Wireless Networks in Rural Areas: Challenges and Solutions *

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Abstract

In this thesis proposal, we discuss the current limitations and challenges in wireless networks, especially in rural, remote or areas with rough terrains. Although traditional wireless networking technologies have already provided communication services in urban areas, they cannot satisfy the communication demands in the rural environment very well. Therefore, two new technologies—WiMAX and VANET—are proposed to solve the problems. The relay technique will be used extensively in rural networks to provide better service while keep the cost low.

We show resource allocation problems in the WiMAX relay and VANET networks and the importance to solve these problems. We analyze the actual problems and propose abstract models for them. With some assumptions, we mathematically formalize some of the problems, show the hardness of the problems and suggest ideas to solve them. We also show some of our preliminary results and some other ideas for the future research. The expected research achievements are discussed for both WiMAX and VANET problems.

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1 Introduction

Wireless communication has boomed in the past decades. It is now an essential part of the modern life in most part of the world. People in urban areas enjoy the convenience and efficiency provided by wireless communication in almost everyday. However, it is still a challenge to provide wireless communication service in the most area of the globe, including rural, remote, and areas with rough terrains. The existing wireless technologies are limited in communication range, terrain robustness, or cost efficiency to provide ubiquitous wireless connections to users in those areas. For instance, the 802.11 WLAN technology can provide broadband networking, but only in a very short range (up to 200–300 meters [1]). The satellite communcation can provide service at almost everywhere, but with very limited datarate and very high price. The cellular technology is the most used in rural areas nowadays. Although there are new generations of cellular technologies, the provided network service quality is still unsatisfactory. It is also cost prohibitive to build cellular towers to cover the entire rural area. Therefore, it is desirable to develop or utilize some innovate technologies to solve the communication problems in rural areas.

In our research, we focus on two families of technologies, the WiMAX (Worldwide Interoperability for Microwave Access, a.k.a., IEEE 802.16 [2]) and the VANET (Vehicular Ad Hoc NETwork). We will use relay techniques to allow multi-hop communication in both WiMAX and VANET, and therefore solve the communication problems in rural areas. We will briefly introduce these two technologies in the following.

1.1 Introduction to WiMAX

The emerging WiMAX technology can offer low-cost, high-speed and long-range communications for applications ranging from broadband Internet access to military and emergency communications. The WiMAX standard [2] provides a highly flexible approach for wireless networking that can be implemented over a wide range of frequencies and different physical layer technologies (including smart antennas).

A WiMAX network is composed of a Base Station (BS) and multiple Subscriber Stations (SS). The BS serves as a gateway connecting the WiMAX network to external networks such as the Internet. Two operation modes are supported by the standard: Point-to-Multipoint (PMP) mode and mesh mode.

Quite similar to a cellular network, a WiMAX network working in the PMP mode is essentially a single-hop wireless network in which an SS always directly communicates with the BS. In mesh mode, a spanning tree rooted at the BS is formed for routing. An SS out of the transmission range of the BS can use other SSs as relay to communicate with the BS in a multi-hop fashion. In this case, the SS working as a relay is often called a relay station (RS). Compared to the PMP mode, the mesh mode can significantly extend wireless coverage and improve network capacity. Also, the cost of a relay station (either static or mobile) is usually much less than that of a base station. Therefore, the mesh mode is desirable for wireless infrastructure in rural areas. IEEE is also currently working on an extension of the 802.16 standard—the 802.16j multi-hop relay specification. A WiMAX relay network is illustrated in Fig. 1.

