Chapter 1

Introduction

Nobel laureate Professor Amartya Sen in his book entitled *Development as Freedom* [**?**] defines *development* as-

> `Development can be seen as the process of expanding the real freedoms that people enjoy.`

Exercising freedom facilitates people a better livelihood in terms of human, social and economic development. ICT plays an increasingly instrumental role in providing more privileges to people. It expedites the delivery of basic services like education, health and food security, improved connectivity, infrastructure, and some innovative ways of expression. ICT can tremendously contribute to the human civilization as it helps individual to raise her/his political, economic and social capabilities [**?**]. Access to ICT can also play a pivotal role in the socio-economic development of rural regions especially in the third world countries [**?**]. Although ICT has brought digital revolution in last two decades, unfortunately, most of the gains of this digital revolution have been restricted to the urban and developed regions leaving the rural and underserved areas aside. Majority of the population of underdeveloped and developing countries are living in rural areas [**?**]. Globally, there are nearly 4 *billion* people not yet using Internet and more than 90% of them are from the developing world [**?**]. This disparity between the urban and rural areas in terms of use of ICT, called *Digital Divide*, is reflected within one country or population, or between industrialized and developing countries.

To lessen digital divide, promotion of ICT for development was consecutively placed in the line of action of several World Summit of the Information Society (WSIS) including the recent ones in the years 2012 and 2014 [**?**]. With

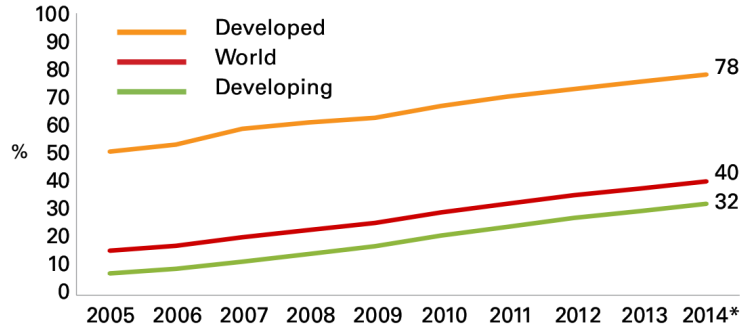

Figure 1-1: Percentage of Individuals using Internet during 2005-2014

concerted efforts from different corners, digital divide is gradually ebbing away and individuals in the developing world are also enjoying or beginning to enjoy the miracles of connectivity and access to information [**?**]. As on 2014, Internet user penetration has reached 40% globally, 78% in developed countries and 32% in developing countries [**?**]. Percentage of individuals using Internet during the period 2005-2014[1] [**?**] is shown in Figure **??**. Digital divide and hence the gap created in socio-economic development resulting from the effect of advancement of ICTs over urban and rural areas is not found to be converging at a rapid rate. WSIS still recognizes the existence of digital divide as a challenge since many disadvantaged groups do not have proper access to the ICTs even today [**?**].

The main reasons for low penetration of ICT in rural areas are- i) low population density (in comparison to urban), and ii) low paying capacity of the population. A rural network solution must therefore be of low cost in order to fit in the paying capability of the people living there. Unfortunately, today's network equipment and protocols predominantly target urban areas.

Wired technologies are considered to be costlier in extending communication infrastructure to rural and underserved areas. Of late, wireless networks have become the technology of choice for increasing access to telephone and Internet services in developing countries. Wireless networks are cheaper, easier and faster to deploy than traditional wired alternatives. Although WiFi was originally designed to provide connectivity for short ranges in indoor environment, through proper planning and adjustment, it can be enhanced for beyond its intended use. WiFi-based long distance (WiLD) network has recently turned out to be an interesting alternative over the other low cost solutions such as WiMAX, cellular networks and satellite links [**?**,**?**,**?**]. Village Telco [**?**] provides telephone infrastructure using WiFi based mesh network in which a link covers upto a few kilometers

[1]Number of users shown for the year 2014 is an estimated figure

of distance. According to Raman et al. [**?**], WiFi-based networks may be 2-3 orders of magnitude cheaper than cellular and WiMAX. Cheaper WiFi has been attributed by wide availability of commodity IEEE 802.11 hardware at low cost and its license free operation in the Industrial, Scientific and Medical (ISM) radio bands.

