A survey on the Performance Optimization in Wireless Sensor Networks using Cross Layer Approach

Piyush Charan, Rajeev Paulus, Mukesh Kumar, Arvind Kumar Jaiswal

ECE DEPARTMENT, SHIATS-DU, ALLAHABAD-211007, INDIA

Abstract- The performance of Wireless Mesh Networks is not optimal by using the conventional layered protocols (TCP-IP). Then the method of optimization at different layers of the protocol stack (TCP-IP) can help to achieve optimal network performance. This method usually results in a clean-slate protocol architecture that is different from the protocol architecture of WMNs. Such a difference actually demonstrates the need for a cross-layer design. Specific features pertaining to WMNs also show the need for cross-layer optimization across different protocol layers. In this paper, the need for cross layer design in WMNs is discussed first. Later in this paper we will discuss the different cross layer optimization schemes and algorithms between different protocol layers are discussed.

Index Terms- Cross Layer Optimization, Wireless Mesh Networks (WMNs), TCP-IP, Routing

I. INTRODUCTION

Wireless Sensor Networks are one of the most promising and a discussed technology in the last decade is the wireless technology which allows users to utilize devices that enable the access to information at any time any place. Wireless networks are comprised of devices that communicate through media such as radio signals and infra-red, and they are generally classified into two categories: infrastructure-based and ad-hoc wireless networks.

- **Infrastructure-based wireless network** consists of base stations localized in convenient places, which provide wireless connectivity to devices within their coverage area. Examples of this category are Wireless Local Area Networks (WLANs) and cellular networks. A WLAN is a flexible data communication system implemented as an extension to a wired LAN within a building or campus.

- **Wireless ad-hoc networks** do not have a pre-established infrastructure. Moreover, nodes connect to each other through automatic configuration when they are in transmission range and willing to forward data for other nodes. In this way, an ad hoc wireless network is formed which is both flexible and powerful.

1.1 Wireless ad-hoc Networks

Wireless ad-hoc networks can be further classified into the following different categories according to their applications

- Mobile ad-hoc Networks (MANETS)
- Wireless Sensor Networks (WSNs)
- Wireless Mesh Networks (WMNs)
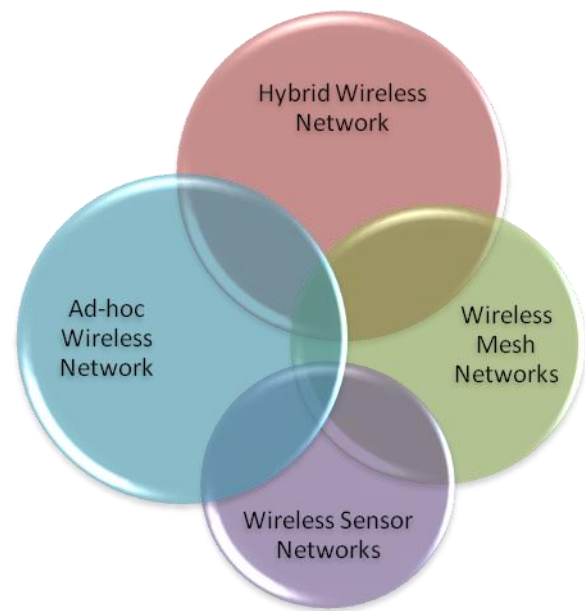- Hybrid Wireless Networks

Fig: 1 Wireless Networks Classification

1.1.1 Mobile Ad-hoc Networks

The MANETs includes devices that are mobile nodes which provide the functionality required to connect users allowing them to exchange information in an environment with no pre-established infrastructure. Therefore, MANET is an infrastructure-less network with highly dynamic topology. Devices are free to move randomly and organize themselves arbitrarily; thus, the wireless network topology may change quickly and is unpredictable.

1.1.2 Wireless Sensor Networks

Wireless sensor networks are formed by spatially distributed tiny sensor nodes that cooperatively can gather and monitor physical parameters or environmental conditions and transmit to a central monitoring node. In addition, sensor nodes are equipped with a

radio transceiver or other wireless communication device, a small microcontroller, and usually a battery as an energy source.