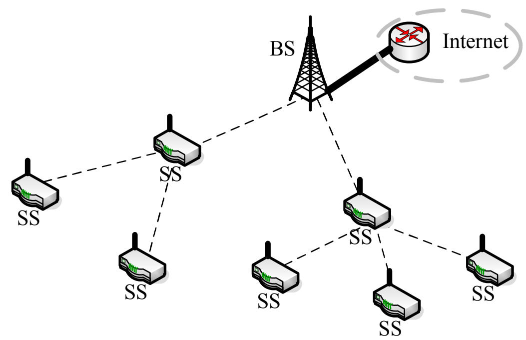

Figure 1: A WiMAX relay network

Traditional wireless networks use omni-directional antenna, which is suitable in populous areas where users are usually densely distributed at all directions. In rural areas, however, smart (directional) antenna may be a much better solution for communications. Unlike a conventional omni-directional antenna which wastes most of its energy in directions where there is no intended receiver, a smart (directional) antenna offers a longer transmission range and lower power consumption by forming one or multiple beams only toward intended receivers. The emerging Digital Adaptive Array (DAA) antennas [3] can even perform fine-grained interference suppression by adaptively forming nulls in certain directions using its antenna elements (a.k.a, Degrees Of Freedom (DOFs)), which leads to better spatial utilization. Therefore, smart antennas can enhance the functionalities of a WiMAX system and help it better achieve the goal of providing long-range and high-speed communications. Although DAA antennas have been extensively studied before, research on mesh networking with DAA antennas is still in its infancy.

1.2 Introduction to VANET

Vehicular Internet access is highly desirable because it will make travel safer and more comfortable. With Internet access, passengers can obtain critical safety information such as accident warnings and road condition reports, retrieve travel related information such as weather forecasts and hotel availability, and enjoy all other traditional Internet applications.

In urban areas, conventional wireless communication infrastructures such as cellular networks are readily available and can be used to provide network access. Research projects such as COMCAR [4] and DRiVE [5] have examined methods of using existing cellular infrastructure combined with new wireless technologies to achieve Vehicle to Vehicle (V2V) and Roadside to Vehicle (R2V) communications and Internet access in urban areas. However, it is well known that cellular networks suffer from limited bandwidth, and moreover, in rural areas there is almost no fixed communication infrastructure available. The coverage provided by wireless carriers is predominantly in urban areas and along major highways. However, 78% of the total roadway miles in the U.S. are in rural areas $(3,084,000$ miles) and 60% of crash fatalities occur on rural highways $(23,876$ fatalities in 2000) [6].

Although WiMAX systems may be good candidates to provide longer communication range and better coverage in rural areas. It is still often impossible or prohibitively expensive to cover the entire area or even just all the highways by setting up WiMAX infrastructures. The cost to install a WiMAX subscribe station on every vehicle can also be a negative factor. We notice that, vehicles do not usually need such a high bandwidth and QoS level that WiMAX networks provide. Therefore, it is better to provide wireless access to vehicles through on vehicle wireless adapters and roadside access points.

Wireless Access Points (APs) can be deployed along the roadside to provide Internet access for mobile vehicles. The mature 802.11-based WLAN technology [1] is an attractive solution since low-cost, off-the-shelf 802.11-based wireless routers and Network Interface Cards (NICs) can be readily used in R2V communications. However, the major weakness of 802.11 radio is its very limited transmission range, which is typically 200–300 meters [1]. To cover wide areas such as highways in rural and remote areas, a large number of APs would be needed, resulting in a very high deployment cost. A feasible solution is to place a small number of APs along the roadside and form an ad-hoc network among vehicles to relay packets for vehicles which are out of the AP range, as illustrated in Fig. 2. In such a hybrid Vehicular Ad-hoc NETwork (VANET), high mobility may cause frequent link breakages, which will have a serious impact on the Quality of Service (QoS) of Internet access. In addition, terrain introduces new challenges for wireless communications in rural areas. Vehicles moving along rural highways may occasionally lose Line Of Sight (LOS) to neighbors or to APs due to the curving roadways and mountains, resulting in poor signal strength and intermittent connectivity.

