Towards Low Latency Networks for Teleoperation

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***Abstract*—Commensurate with the leaps and bounds with which networking has improved over the last few years. The topic of lowering network latency has attained a position of prominence within the last few years. Emerging technologies such as those of teleoperation and virtual reality video streaming have an imperative need for networks with very low end to end delay. This paper explores these different avenues for lowering the latency in networks and reviews the current state of the art in different teleoperation systems. It presents different ways in which the network latency can be reduced and summarizes the most significant literature of the recent past. Finally, it explores the flexible algorithm in Open Shortest Path First (OSPF) Protocol.**

Keywords*— *Networking, Teleoperation, Latency, Robotics, Routing Protocols, Low Latency, Telerobotics

I. INTRODUCTION

Proportionate to improvement that the field of networking and connectivity has had in the recent past, the world is at the cusp of a revolution in which the requirement of a central computing will be decreased and increasing number of systems will rely on the ability to distribute resources with low latency connections between them. This paper explores the general concepts and methods of reducing latency by focusing on the networking domain.

To begin with, a definition is given to the meaning of a low latency networking and an introduction to the topic of teleoperation. Further the most recent literature in the field of teleoperation and low latency networking is explored and analyzed. Each paper is analyzed with the concept of the minimum latency it provides, the bandwidth it runs on, the technology over which it is implemented and finally the novel contributions of the given paper are listed. The paper includes a presentation of one routing algorithm which shows promise in lowering network latency.

A. Low Latency Networking

Low latency networking refers to the principle of reducing the total time taken by a packet from its source until it reaches its destination. The time taken for such packets has reduced greatly since the past, starting from a range of a few seconds, it is now often in the range of milli-seconds. Latency is often associated with the Quality of Service (QoS) of a network and there exists extensive literature on the topic.

The domain of low latency networking has been one that is sought out to be solved since a large number of days. However, in the current day and age there has been an enhanced focus these problems. The reasoning behind this shift in tradition is twofold.

Firstly, the conventional problems that were always approached in the field of networking was to enable a high data rate and high throughput communication. In the initial years of the internet and the dotcom era there were hundreds of competing companies vying for the ability to increase their presence online. The problem of network latency was sidelined due to both the lack of necessity and the pertinent problem of low data rates.

Secondly, the attempts to reduce latency were not driven in a wholehearted way, individuals would try to attempt to reduce latency at their respective level but the whole picture was seldom considered.

The amount of latency in networks can be attributed to various sources. Starting from the structural aspects of a network there are various different sources that can cause an increase in the latency of the network. These different sources will be explored through the literature survey and the underlying causes will be manipulated in order to understand a good way to tackle the problem. A large number of approaches are discussed ranging from statistical methods, hardware methods, protocol-based methods and even reinforcement learning methods.

B. Teleoperation Systems

Teleoperation is the technical word for remote control of a machine, system, or robot. The distance involved might range from millions of kilometres for space applications to millimetres for microsurgery or micro-applications. It falls under the domain of human robot interaction. Teleoperation is most usually associated with technology that allows a human operator to control a distant robot. In the following paper a survey is performed on some of the most recent literature on the various types of teleoperation systems comparing the networks used, the latencies required and their contributions

Understanding the underlying process of networking requires analysis of different domains. From [1] the main sources of delay and techniques for reduction of latency are described, the established sources of delay include structural delays, interaction between endpoints, delays along the transmission path. One of the main techniques that provides an improvement in the end-to-end latency of a system is caching, as mentioned in [1] Google's using a three level cache is able to show 90% hit rate and thus give a sub one second latency for delivering videos. However, this technique cannot be implemented on a teleoperation system as caching the inputs and outputs of such a system is impossible.

Through [2] there is an establishment of the systems that can make a low latency network possible. It suggests that using a system with OpenFlow will improve the networks overall performance. The paper hints at how the natural improvement through Moore's Law will create a reduction in round trip time. Coming to the scenario entailed by teleoperation a large amount of research describes the methods of attempting teleoperation over an unreliable network [3], [4]. Recent papers like [5], [6], [7] show insight into the driving of autonomous vehicles through teleoperation. These papers dictate that a latency of below 300 ms is the minimum requirement for establishing teledriving in a way that is safe for the environment.

