

# A Powerful IPsec Multi-Tunnels Architecture

Abdulellah A. Alsaheel and Ahmad S. Almogren

**Abstract**—This paper aims to introduce IPsec protocol, including its architecture, protocols family and implementations. We propose a performance evaluation setup which allows IPsec implementers to evaluate their IPsec implementation. IPsec as it is known as a set of protocols that work together, with utilizing multiple components in the IPsec architecture to serve one purpose, which is securing the internet Protocol (IP) packets. Security services provided by IPsec in general include: confidentiality, integrity check and authenticity of the data. Since measuring the performance can vary and this variation would end up in inconsistent measuring. This paper represents a good methodology to test IPsec performance and introduces a powerful IPsec architecture that utilizes multi-tunnels.

**Index Terms**—IPsec, StrongSwan, IKE, styling, insert.

## I. INTRODUCTION

In Internet Protocol Security (IPsec), users can communicate through public networks such as internet with having their connection secure. This secure IPsec tunnel can be built between host-to-host or between site-to-site, that tunnel is a one kind of Virtual Private Networks (VPN) as the name suggests, Virtual because it is a tunnel that has been constructed by using multiple hops along a public network such as internet; it is Private since encryption has been used which transfers that data from being public data into private data even though it is transferred through a public medium; and well, it is Networks because it is working as a topology of interconnected computers that may constitute a huge networks or network of networks. Not only IPsec, but many other protocols can build a VPN. Widely accepted and widely used protocols such as Secure Sockets Layer (SSL), Transport Layer Security (TLS) and Secure Shell (SSH). Big difference between these protocols and between IPsec, is that IPsec operates at the third layer at TCP/IP stack which known as Network Layer whereas the other protocols operates at the fourth and the fifth layer Transport Layer and Applications Layer in the TCP/IP stack. The paper is organized as follows: first, we talk about the standard IPsec architecture in Section II. In Section III, we talk about the IPsec implementation. In Section IV, we show the authentication header. Strong Swan is illustrated in Section V. In Section VI, a performance evaluation is shown. Related work is presented in Section VII. IPsec multi-tunnels architecture is depicted in Section VIII. Finally, we talk about the conclusions and the future work in Section IX.

Manuscript received January 23, 2014; revised April 24, 2014. This work was supported in part by King Saud University, Department of Computer Science, Saudi Arabia.

The authors are with the Department of Computer Science, King Saud University, Saudi Arabia (e-mail: cs\_saheel@hotmail.com, ahalmogren@ksu.edu.sa).

## II. IPSEC ARCHITECTURE

Speaking of IPsec architecture involves listing all of the components that contained in IPsec specification. As IETF has provided 12 RFC documents for IPsec protocol, there is RFC4301 specifies IPsec architecture. Fig. 1 illustrates the major components that need to be implemented by IPsec implementations.

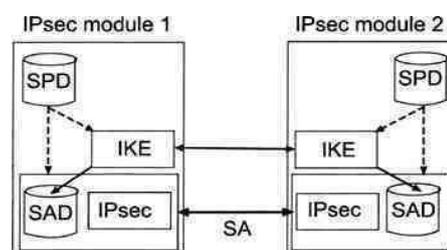


Fig. 1. IPsec standard architecture.

The Security Policy Payload database (SPD): responsible of policies storing, every IP packet need to be compared against the policy and finally it responsible of specifying what action need to be applied on each packet.

The Security Association Database (SAD): responsible of storing algorithms, it has a link with the policy and usually this happens by operating system defined interface such as XFRM interface in Linux systems; if the action specified by the policy was to deal with the packet as IPsec packet then SAD will be responsible of specifying how to deal with the packet.

Internet Key Exchange (IKE) component is responsible for the automatic keying. Since IPsec can operate either with manual or automatic keying; this component is also responsible for generating the security associations SA by utilizing IKE protocol between two parties known as Initiator and Responder.

SA generated by IKE component has specified the key, encryption algorithm, hashing algorithm, and the other party information such as IP address and port number. Before IKE takes place, ISAKMP (Internet security Association for key and management protocol) will be used to initiate an authenticated channel that used by IKE afterward, unlike ISAKMP the IKE protocol use encryption to preserve data confidentiality. IKE is not limited to IPsec protocol, it can be used with any other protocol if the protocol parameters have been specified, for IPsec there is IPsec domain of interpretation document, this document should be considered at IKE implementation to specify what parameters need to be negotiated by IPsec protocol.