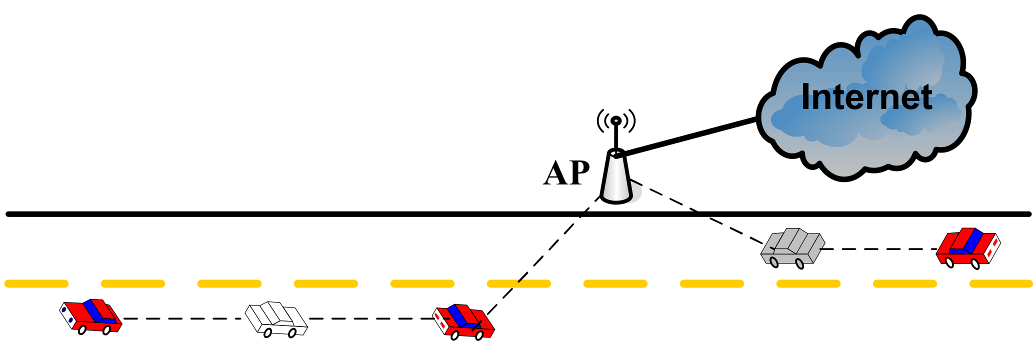

Figure 2: Roadside to vehicle communications

1.3 Use WiMAX and VANET Technologies

WiMAX and VANET technologies can be combined to solve the communication problems in rural areas. For network infrastructure, WiMAX is a good candidate. It can provide high-speed Internet access in a very large area. It is also more cost-effective to set up base stations and subscriber stations than to dig and line cables or optic fibers, especially in rural areas when the population density is low. WiMAX network can also work as the gateway for the VANET. An AP in VANET can be an SS in WiMAX network and use the WiMAX network to connect the VANET to external networks. On the other hand, VANET is a good compliment to the WiMAX network. It can further extend the network coverage to most or the entire highway network, provide network service to vehicles in movement, and avoid the expensive WiMAX infrastructure cost for low bandwidth applications.

In the following chapters, we will discuss the WiMAX and VANET network model, the problems, and possible solutions in detail.

2 WiMAX Relay Networks

2.1 Physical Layer Model

We will study the use of both the traditional omni-directional antenna and the directional antenna.

For the directional antenna, similar as in [3], we focus on DAA (Digital Adaptive Array) antenna, which is a type of well-known smart antennas. A DDA with K elements is said to have K DOFs. In order to enable communications between a pair of transmitter and receiver (link) (v_i, v_j), a single DOF needs to be assigned for communications at each end. In this way, the Signal-to-Noise-Ratio (SNR) can be improved at the receiver, and therefore the transmission range can be increased. Moreover, except for the DOF assigned for communications, the remaining $(K-1)$ DOFs can be used at the transmitter to cancel its interference to other nodes by forming nulls at corresponding directions. Similarly, the receiver can use its remaining $(K-1)$ DOFs to suppress interference from other nodes.

For our research, we assume that the network area is small enough such that the earth curvature can be neglected. Therefore, all nodes are considered being placed on a plane but with some antenna heights. We will use free space model to decide whether there is closure between a transmitter receiver pair. Which means two nodes may be able to communicate only if there exists line-of-sight between their antennas. We also assume that all the nodes will use the same fixed transmission power, and therefore each node will have a uniform transmission range R_T. Note that the transmission range can be boosted with a directional antenna.

In addition, for each node v_i, we can identify a set N_i of neighboring nodes potentially interfering with v_i, using the method introduced in [3]. Briefly, $v_j \in N_i$ if the Signal-to-Interference-and-Noise Ratio (SINR) at receiver v_j (or v_i) will drop below the threshold due to v_i (or v_j) unless nullified. We may also use a more conservative but simpler method, i.e., $v_j \in N_i$ if $\|v_i - v_j\| \leq R_I$, where R_I is the interference range and normally $2-3$ times larger than R_T.

If two links $e = (v_i, v_j)$ and $e' = (v_{i'}, v_{j'})$ are incident, we say there exists *primary interference* in between. In this case, in no way can they be active concurrently due to the half-duplex (a transceiver can only transmit or receive at one time), uni-cast (a transmission only involves a single intended receiver) and collision-free (two transmissions intended for the same receiver cannot happen at the same time) constraints. If nodes v_i, v_j, $v_{i'}$ and $v_{j'}$ are distinct but $v_j \in N_{i'}$ or $v_{j'} \in N_i$, we say there exists *secondary interference* in between. Note that our interference model is different from the symmetric protocol interference model often used for 802.11 networks. A DOF can be assigned at either the transmitter or the receiver to suppress secondary interference.

The WiMAX system can adopt OFDM or OFDMA technologies at the physical layer. In OFDM, different sub-carriers are combined together to serve a link and therefore can be considered as just one single channel. If OFDMA is used, however, sub-carriers are grouped into several sub-channels. Any link can be assigned one or multiple sub-channels. The more sub-channels the link gets, the more data rate it can achieve. It is also possible for different sub-channels to have different SINR for the same link, because the path loss may be variate due to different fading effects, and the interference level on each sub-channels may also be different.

2.2 Mac Layer Model

WiMAX system often adopts adaptive modulation, such that the modulation scheme can vary dynamically according to the actual SINR level. Therefore, we assume that the channels in our system can be heterogeneous, which means different channels on the same link may provide different data rates.

