Rural Area Wireless Mesh Networks

Major Area Examination Writeup

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1 Introduction

Means of communication have achieved tremendous growth in the last two decades and the anywhere-anytime concept is becoming a reality as the ease of deployment and the decreasing cost of usage allow a large fraction of the world's population to use WiFi, cell phones and communication satellites. However, the map of the information world is highly polarized: only 5% of the African population uses the Internet (compared to 70% in North America)[46] and there are more telephones in the city of Montreal, Canada alone than in the whole country of Bangladesh [28]. These examples reveal only the tip of the huge problem of digital divide that can be observed on different levels in our society. On one side of the gap we have the rich, educated and urban, while the poor, illiterate and rural remain on the other side.

There are numerous reasons to strive towards the development of reliable and affordable communication infrastructure for those who currently see the telephone as a luxury. Bridging the digital divide directly leads to more opportunities for economic development. One may argue that our target population needs the more fundamental necessities of life, yet it is obvious that although the basic human needs may not be satisfied, possibilities opened by communication can greatly help in provision for such needs. For a long time, the major communication service provides have neglected rural areas since no adequate business model promised instantaneous profit. However, rural areas, especially the rural areas of the developing world, are the market: more than two thirds of the world's population live in the developing world, and anecdotal evidence shows that these people tend to invest proportionally much more in the communication than their developed counterparts do [10]. Nevertheless, today's wireless network equipment and protocols predominantly target urban areas, mostly being deployed indoors and without any power constraints. Moreover, current technologies are being developed to work in ideal social, economic and political environments. The technology cannot exist independently of the society and the sophisticated bond between the two should be considered while designing novel communication solutions. Finally, various technical challenges that are not present in urban deployments appear when it comes to rural wireless networking, making it an interesting computer science research field.

This paper represents a survey of different aspects of rural wireless mesh networking, the state-of-the-art solutions for the problematic issues and delivers a set of guidelines for the future work in the area. The following sections examine specific computer science and engineering aspects of the problem: different types of rural area networks and the means of planning them are discussed in section 2, MAC Layer issues are presented in section 3 , routing in section 4 while section 5 describes various power saving techniques. In the end, section 6 concludes with performance measurement and network monitoring strategies.

2 Rural Networks

A number of technologies, such as satellites, cellular networks and WiMax, can be utilized for linking rural areas. However, 802.11 based mesh networks stand out as the cheapest, both to deploy as well as to use, and the easiest to implement. In addition, the spectrum used by the 802.11 protocol is unlicensed in most of the world, so cumbersome and expensive bureaucratic processes of obtaining the license can be avoided. Several university research groups are experimenting with deploying wireless networks in rural areas of Africa and Asia. These attempts usually aim to connect those who have information and those who need it. Therefore, long distances that prevent the poor rural population from reaching medical, governmental and other professional services are being bridged by carefully designed wireless links. In a typical deployment the links span from a nearby city to a so called *kiosk* located in a remote village. A kiosk represents a communal establishment hosting computers and local staff that operates the kiosk and helps local population to use it. If the other side of the wireless link serves as an Internet gateway, services such as web browsing, emailing and voice/video conferencing can be supported in a kiosk as well. The abovementioned represents a top down approach that proved to be very successful in India (Aravind eye clinic, SARI project). However the ultimate goal of reaching all community members requires providing network services all the way to people's homes. This is done via covering the area with sector antennae signal [25] or via deploying another, local, mesh network, and here a kiosk would be used as a gateway.

Planning a long distance rural mesh network is a challenging task and probably the best taxonomy of equipment and setup costs can be found in [38]. The same paper explains a heuristic that can be used for designing a cost optimal network, where variables are tower heights, link placement, power levels and antenna types. This work is orthogonal to the optimal channel allocation strategy presented in [32]. The subsequent work from the same research group is FRACTEL [8], a mesh network deployment that considers planing and operating details of both long distance and local mesh links. The authors argue that the long distance and the local network at each village are independent of one another and that the key performance parameters can be tuned by independently considering time slot and channel allocation on the two networks. Besides presenting a novel data ferrying method using local buses, KioskNet[18] examines commonly overlooked aspects of rural area networks - security and user management. Real world deployments show that inexperienced users in these areas are indeed extremely vulnerable to online scams [22].

