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A Hierarchical Bus Rapid Transit System Based on Wireless Sensor Networks

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***Abstract*—Bus Rapid Transit (BRT) system is the key technology of Intelligent Transportation Systems (ITS). This paper is about the research on a hierarchical BRT system based on multi-tier Wireless Sensor Networks (WSN). It maps the features of WSN to BRT system and provides solutions for BRT technologies, such as Transit Signal Priority.**

I. INTRODUCTION

BUS Rapid Transit (BRT) applies the concepts of Intelligent Transportation Systems (ITS) and integrates other management knowledge with existing bus technologies. A BRT system is designed to effectively provide a more efficient and passenger-friendly quality of service. It is an incrementally enhanced transit mode, with good performance on travel time, reliability, identity, safety and security, and system capacity. All these features can be accomplished in multiple ways, such as integrating ITS technologies, special vehicle road infrastructure, larger capacity vehicles, etc. The inclusion of advanced technology in the BRT system design is discussed at length in references [1, 2, 3, 4].

For traffic monitoring and management, according to researches [5, 9, 16], networked wireless sensing and collaborative information processing offer unique advantages over traditional approaches. It brings new ITS technologies to the whole traffic surveillance and control industry. Its feasibility for large scale and everywhere deployment impact ITS in many applications. Sensor units with different sensing and communication capabilities are used to collect and process large scale dynamic traffic information. The wireless communication capability of the sensor networks also allows it to talk to other ITS systems [11].

In this paper, we will present a multi-tier wireless sensor networks for BRT System. It can be used to exchange information among traffic data collection, traffic signal control and traffic management. This paper is organized as following: the second section is about the framework of WSN based BRT System; the third part is about a BRT key technology, Transit Signal Priority System, and its implementation and performance evaluation. The final part is conclusion and future work.

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II. SYSTEM FRAMEWORK

Implementation of BRT systems consists of several ITS technological systems, including Transit Signal Priority Systems, Operations Management System, Driver Assist and Automation System [6], Passenger Information System, Safety and Security, Fare Collection. The suite of individual elements making up the presented, WSN based BRT system includes several key technologies, shown in Figure.1.

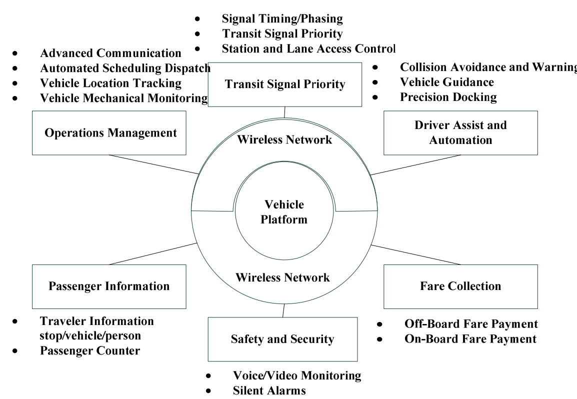


Figure.1. WSN based BRT System Key Technologies

1) Transit Signal Priority System: Transit Signal Priority System is the most important implementation of BRT systems. When a bus approaches an intersection, it can be passively detected, or it can actively send a request, to extend the traffic signal green cycle, so that it can rapidly pass through before the signal turns red. Signal Timing/Phasing modules in this system grant signal priority and improve flow of relevant BRT vehicles after retiming of signals. Station and Lane Access Control modules in this system introduce barriers to restrict entry to only BRT vehicles and make BRT vehicles segregated [12].

2) Operations Management System: Particular operations management technologies such as automated scheduling and dispatch system and automatic vehicle location system can help insure more headway and thus reduce waiting time. The BRT systems should provide Advanced Communication System for data communications among the vehicle, driver, dispatchers and others. There is Vehicle Location Tracking System automatically detects vehicle location, passenger load, schedule adherence, etc and informs Automated Scheduling

Dispatch System. There is also Vehicle Mechanical Monitoring System which helps to manage maintenance and detect possible vehicles problems.