1.1.3 Wireless Mesh Networks

The Wireless Mesh Network (WMN) is a highly promising technology and it plays an important role in the next generation wireless mobile network. WMNs have emerged as important architectures for the future wireless communications.
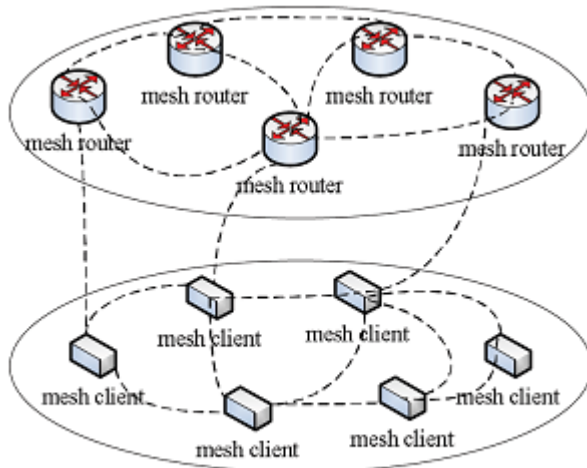

Fig: 2 Wireless Mesh Networks

1.1.4 Hybrid Wireless Networks

The Hybrid wireless network is an ad hoc wireless network that contains a sparse wired network of base stations. The resulting network comprises regular nodes and wired connected base stations. In this way, we could have a traditional cellular network and an ad hoc network mixed together.

II. BACKGROUND AND RELATED WORKS

Cross Layer Optimization- Motivation

Why does the presence of wireless links in the network motivate designers to violate the layered architectures? There are three main reasons: the unique problems created by wireless links, the possibility of opportunistic communication on wireless links, and the new modalities of communication offered by the wireless medium [2]. On the other side, wireless links create several new problems for protocol design that cannot be handled well in the framework of the layered architectures. The classic case of a TCP sender mistaking a packet error on a wireless link to be an indicator of network congestion is an example [3]. Whereas on the contrary, wireless networks offer several avenues for opportunistic communication that cannot be exploited sufficiently in a strictly layered design. For instance, the time-varying link quality allows opportunistic usage of the channel [4], whereby the transmission parameters can be dynamically adjusted according to the variations in the channel quality, just to name one example. Additionally, the wireless medium offers some new modalities of communication the layered architectures do not accommodate. For instance, the physical layer can be

made capable of receiving multiple packets [5] at the same time. The nodes can also make use of the broadcast nature of the channel and cooperate with one another in involved ways.

2.1 Different cross layer design approaches

Today there exists many cross-layer design proposals but the authors in [6] present a survey of several cross-layer design proposals from the literature based on the layers that are coupled. Here, we are more interested in *how* the layers are coupled, in other words, what kind of architecture violation has taken place in a particular cross-layer design. We note that the layered architecture can be violated in the following basic ways:
• Creation of new interfaces (Figs. 3A-C)
• Merging of adjacent layers (Fig. 3D)
• Design coupling without new interfaces
(Fig. 3E)
• Vertical calibration across layers (Fig. 3F)

We find that most cross-layer design proposals in the literature fit into one of these basic categories. We shall now discuss the aforementioned four categories in more detail and point out some relevant examples.

2.1.1 Upward Information Flow

A higher-layer protocol that requires some information from the lower layer(s) at runtime results in the creation of a new interface from the lower layer(s) to the higher layer, as shown in Fig. 3A. Suppose, if the end-to-end TCP path contains a wireless link, errors on the wireless link can trick the TCP sender into making erroneous inferences about the congestion in the network, and as a result the performance deteriorates. Creating interfaces from the lower layers to the transport layer to enable explicit notifications alleviates such situations. For example, the explicit congestion notification (ECN) from the router to the transport layer at the TCP sender can explicitly tell the TCP sender if there is congestion in the network to enable it to differentiate between errors on the wireless link and network congestion [3].
Examples of similar upward information flow are also seen in the literature at the MAC layer (data link layer in general) in form of channel-adaptive modulation or link adaptation schemes [4].
The idea is to adapt the parameters of the transmission (e.g., power, modulation, code rate) in response to the channel condition, which is made known to the MAC layer (link layer) by an interface from the physical.

