Behavioural patterns from cellular data streams and outdoor lighting as strong allies for smart urban ecosystems

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Abstract. The concept of smart urban systems assumes tracking and analysing various signals generated in the environment surrounding inhabitants. The aim is to provide responses which are context-aware and pro-active and allow to increase the inhabitant's life comfort. On one hand, smart outdoor lighting solutions are common and mandatory components for modern urban spaces and municipalities offering considerably energy savings. On the other hand, inhabitants' behavioural fingerprints originating from cellular data streams, produced and stored in base transceiver stations (BTSs), are the most 'democratic' and ubiquitous information which might support modern solutions tuning/fitting lighting parameters to the current needs. This paper presents the fundamental problems of elicitation, classification and understanding of such signals/data for the development of smart systems operating in urban areas with the special focus put on smart outdoor lighting problems. Omnipresence of computing is strongly focused on providing on-line support to users/inhabitants of smart cities. Three important components underlying computational model are discussed in this paper: the method of analysing selected elements of mobile phone datasets through understanding inhabitants' behavioural fingerprints, the multi-agent system supporting the proposed logic and the formalism based on graphs that allows reasoning about inhabitant behaviours. Corresponding scenarios for public transport and outdoor lighting are outlined as well.

Keywords. smart city, cell phone network, base transceiver station, call detail record, behaviour recognition, outdoor lighting, pervasive computing, context-awareness, pro-active system, multi agent system

1. Introduction

The idea of using information and communication technologies to deliver services to inhabitants of urban spaces faces nowadays an unprecedented interest. The aim is to be both more intelligent and more efficient when using various resources. The expected results are energy efficiency, improved quality of life, well-organized municipalities, and an innovation-based sustainable development, as well as many other deliverables. This urbanization trend is becoming word wide. Hence, the idea requires smart analysis of

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information which is generated in urban areas, but also using the network facilities to enable interaction among citizens and systems distributed across such an environment. New and innovative ways of analysing behaviours in urban spaces through understanding the data they generate are needed. New ways to analyse and classify those data, as well as further reasoning, in order to better understand and plan pro-active support offered by systems to inhabitants are a crucial necessity. Intelligent street lighting is an important part of any smart city implementation. The primary purpose of casting light onto dark roads, crossroads, parking areas, and public spaces is to improve safety for both pedestrians and drivers. The important demand is the energy efficiency of street lighting. This demand defines the key objective for the system design. The complex and multifaceted city street lighting control is challenging. Using advanced inhabitant behaviour understanding lighting control technology is gaining management efficiency and cost benefits.

People keep mobile phones with them most of the time. Thus, widespread availability and use of mobile phones, as well as their growing ubiquity, base on wireless networks which guarantee basic communication in the system. BTSs (base transceiver stations) are responsible for communicating with mobile phones within the network. Wireless networks have a great potential to provide information to identify activities of people. Inhabitant movements, locations and events are being recorded. This information is stored in the CDR (call detail record) format. CDRs provide information about the presence of a phone device in a geographic location. Billions of data streams coming from BTSs challenge the traditional approaches to outdoor lighting control. It allows to identify places and movements of inhabitants which is crucial for smart decisions, as well as to work fast and get results in a short time. From a smart lighting perspective cellular data streams contain attractive and valuable information which can be used for management and control light bulbs. The important aspect of this approach that differs from traditional sensor-based approaches is that BTS networks exist practically everywhere, that is it needs no additional expenses to deploy sensors and devices, and the data originating from BTS are 'democratic', that is they register individual behaviours regardless of the age or social status of mobile phone users.

We show that analysing selected information generated by BTS devices can indeed identify inhabitants' behaviours, help understand human mobility and social patterns, and implement scenarios supporting smart outdoor lighting systems. A classification of sensed behaviours for applications that operate in a smart city is proposed. Outlines of smart scenarios are provided. A multi agent system is proposed. A formalism which allows reasoning about inhabitant behaviours in the BTS network is proposed.

