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# TACTICS: Adaptive Framework for Reactive Control of Road Traffic Systems

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**Abstract – This paper proposes an adaptive traffic framework used to respond to continuous traffic changes in a network with control points in key intersections as derived trough complex network analysis. The main actuators of this framework are the intelligent traffic ligths which run the entire adaption algorithm without affecting the current deployed infrastructure. We illustrate the proposed solution through a case study conducted over the city of Timisoara, Romania. Our algorithm was tested using the VISSIM simulator and results show improvements in reducing waiting times and queue lengths over the currently deployed solution based on fixed time plans.**

**Keywords: traffic control framework, intelligent transportation systems, complex network analysis, urban topology, road traffic quality**

## I. INTRODUCTION

Congestion and its side effects are real problems that concern any urban transport system. Intelligent Transportation Systems (ITS) gather the most significant work done in this direction in order to improve urban transportation operations.

Large and complex systems are still being developed and deployed all over the world. A large number of them use a centralized control scheme to coordinate traffic movement based on the input read from pavement installed sensors, cameras, video surveillance, on-car devices and the list could continue [2]. But, all these control systems require a framework to guide the integration of all used smart devices into a real intelligent system.

Based on the data acquisition methods traffic systems can be static or real time. The real time control ones respond to traffic changes by processing the recorded data as they read it. A further analysis reveals that real time traffic systems are reactive or proactive [2]. In the proactive approach, traffic control system is adapting its operations based on the data estimated to be on a certain moment of time. Reactive systems respond to traffic changes with a certain delay, caused by the read time needed to determine actual traffic conditions. Proactive systems were deployed in the early stages of ITS development, but do not seem to have a general solution and continue to motivate the research in this direction. While algorithms trying to forecast traffic conditions are still being developed [3], reactive methodologies are already implemented by systems like, SCATS, SCOOTS, UTOPIA, MOTION or BALANCE [2].

Instead of trying to forecast traffic conditions, another solution is to react quickly and adapt to traffic changes as they occur. Minimizing the reaction time of a system to adapt to traffic changes where reactive systems still have to be improved. The most used traffic actuator by the reactive systems remains the traffic signal [4]. From changing phase order to modifying cycle length and switching between different timing plans to find the right phase order are just few of the currently used solutions [5]. Reactive systems are systems whose role is to maintain an ongoing interaction with their environment rather than produce some final value upon termination. Typical examples of reactive systems are Air traffic control system, programs controlling mechanical devices such as a train, a plane, or ongoing processes such as a nuclear reactor.

TACTICS is the adaptive traffic framework envisioned to respond to continuous traffic changes in a network that implements the three layered formalism proposed in [6]. The main actuators of this framework are the intelligent traffic lights which run the adaptive green time algorithm. The hardware deployment is done without affecting the current infrastructure. A new hardware that uses only video camera detection and communication module will be used, without the need of installing pavement sensors where they are not already installed. The proposed workflow was partially tested as described in [6],

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using the VISSIM [19] simulator. Improvements were obtained in terms of reducing waiting times and queue lengths over the currently deployed solution based on fixed time plans.

This paper proposes a framework for developing a reactive traffic control system based on the adaption of green time values for traffic signals without modifying the cycle length or phase order. As there is no general solution found yet, we define an approach where traffic lights are the only active system components that self adapt and communicate each other in a distributed manner. We cover the exchanged message definition required by TACTICS, in order to change green times to control traffic movements in a traffic network.

## II. STATE OF THE ART

Much work was carried in the area of intelligent transportation systems. From a theoretical point of view most of the traffic theory was based on the background of ideal fluids, at most taking into consideration the compression properties [7]. All these approaches have major problems when applied to real-life traffic, or otherwise stated: real road traffic is neither an ideal fluid nor it behaves like one.

In the last years, the mathematical models for road traffic simulation have been improved. Most of the classical models, inspired by gas or fluid behavior in pipes give non-realistic results in modern traffic situations and are considered inappropriate [8], but in the last decade we witness a refactoring of these models and implementation in simulation tools [9]. Responsible for this effect is the nonlinear and chaotic character of the systems that describe road traffic, the so-called: ”butterfly effect” [8]. The slightest changes in traffic conditions on a road upstream the point of observation induces effects and current models are not able to give accurate “what-if” simulations.