2.1.2 Downward Information Flow

Some crosslayer design proposals rely on setting parameters on the lower layer of the stack at runtime using a direct interface from some higher layer, as illustrated in Fig. 3B. For example, applications can inform the link layer about their delay requirements, and the link layer can then treat packets from delay-sensitive applications with priority [7].
A better way to look at the upward and downward information flow is to treat them as notifications and hints, respectively, as proposed in [8]. Upward information flow serves the purpose of notifying the higher layers about the underlying network

conditions; downward information flow is meant to provide hints to the lower layers about how the application data should be processed.
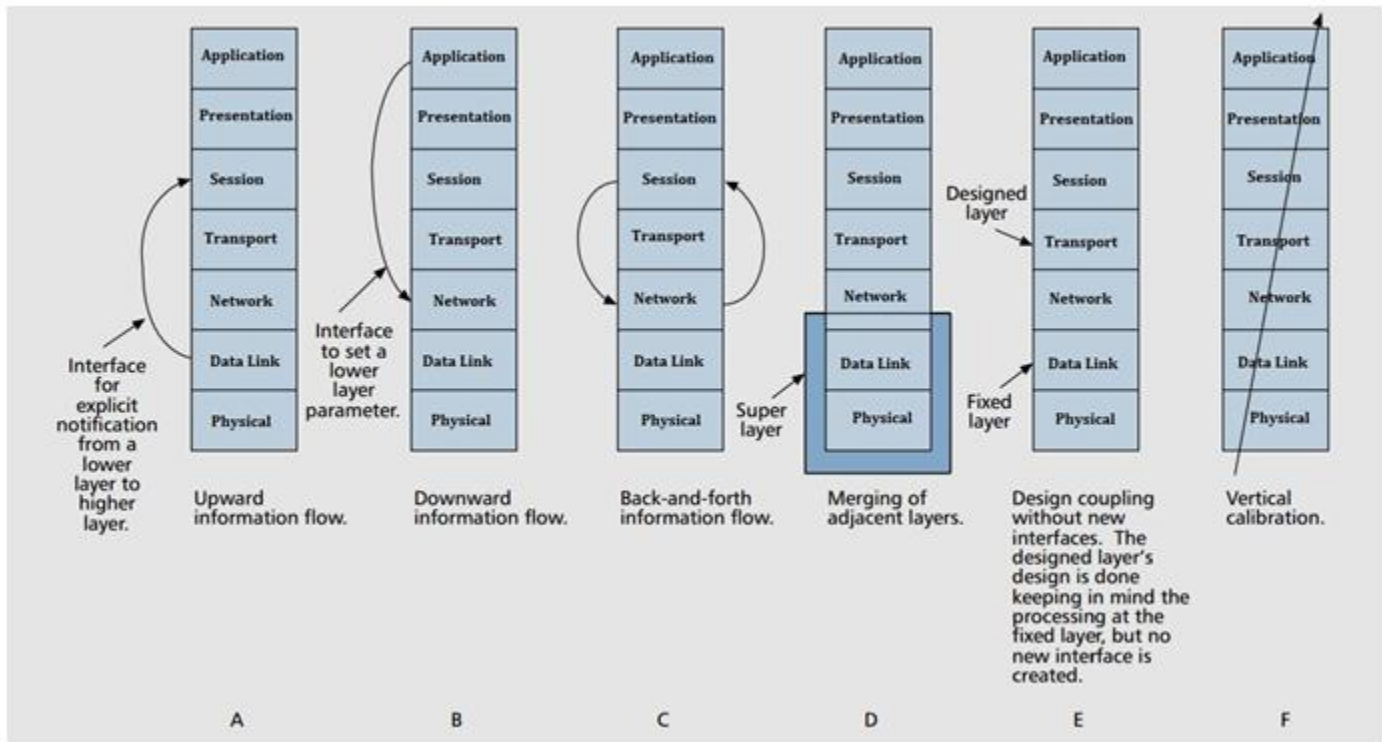

