Symbiotic Highway Sensor Network

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Abstract—**Progression in consumer markets and transportation-related industry demands the capability for highway gateway Internet access to support a wide variety of applications. Forming a symbiotic relationship, both the transportation departments and the Department of Homeland Security would benefit by providing this gateway access to highway motorists in exchange for collecting and delivering roadside sensor data for distribution throughout the Internet. This paper introduces the symbiotic highway network which integrates sensor fields, mobile inter-vehicle ad hoc networks, and the Internet. The supporting experiments employ the Virginia Tech Transportation Institute (VTTI) Smart Road to analyze IEEE 802.11b/g/g+ throughput capabilities between mobile stations and roadside access points. An additional test verifies the capability of static and mobile IEEE 802.15.4 sensor platforms to communicate at city and highway speeds. All of the IEEE 802.11b, 802.11g, and 802.15.4 technologies maintain significant available throughput over a wide range of typical highway driving speeds using 2.4 GHz radio transceivers.**

Keywords- Wireless Sensor Network, Wireless Distribution System, Mobile Ad Hoc Network

I. INTRODUCTION

Connecting highway vehicles to the Internet and collecting data from remote sensor networks are emerging fields which provide valuable services to the consumer, commercial, public safety, Homeland Security, and military markets. The symbiotic network introduced in this paper integrates wireless sensor networks (WSNs), mobile ad hoc networks (MANETs), and roadside access points (APs) to provide the following mutual benefits: sensor networks gain data messaging to the Internet, and mobile stations gain Internet access in exchange for their willingness to forward the sensor data. For the traveler, highway Internet access provides web browsing, email, route directions, roadway conditions, and local area services. In addition to capitalizing on the needs of the traveler, commercial applications also include electronic toll collection, fleet tracking, and on-board vehicular diagnostics reporting.

State Departments of Transportation (DOTs) could employ the Internet and supporting highway mobile ad hoc networks to gather sensor readings from remote sites or to transfer updates to roadside hazard message signs. Fixed sensor sites report local weather conditions on the roadway (temperature, wind speed, road ice conditions, and visibility), bridge structural integrity, vehicular speeds, traffic congestion, and standard roadway usage statistics. DOTs also establish temporary networks to monitor traffic and program roadside hazard message signs throughout highway construction zones. If the sensors are near built-up areas, many state DOTs currently contract dedicated communication lines to gather the information. For temporary construction zone applications, DOTs employ IEEE 802.11-based network bridging systems with multiple line-of-sight radios to link remote sites to leased communications collection points. This sensor data relay technique is both expensive and time consuming to deploy. Likewise, the Department of Homeland Security (DHS) has a need to collect nuclear, biological, and chemical (NBC) data readings from sensors all along the highway, both local and remote locations. The sensitivity of DHS data may require limiting the types of collection vehicles to trusted safety and law enforcement agencies. Finally, the military could use all aspects of the static sensor, mobile ad hoc, and infrastructure hybrid systems to transfer command & control, communications, computers and intelligence (C4I) data throughout the battlefield and theater of operations.

II. OVERVIEW OF SYMBIOTIC NETWORK

The highway environment presents all of the major challenges faced in mobile ad hoc networking. Some of the limiting features include reduced radio ranges, partitioned networks, lowered signal-to-noise ratios (SNRs) due to the Doppler Effect, and limited access to power in remote locations. The symbiotic network shown in Figure 1 mitigates many of these highway challenges by localizing all data transfers to short-range messaging between sensors, vehicles, and roadside access points. Short-range communication preserves the sensors limited energy resources, and ad hoc message passing permits all network users to access the Internet beyond their individual communications range.