[8] and [9] describe techniques that are focused on the human performance with different conditions of network and an algorithm for allowing control of a teleoperated system through a torque feedback system. Given the above reasons for a low latency network one can further go on to describe the techniques that can be used to improve the system parameters. There are various types of network delays but one of the most effective ways in which the latency can be reduced is during the hand-off scenario between two of the networks.

5G mmWave networks have long been attempting to reduce latency to a level that will allow ultra-reliable low latency. The key system requires reworking is the Medium Access Control (MAC). As seen in [10], four techniques exist that would attempt to help the MAC layer congestion. This MAC is not to be confused with the conventional MAC used in the Layer 2 of networking.

[11] is another paper from the 5G domain which talks about the topic of ultra-reliable low latency communication. The paper focuses on the tactile internet and takes into consideration the probability of transmission error. Sticking to the domain of 5G networks [12] evaluates the techniques of giving guaranteed latency bounds on a given network. The paper further goes into analyzing the impacts such latency bounds will have on the network. In conclusion the paper states that although the latency bounds would cause a decrease in the efficiency of spectrum utilization, the overall impact on the network would only be moderate and therefore sustainable.

Moving closer to the domain of Internet Protocol (IP) based networks, [13] attempts to tackle the problem of latency during the handoff procedure in WiMAX networks, this task seems to be focused on a lot by considerable amount of literature. Further the paper proposes a scheme that reduces handoff latency in certain given tasks. Moving to [14], it shows the importance of how Wi-Fi latency is one of the best ways in order to evaluate the overall latency of the network. It describes the reasons why the Wi-Fi models produce such a high latency. Finally, a technique is proposed to reduce the latency by a factor of nearly 0.8 in the median case. Another conventional approach is the usage of Software Defined Networking. As described by [15] an optimum con-troller could mean the difference between a network with low latency and one with much higher latency. [16] combines the above two techniques by attempting to multicast data to both target networks hence enabling lower latency without device modification. [17] gives a good comparison of the performance of all the controllers for software defined networks. One potential solution to the highly researched handoff problem is the proximity based soft handover techniques. As mentioned in [18], some of these techniques can drastically reduce handover latency.

Finally, one look at the routing approaches as mentioned in [19] which states the preferred routing algorithm for lowering the latency of the routers as Open Shortest Path First (OSPF)

[20] talks about a new algorithm that can be used to implement lowered latencies using the controller design itself. One of the newer techniques for enabling low latency within a routing topology is currently being drafted in the [21]. This technique will be explored in depth in the later sections of the paper.

Analyzing the recent literature gives a picture of the requirements by teleoperation-oriented devices. The following section gives an overview of some the most significant modern literature. [22] Measures the metrics of delay in a given using 5G technology, it verified the accuracy and latency constraints that are put forth by the 5G Ultra Reliable Low Latency Network. Within a distance of around 40 metres it showed that the throughput standards were maintained. [23] describes the sources of an increase in the latency of a network for UAVs and employs a latency budget technique, this technique is implemented in the common NS3 simulator.

[24] developed a framework to perform teleoperated surgeries in a semi-automated way, allowing for a limited band width and latencies ranging from 0 to 5 milliseconds during teleoperation. This technique can be considered as a supervised teleoperation technique as the user input is processed before applying to the robot actuator. [25] introduces a compression Technique for 3D video to improve frame rate and latency. This is especially important for 3D video due to the fact that poor latency in 3D Video often leads to disorientation of the individuals.

[26] Performed a feasibility study in order to understand the effectiveness of teleoperation over the 4G network using a variety of operators. The results show promise in using 4G based networks for a complete teleoperation setup. [27] Implements a stereoscopic vision system that presents a virtual reality approach to teleoperation, which helps in the visualization of the three-dimensional position of the robot. The results presented include the latencies with two different types of camera setups.

[28] Proposes a technique for operators to perform ul-trasound using teleoperation in a mixed reality setup. The paper analyzes the throughput and latency of the system. Such systems show great promise in enabling good healthcare in remote areas.