For these systems, primary data is represented by the number of vehicles passing on a road segment over a given time period (possibly also the distribution by categories: cars, trucks, bicycles, pedestrians etc) and the average speed on that given segment of road at any given time of day and any given day of week [misra2011global]. Additional data can be represented by the average acceleration and deceleration when entering and exiting the road and even the statistical distribution of the weight of the vehicles and the number of traffic incidents/accidents.

The problem of improving the capacity of the existing transportation infrastructure was previously addressed from applying the mathematical models presented above to the evolution of control rules to improve system structure and reduce the complexity of city topology [11]. In [9, 10] we can see solutions designed for identifying the critical areas in an existing topology or to predict problems in a proposed one and to perform the simulation and validation (finding the maximum traffic capability) of any particular intersections or road segments. But these approaches require a framework for the implementation of the proposed methodologies.

An adaptive traffic control framework is addressed in [12] and it is used in case of an emergency large scale evacuation. The authors use a methodology based on a model reference adaptive control (MRAC) framework to serve their scope.

The field of Cyber-Physical Systems (CPS) emerged in 2006, integrates the fields of computation and controlling of physical entities. Opposed to traditional embedded systems, CPS is typically designed as a network of interacting elements with physical input and output instead of as standalone devices. The notion is closely related to concepts of sensor networks. Complex, distributed and dynamic systems like the ones providing air and road traffic control and smart cities have been discussed in the CPS community, concluding the need for an inter-disciplinary combination of diverse engineering fields. Several goals and requirements in large-scale CPS have been identified so far, concurrency, real-time capability, distributed control, self-adaption, self-organization, reliability and fault tolerance [13].

Classical engineered solutions focus on centralized approaches relying on global information, but they lack the dynamic dependencies, which make them easy to understand and manage. Centralized approaches, however, assume that collecting data and its processing meet real-time requirements. In large and complex systems, this period of collecting and processing data is longer than entities can wait for a response. Traffic in large road networks is one example of a situation where centralized optimization is almost impossible: continuously collecting dynamic traffic information from all roads, optimizing traffic flows takes too long to be practically deployed in real world networks. New approaches must at least self-adapt to changing demand and loads in the network to route vehicles to their destinations [13].

Self-organization implies previously described self-adaption and also explores new strategies to reach other objectives. Physical environments and conditions may change frequently, requiring methods that detect changes without external request or modification. As a main desiderate for any system is a high reliability and an increased fault tolerance. CPS brings together specific engineering methods and computer science research on embedded systems, scheduling and distributed algorithms, emphasizing the mapping of processes and physical features. A good example of CPS domain is the control of vehicle flows with the goal of reducing congestion and travel times in a road network.

## III. PROPOSED SOLUTION

### A. *TACTICS Framework*

In [6] the authors propose a three layered traffic system control stack, from which they have described the methodology that runs at the first layer. Briefly, their method consists in several steps that use an adaptive mechanism to modify green time values to improve local conditions for a single intersection.

### A1. *Deployment*

In this context, we consider each intersection as part of a higher complexity structure, a network in which intersections communicate to each other to find a global traffic optimum. Because we cannot decouple local intersection's behavior from the entire network, we propose to interconnect the ones identified as the central loading points in terms of traffic load. In [14] the authors proposed the methodology for selecting key nodes that will act in master-slave configuration to reach correlated decisions using a communication mechanism over the network. Complex Network Analysis is used over the entire network and mark nodes with highest betweenness [15] as master nodes. Traffic data collection falls outside the scope of this paper and according to [6] it is a layer 1 specific operation. Selecting key nodes in the traffic network is an operation specific for layer 2 and is directly related to the proposed framework; because it selects the nodes that will constitute the so called Intersection Control Unit, see Fig 1.

Using the three layered optimization stack we define the communication procedure and the specific messages that define the upper layer of the stack. This third and last step is responsible for the system's response and adaption to continuous traffic changes. Each node uniquely identified by a traffic light will be dynamically controlled to act as a traffic officer.

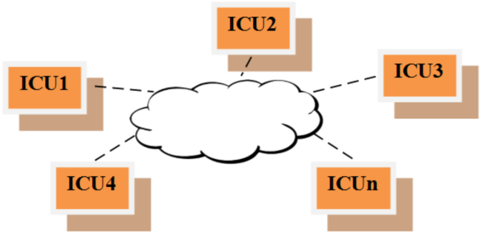

Fig. 1. Traffic network for a city using TACTICS understanding

Our proposed framework defines the physical implementation of the three layered stack proposed in [6]. The first layer runs local adaption mechanisms that change green time values at intersection level based on the detected traffic flow. But, running this algorithm on each intersection is not an optimal solution because of the high number of intersections in a city. The layout of this framework can use the algorithm described in [16] to deploy the system in a real world situation. Because local intersection's behavior must be seen as part of a traffic network, central loading points in terms of traffic load must be selected. STiLO methodology [14] identifies "hot points" and selects the relevant to work in master-slave configuration to reach correlated decisions.