The symbiotic network provides a wireless distribution system (WDS) to transfer data from both the sensor field and MANET to the Internet. The sensors (S#) in the sensor field collect remote data and forward the information to the active

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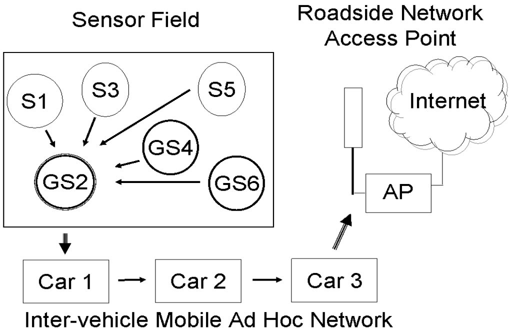

Figure 1. Symbiotic Network Architecture

gateway sensor (S1 → GS2). The gateway sensor then aggregates and transfers the data messages onto the highway to passing mobile ad hoc network stations (GS2 → Car 1) to store and forward to the Internet through the roadside access points (Car 1 → Car 2 → Car 3 → AP → Internet). Each of the individual networks and interfaces is introduced and explained in this section.

Sensor networks offer the ability for applications to monitor and react to distant events, but their remoteness introduces challenges in network control and power. In an effort to make inexpensive sensor platforms ubiquitous, these platforms have limited processor capability, memory capacity, and battery life. Small system platforms which integrate sensors, processors, and transceivers are referred to as *motes*. Table 1 illustrates the power and memory limitations of two leading motes. These mote systems generally operate on two AA batteries (3.0 volts) with an approximate 3000 mAh energy capacity.

In order to interface with the vehicular mobile ad hoc network without causing excessive energy drain on any one node, the gateway sensor nodes (GS#) in the proposed symbiotic network rotate the data traffic and network responsibilities to share their resources in a manner that is self-adaptive to changes in topology, traffic loads, and existing battery conditions. The sensors in the sensor field may be homogeneous, but they must be able to directly communicate with the vehicles on the roadway to serve as a gateway node. Sensor networks attain long network lifetimes by coordinating maximum sleep periods while meeting the latency requirements of all of the sensors in the network [1][2][3]. A proposed WSN MAC protocol called Gateway MAC (G-MAC) is specifically designed for the symbiotic network to collect sensor cluster data and forward it to a mobile network in an energy-efficient manner [1]. G-MAC's innovative architecture is motivated by the requirement for wireless sensor networks to minimize the time radios spend in both the idle and receive modes for extended network lifetime. G-MAC provides the ability for sensors to exchange data within a cluster for data fusion and forward messages out of the sensor network. Combining the advantages of both the contention- and reservation-based protocols, G-MAC provides significant energy savings by employing a centralized node to gather all transmission requirements during a contention-based period and then coordinating their distributions during a reservation-based, contention-free period. Then, without any additional overhead, the gateway duties are efficiently rotated among the nodes to spread out the increased network management energy requirements. After collecting all of the sensor field data messages, the gateway sensor node forwards the data to the mobile ad hoc network.

Table 1. Mote Microcontroller/Transceiver Platform Specifications

Platform	Mica2 [4]	TelosA [5]
Microcontroller	16-bit ATMega 128L	16-bit TI MSP430
MCU RAM	4 kB	2 kB
EEPROM	128 kB	60 kB
Radio	916 MHz Chipcon CC1000	2.4 GHz Chipcon CC2420
Data Rate	76.8 kbs	250 kbs

Next, the MANET collects the sensor data from the sensor gateway and forwards it toward roadside Internet gateway APs. To gather remote data in ad hoc networks, [6] explored the use of remote nodes summoning dedicated data collectors using long-range radios and then exchanging data using short-range radios. The symbiotic network eliminates the need for a dedicated message collector and long-range radios due to the close proximity of the sensor gateways to the abundant number of vehicles on the highway. Store-and-forward messaging bridges mobile network partitions which occur in sparse vehicular traffic conditions and enables reliable message traffic flow. Since highway vehicular traffic may stop during congestion, messages must be capable of propagating forward to the nearest access point. Highway experiments have shown vehicular ad hoc networks maintaining 1 Mbps communications using 802.11b devices within a 400m range of one another [7]. Additionally, simulations have shown that the motion of vehicles on the highway in sparse vehicular traffic conditions decreased message delivery delay through store-and-forward routing [8].