In addition to the traditional data applications like e-mail, e-commerce, and web browsing, real-time applications such as e-learning, e-health care and e-medicine, e-governance, and e-agriculture are also expected to be running over rural wireless networks. The traditional applications are used to transfer texts or other simple types of data where reliability is considered to be the major service requirement. However, the envisioned real-time applications like video-conferencing in rural telemedicine, e-learning (mainly video traffic), Internet telephony (mainly Voice over IP) over rural Wireless Mesh Networks (WMN) have to operate while meeting the user expectations. That is, the QoS constraints like minimum throughput, maximum delay, maximum jitter, and certain percentage of packet loss are required to be ensured by the underlying networks. In other words, such networks must have to support some level of performance guarantees needed for the prospective real-time applications to function. The quality of most multimedia services involving voice and video transmission deteriorate dramatically if delay increases beyond a certain level. Certain minimum level of throughput is also expected in some bandwidth sensitive applications. The traffic generated by the applications like remote surgery whose requirements are critical in nature shall be requiring strict QoS, whereas soft QoS will suffice for some other applications. Wireless networks exhibit unpredictable error rate, data rate, link quality and hence it is difficult to guarantee QoS in such networks [**?**].

The goal of this chapter is to briefly introduce WiFi-based long distance mesh networks as a solution to digital divide problem and discuss the QoS issues addressed by this research in supporting real-time applications over them. The proposed solutions and their innovative aspects are briefly described to highlight the main contributions of this dissertation.

1.1 Challenges and Issues in QoS Provisioning in Multi-hop WiLD Networks

In wired network, QoS issues can easily be handled through over-provisioning of resources as the data rates offered by such networks are very high. However, since wireless systems incur high per-packet overhead with limited bandwidth, and channels are also error prone in nature; the same does not apply to wireless networks. Researchers have revealed that the random-access based MAC protocols such as CSMA/CA do not perform well in long distance multi-hop WiFi-based long distance networks [?, ?, ?, ?, ?, ?]. Therefore, TDMA-based schemes are required to be developed to provide QoS in such networks. QoS provisioning in multi-hop WiLD networks is considered to be very challenging because of the following reasons-

- Unlike traditional wired links, WiLD links cannot be characterized by fixed bandwidth and delay. Long distance WiFi links are unreliable due to existence of signal fading and interference.

- Since the standard CSMA/CA protocol does not perform well in multi-hop WiLD networks, TDMA remains the ultimate choice in provisioning QoS. As it is difficult to achieve fine-grained time synchronization among the nodes in multi-hop WiLD networks, QoS provisioning in TDMA-based MAC protocols is considered to be a challenging task.

- In multi-hop WiLD networks, multiple radios operate simultaneously at the same node. The need for simultaneous packet transmissions and receptions at different adjacent links of a node poses some formidable challenges. In such situations, link throughput and delay performance may vary randomly. Guaranteeing end-to-end performance with unpredictable link performance in multi-hop WiLD networks presents a stern challenge.

- In multi-hop WiLD networks, if the links are allowed to transmit simultaneously at their full capacities, the nodes closer to the gateway may experience traffic congestion. Hence, providing end-to-end bandwidth and delay guarantees for real-time flows in such gateway-based network setting is considered to be a challenging task.

- Unreliable WiLD links may change the quality of a given end-to-end path frequently. Routing protocols must consider the quality of paths while taking

routing decisions. Without integration of proper routing scheme with MAC, assurance of end-to-end QoS is a difficult task.

- QoS-aware MAC level scheduling and routing schemes cannot fully solve the end-to-end QoS issues unless packet forwarding by the intermediate nodes are given due importance.