[29] proposes an improved controller which gives lower latency in Yaskawa robots. The controller shows improvement in the teleoperation capability by lowering the end-to-end latency of the system and cutting down on excess processing. [30] Describes a technique to cope with high latency using video zooming with a sliding window approach. This technique suggests streaming of predicted future sensory inputs by applying an image transformation on the images received.

Although lowering latency is the goal, there are certain techniques which circumvent the problem of lowering latencies through the usage of neural networks and motion prediction.

[31] Describes the technique used to overcome a high internet latency during teleoperation and implements it on an aeroengine problem. [32] Proposes methodology to get tool topologies using deep learning technique. This allows for teleoperation with high precision for surgery even under increased network latency. [33] Proposes a hybrid shared control between the human and the robot which allows for the robustness of the robot operation even at higher latencies. Table I shows a summary of the above papers with a description of the latencies, throughput and platform over which they were implemented.

TABLE I.

Paper	Summary of Modern Teleoperation Literature		
	Network	***Throughput***	***Latency***
[22]	5G	4-8 Mbps Achievable	11-13 ms
[23]	NS3 - IP Based Emulator	65 kbps	16-19ms
[24]	TCP+UDP Deserts Framework	1 KBps	57 ms
[25]	ROS Based - Virtual Network Adapter	50 Mbps	64-74 ms
[26]	4G LTE	3-8 Mbps	< 100 ms
[27]	NDI IP Network	4.5 Mbps	166.67 ms
[28]	ROS Based - Rosbridge	7-10Mbps	270 ms
[29]	ROS Based- WiFi Network	Not Specified	445 ms
[30]	Irrelevant	Not Specified	900 ms
[31]	Internet	Not Specified	968 ms
[32]	ROS Nodes - UDP	Not Considered	Applying delay constraints proposed as future work
[33]	ROS Based- WiFi Network	Not Specified	Applying delay constraints proposed as future work

II. PROBLEM FORMULATION

The problem of lowering latency in a network is formalized in the following sentence. Design a low latency network for teleoperation by lowering the network latency of existing standard architectures.

III. METHODOLOGY

In order to tackle the problem posed by increased latencies, one of the proposed solutions involves the use of dynamic routing protocols. Mentioned in [19] is the fact that Open Shortest Path First (OSPF) algorithm which was benchmarked against its contemporaries shows better performance with regard to throughput and latency. However, open shortest path first protocol has its own set of inherent pitfalls.

Through the usage of Interior Gateway Protocol (IGP) Metrics, OSPF analyzes the shortest cost path possible in order to deliver packets to their destinations. Due to this nature OSPF is susceptible to providing paths that are not the most optimum in terms of their latency. Consider the example Access – Metro - Core topology seen in Figure 1, for a packet that needs to travel from R1 to R3 the OSPF algorithm calculates the default metric for the lowest path to be through the core network. The path taken by the routing algorithm is R1> R4> R7> R8> R9> R6> R3

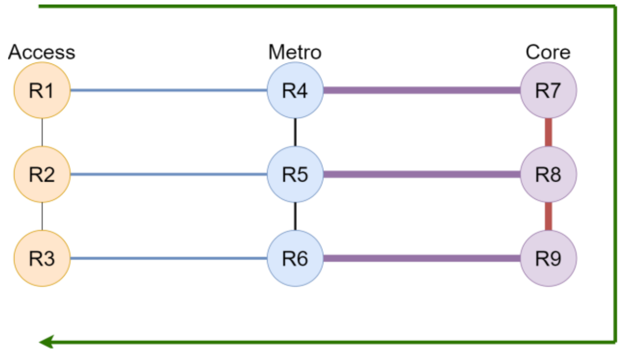

Fig. 1. Access Metro Core Network

As introduced in [21], the flexible algorithm is one of the techniques that can help overcome the pitfalls of the Open Shortest Path First Algorithm. Through Flexible Algorithm one is able to use the low latency path to the router R3. In order to define this path, one must look at the way Flexible Algorithm works. Flexible Algorithms (or Flex-Algos) are algorithms that are used in order to create alternate metrics to deploy networks that can tackle traffic engineering.