After establishing IKE tunnel IPsec should take place, the required parameters for using IPsec will comes from IKE, such as keys and other parameters. Key exchange methods such as Diffie Hellman will be initialized by IKE protocol to be used by IPsec protocol. Last component which is IPsec

base protocol, which is responsible for handling outbound and inbound IPsec packets, this component takes place in the TCP/IP stack and usually it has a user interface that used to control or to monitor the IPsec implementation. IPsec base protocol component implements two protocols Authentication header (AH) and Encapsulated Security Payload (ESP). AH protocol provides data authenticity and integrity. On the other hand ESP provides data encryption and authenticity and integrity as optional. Sometimes AH is used to protect ESP, this approach will offer ultimate data integrity since AH is unlike of ESP is calculating the Integrity Checking Value (ICV) with considering the IP header whereas ESP consider its header and the IP payload only.

### III. IPSEC IMPLEMENTATION

IPsec has two forms of implementation. Either it is implemented in host machine or in a gateway router, each of which has its own advantages. The host implementation [1] guarantees end to end protection, implement tunnel and transport IPsec modes, protection is per flow where each flow will be protected as specified in the policy. Host implementation is classified as native or shim. As the native is natively integrated with the host operating system and it comes bundled at the TCP/IP stack, where on the other hand there is shim implementation which is added by IPsec implementers into the TCP/IP stack between the network layer and the data link layer, this usually known as Bump In the Stack (BITS). As the native implementation has numerous advantages over the shim implementation since it can utilize network services such as path maximum transfer unit (PMTU), fragmentation and many other services provided by network layer. On the other hand shim implementation need add its own services which mean increasing implementation complexity and duplication of already implemented services in the network layer.

For gateway routers implementation they utilize tunneling mode only since many hosts behind them transferring data to the remote site. Same as host implementation, router implementation can be either native implementation means the IPsec implementation is natively implemented in the TCP/IP stack of the router. The other type of the router implementation is Bump In The Wire (BITW) which is similar to the bump in the stack, BITW is a hardware implementation that attached to the router interface responsible for applying IPsec services on the routed packets.

Possible performance improvements for IPsec implementations is to use hardware approaches to improve IPsec performance, such as using dedicated chip for generating keys or random numbers, or to use special hardware for calculating hash values or to encrypt or decrypt data.

### IV. AUTHENTICATION HEADER

In addition to data authenticity and integrity, AH provides replay protection. It places its header between IP header and IP payload. AH uses Hash Message Authentication Code (HMAC) to enforce its protection. Encapsulated Security

Payload (ESP) protects packets by applying encryption, authentication and optionally data integrity if a trailer gets added at the end of the packet, which utilizes HMAC calculations. Its header gets placed between the IP header and the IP payload.

### V. STRONGSWAN

StrongSwan is one of the most prominent IPsec implementations, extra credits for StrongSwan over other IPsec implementation such as OpenSwan, FreeS/Wan and KAME-Tools. Is that StrongSwan is widely adapted in different Linux distributions, and it is up to this date receives new releases. It has many plug-ins and it is well documented. StrongSwan requires enabling some kernel options which are [2]:

```
[CONFIG_XFRM_USER],[CONFIG_NET_KEY],
[CONFIG_INET],[CONFIG_IP_ADVANCED_ROUTER],
[CONFIG_IP_MULTIPLE_TABLES],[CONFIG_INET_A
H],[CONFIG_INET_ESP],[CONFIG_INET_IPCOMP],
[CONFIG_INET_XFRM_MODE_TRANSPORT],
[CONFIG_INET_XFRM_MODE_TUNNEL],
[CONFIG_INET_XFRM_MODE_BEET],
[CONFIG_NETFILTER_XTABLES],
[CONFIG_NETFILTER_XT_MATCH_POLICY].
```

StrongSwan has a set of tools and libraries that constitute its architecture, StrongSwan components are listed as follows [3]:

- 1) charon: component that implements IKE protocol keying.
- 2) libstrongswan: the base component that provide the basic functions used by the tool.
- 3) libcharon: provide the main functions for IKE to be used by charon component.
- 4) libhydra: provide daemon services for charon tool.
- 5) dumm: testing framework.
- 6) ipsec: command line interface that let user control and monitor IPsec functions.
- 7) manager: web interface to control and monitor charon by using libfast.
- 8) libfast: framework to build web applications, this to provide web interface that control and monitor StrongSwan.
- 9) openac: tool to generate certificates attributes.
- 10) pki: public key infrastructure tool.
- 11) sceclient: client that implements SCEP protocol that check the certificates enrollment.
- 12) starter: responsible for handling ipsec.conf file and of the keying process.
- 13) stroke: command line tool that controls charon through stroke protocol.

