Performance Analysis of OpenVPN on a Consumer Grade Router

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Abstract:

Virtual Private Networks (VPNs) offer an alternative solution using Internet Protocol (IP) tunnels to create secure, encrypted communication between geographically distant networks using a common shared medium such as the Internet. They use tunneling to establish end-to-end connectivity. OpenVPN is a cross-platform, secure, highly configurable VPN solution. Security in OpenVPN is handled by the OpenSSL cryptographic library which provides strong security over a Secure Socket Layer (SSL) using standard algorithms such as Advanced Encryption Standard (AES), Blowfish, or Triple DES (3DES). The Linksys WRT54GL router is a consumer-grade router made by Linksys, a division of Cisco Systems, capable of running under Linux. The Linux-based DD-WRT open-source router firmware can run OpenVPN on the Linksys WRT54GL router. For this case study, the performance of OpenVPN is measured and analyzed using a 2^{k-p} fractional factorial design for 5 minus 1 factors where k = 5 and p = 1. The results show that the throughput is mainly limited by the encryption cipher used, and that the round-trip time (RTT) is mostly dependent on the transport protocol selected.

Keywords: Virtual Private Network, Performance Analysis, WRT54GL, DD-WRT, OpenVPN, OpenSSL, Experimental Design, Fractional Factorial Design

Table of Contents

1 Introduction

In the past, enterprises have used leased lines over long distances for secure communication between two networks. Typically this is done in order to communicate data, voice, or other traffic between two geographically-separated sites of a company or with a valued business partner. Leased lines provide dedicated bandwidth and a private link between the two locations. Running leased lines are not always possible or practical for all enterprises and everyday users due to cost, space, and time of installation [Joha08]. Thus, an alternative solution is needed.

Virtual Private Networks (VPNs) were created to address this problem by using the Internet to facilitate communications. Internet access is cheap; however, it is insecure and often bandwidth limited. VPNs are designed to create secure, encrypted Internet Protocol (IP) tunnels to communicate between geographically-distant networks across the Internet. This solution is cost-effective for and available to companies and individuals alike and provides secure access to resources on the remote network.

For this case study, the performance of OpenVPN running under Linux on the Linksys WRT54GL router is analyzed. The sections that follow give background information on VPNs, and describe the VPN solution and router used in this case study.

1.1 Background

Tunneling is a method by which data is transferred across a network between two endpoints. VPNs use tunnels to establish end-to-end connectivity. A packet or frame destined to a remote network is first encapsulated by adding additional header information and is then sent across the network to the remote endpoint. At the endpoint, the header information is removed and the packet is sent out onto the remote network [Joha08]. This process is shown in Figure 1.

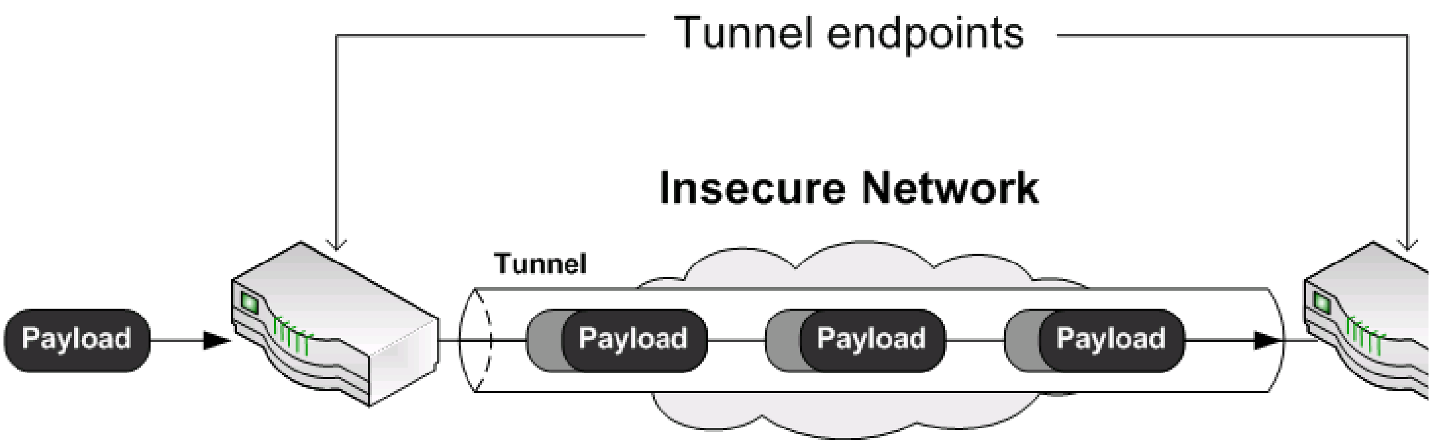


Figure 1: VPN tunnel between two endpoints across an network [Joha08]

There are tradeoffs to using a VPN solution compared to dedicated lines. A VPN offers benefits such as flexibility, transparency, security, and cost. However, it has some drawbacks such as availability and bandwidth [Kolesnikov02]. A VPN connection is very flexible because a user can connect to the remote network from anyplace with an Internet connection. Transparency is achieved through tunneling which allows arbitrary traffic to traverse the VPN. For VPNs, security is provided using authentication and encryption. Authentication restricts access to the network by allowing only authorized users to connect. Encryption provides privacy by scrambling the data in the tunnel. The cost of a VPN is much less than the cost of running dedicated lines, particularly if a freely available open source VPN solution is used. VPN solutions are typically deployed to provide access over the Internet which sometimes varies in the availability and bandwidth of the connection. In this case, dedicated lines provide a clear advantage. They are both highly available and provide guaranteed bandwidth.