The flex algo can use the following constraints for defining path:

1. Traffic Engineering (TE) Metric:

   This is defined upon the total amount of traffic on the current link.

2. Admin Color Constraints

   The networks in flex algorithm can used different color constraints on each link and each interface which gives the ability to maintain routes on independent network areas.

3. Avoid Node Constraints

   The flex algo allows to define certain nodes that need to be avoided in order to maintain certain TE criteria

4. Latency Metrics

   By far the most important criteria for this application is the latency metric-based constraints, these allow to create paths that are within the required latency. By advertising Link State Advertisements (LSA) using the delay measured through a Two-Way Active Measurement Probe (TWAMP), one can maintain an updated database with the lowest latency links. The tag length values (TLV) for the same are used to indicate the type of flexible algorithm.

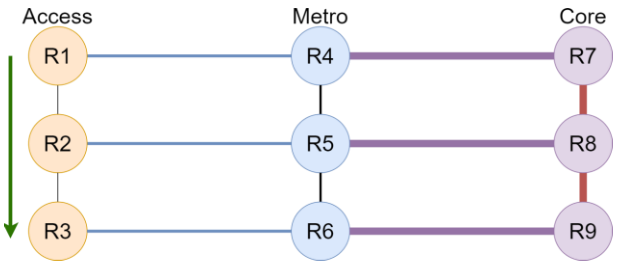

Fig. 2. Flexible Algorithm in Access Metro Core Network

As shown in the Figure 2 one can define a OSPF Flex Algorithm with the link delay serving as the metric, this results in the lowest end to endpoint delay within the network. The implementation of these flex algorithms relies on the presence of certain policies called Flexible Algorithm Definition (FAD). In the topology described in Figure 2 there needs to be one FAD set for the routers R1, R2 and R3 wherein the definition of the FAD includes the fact that this is the path with lowest latency. The high bandwidth flows will be assigned to the other routes R4, R5 and R6.

The above system however has a few drawbacks which include:

- All nodes need to support flex algorithm in order for the system to run.
- There needs to be an extensive configuration in order to set up a flex algorithm.

IV. RESULTS

In order to test the functioning of the Flexible Algorithm, a simulation is created using a virtual router topology, this four-router topology uses a similar blueprint as the Access-Metro-ore Network seen in Figure 1. The topology was implemented using a sandbox. The link delays were measured for transferring a packet through the default OSPF path and the flex algorithm path.

The implementation of the flex algorithm shows promising results. On a virtual sandbox topology, the predicted latency values through the usage of the Flex Algorithm shows a proposed improvement of nearly 71%.

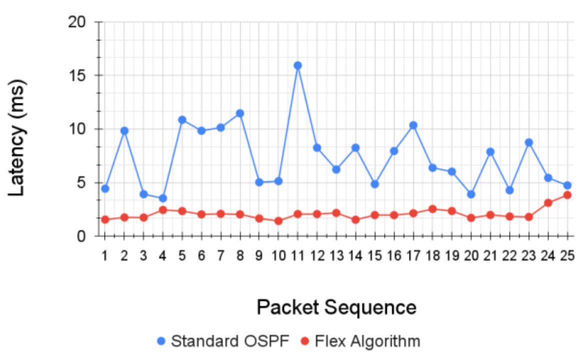

Fig. 3. Latency in Standard OSPF and Flexible Algorithms

As seen in Figure 3, over an average of 25 packets, the default OSPF Path will have a high latency value of about 7.3 ms whereas the flexible algorithm proposes a result of about 2.037 ms. Thus, flexible algorithm paths are generally favored to give better latencies. With an increase in number of routers in the topology, there will be a linear increase in the latency of flexible algorithm while the standard algorithm's latency would increase exponentially.

V. CONCLUSION

The paper surveys the different types of techniques used to implement networks with low latency. It looks over the modern teleoperation papers with an understanding of why low latency networks are required and the current state of the art for such networks. It also reviews the modern literature for teleoperation. Finally, the paper proposes the use of OSPF Flex Algorithms to enable better performance in the situations with low latency as an important criterion.

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