#### A. IPsec Architecture at StrongSwan

StrongSwan uses Iptables as implementation for Security Policy Database (SPD). And uses charon for implementing IKE component. The architecture is separated into two different levels, user level and kernel level. With having charon daemon working at the user level to control and

manage Security Associations (SAs) on the use demand. And it has the kernel level where NETKEY utilized, which typically deals with encryption and decryption, re-keying and SAs. The IPsec architecture is illustrated at Fig. 2.

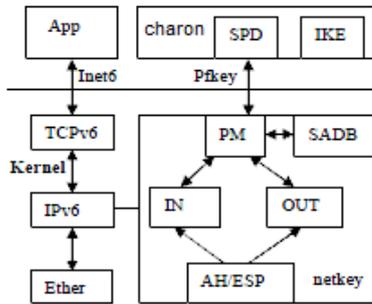


Fig. 2. StrongSwan architecture.

As the majority of IPsec implementations, StrongSwan uses virtual interface to deal with IPsec packets, there is no difference between the virtual interface [4] and the physical interface except that the virtual interface cannot send data to the public networks, in Linux systems this usually referred to as TUN/TAP. For IPsec packets first it needs to be processed by the virtual interface then it needs to be send back to the physical interface to be treated as normal IP packet.

VI. STRONG SWAN PERFORMANCE EVALUATION

As we have tested StrongSwan v5.1.1 on Ubuntu linux distribution. Our network topology is consisted of four machines two of them act as IPsec gateways for their internal networks (i.e. site-to-site network), and the other two machines are acting like client and server with transferring a file over HTTP and FTP protocols as depicted in Fig. 3.

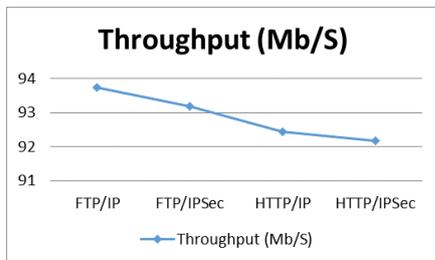


Fig. 3. Throughput vs. protocols.

That can be said, IPsec traffic which is managed by StrongSwan comes with nearly the same throughput as the IP traffic, and this is absolutely very good result.

A. Overall Performance Evaluation

Since IPsec suite has many components and many protocols, it has to be tested by multiple tests that capable to evaluate each IPsec component that may lead to performance improvement or degradation.

Not only that, but find an agreed on methodology for measuring IPsec performance leads to more precise results that let users can compare between different vendors, and it helps the vendors to compare their products against other products in the market.

Test setup can have different forms, depends on the desired network topology at the deployment time. But having fixed criteria is what we are aiming for. One possible test setup for

site to site topology is depicted in Fig. 4.

As you can see Device-Under-Test (DUT), with having IP traffic generator the generate traffic to be sent to DUT2 through DUT1, where DUT1 will encrypts the traffic and DUT2 will decrypts it. On the other side there is the traffic analyzer that checks the sanity of the IPsec packets to see whether if DUT1 and DUT2 had encrypted and decrypted the data correctly or not.

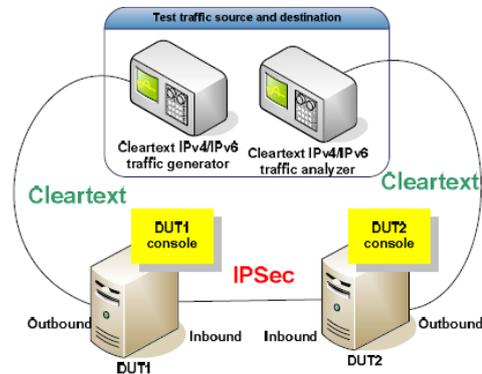


Fig. 4. Performance evaluation setup.