TACTICS implements the characteristics of a cyber-physical system to create a fault tolerant framework for the adaptive control of traffic movements. This system consists in several customized Intersection Controller Units; each of them handles an entire intersection, covering all the signal controllers in that physical location. For each direction a Queue Detector (QD) is installed to determine the queue length for that specific direction. Their results act as input for each Signal Controller (SC) which is responsible for the new green time changes. All the SCs in the intersection are interconnected (Wireless or not) creating the so called Intersection Controller Unit (ICU), see Fig 2. This is responsible for the behavior and the adaption of the entire intersection to traffic changes. Any city, or large portions of it, can be reduced to several independent ICUs which are all interconnected, but with no centralized control center. On each of these units, STiLO methodology is applied to define if it is running in a master or a slave configuration.

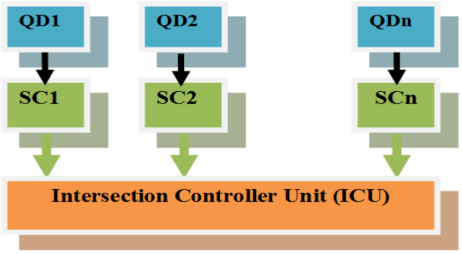

Fig 2. Intersection Controller Unit (ICU)

Fig 3 shows the working flow diagram for each ICU. Literature gives different solutions for real traffic data gathering [17], such as license plate recognition to roadside sensors that log in real time traffic data. Each QD reads the queue length using of-the-shelf car detectors and classification tools. Otherwise, a hardware module capable of estimating the length and dynamics of a queue must be implemented and used for queue detection. Data collected is feed into the Traffic Data Acquisition System which creates the modified Origin Destination table and the traffic/flow matrix of the intersection. The literature gives us different solutions for real traffic data gathering [4, 17, 18], ranging from license plate recognition to roadside sensors that log in real time traffic data. For our proposed framework we have decided to use the video data collection mechanism, mainly for its ease of deployment.

Using the formulas described in [6] these structures provide input for the Adjustment Mechanism working at the SC level. These computations lead to the new set of green times. The new computed values along with the parameters and messages are ready to be sent to the interconnected intersections via Communication Controller. The Feedback Controller also receives these values and it decides to wait or not for an external response. The Communication Controller is responsible for sending the messages to the interconnected intersections and also receiving the corresponding responses. These are parsed and sent to the Feedback Controller which will take them into consideration or not before setting the new green times in the ICU.

One can see that the Communication Controller could be missing and in this case the adjustment works only at intersection level. This happens if the intersection that is being optimized is isolated and it works as standalone or if the communication is offline. This framework uses no redundancy since it can work offline without any centralized control. If the master nodes are to implement the hardware redundancy it will be a cost increase in order to protect of a failure that is not a real threat to the system, since each signal controller can take the role of ICU. Several solutions are to be further studied, like the need of a failure detection module can be implemented to monitor the state of ICU.

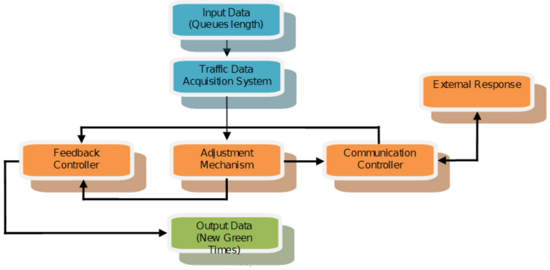

Fig 3. Functional block diagram of an ICU of TACTICS

TACTICS implements the three layered optimization stack in [6], the communication procedure and the specific messages that are defined so that the system responds and adapts to continuous traffic changes. Each node uniquely identified by a traffic light is dynamically controlled to act as a virtual traffic officer. For this framework to be operational, the network topology will have to be defined at deployment time. A procedure for a new node insertion, corresponding to a new traffic signal installation is needed to be defined. Using this mechanism, each node is capable of positioning itself into the network, by knowing his neighbors and it is able to find its role. STiLO must be run for the new deployed node to determine its role in the network.