The topic of sensing and monitoring urban activities basing on mobile phone datasets seems up to the minute and relatively new. In a work by Calabresse et al. [1] a real time monitoring system is described. Buses and taxis, as well as pedestrians movements, are positioned at providing urban mobility. However, this paper considers collections of individual behaviours to provide smart decision. In work by Gonzalez et al. [2] trajectories of anonymized mobile phone owners are discussed. Human trajectories are characterized by a high degree of both temporal and spatial regularity. Work by Isaacman et al. [3] proposes clustering and regression-oriented techniques supporting the identification of semantically-meaningful locations (home, work). Work by Reades et al. [4] offers a new way of looking at the city as a holistic and dynamic system. Some experiments in explorations of urban data collection are discussed. This paper follows up work [5], and smart lighting issues are additionally considered.

Table 1. ME lighting classes according to DIN EN 13201-2.

Class	Road luminance in case of dry road surface			Threshold value	Ambient illuminance ratio
	L_{avg} cd/m^2 [maintenance value]	U_o [minimum value]	U_I [minimum value]	TI %[a] [maximum value]	SR_2 [b] [minimum value]
ME1	2.0	0.4	0.7	10	0.5
ME2	1.5	0.4	0.7	10	0.5
ME3a	1.0	0.4	0.7	15	0.5
ME3b	1.0	0.4	0.6	15	0.5
ME3c	1.0	0.4	0.5	15	0.5
ME4a	0.75	0.4	0.6	15	0.5
ME4b	0.75	0.4	0.5	15	0.5
ME5	0.5	0.35	0.4	15	0.5
ME6	0.3	0.35	0.4	15	-

[a] 5% higher admissible for lamps with low luminance

[b] This criterion is only to be used if no traffic surfaces with own photometric requirements are next to the road

2. Smart lighting infrastructure

The existing solutions for smart outdoor lighting are discussed in this section. Usually they employ only movement sensors which are attached to the fixtures or poles. Understanding such solutions, however, enables transition to a more sophisticated smart control methodology, which is based on the BTS-based behaviour recognition.

The outdoor lighting is one of the key properties constituting an urban space. It enhances safety on roads and in all other public areas. Securing the road and pedestrian traffic is related to two areas: the safety of movement and personal safety on the streets, squares, pedestrian crossings or in recreation areas. The threshold parameters of an illumination are strictly regulated [6]. In particular it must not be switched off in any period during the night time so the only method of reducing the power usage is adjusting the lighting level appropriately to the detected presence of objects.

The following elementary lighting classes are distinguished: for traffic with medium and high speeds (ME), for traffic in conflict areas, such as intersections or roundabouts (CE), for pedestrian and bicycle sequences (S, A). Other classes of subordinate character are distinguished when it is necessary to identify people and objects, when there is a risk of violating the rules, in order to decrease the feeling of uncertainty (ES) or the need for seeing vertical surfaces (EU). Table 1 presents the list of ME classes for street lighting.

The example given below illustrates how the power savings may be obtained for a road lighting installation. Figure 1 shows the averaged daily traffic intensity for subsequent quarters as measured on the selected double carriageway road in the city of Cracow, Poland. The daily traffic estimation was made by multiplying a quarter rate by 4×24. This extrapolation is required to apply the standard CEN/TR 13201:1 [7] which assigns a lighting class (Tab.1) to the road, dependently on its actual traffic flow. Note that we focus on the period when street lighting is switched on. As visible in Figure 1,

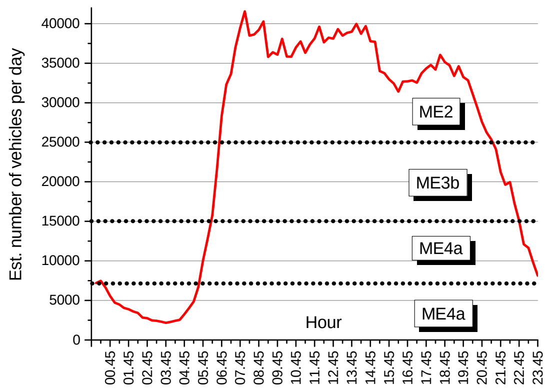

Figure 1. Average daily traffic intensity. Dotted lines separate lighting categories suited to intensity size.

the luminance level may be reduced twice, from 1.5 (ME2 class) to 0.75 cd/m^2 (ME4a class), when the aggregated flow drops from 25,000 to 7,000. In terms of the power usage it means the two times lower energy consumption. The BTS infrastructure containing a number of transceiver stations enables the simultaneous measurement of multiple flows. Having such data the system may predict future states. The trivial example is shown in Fig.4.(left): detecting flows F_1, F_2 (dashed arrows) allows predicting the presence and intensity of the aggregate flow F_3.