A popular criteria which is widely accepted and used is specified in the Table I [5].

TABLE I: PERFORMANCE EVALUATION CRITERIAS

Criteria	Metric
IPsec throughput ESP (tunnel/transport)	B/Sec
IP throughput TCP/UDP	B/Sec
IP + IPsec throughput, ESP (transport/tunnel)	B/Sec
Policy and Security Association adding and removing time	Number of policies and security associations added and removed/Sec
IPsec events (e.g. no valid SA)	Number of handled events/Sec
SAs rekeying	Number of rekeyed SAs/Sec

VII. RELATED WORKS

As [6] proposed a distributed object-based multiple tunnels IPsec architecture that utilizing AgentNodes which are physical machines that report to a console (server), inside of each AgentNode there is a set of defined objects (C++ objects) that interacts across different AgentNodes in a distributed way. Each object represents a TunnelStack which composes an IPsec tunnel (Inbound and Outbound SAs), each TunnelStack object has its own virtual IP Address, also TunnelStack object has full TCP/IP stack that capable of processing: data link, IP and transport layers. Additionally, they use AgentController that responsible for organizing the dispatching process for the sent or received packets across the TunnelStacks. Their work uses shared buffers (queues) accessible from the AgentController and the TunnelStacks, the received packets queue is get filled by using libpcap library that uses a capture thread, AgentController is responsible for re-dispatch the received packet to the corresponding TunnelStack based on the de-capsulated virtual IP address, on the other hand the sending queue is get filled by the TunnelStack objects, libpcap capture thread will captures the sending packets and will place these packets into

the network interface card. While they have proposed a complete concurrent architecture that utilizes multiple IPSec stacks inside each AgentNode but this comes with high complexities which impacts the performance and result in losing the efficiency, they have implemented several inappropriate design choices which have led to sacrificing the efficiency and the compatibility with standard IPSec implementations. Having the architecture components at the user space area as they did with the AgentController and the TunnelStacks result in high context switch rates between user space and kernel space which lead to performance deficiency and extensive the processing power. Also, their design lead to duplicating the TCP/IP stack and it happened by implementing the TunnelStack objects and each of which is a full TCP/IP stack this comes with implementation complexity and code duplication. Also they use libpcap library to capture sent and received packets by TunnelStack objects, libpcap has a negativity to be implemented in this scenario, since libpcap is just duplicating the packet, so the duplicated packet will be dispatched to the corresponding TunnelStack by the AgentController but still the main packet which has been received on the physical interface will be processed and will complete its decapsulation process up to reaching a certain layer that the TCP/IP stack knows it cannot handle this packet and the packet will be thrown after being processed. In conclusion, their contribution result in code duplication, high context switches between user and kernel space and it sacrifices the compatibility with the standard IPSec implementations.

As [7] have proposed another architecture that utilizes an approach that uses caching data segments, they have introduced IPSec Thumbnail Protocol (ITP) which capable of encapsulating and compressing IP packets with defining its own packets format. Their work based on the fact that many data is being sent repeatedly, their target is to eliminate sending redundant data. They slicing the data payload at application layer, each data segments (slices) comes in specified length, the sender should calculate the digest (hash value) for each segment, a list of data segments and their digests will compose a thumbnail, the sender will cache the data segments and their associated digests at the Data Segment Cache Base (DSCB), the receiver on its behalf will decapsulate the thumbnail packet and will extract the data segments and it will cache them at its DSCB, the next time that one machine wants to send a data segments, for each segment it will calculate the digest for the corresponding segment and then it will check the DSCB if the digest is present then the segment will not be placed in the thumbnail packet, instead of that only the digest will be placed assuming that the receiver has the same segment at his DSCB, if the receiver does not have that segment of data, an ITP data request will be sent to the sender which will be required to respond with an ITP data delivery. Their work efficiency is highly related to the data segments length, if the data segments length is too large then it is likelihood that cache hit will rarely present, and if the length is too small then it is likelihood it will has more cache hits but it will has more digests calculations for each packet, caching buffer (DSCP) will be filled faster and also for the additional header which has been added because of the thumbnail packet may has the same

