e is a monotonically increasing function it can only contribute additively by increasing the value of the objective function.

Constraints (a) and (b) ensure that every RP that will be selected has enough free resources in terms of capacity in order to support the new non-priority and priority sessions respectively. Constraint (c) stipulates that every RP that will be selected in order to serve a priority session has to satisfy the Tactile QoS requirements as shown in TABLE I. Constraint (d) states that for every session, only one RP can be selected. Constraint (e) ensures that our optimization variable is a binary variable.

D. Tactile Aware Policy

We base our proposed Tactile aware TE algorithm on MPR's online TE policy which was initially proposed in [18]. We have remodelled MPR's approach to accommodate for the evolutionary Tactile Internet. To this end; we have introduced two types of queues and a new plane selection policy.

Tactile Aware Policy (TAP) segregates the network into a hierarchy in the presence of traffic of both downlink and uplink nature. Every time a packet arrives at the *Ingress*, it is checked whether it belongs to a new session. If the packet that arrives at the *Ingress* does not belong to any existing sessions, then the *Ingress* node should apply the following principles. Firstly, the *Ingress* has to check if there is enough bandwidth in order to support the new session. In the case where there exist enough free resources, the session will be admitted. However,if there are not enough available resources to be used the packet will be dropped and the session will be rejected. When the session has been admitted, MPR's online algorithm will be used in order to route the packet. At this point it is worth mentioning that when a route has been used to route a packet then all the packets that belong to the same session will follow the same route to preserve the same transport conditions. In the following paragraphs TAP's functionalities are described in detail.

Firstly, when a Tactile packet arrives at the *Ingress*, a duplicate is generated. The initial packet will be routed by using the best path in terms of delay and the duplicate packet will be routed on the second best path in terms of delay. The main idea behind the generation of the duplicate packet is to increase the communications reliability which is vital in case of Tactile traffic. The duplicate packet generation helps in reducing the packet loss that is one of the main constrains that needs to be dealt with. When the initial packet has been dropped, there is a possibility that it can be restored by the duplicate. Based on TAP, the packet that arrives first at the *Engress* is considered to be valid. In case of both packets having been delivered successfully, the one that has arrived second will be dropped.

Another major constraint of the Tactile Internet is that the round trip time must not exceed the threshold of $1ms$. In order to achieve this, we classify the packets into two classes. The first class (i.e. priority class) represents the Tactile packets and the second class represents all the other types of packets (i.e., VoIP, Web etc.). To this end; we assume that each router has two queues. One for the priority class packets and one for the packets that belong to the other classes. The router's scheduler will try to serve the packets from the first queue. When the priority queue is empty or the non-priority queue has been used for a long period, it will start serving packets from the non priority queue. However, in the case where a priority packet arrives at an empty priority queue while the scheduler is serving a non-priority packet, the priority packet has to wait until the scheduler pushes non-priority packet to the link. By following this strategy, the queueing delay will be reduced significantly leading to the overall reduction of delay. Finally, priority packets are inserted before the non-priority in case the queue is full of non-priority and priority packets arriving at the queue. The main reason behind that is we aim to avoid starvation of the non-priority class packets and at the same time provide high priority to the priority class packets. The TAP policy is summarized in Algorithm 1.

In the network, a set of users is defined as $\mathcal{U} = \{u : u = 1, ..., U\}$. $\mathcal{T} = \{t : t = 1, ..., T\}$ indicates the set of traffic types. $\mathcal{Q} = \{q : q = 1, ..., Q\}$ represents the set of sessions. c_q^t is defined as the QoS constraint of session q associated with traffic type t. $\alpha^{u,d}$ indicates the traffic rate associated with user u and demand d. We denote the available bottleneck bandwidth for path p_n^d by $b(p_n^d)$.

TABLE I: Traffic types[1] and associated QoS requirements.