Apart from objective, quantitative and qualitative functional aspects, illumination should also meet requirements related to environmental, social and economic demands. At the same time, illumination plays the following roles: strengthening the individuality and identity of places in the city, supporting its promotion by shaping moods, arousing aesthetic sensations and the feeling of pleasure. They may be enabled by a suitable choice of various parameters (e.g., light color, the appearance of luminaire and so on) depending on the individual features of a place (related to restoration etc.). Through the kind of applied light, its color, the degree of rendering colors, the manner and type of adopted luminaire, an urban interior assumes some unique features influencing a recipient's mood and arousing the sensation of pleasure or comfort. The possibilities of acquiring the unique character of a given place is broadened by a combination of street illumination with object illumination.

Summarizing the above considerations: the most important aspect of outdoor lighting besides its functional properties is the energy efficiency. The main objective, imposed on a public lighting is satisfying mandatory requirements included in a standard ([6,7,8]), with a minimal power consumption. To accomplish that the smart lighting system performance has to follow actual road conditions.

Existing smart lighting solutions [9,10,11,12,13] based on LED light sources coupled with a telemetry layer use presence and/or movement sensors which are usually mounted at poles, to monitor the environment state. In this case the emergence of an object in a sensor area causes adjusting light intensity in a given area. In this article we consider replacing the above sensors' output with data incoming from BTS stations. Such a replacement is helpful especially when mounting presence/movement sensors is not feasible due to some reasons (e.g., legal, technological or business). Moreover, BTS-based analytic layer is capable of making much more advanced operations such as identifying, recognizing, predicting and responding to the system's behavioural patterns. For example, the presence of some specific traffic flows (described in terms of an average traffic intensity) may be recognized as a threatening situation which requires not only a street lighting adjustment but also taking some additional steps.

3. Mobile phone infrastructure

Some aspects concerning the BTS infrastructure are discussed in this section. However, considerations are limited to problems which are interesting from the viewpoint of this approach. Systems for mobile communications (e.g. GSM or UMTS) are well established. There are many works introducing the world of data communication procedures, e.g. work [14]. Selected technical aspects of such system are briefly outlined below.

The most obvious part of the mobile phone network is a base station. A *base transceiver station* (BTS) is a piece of equipment that enables wireless communication between a user and the network. Every BTS performs immediate communication with mobile phones. Nowadays, cities and regions are covered with a relatively dense network of BTSs, see for example Figure 2. Although outside the cities networks are less

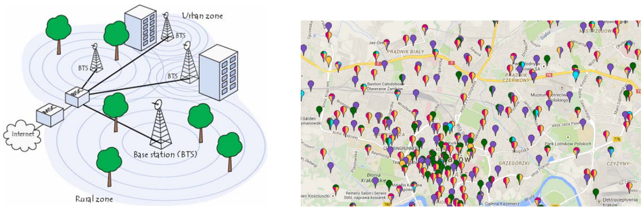

Figure 2. A sample BTS network (sources: `http://www.thelifenetwork.org` and `http://btsearch.pl/`, respectively)

dense, in each case they gather and store important and interesting information about users' activities. Broadly speaking, the entire network system consists of many elements that operate together but an ordinary user is not aware of the different entities within the system.

A *call detail record* (CDR) contains data recorded and produced by telecommunications equipment. It's purpose is to store information about current system usage; however, CDR is rather retrospective. It contains data that is specific to a single instance of a phone call or other communication transaction. The structure of CDR is relatively complex, and its format varies among providers. In some situations CDR can also be configured by a user. The CDR contains variables, e.g. the called number. Variables might be grouped into: variables used for identifying calls, timestamps, information related to signaling, information related to media, statistics, information related to routing, and others. Records are very detailed and contain much information, e.g. point of origin (sources), points of destination (endpoints), the phone number of the calling party, the phone number of the party being called, duration of each call, the amount billed for each call, the route for a call entering the exchange, the route for a call leaving the exchange, call type (voice, SMS, etc.), etc. Some data depends on the service provider and even in case of timestamps there are over a dozen of different fields.

