Urban Traffic Control System Architecture Based on Wireless Sensor-Actuator Networks

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Abstract: **-** This paper proposes a novel architecture for efficient implementation of scalable and flexible urban traffic control in modern cities. The purpose is to optimize the vehicle and pedestrian traffic flows without affecting safety. In a hierarchical three-level control strategy based on qualitative and quantitative processing, the lower level is represented in our view by wireless sensor-actuator network clusters that control the traffic lighting system in a particular intersection, the second level developed on base stations and the highest, third-level, are represented by knowledge-based systems that implement efficient traffic strategies meant for different areas or for the entire city and for coping with other city systems.

Key-Words: **-** Wireless sensor-actuator networks, control systems, monitoring systems, sensor networks, virtual instrumentation, fault detection and diagnosis, distributed parameter systems.

1 Introduction

As you can see for the title of the paper you must Wireless Sensor-Actuator Networks (WSANs) have emerged as a brand-new generation of wireless sensor networks, that can be used as proficient control solutions for large-scale distributed systems [1][2]. WSAN encapsulates two types of network nodes that operate sinergically: sensor nodes designed to observe the environment and actuator nodes designed to actively interact with the environment. From an extensive assortment of possible application domains, the city control systems represent an important challenge.

Modern cities are envisaged as being permanent settlements with high quality of life and high standards of safety offered at acceptable costs [3]. In this perception, numerous new challenges have to be considered in order to solve the city related problems like: easy access to all locations, effortless supply for any entity inside the city with goods and services, best possible city management, etc. Furthermore, the associated operating costs (e.g., financial costs, time, pollution, etc.) are continuously escalating to prohibitively levels. The use of intelligent and autonomous decision making systems to improve the exploitation of the city infrastructure (e.g., traffic, lighting, heat and water delivery, parking, etc.) becomes an attractive option for tackling some of the enumerated challenges, including the proficient reaction to different kind of unexpected/undesired events.

The urban traffic system, being an essential constituent of any modern city infrastructure, has to fulfill the nowadays expectations to provide reduced waiting times, diminished gas consumption, and lower levels of pollution. Efficiency parameters may possibly include the number of vehicles serviced in a specified time interval, the time required to cover a specific trajectory, the pollution and noise levels due to traffic, the highest number of vehicles that can be serviced without queuing as well as parameters that describe exceptional circumstances such as providing the shortest travel time for police cars, ambulances, fire-trucks, etc. The tasks that have to be accomplished might also include finding the optimal route for vehicles, identifying and warning about traffic "hot spots", re-routing in case of accidents and other unpredicted obstacles, redirecting traffic to avoid high pollution levels in a zone, and more.

In these circumstances, the use of a hierarchical control structure is almost a must, combining the advantages brought by the use of both centralized and localized algorithms [4]. Centralized algorithms express global goals and evaluate decision on a central processing unit, which also collects the data sampled by the individual sensing units. Localized algorithms affect city areas and are relying on a small number of neighboring units for taking decisions. In addition, they include a mechanism for percolating the local interactions to the global area, so that large scale decision making is also possible.

In this paper we developed a novel concept for implementing the hierarchical control using an architecture developed around wireless sensor-actuator networks (WSANs). The control hierarchy has three levels: lowest level which controls a single intersection is implemented by a WSAN cluster; the second level that executes the zonal traffic coordination is implemented on the base stations of WSANs; and the highest level that optimizes the traffic parameters for the entire city is implemented as a knowledge-based decisional system on a secured computer.

This architecture has the capability to control the traffic in each intersection by satisfying the set of conditionalities imposed by the strategies and scenarios developed by zonal/city control units.

The rest of the paper is organized as follows. Second section presents the proposed hierarchical control for city traffic. Third section describes our view in implementing the decentralized local and zonal traffic control. In the end, conclusions are offered.

2…Hierarchical control architecture for urban traffic system

Our strategy relies on the assumption that an efficient urban traffic control system has to solve both local (crossroads related) and global (zones or city related) optimization problems with constrictions imposed by other interrelated city systems or by expected/unexpected events [5]. The answer to this multifaceted control problem can be offered by a multilevel control structure.