Finally, the MANET delivers the sensor data to the Internet through roadside APs. FleetNet, an international consortium project initiated in 2000, began the development of linking together vehicles and connecting them to internet gateways along the road [9]. Their objectives were to distribute locally relevant data and provide mobile users location-dependent information and services. The symbiotic network extends this concept by providing service incentives for the MANET stations to collect sensor data and encourages government agencies to build the infrastructure for the roadside Internet exchange.

Extensive research has been conducted to provide network routing in such a dynamic environment [10] [11], and this experimental work evaluates the IEEE 802.11b, 802.11g, 802.11g+, and 802.15.4 link transfer capabilities at highway speeds.

III. SYMBIOTIC INTERFACE TESTING

The following experiments were designed to validate each of the symbiotic network interfaces:

A. Mobile Station to Single Roadside AP

The IEEE 802.11b, 802.11g, and 802.11g+ mobile station to single roadside AP performance evaluation experiments were conducted on the Virginia Tech Transportation Institute (VTTI) and the Virginia DOT Smart Road located in Blacksburg, VA. A pole-mounted 12 dBi sector AP antenna and a 7.8 dBi omni-directional mobile antenna extended the mobile access radio coverage on the road. The performance of each of the protocols was evaluated on two separate quarter-mile segments of the road. Ixia IxChariot™ NetIQ endpoint tests measured throughput and delay for traffic directed from the mobile station to the AP at city and highway speeds – 20 mph through 70 mph. For consistency, each test employed the Buffalo Tech AirStation 125* high speed G54S access point with a wireless adapter using different compression and modulation settings for each of the 802.11b, g, and g+ experiments [12].

The 802.11b/g/g+ roadside AP exchanges shown in Figure 2 illustrate that both 802.11b and 802.11g technologies provide sufficient throughput capabilities across the range of city and highway speeds. The throughput degradation for each protocol is primarily due to the reduced SNR caused by Doppler spreading. The 802.11b direct sequence spread spectrum (DSSS) encoded signal sustained 5 Mbps throughput over the entire range of speeds. Although the DSSS is less bandwidth efficient, the processing gain reduced the effective channel noise and increased energy per bit (E_b/N_o), thereby increasing the SNR. The 802.11g Orthogonal Frequency Division Multiplexing (OFDM) modulated signal achieved a significantly higher throughput rate than 802.11b, but the performance degraded much more rapidly with both the distance from the AP and the vehicular speed. OFDM achieves a high spectral efficiency by dividing the available bandwidth into overlapping, orthogonal sub-carriers or sub-channels. The subsequent lower data rates of each of the sub-carriers reduce the multi-path distortion or delay spread, thus lowering inter-symbol interference (ISI) [13]. These overlapping sub-channels cause OFDM to be particularly susceptible to inter-carrier interference (ICI) in the presence of the Doppler Effect. Delay spreading frequency shifts cause the sub-channels to no longer be orthogonal; therefore, their channels overlap and cause them to interfere with one another.