The WiMAX standard [2] adopts a Time Division Multiple Access (TDMA) based MAC protocol, in which the time domain is divided into minislots, and multiple minislots are grouped together to form a frame. Each frame is composed of a control sub-frame and a data sub-frame. The control sub-frame is used to exchange control messages. Data transmissions occur in the data sub-frame, which includes T minislots with fixed durations, and is further partitioned into an uplink sub-frame and a downlink sub-frame with T^u and T^d minislots respectively. Unlike the PMP mode, T^u does not have to be the same as T^d in the mesh mode. Any method can be used to determine T^u and T^d. For example, they can be set proportional to the uplink and downlink bandwidth demands.

Therefore, the MAC layer resources can be viewed as a total of $K = T \times C$ minislot-channel pairs, which we call transmission blocks, or simply blocks. The scheduling problem is to determine how to allocate these blocks to links in the network.

The WiMAX MAC protocol [2] supports both centralized and distributed scheduling. The centralized scheduling is the focus of our research, since the cost of relay station can be further reduced if it does not need to support complicated signaling or scheduling. In centralized scheduling, BS will gather information from the entire network, compute a scheduling scheme for all the nodes and broadcast the scheme to every other nodes. Centralized scheduling is composed of several phases in the WiMAX standard as follows. In the first phase, each SS transmits an MSH-CSCH Request (Mesh Centralized Scheduling) message carrying bandwidth request information to its parent node in the routing tree. Each non-leaf SS also needs to include bandwidth requests from its children in its own request message. In the second phase, the BS determines the bandwidth allocation for each SS based on all requests collected in the first phase and notify SSs by broadcasting an MSH-CSCH Grant message along the routing tree. Subsequently, each SS computes the actual transmission schedule based on the bandwidth granted by the BS using a common scheduling algorithm. The time period for exercising these two stages is referred to as a scheduling period whose duration is a multiple of the frame duration, depending on the network size. We assume that the bandwidth requests do not change within a scheduling period.

2.3 Network Layer Model

We consider a static WiMAX mesh network with only one base station and some subscriber/relay stations. For larger scale network, multiple base stations might be necessary. However, the network can firstly be divided into several sectors/cells, with one BS per sector/cell. How to divide a network into several cells is out of scope of our research.

We also assume that only the BS contains the gateway to external network, such as the Internet. And all traffic in the WiMAX network are either initiated at or destined to the BS. In other words, data flows between two SSs are not directly considered in our research. Instead, that kind of data flow can be separated into a data flow from SS to BS and another data flow from BS to the other SS. With such assumption, the routing problem in our WiMAX relay network becomes to decide a spanning tree or routing tree rooted at the BS to connect all nodes. The spanning tree can be either static or dynamic in time, depending on the actual problem.

2.4 Problem Definition

We consider two fundamental problems, routing and scheduling, in WiMAX mesh networks with smart antennas. The WiMAX standard [2] specifies a common MAC protocol for both the PMP mode and the mesh mode, including signaling protocols and message structures. But the standard does not specify either the algorithm for computing transmission schedule (i.e., scheduling algorithm) or the routing protocol. The routing problem, i.e., the tree construction problem, has not been well studied for WiMAX mesh networks, especially for WiMAX mesh networks with DAA antennas. However, without careful consideration for interference impact and resource availability, scheduling transmissions along the constructed tree may lead to poor throughput and serious unfairness. In our preliminary work [7], we show a Minimum Spanning Tree (MST) based routing approach performs very poorly.

Scheduling links with DAA antennas is quite different from traditional link scheduling with omni-directional antennas since simultaneous transmissions on two interfering links can be supported as long as DOFs are properly assigned to suppress interferences. The scheduling problem involves both link scheduling and DOF assignment, which makes it more challenging compared to scheduling with omni-directional antennas.

We also consider WiMAX networks with OFDMA techniques. In this case, the scheduling also includes the sub-channel assignment.

In order to get the optimum network performance, routing, scheduling, channel assignment, and DOF assignment should be jointly considered. However, this will make the problem way too complicated and almost impossible to solve. Therefore, we will try to solve the problem by considering only some of the 4 aspects simultaneously at a time. In our preliminary work, we considered the routing, scheduling, and DOF assignment and limit the network to single channel. Now we will consider a problem when the routing and DOF assignment have been previously decided. And what we concern now is how to schedule and assign sub-channels in a multi-hop OFDMA WiMAX relay network.