1.2 Motivation of the Research

WiLD network has a great potential in reducing digital divide [?, ?, ?]. While running audio and video based real-time applications, QoS needs to be provisioned in such resource-constrained networks. In multi-hop WiLD networks, scheduling of transmission with high spatial reuse is a difficult task. Due to the possibility of traffic congestion around the gateway node, provisioning end-to-end QoS becomes more complicated. Moreover, varying QoS characteristics of different path components may not support sustainability of ongoing transmissions. In high load situations, even though proper priority is given by the routing and link level scheduling, end-to-end QoS cannot be achieved without using proper packet scheduling scheme. The above mentioned challenges are yet to be addressed for multi-hop WiLD networks to make them attractive solution for reducing digital divide. Being motivated from this, various QoS schemes have been developed in this research. By virtue of their importance - *minimum throughput* and *maximum delay* have been considered as QoS parameters while designing the QoS schemes.

1.3 Aim of the Thesis

The broad aim of this dissertation is to devise protocols and schemes in order to support required level of QoS over multi-hop WiLD networks.

1. First of all, we try to provision network level QoS by designing an efficient TDMA-based MAC protocol for multi-hop WiLD networks. Transmissions by co-located radios in multi-hop WiLD networks are likely to suffer from interference. We aim at maximizing the end-to-end throughput and minimizing delay by scheduling of overlapped transmission of different nodes through spatial reuse.

2. In order to provision QoS in multi-hop WiLD networks, we attempt to address the congestion problem which occurs around the gateway node. For judicious utilization of network resources and providing QoS to real-time traffic, a QoS-aware dynamic slot allocation scheme based on traffic demands is to be designed in this work.

3. Prioritizing link level transmission opportunities does not imply QoS provisioning in high load situations. To ensure fine-grained QoS to real-time traffic, a packet level scheduling scheme for TDMA MAC is to be designed which will assign priorities to different flows based on their traffic requirements.

4. Sharing of a single path or parts of a path by multiple flows makes the path overloaded which hinders in end-to-end QoS provisioning. To address this issue, we aim to devise a routing scheme to allocate QoS-aware paths to various flows according to their QoS requirements. It is further aimed to incorporate a load balancing scheme to maximize the utilization of network resources. The impact of sudden changes in quality of a path over ongoing transmissions should also be minimized as much as possible.

1.4 Thesis Contributions

In this dissertation, different state of the art protocols and schemes proposed for provisioning QoS in WiFi-based long distance backhaul networks have been investigated. The broad aim is to develop a QoS architecture in supporting various real-time applications over multi-hop WiLD networks. To fulfill this aim, we have contributed a few protocols and schemes particularly in MAC and network layers. The main contributions of this dissertation can be divided into four parts which are outlined in the following subsections in brief.

1.4.1 2C: A TDMA-based MAC Protocol for Multi-hop WiLD Networks

Enhancing network performance in a gateway-based multi-hop WiLD network through the scheduling of maximum overlapped transmission opportunities is a challenging task. The existing TDMA protocols such as 2P [**?**], JazzyMAC [**?**], WiLDNet [**?**], and Lit MAC [**?**] do not properly utilize the network resources par-

ticularly in muti-hop scenario. With an aim to achieve optimum link utilization through maximum possible simultaneous operations, a TDMA-based scheduling scheme for multi-hop WiLD network, called *2C* has been proposed in this work. The nodes in a multi-hop WiLD network are logically arranged into a tree; the root node being the main coordinator. The leaf nodes provide connectivity to the end user nodes whereas the intermediate nodes work as relay nodes. We use the concept of simultaneous Synchronous Operation, *SynOp* [**?**,**?**,**?**,**?**] which allows a node either to transmit to or receive from all of its neighbour nodes simultaneously but not a mix of transmit and receive operations. A TDMA schedule is dynamically generated at each node locally by using an interference-aware node colouring algorithm which implicitly overlaps transmission of nodes with non-interfering links. In the schedule generated, all the nodes belonging to the same level of the tree get the same transmission slot and hence can transmit simultaneously in both upward and downward directions. During any given time slot, nodes at the alternate levels of the tree become active for transmission.