Figure 3: The different types of cross layer designs

2.1.3 Back and Forth Information Flow

Two layers, performing different tasks, can collaborate with each other at runtime. Often, this manifests in an iterative loop between the two layers, with information flowing back and forth between them as highlighted in Fig. 3C. Clearly, the architecture violation here is the two complimentary new interfaces.

As an example, we refer to the network-assisted diversity multiple access (NDMA) proposal [9, references therein], wherein the physical (PHY) and MAC layers collaborate in collision resolution in the uplink of a wireless LAN system. Basically, with improvements in the signal processing at the PHY, it becomes capable of recovering packets from collisions. Thus, upon detecting a collision the base station first estimates the number of users that have collided, and then requests a suitable number of retransmissions from the set of colliding users.

2.1.4 Merging of adjacent layers

Another way to do cross-layer design is to design two or more adjacent layers together such that the service provided by the new *superlayer* is the union of the services provided by th constituent layers, as shown in Fig. 3D. This does not require any new interfaces to be created in the protocol stack. In general, the superlayer can be interfaced with the rest of the stack using the interfaces that already exists in the original architecture.

Although we have not come across any crosslayer design proposal that explicitly creates a superlayer, it is interesting to note that the collaborative design between the PHY and MAC layers (discussed earlier with the NDMA idea) tends to blur the boundary between these two adjacent layers.

2.1.5 Design coupling without new interfaces

Another category of cross-layer design involves the coupling of two or more layers at design time without creating any extra interfaces for information sharing at runtime. We illustrate this in Fig. 3E. While no new interfaces are created, the implementation cost here is that it may not be possible to replace one layer without making corresponding changes to another layer. For instance, [5] considers the design of a MAC layer for the uplink of a wireless LAN when the PHY is capable of providing multipacket reception capability. Multipacket reception capability implies that the PHY is capable of receiving more than one packet at the same time. Notice that this capability at the physical layer considerably changes the role of the MAC layer; thus, it needs to be reconstructed.

2.1.6 Vertical calibration across layers

The final category in which cross-layer design proposals in the literature fit is what we call vertical calibration across layers. As the name suggests, this refers to adjusting parameters that span across layers, as illustrated in Fig. 3F. The motivation is easy to

understand. Basically, the performance seen at the level of the application is a function of the parameters at all the layers below it.

For example, [11] presents an example of vertical calibration where the delay requirement indicates the persistence of link-layer automatic repeat request (ARQ), which in turn becomes an input for deciding the rate selection through a channel-adaptive modulation scheme. Vertical calibration can be done in a static manner, which means setting parameters across the layers at design time with the optimization of some metric in mind. Static vertical calibration does not create significant consideration for implementations since the parameters can be adjusted once at design time and left untouched thereafter. Dynamic vertical calibration, on the other hand, requires mechanisms to retrieve and update the values of the parameters being optimized from the different layers.

2.2 Cross Layer Optimization Algorithms

In the following section, instead of going through all combinations of cross-layer design, we will focus on the ones that are most critical for WMNs. Considering the TCP/IP protocol architecture, the protocol layers that contain most specific features of WMNs include MAC, routing, and physical layer as shown in fig.4. In some cases, the transport layer needs to be optimized with physical layer in WMNs. Thus, in the remaining part of this section, we will investigate the detailed protocols in cross-layer design between *MAC and physical*, between *MAC and routing*, and between *physical and transport layers*. Optimization algorithms across multiple layers are also discussed.
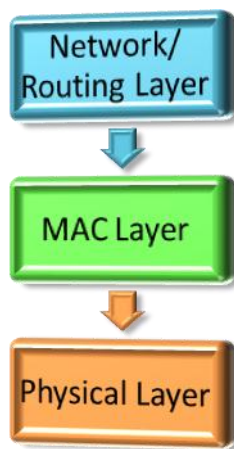

Fig: 4 Cross Layer design Concept

2.2.1 *MAC/Physical Cross-Layer Design*

Cross-layer design between MAC and physical layers is more common than that between any other two layers, because MAC and physical layer are so close to each other. These techniques include the following typical categories.