In general, a VPN solution should take into consideration security, key distribution, scalability, transport protocol, interoperability, and cross-platform availability [Kolesnikov02]. Security is perhaps the biggest concern because there are so many ways to implement security incorrectly. Key distribution is related to security and has to do with the procedure by which keys are distributed to clients. If keys are distributed in an insecure manner, they can be intercepted, allowing an intruder to gain access to the private network. Scalability refers to how well a VPN solution scales in terms of the number of connections and sites. The transport protocol has an effect on the overhead and performance of the VPN tunnel which will be described in a later section. Interoperability refers to devices running the same VPN solution being able to work with each other. Simple, well thought out designs tend to be the more interoperable. Last, cross-platform availability allows the VPN solution to work with multiple operating system platforms.

In the next section, the VPN solution used in this case study which takes these points into consideration is described.

1.2 The VPN

OpenVPN is a cross-platform, secure, highly configurable VPN solution [OpenVPN]. It uses virtual interfaces provided by the universal Network TUNnel/TAP (TUN/TAP) driver and is implemented entirely in user-mode in the least privileged protection ring of the system. This decision was made to provide better security. If a vulnerability is found by an intruder, their access will be limited. However, this does affect performance due to multiple memory copies between kernel and user space. OpenVPN supports peer-to-peer and multi-client server configurations which makes many VPN topologies possible: host-host, host-network, and network-network. It supports creating a Layer 3 or Layer 2 VPN using TUN/TAP devices, respectfully [Feilner06].

Security in OpenVPN is handled by the OpenSSL cryptographic library [OpenSSL] which provides strong security over Secure Socket Layer (SSL) using standard algorithms such as Advanced Encryption Standard (AES), Blowfish, or Triple DES (3DES). Certificates are used for authentication, and symmetric and asymmetric ciphers for encryption. A cipher has several characteristic parameters: key length, block size, and mode. Key length dictates the strength of the cipher. The block size dictates how much data is encrypted in a block. The mode dictates how the encryption cipher is actually used. Other important factors are key distribution and the cryptographic strength of the cipher. OpenSSL uses symmetric and asymmetric ciphers as part of the overall security. However, the security is only as strong as the weakest link. Kolesnikov and Hatch give an example. If a 40-bit symmetric key and a 4096 bit asymmetric key are used for the ciphers, likely the 40-bit key will be the weakest link, making a 4096 bit asymmetric key unnecessarily large [Kolesnikov02].

In OpenSSL, block ciphers are used for symmetric encryption and can be used in different modes. OpenVPN uses a mode called Cipher Block Chaining (CBC) which makes the cipher text of the current block dependent on the cipher text of the previous block. This prevents an attacker from seeing patterns between blocks with identical plaintext messages and manipulating one or more of these blocks [Kolesnikov02].

The philosophy for judging the security of an encryption cipher is based on the test of time. A cipher that has stood scrutiny of the security community for many years with its details published is generally considered strong. If the cipher had any major flaws, they likely would have been found. Some of the criteria for selecting a cipher are security, performance, and availability. The cipher selected should meet security needs [Kolesnikov02].

The cross-platform support in OpenVPN allows it to be deployed to other systems including embedded routers. The router used in this case study is described next.

1.3 The Router

The Linksys WRT54GL router is a consumer-grade router made by Linksys [Linksys], a division of Cisco Systems, capable of running under Linux. A Linux firmware actively being developed is DD-WRT [DD-WRT] which is based on the OpenWrt kernel [OpenWrt]. DD-WRT is released under the GNU General Public License (GPL) and provides an alternative to the stock firmware in the Linksys router. The firmware allows the router to take on many roles: Internet gateway, VPN gateway, firewall, wireless access point, dynamic Domain Name Service (DNS) client, etc. It has a friendly web interface and supports many features beyond the router's original capabilities. It supports OpenVPN through special firmware and can be extended from the console using packages. Console access is given by both Secure Shell (SSH) and Telnet. For basic and advanced configurations, tutorials are available [DD-WRT Tutorials].

OpenVPN, which is supported in the DD-WRT firmware [OpenVPN/DD-WRT wiki], can be used on the router in a variety of different ways. First, key management can be maintained on the router. This allows certificates to be generated for users from the console; however, due to a limited amount of flash memory available, this requires a modification to the Linksys router to add a SecureDigital/MultiMediaCard (SD/MMC) memory card. A tutorial on the OpenWrt wiki describes how to do this [MMC Tutorial]. Second, the VPN package can be configured in several different topologies such as host-network or network-network depending on whether users will connect to the VPN or will access the remote network using a site-to-site connection. Last, the VPN virtual interface can be bridged to the physical network interface, allowing Ethernet frames to traverse between clients and the private network.