3) Driver Assist and Automation System: It is important to warn the dangerous situations for high speed and large capacity BRT vehicles [10]. BRT Driver Assistant System can detect possible collision and take the form of forward, rear, and side hazard warnings, before the driver takes corrective action. Furthermore, BRT vehicles also need to be precisely docked at the stops. Vehicle Guidance (Lane Assist) and Precision Docking application will help to automatically steer and stop the bus at precise locations quickly and reduce station dwell time. It also allows BRT vehicles to travel at higher speeds than otherwise would be possible due to the physical constraints of the right-of-way.

4) Passenger Information System: It includes Stop, Vehicle, and Person Information Systems which help to provide good quality of services. The Stop Information System displays the scheduled and waiting time for next vehicle arrival. The information can be broadcasted to the neighborhood by short range RF or published on the web sites, which can be used for pre-trip planning.

5) Safety and Security: The vehicles and bus stops should be monitored and surveyed by audio and video. More intelligent work can be done based on the raw data, such as incidents detection by the smart cameras. And such incidents can give alarms to drivers, passengers or even operations center.

6) Fare Collection: Various payment schemes can be used to facilitate fare payment off-board and on-board. Some methods can be extended to analyze the passengers OD.

In WSN based approach of BRT system, all the components are connected with infrastructure networks, shown in Figure.2. In the network, high power Beacon/Router nodes form a mesh network along both sides of the road. The traffic signal controllers at the intersections are parts of the network, act as the WSN Coordinator/Sink node and supplemented to support BRT signal priority functions. WSN leaf sensor nodes, with video or other sensors, are used to detect BRT vehicles and collect vehicles and passengers' information. BRT vehicles may install some WSN nodes, dynamically join the network and broadcast its messages. There are also sensors installed on the bus stations, which communicate with BRT vehicles and help precise and safe docking. The Operation Management Center broadcasts the objective traffic control goals to the connected traffic signal controllers using broad band wireless network, such as GPRS, 3G technologies [15].

This system is highly configurable and extendable, taking benefits of the WSN approach. WSN is an Ad Hoc network, in which mobile nodes can dynamically join and cooperate with each other. WSN also provides varieties of traffic data collection methods with different kinds of sensors. The multi-tier WSN architecture can be applied to several BRT components and fit for large scale deployment. The collected traffic data can be easily shared with other ITS components through WSN data aggregation.

III. Transit Signal Priority system Based on Wireless Sensor Networks

A. *Transit Signal Priority System Architecture*

There are several BRT technologies described above, among which Transit Signal Priority will be specially presented in this section.

1) Architecture Diagram

In our approach, Transit Signal Priority System can be separated into information layer, signal priority layer, and management layer, shown in Figure.3.

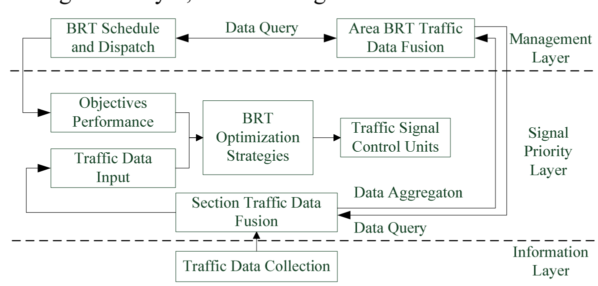
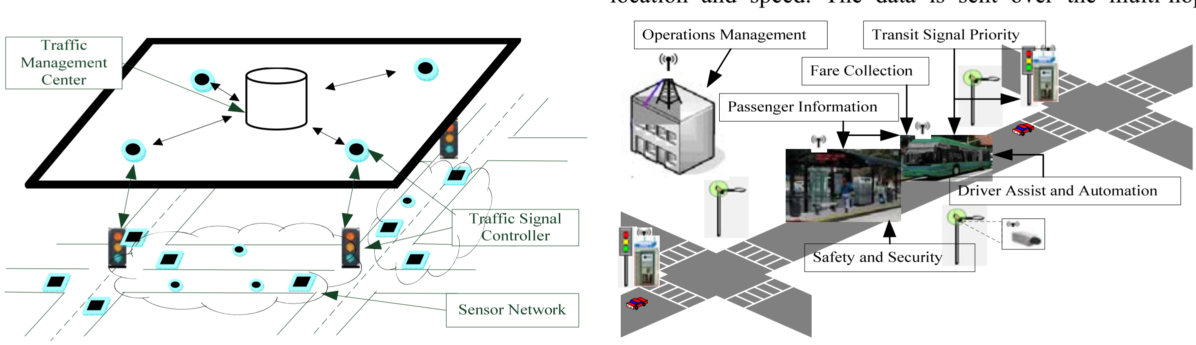