Traffic Class	Data Rate	Mean Duration	QoS requirements		
			Latency	Jitter	Packet loss
Class 0	Low (≈ 150 Kbps)	180 sec	1 ms	20 μs	0.00001 %
Class 1	Low (≈ 150 Kbps)	180 sec	40-65 ms	0.5-2 ms	0.1-0.5 %
Class 2	Medium (≈ 250 Kbps)	300 sec	4-5 s	*none*	5 %
Class 3	Low (≈ 128 Kbps)	200 sec	300-600 ms	2 ms	5 %
Class 4	High (≈ 500 Kbps)	360 sec	300 ms	30 ms	1 %
Class 5	Low (≈ 100 Kbps)	90 sec	*no specific requirement*		

[1] Applications examples; Class 0 : Haptics, Class 1 : VoIP, Class 2 : streaming video, Class 3 : streaming audio, Class 4 : interactive video, Class 5 : best effort data.

Algorithm 1 Tactile Aware Policy

procedure E-POLICY-PS($P_n^d, \tau, q, \mathcal{N}, V$)
  packet arrives at the Ingress r $\in$ V destined to the Egress $g \in V$
  if packet does not belong to an existing session (i.e. new session) **then**
    Perform lookup and check traffic class $t \in \tau$
    Obtain QoS requirements c_q^t for traffic class t
    if $\left\|\alpha^{u,d}\right\|_0 \leq b(p_n^d)$, for any [2] $n \in \mathcal{N}$ **then**
      Admit the session
      if the arrived packet $\in$ Tactile traffic class **then**
        Add packet to the priority class.
        Duplicate the concerning packet
        Add duplicate packet to the priority class
        Select RP ξ_1 with the lowest cost $f(\xi)$ and ξ_2 with the second lowest cost $f(\xi)$ for the session associated with user u given: $f(\xi_1) \leq f(\xi_1) \leq ... \leq f(N - \bar{\Xi})$.
        Route the original packet by using x_1 and the duplicate through ξ_2.
      else
        Add packet to the non-priority class.
        Select RP ξ in a random manner
        Route the packet through ξ.
      end if
    else
      Reject Session
    end if
  else
    Add packet to the same class as the previous ones that are part of the same session
    Route packet by using the already assigned RP to the previous packets that belong to the same session
    if arrived packet $\in$ Tactile traffic class **then**
      Generate a duplicate of the concerning packet
      Route the duplicate by using the already assigned RP to the previous duplicates that belong to the same session
    end if
  end if
end procedure

IV. Performance Evaluation

In this section, we present and analyse the results that were obtained for the two proposed topologies using C++ and packet-level NS2 simulations interfaced with Matlab. RPs are created through the offline algorithm before NS2 is applied for traffic injection. Subsequently, incoming sessions that belong to different traffic classes (as represented in TABLE I) are generated randomly. The results demonstrated correspond to Haptics traffic performance. It is notable that the traffic type sessions are uniformly distributed. The simulations last for 12 seconds in real time where we record the results at a sampling rate of 10 times per second. Traffic is injected into the network in increasing manner by reducing the inter-arrival times of generated sessions, up to 750MB over the course of 12 seconds, where full network utilisation and significant congestion occur between the 11s and 12s intervals. Since the topologies correspond to campus or metropolitan networks, we set the propagation delay of each link to 0.007ms (assuming an upper bound for the length of the cable up to 20km). Transmission and processing delays are added as part of the NS2 router and queueing model. When a new session arrives at the Ingress, it will check if there exists enough available bandwidth on the set of RPs in order to admit the session regardless of the method used (OSPF, TAP). TAP online TE mechanism as described in subsection III-D is applied to route the traffic. MPR and the generation of the duplicate packets have been implemented using NS2 whereas the priority queueing model has been developed using C++. We compare our proposed policy with OSPF and an optimal case of TAP. First of all, we derived an optimal bound for TAP by allowing only packets of Tactile nature to flow through the network. Subsequently, as mentioned above, we allowed for different types of traffic (i.e. including Tactile) to flow through our topologies in order to evaluate the performance of our algorithm under a realistic scenario. Our results that are represented in terms of the most critical metrics (i.e. delay, jitter, throughput and packet loss) pertain to Haptics traffic performance.