VPNs provide a cost-effective alternative solution to leased lines and are able to create secure connections between two end-points. OpenVPN is a VPN solution which can run on an embedded router running Linux. The Linksys WRT54GL router can run Linux through a firmware upgrade to the DD-WRT firmware. In the next section, the characteristics of a VPN will be discussed as they relate to performance analysis.

2 VPN Characteristics

There are many characteristics of a VPN that affects the performance of the system. In the sections that follow, the transport protocol is discussed, a set of performance metrics are defined, and the system parameters are identified.

2.1 Transport Protocol

The transport protocol used for the VPN tunnel will have an impact on the performance of the VPN. If the Transport Control Protocol (TCP) is used, it will have an undesirable effect when TCP is used in the tunnel as well. This is called TCP stacking. TCP is a connection-oriented protocol that was not designed to be stacked. It assumes an unreliable medium and retransmits packets when a timeout occurs. TCP uses an adaptive timeout which exponentially increases to avoid an effect known as meltdown. The problem occurs when both TCP protocols timeout. This is the case when the base connection loses packets. TCP will queue a retransmission and increase the timeout, trying not to break the connection. The upper-layer protocol will queue retransmissions faster than the lower layer due to having a smaller timeout value. This causes the meltdown effect that TCP was originally trying to prevent. The User Datagram Protocol (UDP), a datagram carrier having the same characteristics as IP, should be used as the lower layer protocol [Titz01].

2.2 Performance Metrics

Network performance is measured using a set of performance criteria or metrics. For OpenVPN, the service provided is access to the private network. The response time, throughput, and utilization are used to characterize the performance of the VPN. In the case that errors occur, the probability of errors and time between errors should be measured [Jain91]. A list of selected performance metrics are below:

1. Overhead
2. Round-trip time
3. Jitter
4. TCP throughput
5. Router CPU utilization
6. Client CPU utilization
7. Probability of error
8. Time between errors
9. Link utilization

Every VPN packet incurs overhead from the encapsulation process. When a payload is sent through the VPN tunnel, headers/trailers of various protocols are added to the payload to form a routable packet. Additional overhead comes from encryption ciphers used to secure the tunnel. The effects of overhead can be alleviated by using compression to reduce the amount of data transmitted [Khanvilkar04].

The overhead in OpenVPN is a function of the interface, transport protocol, cryptographic algorithm, and compression. The fixed overhead added to each packet is 14 bytes from the frame header and 20 bytes from the IP header. The transport protocol, used to form the VPN tunnel, contributes 8 (32) bytes from the UDP (TCP) header. The cryptographic algorithm used to secure the tunnel will contribute to the overhead depending on the algorithm. Part of the overhead includes the hash from the medium access control (MAC) algorithm, such as MD5 (128-bits) or SHA-1 (160-bits), and zero padding for block encryption ciphers. Compression of uncompressible data adds at most one byte of overhead. Other minor contributions come from sequence numbers and timestamps that are included to defeat reply attacks [Khanvilkar04].

The round-trip time (RTT) is the time it takes for a packet to reach a remote host and return back and is related to the latency of the connection. Latency through a VPN tunnel is dependent on the machine hardware, the link speed, and the encapsulation time. Higher latencies in OpenVPN are caused by multiple copies between kernel and user space, and the compute-intensive operations of encryption and compression. Latency can be improved, generally, by using faster hardware and better algorithms [Khanvilkar04]. Jitter is the variation in the latency of packets received by a remote host. For applications with streaming connections, jitter can be alleviated by buffering the stream. However, this adds delay in the connection which is intolerable for some applications such as Voice over Internet Protocol (VoIP). Low latency and low jitter are better for these metrics.

Throughput is a measure of the amount of payload data that can be transmitted end-to-end through the VPN tunnel. It does not include the overhead incurred by protocol headers / trailers, and the VPN tunnel. Similar to the latency, the throughput is limited by the machine hardware and encapsulation time; although it can be improved by using faster hardware and better algorithms. Throughput is a critical performance metric which will limit the number of users whom the VPN can support. Thus, higher throughput is better.

The performance of a VPN solution is often limited by the CPU on one or both of the endpoints which must encapsulate, encode, transmit, receive, and decode packets. Monitoring the CPU utilization of each device allows us to identify the bottleneck in the network communication. For this metric, utilization in the middle of the range is better.

The link utilization is the ratio of the physical network interface throughput to the link speed. In this case, the throughput is the total throughput of all packets transmitted including overhead. This metric is not directly useful, however, it can be used indirectly through a calculation to gauge the efficiency of the packets transmitted through the VPN tunnel. Higher link utilization is better only when the throughput is also higher.

Errors can sometimes occur in network communication causing packets to be lost, corrupted, duplicated, or out of order. When an error occurs, it is important to know the probability of it happening again, and the time between errors. A related metric is packet loss which gives the percentage of packets that were lost or corrupted. No errors are ideal, but low error rate is acceptable.

2.3 System Parameters

The performance in OpenVPN is affected by many parameters ranging from the hardware to the configuration. A list of these parameters is below.