Figure.3. Transit Signal Priority Systems Architecture

At information layer, several kinds of sensors are used to detect BRT vehicles and collect their information, such as location and speed. The data is sent over the multi-hop



a. System Abstract

b. System Deployment

Fig.2. WSN Based BRT System Overview

wireless sensor networks and aggregated to the signal priority layer, where BRT optimization strategies take the information as input and compare it with Management Layer performance objectives, then make signal priority with various methods. The output optimized signal control strategy is finally sent to signal control units. Taking advantage of scalable WSN features, the road section traffic data can be aggregated to the area traffic data. Traffic Management Center can query this data and make more precise schedule and dispatch management.

There are several BRT Signal Priority strategies. Our approach is shown in Figure.4, which is based on the on-time schedule theme. The priority signal can be given only when BRT vehicles are behind schedules. If signal controller predicts that BRT vehicles would be delayed, it starts the following signal priority process.

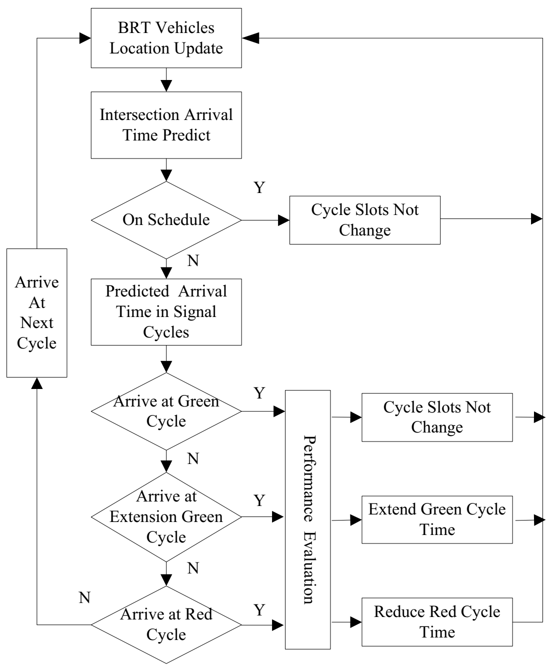


Figure.4. BRT Signal Priority Process

2) WSN for BRT Signal Priority

According to researches [5, 9, 16], lots of WSN features can be mapped to the Traffic Control. By adding other sensing modalities to the traffic multi-functions wireless systems, it can be used to exchange information between different ITS systems and extend ITS concepts [8, 13].

Our Multi-tier Wireless System for BRT signal priority is briefly shown as Figure.2.a. Since this Multi-tier WSN is deployed along the roads, its topology is highly specified according to the environment, shown in Figure.5. Clustered sensor nodes for BRT vehicles detection, (2~4) in Figure.5, which can be video sensors or magnetic sensors, are around the beacons/router nodes, (1) in Figure.5, which form an Ad-hoc multi-hop mesh network. Data is aggregated to the sink/gateway node, (5) in Figure.5, which is installed as a module on the Traffic Signal Controller at the intersections. This mesh network is very robust. Taking node (1) in Figure.5 as an example, when this node is power down or removed from the network, the network route changes the transit path accordingly, dashed shown as Figure.5.

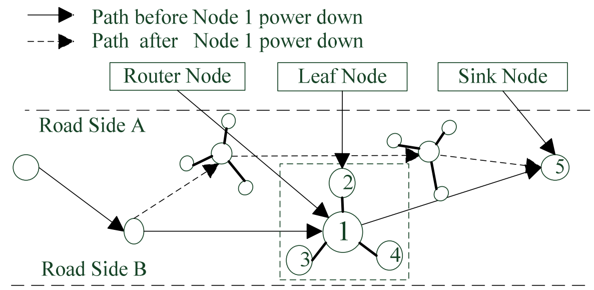


Figure.5. WSN for BRT Signal Priority

In paper [17], the nodes near the gateway are always busier and consume more power. Therefore, some strategies should be implemented to reduce the nodes power consumption. A simple scheme is that each base bone node adds its data to the MAC transmission packet and forward to the next. If a vehicle is present, the node composes a transmission packet with MAC header, data frames number, data frame, the appropriate time, node ID, and Cyclic Redundancy Code (CRC). As mentioned before, each node has its own data frame, which consists of a node ID and collected data. Since the nodes are limited, the largest MAC transmission packet data section is large enough to hold all information. This scheme can dramatically reduce the network power consumption with only tolerable massages delay.