Hierarchical control can be perceived as a strategy to solve complex control system problems by decomposing them into simpler sub-problems and assembling their solutions into a "functioning" hierarchical structure [6]. Exploiting hierarchical control for urban traffic system reveals two significant advantages in contrast with conventional flat methods: first, hierarchical structures are scalable [7], which is essential for very complex systems, such as urban traffic; second, hierarchical control provides additional flexibility in changing the control application, such as in adding or removing monitored entities (streets and zones in our case), or integrating the city traffic control system with other applications, such as street lighting management or city transportation system.

Fig. 1 illustrates our proposed control structure for the urban traffic control system that includes on the lowest level the Intersection Traffic Units (ITUs), on the intermediate level the Zone Traffic Coordination Units (ZTCUs) and, on the highest level, the Traffic Coordination Unit (TCU)). Its main functions are: a) to control and monitor the street traffic in normal and special conditions; b) to minimize the overall energy consumption and pollution; c) to diminish the operation costs of the traffic control system; d) to generate statistics and

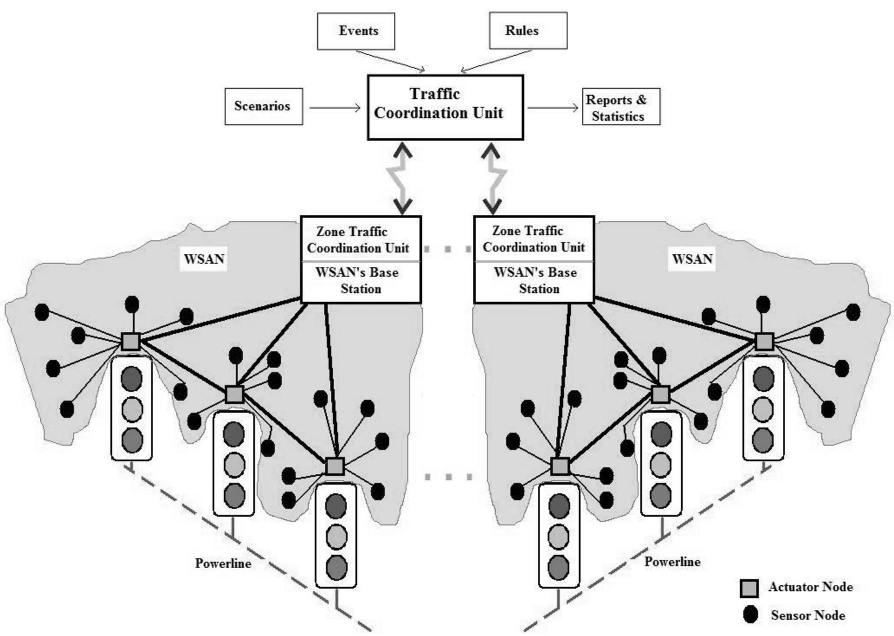

Fig. 1. WSAN based city traffic control system

reports; and f) to help secure functioning even in case of malicious attacks.

In order to control the urban traffic in a city area, a cluster-based WSAN (Fig. 2) has to be deployed. Each WSAN cluster includes several traffic measuring sensor nodes and one actuator node that plays the role of cluster head. This actuator node replaces the traffic light controller for the intersection and solves the following problems: aggregates the measurement data provided by sensor nodes that belong to that specific cluster; performs the local control algorithm; provides the time intervals for each phase of traffic lights; forwards data to other clusters (adjacent intersections) or to base station with the role of ZTCU.

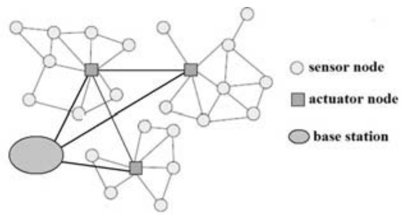

Fig. 2. Cluster-tree topology for WSAN

The main components of our hierarchy are presented in Fig.3.