1. Network topology
2. Memory
3. Speed of the router CPU
4. Speed of the network
5. VPN topology
6. Interface
7. Transport Protocol
8. Encryption cipher
9. Encryption key size
10. Compression algorithm

The network topology will affect system performance. For example, a topology in which the client is located far from the OpenVPN server will have to contend with network traffic unlike a client that is directly connected. Hardware factors such as memory, speed of the router CPU, and speed of the network can all affect system performance. At least one of these three hardware factors will be a bottleneck in the system. The VPN topology, such as host-host, host-network, and network-network, will affect system performance. The choice of the interface, transport protocol, encryption cipher, key size, and compression algorithm will all affect system performance. This is due to additional overhead and compute-intensive operations.

The transport protocol, if it is TCP, for the VPN tunnel will have an impact on the network performance. UDP is a protocol which has the same characteristics as IP which will not suffer from meltdown caused by retransmissions. There are many metrics that are used to measure network performance. While not all of them are significant, each one should nonetheless be included in the performance analysis. There are many system parameters that affect the performance of the VPN. Only a subset of these parameters can be changed. For the performance analysis done in the next section, a set of factors were chosen and varied in a 2^{k-p} fractional factorial design.

3 Performance Analysis

There are three evaluation techniques that can be used for performance analysis: analytical modeling, simulation, and measurement. For assessing the performance of OpenVPN on the Linksys WRT54GL router, measurement was chosen. The performance can be measured and analyzed through a series of experiments using the experimental design method described by Jain called 2^{k-p} fractional factorial design [Jain91]. This method is intended to determine the effects and percent variation of the effects for each factor and their interactions. Confidence intervals can also be calculated to determine the significance of each effect. In the sections that follow, the measurement tools used and the experimental setup are described. The results of the study are then presented.

3.1 Measurement Tools

Assessing the performance of OpenVPN requires the use of several measurement tools for generating, measuring, and monitoring network traffic. The tools used in this case study are *wireshark*, *iperf*, *ping*, and *sar*. Of these four tools, *wireshark*, *iperf*, and *ping* are available for both Windows and Linux. Although Windows has a *ping* tool, it is limited and not sufficient for the latency and packet loss tests in this case study. The last tool, *sar*, is available only on Linux. A description of each tool is given below.

- *Wireshark*, formally *Ethereal*, is a network protocol analyzer with a rich feature set for capturing and analyzing network traffic. It has deep inspection and filtering capabilities of hundreds of protocols, making it a valuable tool for monitoring network traffic [Wireshark]. In this case study, it was used to monitor VPN-encapsulated packets and normal packets.

- *Iperf* is a network testing tool for creating and measuring TCP and UDP streams. It has options for controlling several network parameters including maximum segment size (MSS), buffer length, TCP window size, and TCP no delay (for disabling Nagle's Algorithm). The TCP test will generate traffic at full speed and measure the bandwidth between two endpoints. The UDP test will generate traffic at a given bandwidth and measure the jitter (variation in the latency) and packet loss between two endpoints [Iperf].

- *Ping* is a network testing tool for measuring latency and packet loss between two endpoints using the Internet Control Message Protocol (ICMP). A large number of packets can be transmitted using a flood ping. A flood ping works by transmitting one packet at a time and waiting for a reply or timeout. If a timeout occurs, the packet is counted as lost.

- *Sar* is a system activity collection and reporting tool found in the sysstat utilities package [SYSSTAT]. It is able to collect and report information on CPU and network interface activity over a period of time. This information can be collected in parallel with the TCP bandwidth, UDP jitter, and latency tests.

3.2 Experimental Setup

The goal of this case study is to evaluate the performance of OpenVPN on a consumer grade router running the DD-WRT firmware. The router is a Linksys WRT54GL v1.1 with 16 MB RAM, 4 MB flash memory, and a 200 MHz processor.

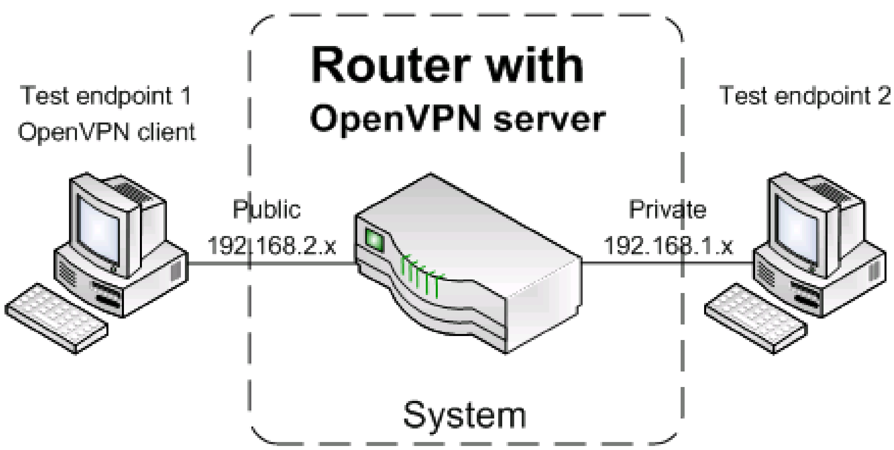


Figure 2: System definition for the study of OpenVPN on a consumer grade router

The system definition, shown in Figure 2, consists of two systems connected to a router in the middle. The first system is the OpenVPN client which needs to establish a VPN tunnel to access the internal private network. It is the first test endpoint for the performance tests. The router is the OpenVPN server which is the system under test (SUT) [Jain91]. The second system is a computer on the private network which is the second test endpoint. The specifications of these two test systems are shown in Table 1.