Traffic traces from these networks point to voice/video communication as one of the most important applications. The usage patters reveal that people tend to use provided infrastructure to contact members of their own communities, and that the local community is the resource one uses when a technical expertise is needed. The Rural Telephony project [37] shows that the people are willing to pay for the short casual local calls that are the most dominant types of calls observed. These facts lead us to the conclusion that easily deployable local mesh network providing good voice/video communication performance may be more beneficial than just a single long-distance link that allows a single point in the village to be connected to the Internet. Moreover, a kiosk as a centralized point may not always serve its purpose of bridging the digital divide, but may actually introduce a new divide. Evidence from SARI [26] show that phenomenon in heterogenous villages: if a kiosk is placed in the area where one part of the population is unwelcome (religious casts, poorer people, different ethnicity) or if the person in charge of maintaining and advertising the kiosk is either not doing his job well or is not respected in the local community. The bottom up, grassroots, mesh network would be perceived more as a communal effort than as a foreign body. Possible negative effects like free riding [2] should be thought of while designing protocols for such networks. Of course, in the ideal case, this network would eventually be connected to an internet gateway, though this can be regarded as a completely independent problem.

3 MAC Layer

3.1 Long Distance MAC Layer Solutions

IEEE 802.11 family of standards is designed for relatively dense urban deployments, short communication distances and omni directional antennae. The taxonomy of the problems that are observed if the protocol is used for long distance communication with directional antennae can be found in "Tuning 802.11 Inside-Out" paper by Bhagwat et al [6]:

- the timeout value used for link level acknowledgments is too small to allow an acknowledgment to travel long distances, which triggers unnecessary retransmissions;
- similarly, the contention window time slot requires adaptation to long distance lines. If a node senses a medium for DIFS (maximum 50us on most cards) before sending it will not receive any transmissions that might have started at nodes that are about 15km or more apart;
- as propagation times increase with distance, the sender waits for a longer time for the ACK to return. This decreases channel utilization.

Furthermore, the following physical layer properties helped shape MAC protocols for long distance links:

- directional antennae leak signal (”side-lobes”) and the coexistence of two or more antennae on the same node requires carrier sense disabling
- it is possible to have two or more carefully placed antennae on the same node either all simultaneously transmitting or receiving but not some transmitting and some receiving at the same time (SynOp in [6])

These findings lead to 2P [33], a two phase MAC protocol that loosely synchronizes nodes in a bipartite graph achieving network wide SynOp and has carrier sensing and link level acknowledgments disabled. 2P assigns the same time share to uplink/downlink traffic and switching from one phase to another is performed when a ”marker” packet is received by a node on all of its interfaces. A timeout timer makes sure that in case of a lost ”marker” node switches its state after a relatively small delay. The experimental results from [33] show the superiority of 2P over the traditional 802.11 MAC protocol over long distance links. The WiLDNet protocol [31] extends the idea further by introducing adaptive loss recovery and more sophisticated means of node synchronization. Long distance networks experience very high and variable packet loss rates induced by external factors; therefore, tuning the number of retransmissions and the amount of FEC should be adjusted dynamically. WiLDNet uses loose implicit synchronization that relies on time stamping of each packet by the sender and a smoothing function that, by examining the timestamps, infers when a phase switching should occur. 2P and WiLDNet are implemented on a number of working deployments throughout the world, becoming a *de facto* standard for long distance WiFi communication. An alternative suggested by Balakrishnan et al [4] is to dynamically adjust protocol parameters to the link distance. Although the authors propose efficient ways to achieve the tuning, the problem of underutilization remains as the link distance rises.

The main flaw of TDMA protocols like 2P and WiLDNet is that the chunk of time awarded to each of the directions on a link is fixed and does not necessarily correspond to the actual needs. This can lead to low link utilization in case of asymmetric traffic. RTDMA-DA [11] is a distributed protocol that allows nodes to reserve the necessary time slots making it more responsive to varying bandwidth needs. Unfortunately, this reservation scheme works only for a square grid topology and does not account for possible control packet losses.

The area of long distance wireless networking is still in need of an efficient MAC layer protocol that would work well with varying bandwidth demands and in an arbitrary, not only bipartite, topology.

3.2 TDMA MAC Protocols

Time voice and video communication as the main application on a wireless mesh requires strict packet delivery delay and jitter boundaries. With standard 802.11 MAC protocol, the fact that a node has to contend for a medium before each transmission prevents any guarantees on delivery performance and fairness in such a network. The quality of service can be provisioned either by allowing the nodes transmitting time-critical traffic more opportunities to get the medium or explicitly reserving time slots for them. Both of these are targeted by IEEE 802.11e standard focusing on QoS. In a centralized AP environment the functionalities related to QoS are EDCA (Enhanced Distributed Channel Access) and HCCA (HCF (Hybrid Coordinator Function) Controlled Channel Access) for contention and time division respectively. However, in a mesh network there is no single point that is able to arbitrate channel access for the nodes.