First of all, we summarize the major notations in Table 1.

Now, we are ready to define the scheduling problem.

Definition 1 *Given m links, the queue length q_i of each link e_i, and a total of K blocks. The scheduling problem seeks an interference-free block assignment*

Table 1: Notations

I_i^j	The interference matrix
K	The number of blocks
n/m	The number of nodes/links in the network
q_i	The length of queue at node v_i at the beginning of a frame
r_i^k	The data rate that can be supported by block k at link e_i
R_T/R_I	The transmission/interference range
$T/T^u/T^d$	The number of minislots in a frame/uplink sub-frame/downlink sub-frame

that assigns a subset B_i of blocks to each link e_i such that the utility function $\sum_{i=1}^{n} q_i \min\{q_i, \sum_{k \in B_i} r_i^k\}$ is maximized.

We choose the above objective function because it is known that if a scheduling algorithm can achieve the above objective in each frame or minislot, then it can keep the system stable, i.e., the queue in every node bounded [8]. Such a stable scheduling algorithm is also considered to achieve 100% throughput or maximum throughput [9].

Next, we present an ILP for the scheduling problem. The decision variables are described as follows.

1. $x_i^k = 1$ if block k is assigned to link e_i, $x_i^k = 0$ otherwise. (mK such variables)

2. y_i, the effective data rate obtained by link e_i according to the assignment. (m such variables)

ILP

$$\max \sum_{i=1}^{m} q_i y_i \tag{1}$$

subject to:

$$y_i \le q_i, \qquad \forall i \in \{1, \ldots, m\}; \tag{2}$$

$$y_i \le \sum_{k=1}^{K} x_i^k r_i^k, \qquad \forall i \in \{1, \ldots, m\}; \tag{3}$$

$$\sum_{j:I_i^j=1} (x_i^k + x_j^k - 1) \le 0, \quad \forall i \in \{1, \ldots, m\}, \forall k \in \{1, \ldots, K\}, \tag{4}$$

$$x_i = \{0, 1\}, \qquad \forall i \in \{1, \ldots, m\}. \tag{5}$$

In this formulation, constraints (2) and (3) make sure that

$$y_i = \min\{q_i, \sum_{k \in B_i} r_i^k\}, i \in \{1, \ldots, m\} \tag{6}$$

Constraint (4) is the interference constraint, which ensures that if two links interfere with each other, they are not given the same block. The objective function is to maximize the aforementioned utility function.

As mentioned before, a similar scheduling problem in OFDMA-based WiMAX single-hop networks has been shown to be NP-hard in [8]. It can be considered as a special case of the scheduling problem studied here since in a single-hop wireless network, every pair of links interfere with each other and no special reuse is allowed. Therefore, our problem is much harder.

2.5 Related Work

Transmission scheduling in WiMAX mesh networks with omni-directional antennas has been studied recently. Different centralized heuristic algorithms have been proposed for scheduling and/or routing in [10, 11, 12, 13] with the objective of maximizing spatial reuse. In [14], Cao *et al.* introduced a new fairness notion that is imposed contingent on the actual traffic demands. They presented an optimal algorithm to solve a scheduling problem whose objective is to maximize network throughput within their fairness model. In [15], the authors focused on QoS support and proposed routing and scheduling algorithms to provide per-flow QoS guarantees. In [16], a distributed algorithm was presented to provide fair end-to-end bandwidth allocation for single-radio, multi-channel WiMAX mesh networks. In [17], Sundaresan *et al.* showed that the scheduling problem to exploit diversity gains alone in a 2-hop 802.16j-based mesh network is NP-hard. They then provided polynomial-time approximation algorithms. They also proposed a heuristic algorithm to exploit both spatial reuse and diversity. The general link scheduling for multi-hop wireless networks with omni-directional antennas have also been studied in [18, 19].

Smart antennas have also received tremendous research attention. MAC protocols have been proposed in [20, 21] for 802.11-based ad-hoc networks with switched beam antennas. In [3], the authors presented a constant factor approximation algorithm for DOF assignment and a distributed algorithm for joint DOF assignment and scheduling in ad-hoc networks with DAA antennas. The authors of [22] presented a centralized algorithm as well as a distributed protocol for stream control and medium access in ad-hoc networks with MIMO links. A constant factor approximation algorithm was proposed for a similar problem in [23]. A unified representation of the physical layer capabilities of different types of smart antennas, and unified medium access algorithms were presented in [24]. In [25], Hu and Zhang devised a MIMO-based MAC protocol. They also studied its impact on routing and characterized the optimal hop distance that minimizes end-to-end delay. Cross-layer optimization for MIMO-based wireless networks has also been studied in [26, 27]. In [26], Bhatia and Li presented a centralized algorithm to solve the joint routing, scheduling and stream control problem subject to fairness constraints.