System	Description

Test endpoint 1 (test client)	Cento OS 5.2 Linux, AMD Athlon XP-M 2600+, 1.83 GHz, 2.0 GB of RAM, ASUS A7V880 motherboard, VIA KT880 chipset
Test endpoint 2 (test server)	Windows XP Professional, Service Pack 3, AMD Athlon XP 2000+ (Thoroughbred), 1.67 GHz, 768 MB of RAM, ASUS A7V8X-X motherboard, VIA KT400 chipset

Table 1: System specifications for test endpoints

To facilitate the testing process, a Python script, on test endpoint 1, is used to automatically run each test and collect data results which are saved in a log file. There are three tests that are run: TCP bandwidth test, UDP jitter test, and latency test. The TCP bandwidth test uses *iperf* to generate traffic from a workload, and to measure the bandwidth over multiple time intervals. Simultaneously, CPU and network activity are measured using *sar* over the same time intervals. The UDP jitter test also uses *iperf* to generate traffic from a workload, and measures the jitter and packet loss across the VPN tunnel. As with the TCP test, *sar* is used to measure CPU and network activity. The latency test uses *ping* to flood small packets to the remote host and to measure the return-trip time (RTT) and packet loss across the VPN tunnel. The RTT is related to the latency of the connection, and the packet loss can be used to get the probability of error.

Many of the system parameters were fixed to a single value for a reduction in the number of total experiments needed. Some parameters are determined by the hardware which cannot be changed such as memory, router CPU speed, and network speed. The other parameter values were chosen based on recommendations given in the OpenVPN documentation. These parameters are shown in Table 2.

Fixed Parameter	Value
Memory	16 MB RAM
Speed of router CPU	200 MHz
Speed of network	100 Mbps
Encryption key size	256-bit
Digest	SHA1
TLS cipher	DHE-RSA-AES256-SHA

Table 2: Parameters fixed in the experimental setup

In the fractional factorial design, five factors were chosen and are listed in Table 3.

	Factor	Level (-1)	Level (+1)
A	Interface	TAP (bridged)	TUN
B	Protocol	UDP	TCP
C	Cipher	None	AES-256
D	Compression	None	LZO
E	Workload	Text	Video

Table 3: Factors in fractional factorial design

OpenVPN supports creating tunnels using two devices: TUN and TAP. The primary distinction between these two is the layer at which they operate. TUN, which stands for Network TUNnel, operates at Layer 3 of the OSI model and will not transmit any Layer 2 protocols through the VPN. TAP, which stands for Network TAP, operates at Layer 2 of the OSI model. It is capable of sending Layer 2 protocols through the VPN, but needs a bridge between the virtual network interface controller (NIC) and the physical NIC. If bridging mode is not used, then additional routing table entries are needed to route packets between the client and remote network [OpenVPN HOWTO].

Two transport protocols supported by OpenVPN are UDP and TCP. The performance of the VPN depends on the protocol used. UDP is a datagram packet which has less overhead and shares the same characteristics of IP. TCP, however, is a connection-based protocol which assumes an unreliable medium. Consequently, it has more overhead, and will encounter adverse effects from packet loss as described in Section 2.1.

Many ciphers are available in OpenVPN which uses the OpenSSL cryptographic library. For this factor, a comparison is being done between no encryption, and encryption using the Advanced Encryption Standard (AES) algorithm. This algorithm is recommended by the National Institute of Standards and Technology (NIST) federal agency for secure communications [NIST].

In low-throughput links, compression is a way to increase the overall throughput. The throughput achieved, however, is dependent on the workload. For this study, the performance is tested both with and without compression and for different workloads. Two workloads were chosen: text, and video. The text workload consists of highly compressible RFC documents and the video workload consists of uncompressible MPEG video.

The 2^{5-1} fractional factorial design for measuring the effects of each factor is shown in Table 4. The design is the equivalent of a 4 factor design, except that the ABCD interaction is replaced with factor E, the workload. The confounding effects for this design are shown in Table 5.