The adaptive green time mechanism is the core of this algorithm, because it is determines and sends the new green times to the traffic signals operating in intersections. The dynamic of each traffic light-controlled intersection is defined using a set of only three parameters and new green time values are derived based on their values. These are, green time value, meaning the time which allows traffic to flow through an intersection, traffic flow, representing the number of vehicles passing on a specific direction and cycle length, which is the timeframe between two consecutive green times.

Several steps are performed for changing traffic signal timings. First step is to determine whether a local intersection has a problem in managing passing traffic flow through it. Next step is to determine if it is possible to make changes locally or not, based on the input values read. If the intersection can respond to traffic changes by changing its own green time values then it will determine the changing coefficient that will be sent to the interconnected ones. In case the current intersection is identified using STiLO as master than it communicates to the slaves the changes made on the impacted directions. It also notifies the other interconnected masters about the changes. The greenTimeIncrease and the coefficient_level are computed and sent to the connected intersection. The response is expected during the same cycle in to know if changes are accepted or not. The algorithm starts over and reads traffic data after each cycle is over.

Depending on the desired goal, different sets of parameters can be selected as input data; similar to vehicle to infrastructure, V2I, or infrastructure to vehicle, I2V, which use physics parameters (speed, acceleration). These cover the behavior of any intersection and provide all the information needed to assess new timing plans. Due to reduced number of operations this will need low computational power. In a real-world system, measuring and collecting data traffic values still represents a challenge.

### A.2. *Adapting Green Time Values*

The adaptive green time mechanism is the core of this algorithm, because it is responsible for effectively determine and send the new green times to the traffic signals operating in intersections. We start by defining the dynamic of each traffic light-controlled intersection using a set of only three parameters and we will derive new traffic signals based on their values. These are, green time value (Gt), meaning the time which allows traffic to flow through an intersection, traffic flow (td), representing the number of vehicles passing on a specific direction and cycle length (Cl), which is the timeframe between two consecutive green times.

Several steps must be performed in order to change traffic signal timings. First is to determine if the local intersection has a problem in managing passing traffic flow. Next is to determine if it is possible for it to make changes locally, based on the input values read and it will compute the changing coefficient that will be sending to the interconnected ones. If the current intersection was identified by the algorithm as a master than it will communicate to the slaves the changes made on the impacted directions and also will notify the other interconnected masters about the changes. As the results are sent, a response is expected during the same cycle in order to know if changes were made or not. The algorithm restarts and reads traffic data on each cycle.

### B. *Inter Traffic Signal Communication*

As for reading and computing new green times the methodology was described earlier, it is the communication part that we will detail in this part.

We define two types of messages: requests and reports, to be exchanged between master and slave intersections. Their format is defined in Fig 4 and has a minimal format in order to be easily implemented regarding the transmission method used (TCP/IP, Bluetooth etc).

| Message ID | Message Type | Source | Target | Payload |
|---|---|---|---|---|

Fig 4. Message format used by TACTICS

Based on the resulting coefficient values and on the adaptive green time methodology, six Message IDs are defined: REQ_INC_LOW, REQ_INC_HIGH, REQ_DEC_LOW, REQ_DEC_HIGH, REP_YES, REP_NO and an optional ACK can also be used, but this depends on each intersection load. REQ_INC_LOW and REQ_INC_HIGH each correspond to a request for increasing the green time value with low or high coefficient as described in [14]. The same applies for REQ_DEC_LOW and REQ_DEC_HIGH where they represent a request for decreasing the green time values. REP_YES and REP_NO are the reports sent by the slave intersection as an answer to each of the before mentioned requests.

A bidirectional communication is proposed to exchange information using a simple request-reply report, where each intersection notifies the interconnected one about the changes that is going to perform. Each intersection will also take into consideration the incoming requests if its local conditions permit it. When the other intersection acknowledges the message, it means that the information will be used for the next timing adjustments and a negative answer means the information cannot be used because of the already calculated green times. Time aspect is important because there is no synchronization of traffic signals.

The main target of the proposed framework is to assure the environment for traffic optimization process in order to ensure a continuous traffic flow between key intersections inside an urban traffic network. Each intersection is seen either as a standalone entity or part of a complex network described by three parameters: green times, traffic flow and cycle lengths. By correlating intersections and interconnecting nodes to operate in synergy, faster flow will be achieved at network level.

Several cases are identified: one is when the green time of the slave intersections overlaps the master green time value and the second is the case when the response from the slave is received during maser's green time. In the first case the request from the master is not reaching the slave in the current cycle which means no response from the slave. This is the specific case in which the master will adapt its green time without any change from the slave. The adaption from the slave will take place in the next cycle following the response to master.