B. System Integration

1) Sensor Nodes Design

(1) Router Sensor Nodes: A typical sensor node [18] is shown in Figure.6. It adopts ATMEL 8 bits ultralow power ATMegal1281V MCU and wide range AT86RF230 RF Transceiver (Radio), RF transmission power is programmable from 3 dBm to -17.2 dBm. With 10 bits ADC channels and I2C, SPI, UART, it can be easily connected with several sensors.

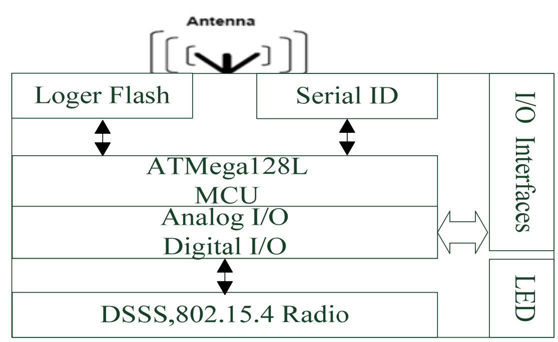


Figure.6 A Typical WSN Node

AMR and acoustic sensors are well discussed according to document [7]. The earth's magnetic field strength is roughly equal to a half-gauss in magnetic flux density, so a low field and high sensitivity magnetic sensor is needed to measure the disturbance of the magnetic flux lines when the Earth's magnetic field penetrates a vehicle. And the sensor should be able to classify the BRT vehicles from the others. The small size magneto-resistive sensor is very suitable, in which Anisotropic Magneto-Resistive (AMR) is more widely used than Giant Magneto-Resistive (GMR) type sensor.

(2) Video Sensor Nodes: In our approach, we also use video based sensor to detect BRT vehicles. The Crossbow Imote2 is very fit for the use [18], shown in Figure.7. Marvell high performance, low power consumption PXA271 processor provides the ability for complex video process with enhanced multimedia support. Imote2 also supports CMOS Camera interface and USB based web camera which can be used for low cost video surveillance. It is also integrated with TI CC2420, an 802.15.4 compliant RF chip, which can be programmed to communicate with other sensors or router nodes.

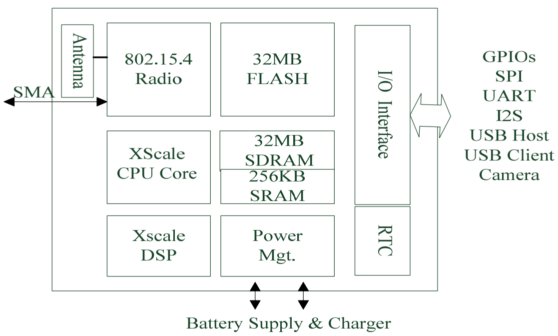


Figure.7. Video Sensor Node Hardware

The software architecture of video sensor node is shown in Figure.8. It uses embedded Linux and TinyOS compliant 802.15.4 MAC kernel driver for RF chip. The image processing can be done by applications based on provided OpenCV libraries. After video processing, the needed traffic data is collected, such as vehicles detection and vehicles velocity. We have developed a video-based vehicle counting system on TI DSP platform and the previous work can be easily ported to Imote2 platform [19].

BRT Supported Applications		
User Libs	Video Process Libs	Receiver & Sender
Linux Kernel	Camera Driver	802.15.4 TOSMAC Driver
Hardware		

Figure.8. Video Sensor Node Software Architecture

(3) Signal Priority Controller: The road section wireless sensor network gateway node is installed as a module on Traffic Signal Controller. The gateway node is connected to signal controller through cables (Ethernet ad UART). Traffic Signal Controller receives the data from the gateway and makes the signal priority with several strategies. Traffic Signal Controller also communicates with Traffic Management Center (TMC) through the broad band communication module installed [14]. Our Signal Priority Supported Traffic Signal Controller is highly modularized, shown in Figure.9. It can figure out BRT vehicles arrival time and decide how to give priority through analyzing the received data, and then change the green/red cycles accordingly, the algorithm is shown in former Figure.4.