Time division multiple access (TDMA), if implemented adequately, allows each link to send its data in a conflict-free time slot, and if these slots correspond to the node’s traffic needs the quality guarantees can be made. The theoretical work in [34] presents general results on the optimality of different slot allocation algorithms and concludes that Progressive Minimum Neighbors First (PMNF) graph coloring algorithm gives the best solution. Unfortunately the algorithm requires global network knowledge and it’s hard to claim that it can be actually implemented. In [17] Gronkvist et al. set the analytical expressions for throughput of different access techniques: fixed TDMA, traffic adaptive TDMA, spatial reuse TDMA and prove that the best results are obtained with link-level granularity spatial reuse TDMA.

Concrete protocols developed to provide distributed TDMA functionality such as FPRP[47], ASAP[24] and USAP-ma[23] are facing a serious problem of time synchronization. The synchronization can be achieved using GPS or by sending periodic broadcast packets from a single source to all the nodes, however a fragile wireless medium makes this a challenging task. Adapting to varying traffic loads is the subject of the work by Kanzaki et al. in [24] and [23], their protocols dynamically change the number of slots in a cycle according to the control messages that are exchanged among nodes in a single collision domain.

Sticky CSMA/CA [41] is a dynamic TDMA-style MAC protocol that supports both real-time voice and delay-insensitive traffic without requiring explicit synchronization. It utilizes the fact that VoIP packets are sent with a certain periodicity. Nodes sense the medium and maintain a carrier sense table to keep track of the ongoing periodic flows. When a new voice flow is admitted it is given one of the free time slots in the node's carrier sense table. Delay-insensitive traffic has lower priority than real-time traffic and fills in the gaps remaining after the real-time flows have been accommodated. The authors show that Sticky CSMA/CA can support more than twice as many calls as 802.11b and 802.11e even when the background, delay-insensitive, traffic is present. However Sticky CSMA/CA fails to deliver the same performance improvements for non-periodic but still delay and jitter sensitive traffic such as real time video. Further analysis and modeling of different video and voice codecs as well as user behavior (call length, inactivity periods) should allow fine tuning of TDMA protocols' parameters.

The Overlay MAC Layer [35] takes the MAC TDMA functionality on a higher layer while keeping the standard 802.11 MAC layer. It uses a distributed algorithm to assign time slots to nodes with loosely synchronized clocks, to improve fairness in 802.11-based multi-hop networks. Capacity improvement is the subject of multi-channel protocols SSCH [3] and MMAC [42]. The former uses seeded channel hopping to ensure that the communicating nodes access the same channel while the latter requires all network nodes to periodically switch to a common control channel and negotiate their future channel selections. The future MAC protocol should utilize channel hopping for capacity purposes yet provide fine granularity TDMA for each of the admitted voice/video flows.

4 Delay Tolerant Routing

DTN style networks cover a significant number of diverse networks where the link failures are a norm rather than an exception. Having in mind the possible scenarios and the complexity of the routing, most of the solutions target a single domain of DTN deployments. Therefore, Saratoga [45] utilizes highly asymmetrical space and satellite links, the CAM [13] framework relies on existing human interactions in order to transfer data carried by mobile phones, while the protocol described by Thomas et al. [44] ensures probabilistic routing among independent groups of mutually connected nodes. Networks where data has to be delivered via mobile nods and where end-to-end path may not exist in any point in time represent another important field of research. The initial extreme solutions such as direct delivery and epidemic routing evolved to more moderate and intelligent approaches like Prophet and integrated DTN and MANET routing [30]. At each node, the former protocol stores and dynamically updates a delivery probability vector to all other nodes, while the latter presents a hybrid scheme that combines AODV and DTN-style routing, leaving the choice of which to use, with current network conditions in mind, to the application.

Obviously a lack of *oracle* that would supply the information on the future state of the links in the network to the routing protocol makes every solution far from optimal. Even with scheduled node mobility relaying on a town's public bus system, optimal routing might not be achieved [5]. For this setup Balasubramanian et al. propose RAPID, a heuristic that tries to find a path that satisfies a different routing metric. However, the networks in the scope of this paper are immobile and influenced by human user behavior (daytime activity patterns, scheduled power outages) that are easily traceable. This is considered in work by DeRenzi et al [13] where the proposed *social routing* is based on traveling habits of a person ferrying the data.