Theoretically achievable saturation throughput and network initialization overhead of the proposed scheme are derived. Performance of 2C protocol has been evaluated through simulation study and results are compared with 2P [**?**]. 2C enhances the overall performance of multi-hop WiLD networks significantly. In both normal and saturated load situations, the proposed scheme provides CBR (Constant Bit Rate) throughput enhancement close to the maximum achievable throughput. Throughput performance of 2C for CBR and FTP traffic have been enhanced by 57.15% and 44.5% respectively over 2P. The delay performance for the CBR traffic is improved considerably in single hop as well as multi-hop scenarios than that of 2P. It paves the way in supporting of delay sensitive traffic such as VoIP and video conferencing. Performance enhancement observed in terms of throughput and delay of CBR traffic over multi-hop WiLD network assures network level QoS for real-time applications.

1.4.2 DQBA: A Dynamic QoS-aware Bandwidth Allocation Scheme for Multi-hop WiLD Networks

In this work, we have proposed a dynamic bandwidth allocation scheme for multi-hop WiLD networks which aims at utilizing the unused time slots of other nodes. Initially, the available bandwidth of a node's upward link is equally distributed among all the links associated with its 1-hop children. The initial static time slot allocation process facilitates limited but assured traffic forwarding over multiple

hops avoiding congestion [?] around the gateway node. However, the statically allocated time slots of different nodes are not utilized fully all the time. Therefore, the unused time slots of different nodes can be reallocated to the more needy nodes. To this end, a dynamic slot scheduling scheme based on traffic demands from the children nodes is developed. The immediate parent of a needy node initiates the dynamic slot assignment process based on the traffic demands raised by all of its children nodes. The parent node tries to allocate the unused time slots among the nodes having real-time traffic. If the demand of any children node cannot be met, the parent node forwards the bandwidth request (in terms of time slots) to its immediate parent (node belonging to the next higher level of the tree). The second hierarchy parent tries to satisfy the request of its children in the similar manner. This process continues till the bandwidth demand reaches the 1-hop children of the root node. In this fashion, the unused slots can gradually be carried from any level of the tree to the needy nodes. However, 20% of the total bandwidth of each link are not allowed for reallocation in order to avoid bandwidth starvation problem of the nodes. The nodes from which the allocated bandwidth are taken away can regain those as an when they get some real-time traffic. An admission control mechanism is also integrated to the bandwidth allocation scheme in order to continue the QoS support to the ongoing transmissions.

Performance of DQBA has been evaluated and the results are compared with TreeMAC [?]. Evaluation of performance is carried out in single as well as multi-hop situations considering the following two cases- i) balanced traffic load on each link, and ii) load on one each sub-tree of a tree only. Simulation results show that in equal load situation, the real-time traffic quickly converges to their saturation throughput compromising the bandwidth share of best-effort traffic. In the case of single sided screwed load, almost all the all the anticipated time slots are carried to the needy nodes. Using the dynamic slot scheduling and the admission control scheme, the proposed protocol significantly improves the end-to-end throughput and delay for real-time traffic between the gateway and any given children node.

1.4.3 RPS: A Real-time Packet Scheduling Scheme for TDMA MAC

In this work, we have proposed an integrated approach combining a flow based anticipatory packet scheduling and a localized admission control scheme. Classifying the real-time traffic into three specific categories according to their delay

and bandwidth requirements, the scheduling protocol ensures a fine-tuned QoS guarantee for the already admitted flows over TDMA-based MAC protocols in WiLD networks. This scheme schedules the real-time packets anticipating their arrival based on their periodicity. The scheduling protocol provides an early and larger transmission opportunity to delay and throughput bound real-time traffic respectively. In order to maintain QoS guarantees for the active flows, the protocol relies on a localized call admission process which can locally take the decision about a new call admission rather than involving all the nodes on the transmission path. Admission control algorithm first checks whether an incoming flow can be admitted in the link level with QoS support or not. If link level admission can be supported, a slot level admission control procedure is carried out in order to check the slot's capability for QoS support.