1) Multiple coding and modulation schemes. When a different coding and modulation scheme is used, the transmission rate on a link also changes.

2) Advanced antenna techniques. The examples include directional antennas and smart antennas.

3) MIMO. Based on multiple antennas for transmission and reception and advanced signal-processing techniques, the transmission rate of a wireless link can be significantly increased by MIMO.

4) Orthogonal frequency-division multiplexing (OFDM) technologies. OFDM can be used to build OFDM/TDD, OFDM/FDD, or OFDMA systems, as specified in IEEE 802.16. It can also be used as a building block for ultrawideband (UWB) systems.

5) UWB. Very high transmission rate is achieved using ultrawide bandwidth. UWB can be pulse-based like direct-sequence (DS) UWB as specified by UWB forum [12] or OFDM-based like multiband-OFDM (MB-OFDM) supported by WiMedia Alliance [13].

2.2.2 *Routing/MAC Cross-Layer Design*

A routing protocol of a multihop wireless network determines a path for any packet from its source to destination. In its simplest form, a routing protocol can just consider connectivity between nodes, i.e., as long as connectivity can be maintained, a routing path is set up. However, to enhance performance, other routing metrics and mechanisms must be taken into account.

Routing/MAC cross-layer can be done in a simple loosely coupled scheme as follows. A routing protocol collects information in the MAC layer, such as link-quality, interference level, or traffic-load information, to determine the best routing path. Such a method can only achieve a limited performance gain, since the MAC layer is considered but not optimized accordingly. In order to optimize the performance of routing and MAC protocols together, the working mechanisms of a MAC protocol must be explored and optimized as part of the tasks of routing/MAC cross-layer design.

It is well known that a MAC protocol can be reservation or random-access based. For a random-access-based MAC, no mechanism is available to fine-tune theMAC layer performance by considering information from the upper layer. Instead, a node just tries its best to access the medium. Such a MAC has a great advantage of simplicity and has another advantage of being decoupled from upper protocol layers. However, the shortcoming is that the MAC itself has low performance, and routing protocol can even have worse performance since no chance of cross-layer optimization is available. Such a problem reflects one of the many issues of applying CSMA/CA MAC protocol to WMNs. There are two possible solutions to this problem. One is to modify the random-access protocol so that it becomes closer to a reservation protocol. For example, the 802.11e hybrid channel-access control includes mechanism of scheduling and reservation, which works together with CSMA/CA to improve the performance of 802.11 MAC. The other solution is to have overlay protocols. For example, we can develop a TDMA protocol overlaying CSMA/CA [14].

2.2.3 *Transport/Physical Cross-Layer Design*

In a multihop wireless network, the capacity of a link is usually variable due to factors such as interference, time-varying channel quality, fading, and so on. Without a fixed capacity in these links, an end-to-end transmission mechanism, i.e., a transport-layer protocol, needs to be optimized by considering the varying link capacity. This motivates the need for cross-layer design between transport layer protocol and physical-layer techniques.

Transport-layer protocol can be simple or complicated, depending on what services need to be provided at the transport layer. The two most well-known transport-layer protocols are TCP and UDP. For UDP, the mechanism is very straightforward; a source node just sends its desired traffic rate without considering what will happen in the intermediate nodes and links from itself to the destination node. TCP works significantly differently. A source node needs to adaptively adjust its transmission rate according to the congestion condition in the network. The congestion can be real congestion on a certain link or poor quality in a link.