2.6 Preliminary Work

In [7], we studied routing and scheduling in WiMAX mesh networks with smart antennas. For routing, we formally defined the Interference-aware Tree Construction Problem (ITCP), which offers full consideration for interference impacts and DOF availability. We presented a polynomial-time algorithm to solve it optimally. It has been shown that the trees constructed by our algorithm outperform the well-known MST and BFS trees by simulations. We consider a special case of the scheduling problem where the number of DOFs in each node is large enough to suppress all *potential secondary interference*. We present a polynomial-time optimal algorithm to solve it. We present an effective heuristic algorithm for the general case scheduling problem, whose performance is justified by extensive simulations. Our simulation results showed that compared with other solutions such as first-fit+BFS solution, our interference aware routing and scheduling scheme can improve throughput by 154% and fairness index by 177% on average. We have also found out that the marginal gain of adding DOFs to each transceiver in the networks decreases. In our simulation, the network performance can achieve near the best with 3 DOFs for the most of the time. Adding more DOFs will not significantly improve the throughput or fairness of the network.

2.7 Research Plan

Since the block assignment problem is likely to be NP-hard, we will use heuristics to solve it. We will study greedy based heuristic and propose some other heuristics for this problem. To allocate blocks to links one by one may be considered. It is also possible to relate this problem to the maximal weighted independent set or the multiple knapsack problem (which are all NP-complete) and apply similar heuristics. We can also try to relax the ILP to an LP first, solve the LP, and then round the LP solution to get an ILP solution to the original problem. However, the rounding scheme must be carefully designed to make sure the rounded solution is both feasible for the ILP and has decent quality.

We will evaluate the proposed heuristics both theoretically and using simulations. For all the heuristics proposed, we will analyze their time complexities. We will also study the approximate ratio of all the heuristics and try to come up with proofs for some of them. An ILP solver can be used to compute the optimal solutions for some small problems. The optimal solutions can be a baseline for other heuristic to compare with. For problem instances with larger size, ILP solver may not be able to get a solution within reasonable time. Therefore, heuristics will only compare their performance with each other.

Since the problem we consider is centralized and static in natural, we will implement all the algorithms and heuristics, and simulate scenarios using a custom-written program. A more complicated simulator will be needed only if the proposed heuristics have been justified and incorporated into some actual WiMAX protocol implementations.

The estimated publications of our research on the WiMAX relay network will include at least one high-quality paper with both theoretical and practical contributions. We will submit our papers to some prestigeful conferences/journals.

3 Vehicular Ad Hoc Networks

3.1 System Model

We consider a hybrid VANET composed of vehicles constrained to move on roadways and APs deployed sparsely along the roadside. Each vehicle/AP is equipped with an 802.11 radio transceiver and a GPS receiver. Therefore, the vehicles are fully aware of their locations and mobility parameters such as speed and direction at all times. Each stationary AP is directly connected to the Internet by high capacity cables. We assume that information can be exchanged among APs via the wired network with a very short delay. We are only concerned with uni-cast communications between the Internet and vehicles. In addition, both APs and vehicles are assumed to transmit at the same fixed power level with transmission range R. Two nodes are considered to be able to send packets to each other if the distance between them is at most R and there is line-of-sight in between. When a vehicle is out of transmission range of an AP or terrains block their communications, other vehicles will be used to relay the data traffic. According to the WAVE/DSRC specifications [28], each vehicle is required to broadcast a beacon message to notify all of its neighbors about its existence, location, and mobility information, for safety reasons. The frequency of the broadcast is required to be at least several times per second. Therefore, we can utilize this mechanism to exchange node information among the entire interested region (maybe a service area of an AP), at a very small cost of increasing the broadcast packet size. In this way, an AP can obtain location and mobility information of all vehicles in the interested area. Moreover, by exchanging this information among APs via the wired network, each AP can be aware of all vehicles in a wide region. We further assume that all the vehicles' movements are constraint on highways and each AP has a digital map and knows the position information about all the highways in the interested area.