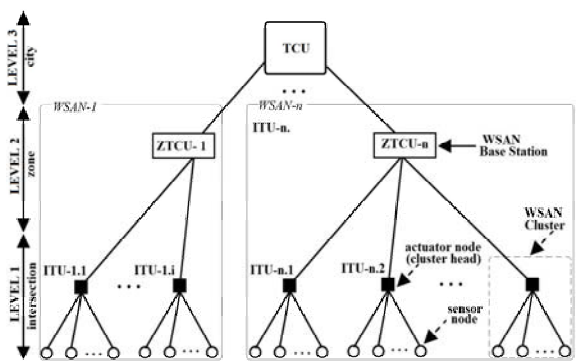

Fig. 3. Control system hierarchy for urban traffic

• *Intersection Traffic Unit (ITU):* The control loop for this level includes a WSAN cluster with its wireless sensors nodes used for measuring traffic parameters and with its actuator node that implements both actuator and control functions. ITU receives inputs from sensor nodes within its cluster, such as inductive loops embedded in the pavement, video cameras, etc., on the traffic intensity in each direction, the length of the vehicle queues, the time taken for a vehicle to move through the intersection, and more [4]. The control algorithm implemented on this level of the hierarchy embodies a knowledge-based system with the main objective of optimizing the traffic parameters for a specific crossroad based on the measurements provided by traffic sensors included in the corresponding cluster of a WSAN. The ITU behavior can be extended with actions for preferred “vehicles”, like bicycles or pedestrians, which ought to have higher priority to pass through the intersection. ITU might also include a “default” behavior which is executed whenever the controller fails to converge on a predictable operation.

• *Zone Traffic Coordination Unit (ZTCU):* ZTCU is located on the WSAN base station and coordinates the operation of ITUs in a group of intersections to optimize the traffic through each of them based on specific actions that involve redirecting the traffic flow, implementing “green waves”, etc. Zone Traffic Coordination Unit receives data from the participating ITUs, such as traffic characteristics, vehicle queues, moving obstacles, and so on. It might also receive inputs from the upper most Traffic Coordination Unit (see next item) about the targeted traffic efficiency goal, like avoiding long queues and minimizing the delay of vehicles. ZTCU computes optimal strategies for different traffic situations (patterns) in the intersections. Zone Traffic Coordination Unit is in charge for implementing zonal street traffic strategy to satisfy the traffic objectives and constraints specific for that area (e.g. the implementation of “green wave” as an intentionally induced phenomenon in which a series of traffic lights are coordinated to allow continuous traffic flow over several intersections in one main direction). ZTCU is implemented as a knowledge-based system that provides reference values for each ITU and assures the completion of energy-efficiency mechanisms for WSAN under its jurisdiction by scheduling the ‘sleep’ and ‘idle’ states of sensor nodes using WSAN base station.

• *Traffic coordination unit (TCU):* TCU is the highest-level controller. It is implemented as a knowledge-based system, which distributes the tasks to the zonal ZLCUs and solves the interactions between different city utilities systems, so that the overall objectives and constraints for the entire city are met. It maintains connections to all other systems within City Control Unit (e.g., Traffic Control Coordination Unit, Disaster Management Unit, Transportation, Public Health, Utilities’ Delivery Systems, etc.), and responds by adjusting the traffic parameters in case of unscheduled events like decreasing the traffic flows through the areas with traffic jams, street work, car crashes, etc. or coordinating the urban traffic in case of disasters. Moreover, TCU tunes the ZLCU parameters in connection with scheduled events, e.g., fairs, concerts, sport competitions, community events and many more. Deterministic strategies, rules and scenarios are employed in the decision making process at this level.

3 Decentralized local /zonal traffic control

Based on continuous improvements in communication, computing and sensing technologies, a novel category of wireless networks evolved: wireless sensor-actuator networks. WSAN is a noteworthy category of wireless sensor networks developed as a technology in the last couple of years, formed of two basic kinds of nodes that work in a collaborative manner [8]:

a) sensor nodes which are tiny, low-cost devices with limited energy, computation, sensing and communication resources; They operate as passive devices that only collect data about the environment or physical systems, and transmit the gathered data to controllers/actuators through single-hop or multi-hop transmissions.

b) actuator nodes which are high-priced and resource-rich devices provided with a sufficient amount of energy, stronger computation power, extended communication range; they have the ability to take decisions and perform appropriate tasks in reaction to the sensor measurements to modify the behavior of the environment or physical systems.

In our method for hierarchical city traffic intelligent control, we rely on the WSAN architecture presented in Fig. 4(a), where there is no explicit controller entity, controller's function being provided by potent actuator nodes.