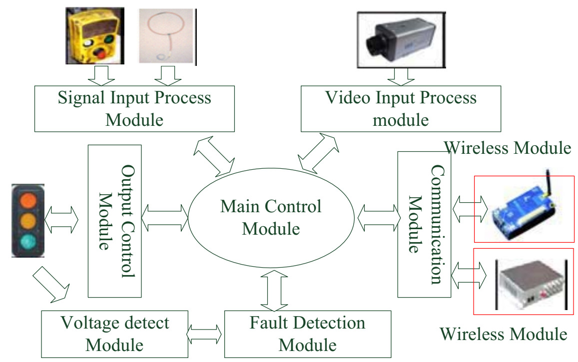


Figure.9 Signal Priority Supported Traffic Signal Controller

C. *Performance Evaluation*

BRT vehicle detection is the critical component for the implementation of the signal control strategies. For a high-speed approach, advanced detection is required at 200 to 300 meters upstream of the intersection, as well as the speed and classification of vehicles at real-time.

Our test bed consists of several IRIS and Imote2 nodes from Crossbow, and a BRT signal priority supported Traffic Signal Controller, show in Figure.10, and described in section B.

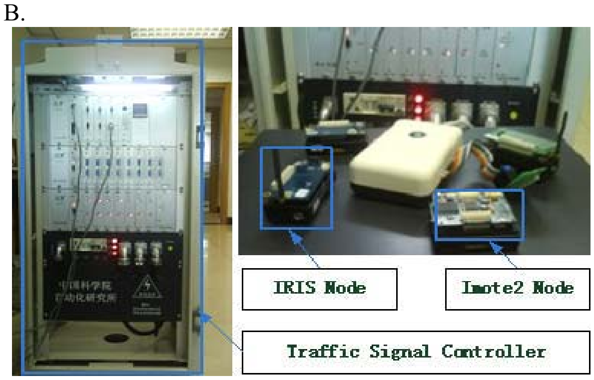


Figure.10 Signal Priority System Test Bed

The delays in BRT signal priority system consist of several parts. The first one is the time Imote2 video sensor node spending in vehicle detection video frames processing. An edge detection sample application of is run for delay evaluation in this case. The second one is the time spent in WSN messages forwarding, which consist of Imote2 to IRIS node time, and IRIS node to Signal Controller gateway node time. The third delay is the time consumed by a real time thread running in Signal Controller which gets and processes the message from the Ethernet port, mainly consists of task preempt latency and IRQ response latency.

The delay testing method is as following: (1) Imote2 gets the timestamps before and after processing the video frame and then gets the delta time; (2) Imote2 sends the wrapped timestamp to the WSN after video processing. Signal Controller receives the timestamp data, unwrap it and compares it with the synchronized local timestamp and then gets the delta time. (3)Finally, Signal Controller gets the timestamp before and after processing the messages and then gets the delta time. The maximum delays measured on the test bed with 100 test cases are as TABLE I.

TABLE.I. SYSTEM MAX DELAYS

Delays	Time (ms)
Imote2 Event Processing	950
WSN Msg Forwarding	164
Signal Controller Msg Processing	710
Total	1824

For a typical intersection timing tables, the whole delay is acceptable and should be considered in the Signal Priority strategies, especially in vehicle arrival prediction algorithm. However, the delays should be further analyzed with software optimized and performance improved.

IV. CONCLUSION AND FUTURE WORK

BRT system is a key component of ITS. Lots of researches are conducted to improve its performance. With more widely and proved efficiency uses of WSN in ITS, this paper intents to bring out the research on a novel, extendable BRT system based on Multi-tier Wireless Sensor Networks. It helps to map the good features of WSN to BRT systems and provides solution for BRT technologies, such as Transit Signal Priority in details. There are lots of things to be done for a WSN based BRT system with full features, such as collision warning, and vehicle assist and automation etc. Our future work includes: (1) Implement more functions of BRT Transit Signal Priority system and enhance its real time performance. (2) Evaluate BRT signal priority impact on other ITS components. (3) Implementation of more BRT technologies based on the multi-tier wireless sensor network.

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