I	A	B	C	D	AB	AC	AD	BC	BD	CD	ABC	ABD	ACD	BCD	E
1	-1	-1	-1	-1	1	1	1	1	1	1	-1	-1	-1	-1	1
1	-1	-1	-1	1	1	1	-1	1	-1	-1	-1	1	1	1	-1
1	-1	-1	1	-1	1	-1	1	-1	1	-1	1	-1	1	1	-1
1	-1	-1	1	1	1	-1	-1	-1	-1	1	1	1	-1	-1	1
1	-1	1	-1	-1	-1	1	1	-1	-1	1	1	1	-1	1	-1
1	-1	1	-1	1	-1	1	-1	-1	1	-1	1	-1	1	-1	1
1	-1	1	1	-1	-1	-1	1	1	-1	-1	-1	1	1	-1	1
1	-1	1	1	1	-1	-1	-1	1	1	1	-1	-1	-1	1	-1
1	1	-1	-1	-1	-1	-1	-1	1	1	1	1	1	1	-1	-1
1	1	-1	-1	1	-1	-1	1	1	-1	-1	1	-1	-1	1	1
1	1	-1	1	-1	-1	1	-1	-1	1	-1	-1	1	-1	1	1
1	1	-1	1	1	-1	1	1	-1	-1	1	-1	-1	1	-1	-1
1	1	1	-1	-1	1	-1	-1	-1	-1	1	-1	-1	1	1	1
1	1	1	-1	1	1	-1	1	-1	1	-1	-1	1	-1	-1	-1
1	1	1	1	-1	1	1	-1	1	-1	-1	1	-1	-1	-1	-1
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Table 4: 2^{5-1} fractional factorial design; A = Interface, B = Protocol, C = Cipher, D = Compression, E =

Workload

I	A	B	C	D	AB	AC	AD
ABCDE	BCDE	ACDE	ABDE	ABCE	CDE	BDE	BCE
BC	**BD**	**CD**	**ABC**	**ABD**	**ACD**	**BCD**	**E**
ADE	ACE	ABE	DE	CE	BE	AE	ABCD

Table 5: Confounding effects of 2^{5-1} fractional factorial design

3.3 Experimental Results

The results of the 2^{5-1} fractional factorial design are presented in the section below. There are a few general observations that I made while running these tests. First, the CPU utilization of the router was always at 100% during these tests. This indicates that the router was consistently the bottleneck. The CPU utilization of the router was not reported because there was no mechanism for obtaining this information automatically from the router. Second, the CPU utilization of the client machine was always low, indicating that it was never the bottleneck.

The overhead of the VPN tunnel can be estimated empirically using the network activity information gathered by *sar* during the TCP test. The overhead is simply the difference in the throughputs of the physical and virtual network interfaces divided by the number of packets per second transmitted. The equation is shown as follows:

$$\text{overhead} = \frac{\text{physical network interface throughput} - \text{virtual network interface throughput}}{\text{packets per second}}$$

For each experiment in the TCP test, traffic was generated from the client to the server and multiple metrics were measured: bandwidth, link utilization, and CPU utilization. The results shown in Table 6 are the mean value of 5 replications. These results show that the link was highly underutilized and that the client CPU was not a bottleneck in these experiments.

The overhead was estimated only for experiments that did not involve compression since compression reduces the packet size in the physical interface. The results show the smallest overhead of 51 bytes for the UDP protocol without encryption. This number is an estimate of the overhead due to the encapsulation of packets in the VPN tunnel. It does not show the overhead due to headers in the payload itself. For Layer 3 VPNs, which use the TUN interface, the payload does not contain any Layer 2 header information which reduces the overhead by 14 bytes.

The largest bandwidth of 8.87 Mbps is measured for the TAP interface with bridging using the UDP transport protocol for the tunnel and no encryption. The bandwidth is cut to less than half to 3.70 Mbps when encryption using AES 256-bit is enabled.

					TCP Tests			
Interface	**Protocol**	**Cipher**	**Comp**	**Workload**	**Overhead (Bytes)**	**BW (Mbps)**	**Link %**	**Client CPU %**
TAP (br)	UDP	None	None	Video	51.0	8.87	1.20%	4.12%
TAP (br)	UDP	None	LZO	Text		8.02	0.70%	5.92%
TAP (br)	UDP	AES256	None	Text	100.0	3.64	0.51%	3.48%
TAP (br)	UDP	AES256	LZO	Video		3.70	0.52%	3.58%
TAP (br)	TCP	None	None	Text	76.5	6.17	0.85%	3.76%

TAP (br)	TCP	None	LZO	Video		6.27	0.87%	3.90%
TAP (br)	TCP	AES256	None	Video	127.5	3.26	0.47%	3.54%
TAP (br)	TCP	AES256	LZO	Text		3.83	0.36%	4.42%
TUN	UDP	None	None	Text	51.0	7.38	0.99%	3.30%
TUN	UDP	None	LZO	Video		7.32	0.98%	3.56%
TUN	UDP	AES256	None	Video	98.0	3.35	0.46%	3.16%
TUN	UDP	AES256	LZO	Text		3.66	0.33%	4.16%
TUN	TCP	None	None	Video	76.5	5.67	0.77%	3.28%
TUN	TCP	None	LZO	Text		6.11	0.53%	4.70%
TUN	TCP	AES256	None	Text	125.0	3.05	0.43%	3.30%
TUN	TCP	AES256	LZO	Video		3.00	0.42%	3.30%

Table 6: Client-to-server TCP test results for 2^{5-1} fractional factorial design; the values shown are the mean of 5 replicatons