3.2 Problem Definition

In our VANET network, there are several fundamental problems.

The first problem is vehicular data communication. In this problem, we need to find out route to connect a vehicle to one of the AP, such that data communication can be set up between the vehicle and the external network. Vehicles will also use this mechanism to report emergency events to AP. Note that the route may be initiated by either a vehicle or an AP. Also, the route may be intermittent, which means it can be composed of several links that can only be active at different time intervals. In this case, the data will be sent from node to node in some time, and will be carried by a vehicle, waiting for the next hop occasionally. For different type of application, the service quality priority may be different. To transmit an emergency message, the delay is essential. To download information from Internet, the throughput may be more important and the delay can be tolerated in some extent.

The next problem is geo-cast. In this problem, a message does not have a specific intended receiver. Instead, it has a destination area where all vehicles in the area should receive the message. Geo-cast can be used to disseminate some road condition or accident information. The packet delivery ratio and delay are two of the most important measures in geo-cast. Moreover, it is often desirable that the geo-cast message will "stay" in the destination area in its lifetime. Such that not only those vehicles currently in the area will receive the message. Any vehicle entering the area in the future will also get the message.

The last problem is broadcast/multi-cast. Broadcast can be initiated by either a vehicle or an AP. The destination of a broadcast can be all vehicles or some vehicles satisfying certain criteria. For example, a traffic congestion alert message may only be valuable to vehicles moving in one direction. Another example is that some road condition alerts may only affect heavy loaded vehicles.

3.3 Related Work

Protocols have also been proposed for information dissemination in VANETs. In [29], the authors defined a message propagation function that encodes information about both target areas and preferred routes. They showed how this function can be exploited in several routing protocols and evaluated the effectiveness of their approach via simulation. Several vehicle-assisted data delivery (VADD) protocols were proposed to forward packets to the best road with the lowest data delivery delay [30].

V2V communication has been extensively studied [31, 32, 33, 34]. In [33], the authors evaluated the performance of a reactive routing protocol (AODV) and a geographic routing protocol (GPSR) based on realistic vehicular traces. They also presented the Preferred Group Broadcasting (PGB) strategy and the Advanced Greedy Forwarding (AGF) technique to enhance the performance of reactive and geographic routing respectively. A position-based connectivity aware routing protocol has recently been presented for V2V communications [34]. In [32], the authors proposed a prediction-based routing protocol to support the communications between mobile Internet gateways and vehicles. Lochert et al. [31] considered VANET routing in a city environment and presented a position-based routing protocol. In [35], the authors developed a statistical traffic model to study key performance metrics of interest in disconnected VANETs, such as average re-healing time and suggested that a new routing protocol is needed for such networks. However, ad-hoc routing for R2V communications has not been well addressed before, especially in the context of rural areas where network sparsity and terrain are significant factors.

3.4 Preliminary Work

In [36], we proposed to utilize the trajectory estimation combined with terrain information to predict the line-of-sight (LOS) and path loss of a link in the future. In our scheme, the node's future positions are predicted using a weighted average of historical velocities and accelerations. Simulations have been done using OPNET with terrain modeling techniques. Results suggested that, under typical mobility (speed, direction), the trajectory and link quality can be effectively predicted in a couple minutes for mobile nodes even in rugged terrain. The prediction and estimation can be used to improve the performance of other scheduling/routing processes and thereby enhance the network performance.

In [37], We proposed a novel routing protocol to provide reliable R2V communications suitable for rural areas, in which the stationary APs play a key role in route maintenance. The protocol includes a novel prediction algorithm which can predict the lifetimes of wireless links in a multi-hop network based on mobility parameters such as speed and direction, as well as the local terrain. The protocol uses routing algorithms which can find stable paths for packet forwarding based on the prediction. In the protocol, APs perform route maintenance by proactively replacing the current unstable routes with new routes that have longer lifetimes. In this way, service disruption can be minimized and the packet delivery ratio can be improved. Simulation results based on OPNET Modeler and the rural roadways in the Yellowstone National Park show that the proposed protocol substantially outperforms existing ad-hoc routing protocols. On average, our routing protocol outper-