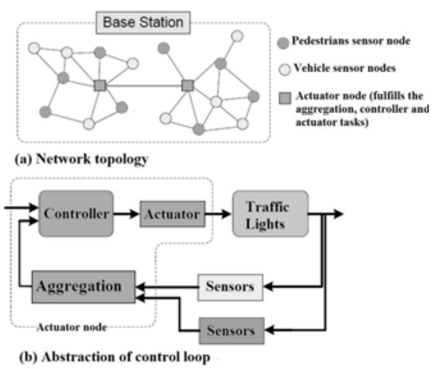

Fig.4. WSAN architecture without explicit controllers

Traffic parameters are measured by various types of sensor nodes and are deployed in the proximity of crossroads for vehicle queue measurement and pedestrian detection (Fig.5) [9].

The data collected by sensors will be sent straightforwardly to the corresponding actuators via single-hop or multi-hop transmissions. The actuator nodes, acting as both actuators and controllers (Fig. 4(b)), process the incoming data by aggregating the measurements provided by sensor nodes within their cluster, by performing the required traffic control algorithms and taking proper actions (e.g. increase or decrease the time intervals for each phase of traffic lights, reporting the crossroads status to the base station, etc.).

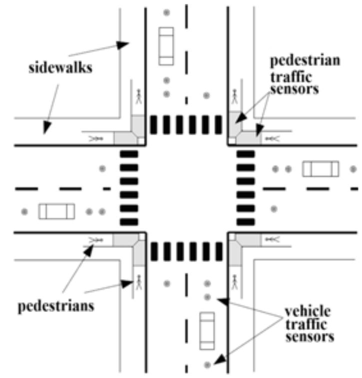

Fig.5. Sensor placement example in an intersection

In order to obtain realistic information from a great variety of sensor nodes that can be deployed in an intersection, all the measurements are sent using secure transmissions to the actuator node, where an aggregation algorithm provides the parameters for local traffic control. Such parameters can be the length of the vehicle queues on each traffic lane, the presence of the pedestrians, the average speed of the vehicles passing through the intersection, etc. and other traffic-related parameters like weather or road conditions (temperature, quantity of precipitations, icy roads, etc.). Moreover, data aggregation techniques are useful in overcoming individual sensor calibration issues and improving confidence in observations that are derived from multiple sensors [10]. The aggregation methods that are relevant to be implemented on actuator nodes vary from majority voting algorithm to average techniques and depend on the number of sensors that provide the same information and on the type of information they are providing.

The controller algorithm implemented on the actuator nodes of WSANs have to work according to the following specifications:

• all the global parameters required for the intersection traffic control are sent by Zonal Traffic Coordination Unit to actuator nodes through zonal base stations whenever is necessary;

• each actuator node plays the role of a crossroad traffic light control unit, having access to long-lasting electric power; Thus, even complex control algorithms can be implemented on this type of nodes.

• controller's inputs are measurement values provided by different types of traffic sensors; This means that the information provided by sensor nodes

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has to be aggregated on actuator node before it is processed by the control algorithm.

• controller's output is the time intervals for each traffic light phase and the sequence of phases that conduct to an optimization of the traffic flows.

Significant positions in our strategy have the zonal base stations which are considered to be laptop class devices and have to fulfill the following tasks: i. gathering relevant data from WSAN clusters and their transmission to City Coordination Unit for report purposes; ii. transmitting the global control parameters meant for zonal strategy implementation to all actuator nodes under their jurisdiction; iii. applying energy efficient schemes for sensor networks in order to preserve their batteries (e.g. sensor nodes are maintained in their 'sleep' state and are shifted to their 'idle' state only when necessary).

An important advantage in implementing our architecture for city traffic control system arises from a potential enhancement: the use of the same WSANs for controlling the urban lighting. Such an extension of our architecture is based on the traffic sensors already deployed for lighting control and on the processing power of the actuator nodes which can cope with the city lighting control, too.

4 Conclusion

In this paper we presented the architecture of a hierarchical city traffic control system based on the use of wireless sensor-actuator networks. The first level of the hierarchy is represented by WSAN clusters that individually control the corresponding traffic lights in the related intersections. The second level is represented by the zonal control systems implemented here as knowledge-based systems. The higher level is meant for coordinating the local controllers in special cases, like disasters, concerts, etc. and to interact with other city control systems. It has to be developed as a knowledge-based system that selects an optimal strategy and, by this, computes the control parameters for ZTCUs. This approach has some major advantages like scalability, adequate handling of expected or unexpected events and simple integration of urban traffic control with city lighting control system.

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