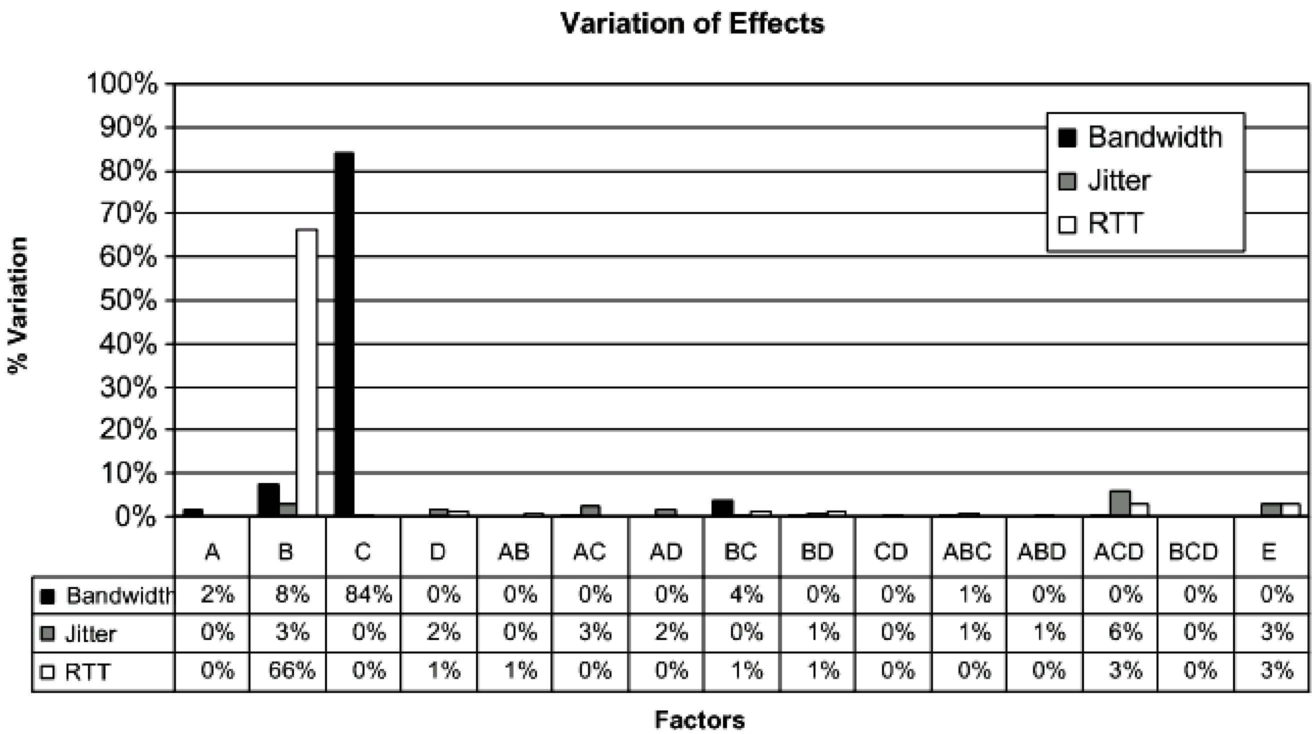
The UDP and latency test results are shown in Table 7. For both tests, the packet loss percentage is 0% indicating that no errors occurred in the VPN tunnel. The jitter measurement was done using large packets equal to the MTU size with a fixed UDP bandwidth of 1 Mbps. Although not shown, the jitter measurements were found to be sensitive to the UDP bandwidth and payload length, but not to the factors under test.

					UDP Tests		**Latency Tests**		
Interface	**Protocol**	**Cipher**	**Comp**	**Workload**	**Jitter (ms)**	**Loss %**	**RTT (ms)**	**Loss %**	**CPU %**
TAP (br)	UDP	None	None	Video	6.2	0.00%	1.3	0.00%	7.02%
TAP (br)	UDP	None	LZO	Text	6.2	0.00%	1.3	0.00%	6.62%
TAP (br)	UDP	AES256	None	Text	6.3	0.00%	2.3	0.00%	5.22%
TAP (br)	UDP	AES256	LZO	Video	6.3	0.00%	2.2	0.00%	5.34%
TAP (br)	TCP	None	None	Text	6.5	0.00%	15.1	0.00%	0.40%
TAP (br)	TCP	None	LZO	Video	6.1	0.00%	12.7	0.00%	0.76%
TAP (br)	TCP	AES256	None	Video	6.3	0.00%	7.9	0.00%	2.34%
TAP (br)	TCP	AES256	LZO	Text	6.6	0.00%	14.9	0.00%	0.52%
TUN	UDP	None	None	Text	6.2	0.00%	1.9	0.00%	5.14%
TUN	UDP	None	LZO	Video	6.4	0.00%	1.9	0.00%	5.04%
TUN	UDP	AES256	None	Video	6.3	0.00%	2.8	0.00%	4.10%
TUN	UDP	AES256	LZO	Text	6.2	0.00%	2.8	0.00%	4.20%
TUN	TCP	None	None	Video	6.2	0.00%	8.4	0.00%	1.50%
TUN	TCP	None	LZO	Text	7.0	0.00%	15.1	0.00%	0.50%
TUN	TCP	AES256	None	Text	6.3	0.00%	11.2	0.00%	1.84%
TUN	TCP	AES256	LZO	Video	6.3	0.00%	10.5	0.00%	0.82%

Table 7: UDP and latency test results for 2^{5-1} fractional factorial design; the values shown are the mean of 5 replications

Using the analysis technique described for a 2^{k-p} fractional factorial design, the effects and the percent variation were calculated [Jain91]. The percent variation of the effects is shown in Figure 3. 84% of the bandwidth is explained by encryption cipher (C). Another 8% is explained by the transport protocol (B). There is a small 4% interaction (BC) between the encryption cipher and the transport protocol of the bandwidth.