Topology	OSPF	Optimal	TAP
T_1M_1	47.6274	0.818168	0.889203
T_1M_2	47.6274	0.80454	0.875463

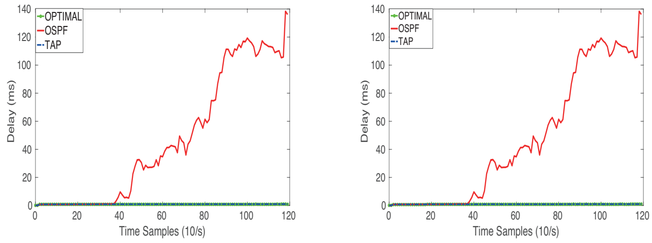
TABLE II: Average delay (ms)

1) Delay (ms)

We use TABLE II to project our data because the difference between the optimal case and TAP is not possible to be visualised on the graphs. As it can be observed from TABLE II, T_1M_2 topology has a slightly better performance in terms of the expected delay as T_1M_2 has more links compared to T_1M_1. Consequently, the traffic can be distributed better over the network due to the existence of more RPs; therefore, the mean delay will be reduced as the queues are less cramped and longer routes do not affect the delay. As expected, TAP performs to some extent worse than the optimal. The main reason behind this deference is the fact that a non-priority packet being served while a priority packet arrives at the empty priority queue. In this case, extra queuing delay will be added to the priority packets leading to an increase in the expected delay. In general, TAP performs extremely well in terms of delay even when the traffic congestion in the network is significantly high. To be more specific, the delay would never exceed the threshold of 1 ms. On the other hand, as illustrated in Fig. 2, the plain vanilla of OSPF can not support Haptic communications due to the high values of delay incurring cyber sickness to Tactile applications. The main reason behind this big difference between OSPF and TAP is that OSPF does not facilitate any priority for the packets that belong to the

[2]It is important to note that at-least two RPs in case of the Tactile traffic class and one for the other traffic types were present throughout the simulation time up to the congestion point as enforced by the algorithm

Tactile class and lack of diversity. Consequently, the queueing delay will be extremely high.



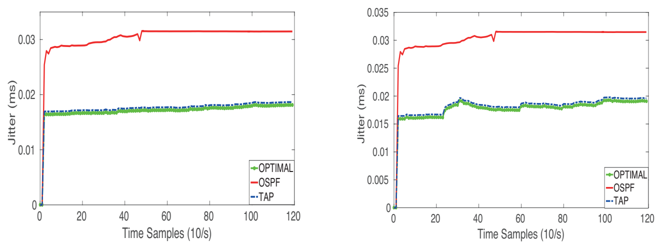
(a) Delay for T_1M_1 topology

(b) Delay for T_1M_2 topology

Fig. 2: Delay for our investigated topologies

2) *Jitter (ms)*

Jitter is a crucial QoS factor in the assessment of network performance. In the case of Tactile applications, jitter should not exceed the threshold of $20\mu s$. In Fig. 3, the variation in latency for a randomly chosen *Ingress-Egress* pair is measured. The same *Ingress-Egress* pair was used for both of our proposed topologies. As observed in Fig. 3, the overall trend shows an increase in jitter. This is due to the larger variations of packet delay resulted from the increasing congestion in the network. Furthermore, both TAP and the optimal case perform extremely well (i.e. they never exceed the threshold of $20\mu s$). Meanwhile, OSPF's jitter values are around $30\mu s$. To this end, OSPF's performance is reflective of its inadequacy in supporting Tactile applications. Finally, TAP performs slightly worse than the optimal scenario due to two main reasons. Firstly, the duplicate packet uses a different path from original packet that has a generally higher delay. Consequently, when the original packet has been dropped, the duplicate packet with a higher delay is considered leading to a higher variation of flows delay. Secondly, in the optimal case, only packets belonging to Tactile class are allowed to flow through the network. To be more specific, there are no other packets belonging to other traffic classes that would add extra queueing overhead leading to higher delay variations. Therefore, optimal case performs slightly better than TAP in terms of jitter.