Each semaphore has its own working time: cycle length, number of phases, changing order and the list could continue. Because of this aspect, rules must be described, so the communication between the intersections is optimal and also to avoid unnecessary overhead inside ICU. All computations are done during the first red time period after a cycle is completed. In this interval, the new green times and coefficient levels are determined based on each specific methodology. All other requests coming from slave intersections in the next period will be taken into account only in the next cycle.

Another rule is that no answer is kept more than one cycle. When the request from the master is not reaching the slave, because of a larger cycle length and in this case, the master is always changing its values and sending new requests until it gets a response. If the communication is lost, each intersection acts as master without sending any message. Statistically, acting as master an intersection could improve locally for short time and because any congestion is limited in time it could cover the time needed to pass that situation.

## IV. CASE STUDY

The case study follows the changes made in the system before the framework implementation and after. An indicator of the improvements in the network will be the time a queue is decreased, with no adaption and using the proposed adaptive framework control system. The proposed methodology finds the optimal traffic balance for all directions in a single intersection and communicates its results with the interconnected ones in order to achieve a more balanced network. But, continuous recalculation will naturally lead to a point in time when adapting green times is not possible anymore.

The proposed working model was evaluated using the VISSIM simulator, a microscopic simulation tool that provides conditions for testing different traffic scenarios in a realistic manner. With VISSIM, the urban network was defined around the central part of Timisoara city and it simulated several groups of traffic lights working using TACTICS framework configuration.

Results present several traffic controlled intersections, subject to the adaptive traffic signal control, all in central area of Timisoara. Using VISSIM, specific queue counters were set on each direction to monitor traffic flow. These counters record traffic data passing through during simulation time. Two parameters are of specific interest: average queue and maximum queue length. One central intersection adapts its green time phases dynamically, according to the described methodology. Traffic values are injected into the urban network using VISSIM specific traffic data zone generators. During simulation, green times were adapted with five and ten time units, increasing green time for the directions heading north and decreasing south heading direction.

To determine the impact over one of the studied intersections, traffic conditions were measured on all four exits, recording values before and after adaption of green times. The results show improvements at local intersection level for the intersection that adapts signal timings. Compared with the initial value, there are moments in time when the improvements reach almost 40% percent for the Average Queue Length, see Fig 5 and Fig 6. This parameter describes a more dynamic intersection, with shorter waiting times. Meanwhile, the Maximum Queue Length parameter shows an interest aspect when it reduces the pick the value, fact that is caused by the progressive response to the increasing traffic conditions.

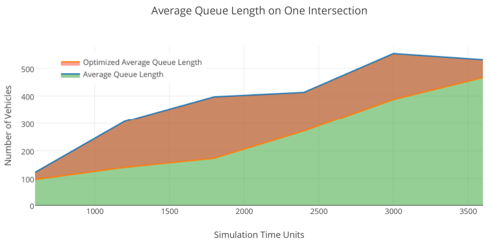

Fig 5. Queue Length for one intersection VISSIM simulation results

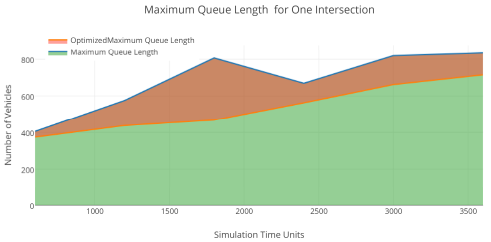

Fig 6. Maximum Queue Length for one intersection VISSIM simulation results

## V. CONCLUSIONS AND FUTURE WORK

In this paper we proposed and tested in simulation an adaptive traffic control framework, designed to respond to dynamic changes in traffic conditions by using intelligent traffic signaling. We described our approach to be an efficient one in terms of new hardware required and communication overhead needed. Because it requires only a new module per intersection and it uses current infrastructure without any additional pavement installed sensors.

TACTICS is designed to interact with already installed traffic monitoring ITS technologies and proposes a self adapting methodology, without any centralized control using a low message overhead for each intersection due to its small number of exchanged messages. The results presented in the case study, show also low message overhead which makes this framework an energy efficient one.

The cost for the new hardware installed in each intersection is estimated to be around 12.000 Euros based on our calculation. This certifies that this solution is a low cost one compared to the costs of installing an intelligent solution for an intersection, which usually reach 30.000 - 40.000 Euros.

## ACKNOWLEDGMENT

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