Cross-layer design between TCP and physical layer for a multihop wireless network has been researched for several years. One method is the congestion-control algorithm of TCP which is optimized by considering the information collected from the physical layer in this the physical-layer information is used to differentiate packet loss due to congestion from that due to link-quality-related loss. Such optimization can only achieve limited performance improvement, because the interaction between TCP and physical layer is not considered. However, when a link is congested, the physical layer can adjust its parameters, like for example the transmit power, to avoid congestion, which will also help TCP achieve better performance. Similarly, when a link experiences low quality, the physical-layer parameters, such as coding rate or transmit power, can be adjusted to enhance the link quality.

III. CONCLUSION

As explained in previous sections, it is pretty obvious that the cross-layer design can definitely improve the network performance. However, issues can come together with benefits, as explained as follows:

System complexity: For many cross-layer design schemes, it can easily be shown that they achieve great performance through simulations or even prototypes. However, when coming to the actual implementation of these schemes, we face to several complexities in modifying protocols in different layers. These modifications can impact the maintainability of the software, stability of different protocol modules, and flexibility of porting codes to different platforms.

Protocol interoperability and compatibility: With crosslayer design, the standard working mechanism in the protocol stack is broken. Thus, a wireless network with cross-layer design can easily be incompatible with other networks, and thus, interoperation between different networks is difficult to maintain. Consequently, a cross-layer design scheme should have a remedy to standard compatibility. However, it can be imagined that, even if interoperation can be maintained via such a remedy, the benefits of cross-layer design may diminish when networks with and without cross-layer design have to work together.

Evolution capability: In a layered-protocol architecture, protocols in one layer can evolve separately without disrupting the functionalities of protocols in another layer. When cross-layer design is adopted, any upgrade or change in protocols must be coordinated among different protocol layers. This requirement significantly limits the capability of product evolution.

It should be noted that such issues usually do not exist in a layered design scheme. To avoid such issues, tradeoff should be made between performance improvement via cross-layer design and benefit loss of layered design. However, technically, it is extremely difficult to carry out a reasonable tradeoff since issues such as system complexity or protocol interoperability is not easy to quantitatively be evaluated. Thus, in this paper, we suggest several rules that can be followed to avoid blind use of cross-layer design.

1) Achieve enough margin of performance improvement. Cross-layer design brings network-performance improvement with a price of high system complexity. Thus, to compensate the cost, the performance improvement must be significant enough. Multiple performance metrics may need to be considered together to evaluate the overall network-performance improvement. In fact, using cross-layer design, we can easily see some performance improvement in throughput, delay, packet loss, etc. However, if the improvement is only a small percent, e.g., 5%, then it is not a wise strategy to adopt crosslayer design, since such performance improvement can easily vanish due to uncertainties in a wireless network like interference, noise, shadowing, etc.

2) Explore any possible opportunity that can improve network performance using layered-protocol design. For cross-layer design, benefits always come together with issues. Thus, the best strategy is to explore the capability of layered-protocol design as much as possible. The theoretical research work on "layering as decomposition optimization" can be used as guidelines in doing so.

3) Carry out cross-layer design without compromising framework specified by standards. In order to ensure standard compatibility to the great extent and, thus, to maintain interoperability and evolution capability, it is a good strategy to carry out cross-layer design under the framework of standard specifications.

4) Push standardization of cross-layer design framework and methodology. To further improve the viability of cross-layer design schemes, standardizing the framework of cross-layer design is necessary.

REFERENCES

[1] Akyildiz, I.F. and Xudong Wang, "A survey on WMNs," *IEEE Communications Magazine*, 2005.

[2] V. Srivastava, Mehul Motani, "Cross-Layer Design: A Survey and the Road Ahead," *IEEE Commun. Mag.*, Dec. 2005, pp. 112–119.

[3] S. Shakkottai, T. S. Rappaport, and P. C. Karlsson, "Cross-Layer Design for Wireless Networks," *IEEE Commun. Mag.*, vol. 41, no. 10, Oct. 2003, pp. 74–80.