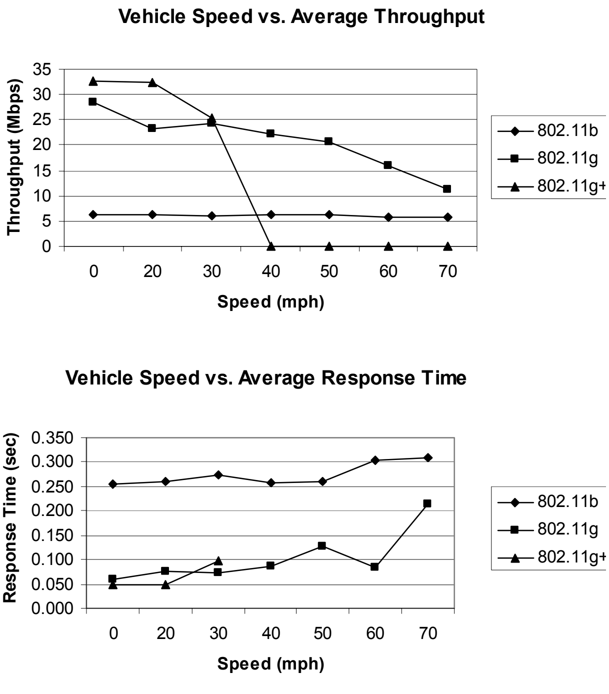

Figure 2. Mobile to AP Average Throughput and Response Time

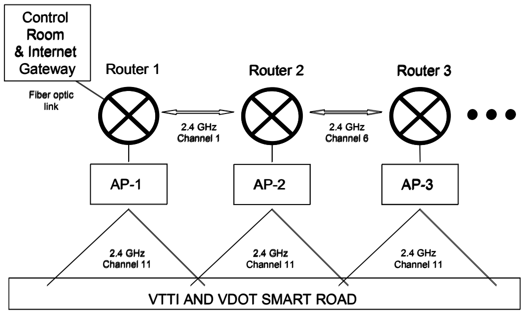

Figure 3. 802.11g Multi-hop Extended Service Set

The single AP roadside test also revealed that the advantages of the 802.11g+ high speed mode (125 Mbps physical rate) were only attainable at extremely low vehicle speeds. This technology typically employs dynamic packet bursting, fast frames, and hardware data compression to achieve additional throughput. Dynamic packet bursting is an IEEE 802.11e quality of service (QOS) technique designed to increase throughput by decreasing the interframe spacing and successively sending frames without additional channel contention [15]. While packet bursting increases the number of successively transmitted frames, fast frames increase the data payload to a negotiated size in order to increase effective throughput [16]. The combined effects of these techniques reduce the SNR fade margin and allow the Doppler Effect to quickly attenuate the signal. This 802.11g+ failure occurred between 30 mph and 40 mph in the mobile station to single AP experiment.

B. Mobile Station to Multiple Roadside APs

An additional set of mobile to roadside AP tests evaluated the performance of linking overlapping APs with multiple radios and routers to form a wireless distribution system layout as shown in Figure 3. This configuration created a continuous extended service set (ESS) to deploy in highway locations not offering adequate continuous line-of-sight coverage. Enhanced with pole-mounted 13.5 dBi Yagii antennas for the WDS, a mobile test successfully evaluated IEEE 802.11g technology using CISCO routers and radios. Figure 4 shows the 20 mph and 60 mph results of the 802.11g ESS maintaining data rates between 10 Mbps and 20 Mbps as the vehicle traveled over a mile and accessed four APs. The data rate fluctuations were due to the time varying multipath signal fading which reduced the SNR and transmission data rate. The ESS performance can be optimized by tuning the AP handoff SNR and orienting the AP sector antennas to provide the maximum coverage based

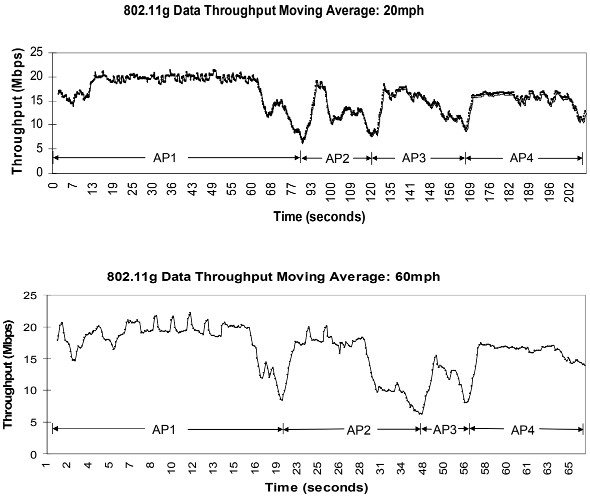

Figure 4. 802.11g Multi-hop Throughput Experiment

upon the anticipated handoff location. For example, in the 60 mph test shown in Figure 4, the mobile station maintained an association with AP2 beyond the point on the road where it passed AP3's sector antenna. In this case, tuning the SNR transition level to a higher threshold would cause the mobile device to switchover to AP3 earlier and increase the data throughput. The IEEE 802.11g ESS experimental results show that the network can maintain higher throughput levels than the maximum effective 5.5 Mbps associated with IEEE 802.11b technology at highway speeds.