The jitter is not explained very well by the model and is relatively independent of the changes in the factors. The percent variation in the round-trip time (RTT) is 66% for the transport protocol. Another 3% is explained by the interaction (BE) between the transport protocol and the workload which is confounded with interaction ACD.



	A	B	C	D	AB	AC	AD	BC	BD	CD	ABC	ABD	ACD	BCD	E
Bandwidth	2%	8%	84%	0%	0%	0%	0%	4%	0%	0%	1%	0%	0%	0%	0%
Jitter	0%	3%	0%	2%	0%	3%	2%	0%	1%	0%	1%	1%	6%	0%	3%
RTT	0%	66%	0%	1%	1%	0%	0%	1%	1%	0%	0%	0%	3%	0%	3%

Figure 3: Variation of effects for 2^{5-1} fractional factorial design

3.4 Future Work

The tests performed in the 2^{k-p} fractional factorial design should be extended to include server-to-client tests, and simultaneous bidirectional traffic tests. Although it is possible to get this information, it is not easy to do this in an automatic way, and will require extension of the test script. The design should also be extended to include other factors that will potentially affect the performance of the VPN such as payload length, encryption key size, encryption digest, TLS digest, etc. Using the results from the 2^{k-p} fractional factorial design, a one or two factor design should be done to analyze the effects of the most sensitive factors such as the transport protocol and encryption. The test bed can also be expanded for testing a site-to-site VPN topology involving two routers. Last, the effects of communication with multiple clients should also be tested.

In addition to these tests, the results should be verified using another evaluation technique such as analytical modeling. Some of the contributions of the overhead were modeled in this paper, but this work needs to be expanded to explain changes in performance as well. This will allow us to understand how each of these factors affects the performance and why.

4 Summary

The Linksys WRT54GL router is an inexpensive router that can easily be upgraded for extended functionality using an open-source Linux firmware called DD-WRT. This allows a VPN package such as OpenVPN to be set up to allow remote access to the internal network. OpenVPN is a flexible, cross-platform solution that is highly configurable and fairly easy to set up using available tutorials.

The performance of OpenVPN depends on the router hardware, and the configuration parameters. The throughput was found to be limited by the router CPU, and is not sufficient for fast connections such as 10/100 Mbps LANs. It is sufficient for slower connections such as most Internet connections. Measurements were presented for traffic generated from client to server. The encryption cipher was found to significantly reduce total throughput. For a configuration using the TAP interface with bridging, UDP transport protocol, AES256 cipher, and no compression, the throughput was 3.64 Mbps. 96% of the variation in the throughput was explained by the transport protocol, encryption cipher, and the interaction between the two; the encryption cipher explained the majority (84%) of the variation. The jitter in the latency was found to be relatively insensitive to the factors tested at around 6.3 ms. The round-trip time (RTT) was significantly larger for the TCP transport protocol explaining 66% of the variation. The next significant factor was the workload (3%), followed by the interaction between the workload and the encryption cipher (3%). This interaction is confounded with the interaction between the interface, cipher, and compression factors. For the same configuration above, the average RTT was 2.3 ms.

Although the encryption cipher accounted for the majority of the variation in the throughput, it is an important feature in VPNs. Future work is to investigate effects of different encryption algorithms with varying key sizes on the throughput that are still considered strong. One criterion for choosing an encryption algorithm is whether or not it is acceptable for use in ecommerce.

In conclusion, the Linksys WRT54GL router provides a cost-effective solution for setting up an OpenVPN server for remote access over the Internet. This solution is throughput-limited, but should be sufficient for most Internet connections. It is an appropriate solution for most home users and small businesses depending on their needs.

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List of Acronyms

Acronym	Definition
3DES	Triple DES
AES	Advanced Encryption Standard
CBC	Cipher Block Chaining
CPU	Central Processing Unit
DES	Data Encryption Standard
DNS	Domain Name System
GPL	General Public License
ICMP	Internet Control Message Protocol
IP	Internet Protocol
LZO	Lempel-Ziv-Oberhumer
MAC	Medium Access Control
MMC	MultiMediaCard
MPEG	Moving Picture Experts Group
NIC	Network Interface Controller
NIST	National Institute of Standards and Technology
OSI	Open Systems Interconnection
RAM	Random Access Memory
RFC	Request for Comments
RTT	Round-Trip Time
SD	SecureDigital
SSL	Secure Socket Layer
SUT	System Under Test
TAP	Network TAP
TCP	Transport Control Protocol
TLS	Transport Layer Security

TUN	Network TUNnel
UDP	User Datagram Protocol
VoIP	Voice over Internet Protocol
VPN	Virtual Private Network

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