length of the data segment and this may end up with no improvement at all, this to state that specifying the data segment length is critical in their work, they have decided to use 256 bytes as data segment but it is not efficient to have a fixed data segment size, since each type of application will requires a different data segment size to have a high cache hits, as example in case of sending a file over File Transfer Protocol (FTP) with 256 bytes as data segment length it is likelihood that no two blocks of that file or any other file will have the identical digest, but in case of Secure Shell (SSH), Telnet or Hypertext Transfer Protocol (HTTP) this may work. Since they are using special packets format (thumbnail), their approach is sacrificing the compatibility with standard IPSec implementations. In case of a sender sent a thumbnail packets which include some digests that the sender assumes the receiver already have them while the receiver does not, for each thumbnail packet the receiver will send a data request packet with the corresponding missed data segments, additionally the receiver needs to store them till the data delivery packet which has the missed data segment comes from the sender, if many packets that have missed data segments arrived, then the receiver buffer can be overwhelmed by the buffered thumbnail packets that await their data segments to come from the sender.

#### VIII. IPSEC MULTI-TUNNELS ARCHITECTURE

Our novel approach is proposing a real concurrent IPSec architecture, as there are many other related works that delivered type of improvement through proposing new IPSec architecture [8], our IPSec architecture uniquely utilizes multi-tunnels between IPSec devices; this without negotiation should result in performance improvement. As opposed to [6] and [7] our approach does not sacrifice the compatibility means it will works smoothly with standard IPSec implementations. IPSec in normal situations establishing a pair of tunnels between two parties, each pair of two tunnels and each tunnel is associated with a SA, the ESP and AH headers are responsible to carry out the SA id at each IPSec packet, the SA id is known as Security Parameter Index (SPI), SPI is enough to specify the SA but usually IPSec implementations use SPI and IP source and destination address to retrieve the corresponding SA from the SA database in order to apply the security services on network packets. Our approach is taking advantage of establishing two or more pairs of SAs instead of one pair of SAs, if the two parties have implemented our IPSec architecture then at least there will be three pairs of SAs, since the in addition to the main (standard) pair of SAs the initiator will establish its duplicated pair of SAs, and the responder may do the same if it has implemented our approach too, if only one party (either initiator or responder) has implemented our approach then there will be only two pairs of SAs. As opposed to [6] who have implemented duplicated TCP/IP stacks at each machine, our approach is using one TCP/IP stack.

As it is shown in Fig. 5, our architecture has fully implemented at kernel level which does not increase the context switches between user and kernel levels. Whenever a host wants to establish a pair of SAs with remote party, the

IPSec tunnel establishing process should go through the SAs-Controller which is responsible of delivering two IKE negotiations [9] with the remote host, instead of the standard IPSec procedure which establish only one pair of SAs.

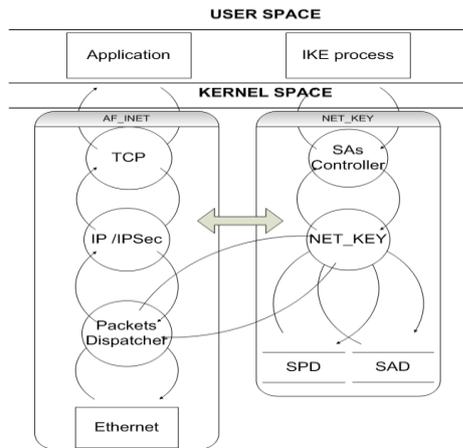


Fig. 5. IPSec multi-tunnels architecture.

The implementation will always consider establishing two pairs of SAs (two IKE negotiations) no matter if the local host was an IKE initiator or responder, in the case of being a responder it will re-act as an initiator to establish the additional tunnel. The second major component is *Packets Dispatcher* which is responsible of placing the IPSec packets into the corresponding tunnels that reach the specified remote host, the packets dispatcher will choose the best tunnel in a way that guarantees that all the established tunnels will be utilized effectively, each established tunnel has a queue that holds IPSec packets, *Packets Dispatcher* is responsible of specifying the SPI of the chosen tunnel which might be retrieved by querying SAD database, it is essential to balance the IPSec packets across the established tunnels evenly.