C. Gateway Sensor to Mobile Station

The gateway sensor to mobile station interface tests employed both Moteiv Telos A and Crossbow Mica2 low-power wireless sensor modules to verify the ability for IEEE 802.15.4 low-rate wireless personal area network (LR-WPAN) platforms to transfer data at highway speeds. The Telos 2.4 GHz modules utilized on-board, inverted-F microstrip antennas, and the Mica2 916 MHz modules utilized an attached quarter-wave dipole antenna. Both platforms specify an approximate 125m outdoor transmission range. With the transmitting sensor modules placed on the roadside and elevated to one meter, a passing mobile module mounted on a car successfully received packets while traveling at speeds ranging from 20 mph to 70 mph.

Table 2. Telos A and Mica2 Gateway to Mobile Sensor Transfer

Speed Trial	Telos A Transfer	Mica2 Transfer
Static (baseline)	3,890 bytes/s	948 bytes/s
20 mph	49,400 bytes	6,050 bytes
30 mph	29,800 bytes	5,145 bytes
40 mph	24,900 bytes	3,920 bytes
50 mph	19,700 bytes	3,690 bytes
60 mph	15,400 bytes	2,660 bytes
70 mph	14,100 bytes	2,160 bytes

Table 2 shows the experimental transfer capability results for each of the two platforms at various highway speeds. With a 30 byte packet size, the static baseline entry for each device reveals that the Telos CC2420 250 kbps radio is capable of transmitting a maximum 130 packets/s, and the Mica2 CC1000 76.8 kbps radio is capable of transmitting a maximum 32 packets/s. Also, a vehicle traveling 70 mph has the ability with the Telos A motes to collect more than 14,000 bytes in one pass. Each packet includes a 5 byte MAC header (2 byte address, 1 byte active message type, 1 byte group id, 1 byte payload length) and a 2 byte CRC field. Since every packet must contend for the channel and respond with a physical layer acknowledgement, the effective transfer rate will significantly increase as the size of the packet approaches the IEEE 802.15.4 128-byte maximum packet size. Another test showed that the 70 mph data transfer increased by 28% from 11,000 bytes to 14,100 bytes by increasing the Telos A packet size from 20 bytes to 30 bytes. With regard to vehicular velocity, analysis of the data showed that the Doppler Effect had almost no influence on the transfer of data at the various speeds for the DSSS 250 kbps transmissions. The reduced data transfers for higher speeds were the result of reduced time within the transmission range of the static mote.

IV. CONCLUSION AND FUTURE WORK

The experiments conducted for this paper clearly validate the IEEE 802.11b/g and 802.15.4 interface capabilities at highway speeds and show that the symbiotic network concept is a viable option for a wireless store-and-forward distribution system. The IEEE 802.11g equipment sustained more than a 15 Mbps throughput capacity in transferring data from a mobile station to an Internet gateway access point, and the IEEE 802.15.4 wireless sensor platforms exchanged more than 15 kB of sensor data in one pass at 60 mph. Future research to further enhance the transmission links includes testing the new multiple input, multiple output (MIMO) smart antenna beamforming technologies. Also, evaluating the optimization opportunities in AP handoff SNR thresholds, sector antenna orientation on the roadway, and SNR-based data rate shifting will increase the available throughput capabilities of existing technologies. The symbiotic sensor network provides a cost-effective solution for sensors to preserve their limited energy resources while transferring data from remote sites to locations around the world. Given the numerous commercial markets and the proven wireless technology, the symbiotic network is today's solution for merging the highway onto the Internet.

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