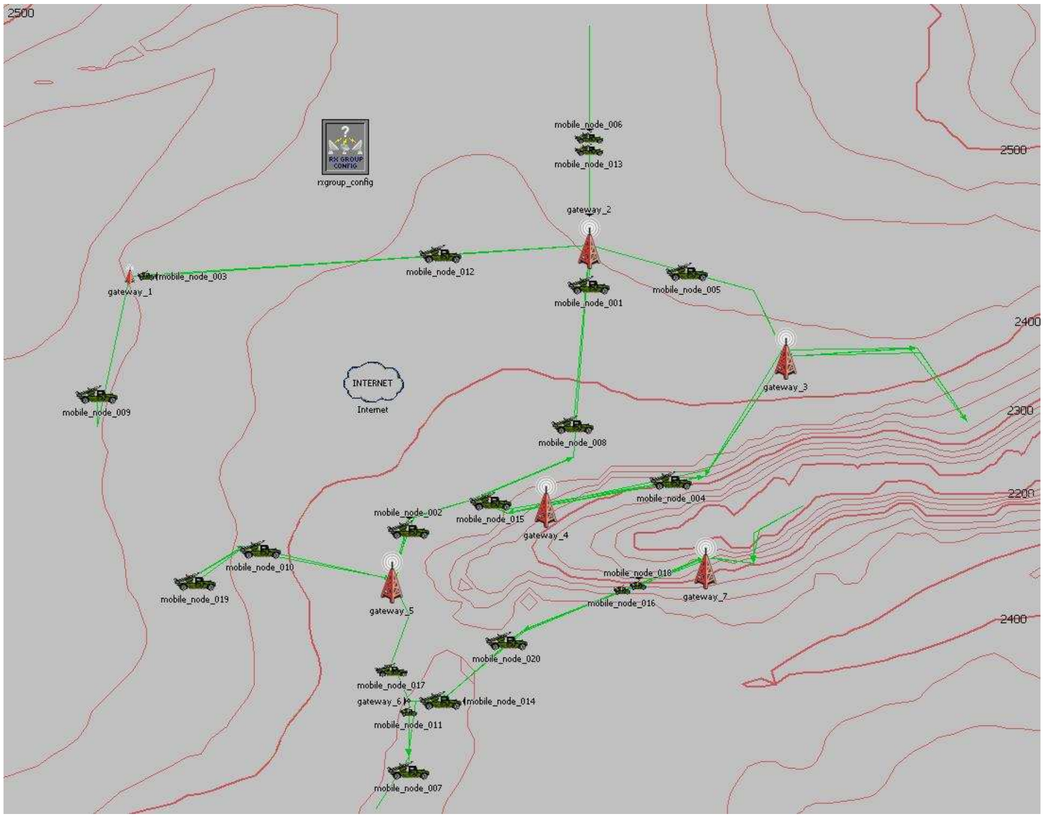

Figure 3: Map of roadways and terrains near the Canyon Junction

forms DSR by 18.4% in terms of packet delivery ratio, by 16.9% in terms of control overhead, and by 47.2% in terms of average packet delay. To our best knowledge, we were the first to study R2V communications in the context of rural areas and propose an efficient routing protocol.

3.5 Research Plan

We plan to study the ad hoc network routing techniques, the disruptive tolerant networking techniques, the geographic routing techniques, and how these techniques may be applied to solve our VANET problems. From our previous work and other related works, we feel that the data muling/forwarding scheme combined with geographic information and mobility prediction has the potential to provide a good solution. On the other hand, the typical routing process (route discovery, route response, route maintenance) may be delay and disconnection intolerant and therefore not suitable for VANETs in rural areas. Thus, we will first study the mobility and trajectory prediction problem and propose an algorithm that is capable of considering the road topology, the past and current mobility of vehicles, and the planned itinerary of vehicles if possible. Then, we will utilize the mobility/trajectory predict result and propose some heuristics to solve the routing problems in VANET. Different routing problems have different priorities of objectives. Therefore, we need to propose many heuristics and combine them to design a routing protocol. The heuristics running on vehicles should be distributed but the heuristics running on APs can be centralized since all APs are able to exchange information among them with low communication overhead.

Because of the dynamic nature and the complexity of our problems, we do not anticipate to have much theoretical contributions. Instead, we hope to propose valuable realistic routing solutions and will justify the performance of our heuristics/protocols by extensive simulations. We will implement our routing protocols in OPNET and use it for most of our simulations.

The expected output of our work on VANET will include at least one high quality paper published to a high-end conference/journal of wireless networking or vehicular technology area.

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