Link-state-based DTLSR [12] explicitly targets rural area wireless mesh networks. Demmer and Fall advocate the use of history information (capped at 24 hours) to infer the probability of a path being viable in the near future. The approach is appealing for its ability to find paths that will result in minimum estimated expected delay (MEED) even if an end-to-end connection may not exist at any point in time. Yet, several other metrics besides MEED should be considered since applications as diverse as VoIP, real time video transfer and medical information files are to be supported.

Finally, distributing information in a peer-to-peer fashion can be a crucial application of rural area networks. Work by Lee et al. [27] proposes a network-coding-based swarming protocol that improves file distribution over loosely connected vehicular ad hoc networks. Rural networks could utilize a similar approach for spreading common interest files such as critical software patches or Wikipedia updates.

5 Energy Efficient Protocols

Erratic and sporadic power supply is the most commonly reported problem observed in rural area networks [39]. Designing robust network hardware and software to cope with power glitches is one aspect of the solution. The other one is to utilize batteries as an alternative source when the grid power is not available. Since battery power is limited energy saving strategies, such as lowering the energy required for transmission of a bit of data, equal utilizing of each node in the network (preventing certain nodes from running out of power quickly) and performing device shut down when a transmission is not scheduled should be implemented.

Wireless sensor networks research produced several MAC layer protocols that enable nodes to "sleep" and conserve power. Flexible power scheduling [19] uses idle slots in a cyclic schedule to turn off nodes. In X-MAC [7] the sending node emits a preamble before sending the first packet in a bunch, the receiving nodes periodically wake up and sense the environment, staying awake only if the transmission is intended for them. However, sensor motes are more responsive and easier to power up and down than the hardware used in WiFi mesh networks.

Early experiments [14] on wireless NIC energy consumption point out that significant savings can be made by having devices "sleep" when not transmitting or receiving. However, the practical deployments that followed showed that a wireless card spends an order of magnitude less power than a computer board hosting it [29]. Developing a solution that allows quick powering on and off is a subject of [20][29] and [40]. Wake-on-WLAN [29] uses 802.15.4 sensor motes to register an incoming 802.11 transmission and power on the device it controls. In a network with long periods of inactivity this provides substantial energy savings. Turning the intermediate wireless routers off imposes new challenges on routing protocols and the two problems should be considered together. Also the users paying for the electricity may want to optimize by switching their equipment on only if they want to use it. This would hamper the performance to the others who are using it as a relay to the gateway. The means of preventing free riding are well known [2] in social sciences and should be used when designing power saving protocols.

6 Performance Measurement and Network Monitoring

Wireless mesh networks face multiple problems such as interference [36] and congestion [21] that arise from the fact that the protocol was not designed for multi-hop networks. The achievable throughput and fairness drop significantly with every further hop [15] . Consequently, the efforts from the research community targeted these problems; however, IEEE 802.11s, a standard for wireless mesh networks, is not finalized yet.

Besides these, rural area wireless mesh deployments [9][39] reveled the following new issues:

- power glitches result in hardware failure or unexpected component behavior (router resets, wireless card on but not transmitting, etc)
- external interference is varying and highly influences link quality

The additional findings include:

- The link abstraction does hold
- Rate adaptation can be done based on SNR values
- The effect of the packet size on the transmit rate is not significant
- Weather conditions do not impact the performance
- Antenna placement on a single node should be considered carefully

Comparing to the well known Roofnet [1] deployment we observe much lower impact of multi path fading on link quality. Clearly when the number of obstacles (buildings) is lower and the distances are longer multipath fading is less of a problem. On the other hand, external interference seems to play a major role in varying link quality, a phenomenon not observed in Roofnet deployment. The most recent findings [16] suggest that the conclusions from [1] are very likely incorrect. Managing and monitoring rural area networks is characterized by the following four obstacles [43]:

- Local staff tend to have limited knowledge of wireless networks;
- fluctuating power quality causes hardware failures;
- many wireless nodes are in remote locations;
- the failure of a single link may make parts of the network inaccessible remotely.

The framework proposed in [43] suggests building a sustainable monitoring system that should be educative in its nature. The harsh conditions require software and hardware components that are not sharing the same fate as the main communication equipment. Since the deployments are remote, possible problems should be anticipated so that a number of visits can be lowered.

7 References

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