## IX. CONCLUSION

We have covered the main aspects of IPSec protocol, including its relationship with other protocols such as Internet Key Exchange (IKE) and ISAKMP. We have identified IPSec architecture which includes the main components such as Security Associations Database (SAD) and Security Policy Database (SPD). We have introduces its protocols AH and ESP and their differences. We have seen how IPSec implementation can be adopted into the TCP/IP stack in two forms as native or shim. We have digged into StrongSwan one of the best IPSec implementation at Linux systems. We have introduced consistent criteria to evaluate IPSec implementations. We have reviewed two proposed IPSec architectures and we have listed their pros and cons, IPSec architecture performance improvement should eliminate implementing components at user space since this will lead to high context switches rate between user and kernel space since IPSec itself is implemented at kernel space, the reviewed architectures sacrifice the compatibility with standard IPSec implementations, using caching mechanisms may improve IPSec performance but the data segment length is critical these types of approaches and the data segment length should be determined based on the type of the

application that is being sent. Finally we have introduced our IPSec multi-tunnels approach that establishes more than one pair of SAs tunnels, and we presented the architecture components that responsible for establishing the additional tunnel and the component that responsible for balance the data across the established tunnels, our architecture is fully implementable at kernel level which will eliminate increasing the context switches, and as opposed to the other works it does not sacrifice the compatibility with IPSec standard implementations.

## REFERENCES

- [1] H. Dhall, D. Dhall, S. Batra, and P. Rani, "Implementation of IPSec protocol," in *Proc. Second International Conference on Advanced Computing & Communication Technologies*, 2012, pp. 176-181.
- [2] Required kernel modules. (Oct. 2013). [Online]. Available: <http://wiki.strongswan.org/projects/strongswan/wiki/KernelModules>
- [3] StrongSwan developer documentation. (Oct. 2013). [Online]. Available: <http://wiki.strongswan.org/projects/strongswan/wiki/DeveloperDocumentation>
- [4] L. Liu and W. Gao, "Building IPSec VPN in IPv6 based on openswan," in *Proc. IFIP International Conference on Network and Parallel Computing Workshops*, 2007, pp. 784-787.
- [5] M. Barylski, "On IPSec performance testing of IPv4/IPv6 IPSec gateway," in *Proc. IT 2008 1st International Conference on Information Technology*, 2008, pp. 1-4.
- [6] S. Wang and H. Lv, "A distributed object-based IPSec multi-tunnels concurrent architecture," in *Proc. 2011 International Conference on Computational Problem-Solving (ICCP)*, 2011, pp. 471-476.
- [7] Y. Zhang, Z. Li, S. Mei, L. Xiao, and M. Wang, "A new approach for accelerating IPSec communication," in *Proc. International Conference on Multimedia Information Networking and Security*, 2009, pp. 482-485.
- [8] M. Fahandezh, M. Bondy, and S. Erfani, "A framework for implementing IPSec functional architecture," in *Proc. Canadian Conference on Electrical and Computer Engineering*, 2009, pp. 71-76.
- [9] L. Yu, S. Jia, C. Xu, J. Guan, and D. Gao, "An IPsec seamless switching mechanism with high availability and scalability by extending IKEv2 protocol," in *Proc. 2011 International Conference on Advanced Intelligence and Awareness Internet*, 2011, pp. 25-29.



**Abdulallah A. Alsaheel** was born in Saudi Arabia, Riyadh on August 29, 1987. He received a bachelor degree in computer science from Imam Mohammed Bin Saud University in Saudi Arabia, in 2011. Currently he is pursuing his master degree in computer science at King Saud University in Saudi Arabia.

He is a software developer at Ministry of Defense in Kingdom of Saudi Arabia. His research interests include network security, software vulnerability and

malware analysis.

Mr. Alsaheel has been awarded at different competitions. He has achieved the first prize in "the first scientific conference" in Al-Imam University, by participating with his research about the honeypots and improving Snort. He has achieved the first prize in the "best information security graduation project" competition at King Saud University-COEIA competition. He has participated "Google Summer of Code" -GSOC- and passed the program successfully by improving "Cuckoo Sandbox" of honeynet.org.

**Ahmad Al-Mogren** obtained his PhD degree in computer sciences and telecommunications from Southern Methodist University, Dallas, Texas, USA in 2002. Previously, he worked as an assistant professor of computer science and the head of the Scientific Council at Riyadh College of Technology. He also served as the dean of Computer College and the head of the Council of Academic Accreditation at Al Yamamah University. Presently, he works as the vice dean for Quality and Development at King Saud University in Saudi Arabia. He has taught several courses such as computer networks, mobile computing, databases, digital communication, clustering and fault tolerance. His research areas of interest include networking and data consistency.