CDRs, as collections of information, have a special format [15]. Below is a sample fragment of a CDR text decoded from the binary format. The first row must contain a header row which includes the field names:

```
Call Type,Call Cause,Customer Identifier,Telephone Number Dialled,
Call Date,Call Time,Duration,Bytes Transmitted,Bytes Received,
Description,Chargecode,Time Band,Salesprice,Salesprice (pre-bundle),
Extension,DDI,Grouping ID,Call Class,Carrier,Recording,VAT,
Country of Origin,Network, Retail tariff code,Remote Network,APN,
Diverted Number,Ring time,RecordID,Currency
```

The meaning of the columns is not analysed here since they are intuitive and the detailed discussion is outside the scope of the paper. There are many events that generate a CDR record, e.g. data services, such as SMS and Internet access. The gathered information allows to obtain BTS locations according to a mobile phone activity, i.e. changing a location from one BTS to another. Location information is extracted as part of the interaction data. These location observations, i.e.

- the moment of the phone's/object's entry into the area of a station (log in), and
- the moment they leave that area (log out),

are of fundamental importance to the considerations given in the following sections of the paper.

4. Behaviour extraction and understanding

Extracting behaviours from cellular data streams, which are stored in BTS stations, is discussed in this Section. BTS devices constitute a rich source of information which can be used by smart and context-aware systems. This information is related to many aspects of users'/inhabitants' behaviours. From all the information generated and stored in BTSs, the most important for these considerations are events describing the presence of the mobile phone in the BTS area.

Events obtained from the BTS network can be used to provide the following classification of user behaviours:

1. **Static behaviour**, that is without moving outside the BTS area. Some scenarios which are appropriate for such behaviour are proposed, however, this scenarios do not rather refer to lightening system and that is why they are very briefly discussed. The aim of such scenarios is to increase the inhabitant's comfort of staying in a particular area, for example, providing information about local customer services, shops or special offers. If preferences (behaviour in the past) also taken into account, then support becomes more mature and valuable. For example, people working in local offices, when approaching the habitual and observed time for their lunch, are notified about current opportunities (restaurants, shops, etc.) in their neighborhood as they are suggested.
   Another example of such support might be the situation when two people are informed about the possibility of their meeting as a result of being in the same geographic location, if such a meeting has been "ordered" before (e.g.: when I am in the same area as the person X, please notify and make an appointment).

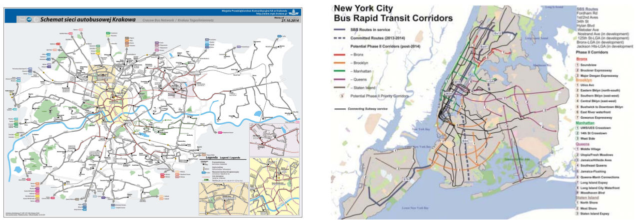

Figure 3. A sample city bus networks (sources: `http://www.mpk.krakow.pl/pl/mapki-komunikacyjne/` and `http://www.streetsblog.org`)

2. **Dynamic, or mobile, behaviour**, that is related to the movement of both individual users or groups of inhabitants, between neighboring BTS points. It seems that dynamic behaviours, as understood here, give a great number of possibilities to introduce pro-active scenarios. The desired effect is particularly evident when applying some additional, and free, technologies related to the geographical location and maps, e.g. *OpenStreetMap* OSM [2], or maps of existing urban infrastructure networks, e.g. public transport lines, c.f. Fig. 3. Dynamic behaviours, due to their great potential for interesting uses, are discussed separately.

Scenarios related to dynamic behaviours are of fundamental importance in the paper. The consideration given below is focused on the classification of different types of travel in the urban area. The purpose of this classification is to distinguish two kinds of situations which relate to the observed quick move:

1. a group of people traveling in public transport, i.e. simultaneously traveling groups of persons (phones) after finding that this is not a solitary case of traveling by private cars – confirmation of this case is a result of the following observations: the comparison to a similar behavior in the past, quick change of BTS areas, i.e. switching between BTSs, and comparison of the current travel route with public transport lines, c.f. Fig. 3;
2. people traveling by private cars – evidence of this case might be a result of the following observations: a greater speed of a travel comparing groups traveling by public transport, traveling outside the area of public transport lines, etc.