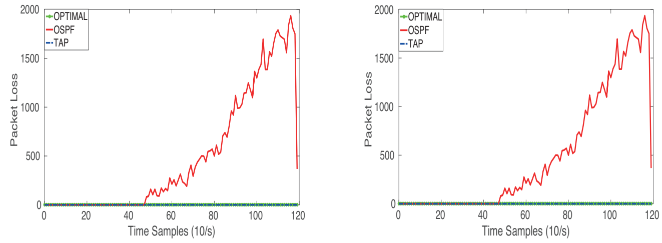
(a) Jitter for T_1M_1 topology

(b) Jitter for T_1M_2 topology

Fig. 3: Jitter for our investigated topologies

3) *Packet Loss Rate*

In the case of the Optimal scenario where only Tactile packets flow through the network, the traffic level is not so high to cause a queue overflow leading to no packet loss as observed in Fig. 4. The loss rate in the case of TAP is the same as optimal. This happens due to two main reasons. Firstly, each router has two queues; one for priority packets and the other for the non-priority packets. This leads to non-priority packets not adding extra queuing delay to priority packets which would otherwise cause packet drop due to buffer overflow. Secondly, even in the case where a priority packet has been dropped, it will be restored using a duplicate packet III-C. Namely, for T_1M_1 topology we manage to restore 13 packets by using the second flow and 8 for T_1M_2. More packets that belong to the first flow have been dropped in case of T_1M_1 as compared with T_1M_2 as T_1M_1 topology has a lower meshing relative to T_1M_2; Therefore, fewer RPs are available as investigate in [18]. Conversely, when the congestion throughout the network is high, OSPF performs poor making it a non candidate routing protocol for Tactile packets. The overall achieved loss rate of TAP for Tactile traffic was initially $5.0839 * 10^{-5}$ for T1M1 and $3.123 * 10^{-5}$ for T1M2. By duplicating sessions for Tactile traffic, we completely eliminated the loss rate for both topologies.



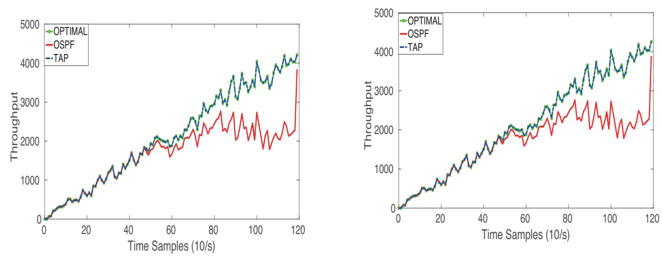
(a) Packet loss for T_1M_1 topology

(b) Packet loss for T_1M_2 topology

Fig. 4: Packet Loss for our investigated topologies

4) *Throughput (packets/s)*

Fig. 5 illustrates the achieved network's throughput under varying traffic classes with an increasing traffic rate injected through the network (i.e. totalling 750MB over the course of 12 seconds). As observed, the achieved throughput of TAP is similar with that of the optimal cases. This can be justified by the fact that TAP achieved the same packet loss rate as the optimal case. Meanwhile, OSPF protocol performs poorly when the level of congestion throughout the network is high.



(a) Throughput for T_1M_1 topology

(b) Throughput for T_1M_2 topology

Fig. 5: Throughput for our investigated topologies

V. Conclusion

In this study, a reliable novel routing policy has been proposed in order to serve Haptic communications effectively over an all-IP access network. Two different access network topologies of different meshings have been investigated under a realistic traffic scenario with a varying range of traffic classes. It has been shown that our policy performs extremely well for different levels of congestion (outperforming OSPF and performing not far from the optimum). Moreover, as TAP is based on MPR that is a purely IP traffic engineering approach, it would render negligible communication overhead in the network. For future work, more traffic variations will be investigated followed by the application of feedbacks and integration with extended traffic models for Haptics. Other intelligent and selective packet duplication strategies will also be investigated.

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