[4] Z. Ji *et al.*, "Exploiting Medium Access Diversity in Rate Adaptive Wireless LANs," *Proc. ACM Annual Int'l. Symp. Mobile Comp. and Net.*, Philadelphia, PA, Oct. 2004.

[5] L. Tong, V. Naware, and P. Venkitasubramaniam, "Signal Processing in Random Access," *IEEE Sig. Proc.*, vol. 21, no. 5, Sept. 2004, pp. 29–39.

[6] V. T. Raisinghani and S. Iyer, "Cross Layer Design Optimizations in Wireless Protocol Stacks," *Comp. Commun.*, vol. 27, 2004, pp. 720–24.

[7] G. Xylomenos and G. C. Polyzos, "Quality of Service Support over Multi-service Wireless Internet Links," *Comp. Net.*, vol. 37, no. 5, 2001, pp. 601–15.

[8] L. Larzon, U. Bodin, and O. Schelen, "Hints and Notifications," *Proc. IEEE Wireless Commun. and Net. Conf.*, Orlando, FL, Mar. 2002.

[9] G. Dimic, N. D. Sidiropoulos, and R. Zhang, "Medium Access Control — Physical Cross-Layer Design," *IEEE Sig. Proc.*, vol. 21, no. 5, Sept. 2004, pp. 40–50.

[10] T. Elbatt and A. Ephremides, "Joint Scheduling and Power Control for Wireless Ad Hoc Networks," *IEEE Trans. Wireless Commun.*, vol. 3, no. 1, Jan. 2004, pp. 74–85.

[11] Q. Liu, S. Zhou, and G. B. Giannakis, "Cross-Layer Combining of Adaptive Modulation and Coding with Truncated ARQ Over Wireless Links," *IEEE Trans. Wireless Commun.*, vol. 3, no. 5, Sept. 2004, pp. 1746–55.

[12] [Online]. Available: http://www.uwbforum.org

[13] [Online]. Available: http://www.wimedia.org

[14] X. Wang, W. Wang, and M. Nova, "Distributed TDMA for wireless mesh networks," Mar. 9, 2005. U.S. Patent Application 11/076738.

AUTHORS

Rajeev Paulus is working as a Asst. Prof. in the Department of Electronics & Communication Engineering in SHIATS, Allahabad. He received his M.Tech. Degree in Electronics & Communication Engineering from Motilal Nehru National Institute of Technology, Allahabad, India and he is currently pursuing his Ph.D. Degree from the Department of Electronics & Communication Engineering of Sam Higginbottom Institute of Agriculture, Technology and Sciences, Allahabad, India. His research is focused on Wireless Sensors Networks and Computer Networks.
EMAIL: rajeevpaulusphd@gmail.com

Mukesh Kumar is working as a Asst. Prof. in the Department of Electronics & Communication Engineering in SHIATS, Allahabad. He received his M.Tech. Degree in Advanced Communication Systems Engineering from SHIATS, Allahabad in 2009. His research is focused on Wireless Sensors Networks and Computer Networks.
EMAIL: mukesh044@gmail.com

Piyush Charan received his B.Tech. Degree in Electronics & Communication Engineering in 2010 from Integral University, Lucknow, India and he is currently working towards his M.Tech. Degree in Wireless Communication Engineering from the Department of Electronics & Communication Engineering of Sam Higginbottom Institute of Agriculture, Technology and Sciences (SHIATS), Allahabad, India. His research is focused on Wireless Sensors.
EMAIL: er.piyush.charan@gmail.com

Prof. Arvind Kumar Jaiswal is working as Head of Department in the Department of Electronics & Communication Engineering in SHIATS, Allahabad. He received his M.Sc(Tech). Degree in Electronics & Radio Engineering in the year 1967 from University of Allahabad, India. His research is focused on optical Wireless Networks, Advanced Communication, Antenna and Wave propogation, optical fiber communication and control system.
EMAIL: akjaiswal@gmail.com