Delay performance of the proposed scheme has been evaluated using M/G/1/K queuing system. Performance evaluation through simulation studies have shown that the proposed packet scheduling scheme offers consistent throughput guarantees for real-time traffic. Delay over multiple hops is also significantly reduced using the proposed protocol.

1.4.4 QGMR: A QoS-aware Gateway-based Multi-path Routing for Multi-hop WiLD Networks

In multi-hop WiLD mesh networks, multiple paths from a leaf node to the gateway node may be available with varying characteristics. The QoS requirements of different real-time applications also vary considerably. In that situation, QoS-paths chosen for a particular real-time flow may not remain optimal for long. Hence, guaranteeing QoS path for real-time flows becomes a challenging task. In this work, We have proposed a QoS-aware gateway-based multi-path routing scheme, called *QGMR* for provisioning end-to-end QoS in multi-hop WiLD networks. QGMR uses two routing metrics: *expected end-to-end path bandwidth* and *end-to-end delay* to discover throughput and delay sensitive paths respectively. We have proposed a multi-path route discovery mechanism to find multiple maximally disjoint QoS-feasible paths between a given node and the gateway based on these two routing metrics. A source node initiates the route discovery process by broadcasting a route request specifying its QoS demands. Intermediate nodes while processing route requests perform hop-by-hop admission control based on QoS requirement of the route request. The gateway node stores all the route requests received through different paths which satisfy QoS requirements of the

requested flow. Finally, the gateway node selects a set of maximally-disjoint paths from all the reported paths and replies to the source node through the selected paths. On receiving the route reply packets, the source node selects the suitable paths for communication. In order to avoid congestion and maintain quality of the already admitted flows, an admission control and load balancing scheme is incorporated in the routing protocol. For this purpose, a flow register is used by all the nodes to maintain the ongoing flows going through them. For throughput sensitive flows, the packets are sent using multiple QoS paths distributing the packets on them. On the other hand, only one path is used to forward the packets belonging to a delay sensitive flow. In the event of significant change in link quality, route update process is initiated which results in updating of path tables accordingly.

Performance of the proposed protocol has been evaluated and the results obtained are compared with AOMDV protocol [**?**]. The simulation results have shown that the proposed scheme can support more numbers of VoIP, videoconferencing, and video streaming connections than that of AOMDV. Significant improvements in terms of end-to-end throughput and delay have also been observed.

1.5 Thesis Organization

The rest of the dissertation is organized as follows:

- Before going to discuss about the thesis contributions, a state of the art literature survey on QoS-aware link as well as packet level transmission scheduling, dynamic bandwidth utilization schemes and multi-path routing approaches in multi-hop WiLD networks are presented in Chapter **??**.
- Chapter **??** presents the proposed TDMA-based MAC protocol for multi-hop WiLD networks which maximizes overlapping of transmission opportunities or time slots among the nodes of the network.
- Chapter **??** is about the dynamic bandwidth allocation scheme that is designed for multi-hop WiLD networks. It discusses how the proposed bandwidth allocation scheme efficiently utilizes the unused time slots of other nodes. The method of provisioning QoS to the real-time flows by avoiding congestion problem is also discussed.
- A QoS-aware real-time packet scheduling scheme for TDMA MAC is discussed in Chapter **??** which provides granular level of QoS to real-time ap-

plications.

- Chapter **??** is about the QoS-aware gateway-based multi-path routing scheme proposed for provisioning end-to-end QoS in multi-hop WiLD networks. QoS-aware multiple path discovery mechanism to find multiple candidate QoS paths is discussed in details. Furthermore, a flow-based admission control and a load balancing mechanism incorporated to the routing scheme are also discussed.

- Finally, Chapter **??** concludes the dissertation by summarizing the overall contributions and suggesting some future directions of research in this area.