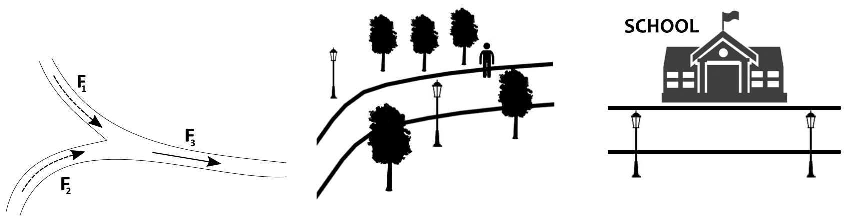

Figure 4. Sample lighting situations: **left**: flows F_1, F_2 aggregate to F_3; **middle**: a sharp curve; **right**: a school.

The following sample support for inhabitants is considered a result of dynamic behaviour:

[2]OSM is a project to create a free editable map of the world.

- **scenarios for outdoor lighting**, that is basic scenarios for this research, assuming increasing/decreasing illumination of outdoor lighting systems when:
  - ∗ there is the increased volume of traffic at selected important points/streets, c.f. Figure 4.(left);
  - ∗ reaching places/squares with the expected larger number of passers-by;
  - ∗ approaching bus stops, for public transportation, see scenarios below;
  - ∗ approaching dangerous points, c.f. Figure 4.(middle), pedestrians (detected by sensors, or discovered from cellular data) are behind a sharp curve, perhaps in a park, and the system predict approaching vehicles, then for safety reasons bulbs from dimming positions are brightened up to full;
  - ∗ passing near places/points with a very special/careful attention, e.g. schools, c.f. Figure 4.(right) bulbs are brightened up to full;
- **scenarios for public transport**, that is other scenarios divided into two groups:
  1. (group) trip by public transport
     - ∗ finding convenient transfers for travelers if transfers are expected;
     - ∗ in the case of transfers with a long waiting time for a new connection: finding bar/cafeteria facilities in the area in advance to make a reservation;
     - ∗ propose to notify people at home (destination) about the arrival time, or notifying of the planned arrival in advance a certain number of minutes before;
     - ∗ finding alternative connections and transfers, if there are traffic jams which slow down a trip or make it difficult;
     - ∗ notification of friends/colleagues about a common trip in the same vehicle of public transport, this fact can be confirmed by on-line analysis of social networks (e.g.: Facebook, Instagram, etc.);
     - ∗ some others;
  2. (individual) trip by a car
     - ∗ propose to notify people at home about the arrival time, or notifying of the planned arrival in advance a certain number of minutes before;
     - ∗ warning regarding the approaching critical locations, schools, places, crossroads, etc., this service requires gathering additional data form OpenStreetMap;
     - ∗ some others.

5. Multi-agent system and an ecosystem

In this section we introduce the agent system structure that supports the IoT services mentioned in the previous sections. Let us consider the structure of a system supporting the simple task of determination of the way in which the owner of a mobile phone travels, that is whether travel is done via public transportation or via private car.

The outline of the proposed agent system is shown in Fig. 5. The basic types of agents are:

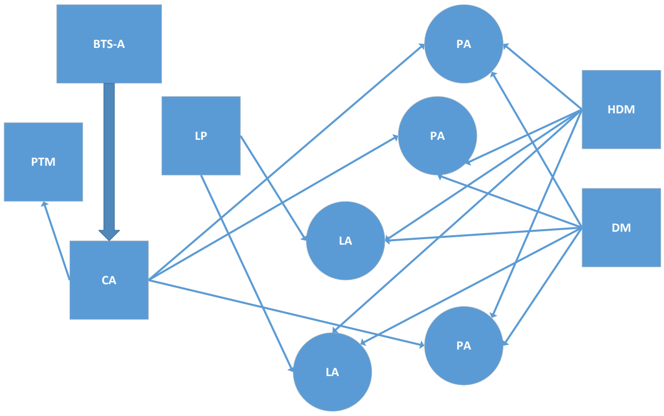

Figure 5. A sample agent system for a lighting and public transportation system

- a *personal agent* PA, that maintains the trace of the current route of a mobile phone in the entire city among BTS areas, as well as its stored characteristic, taking into account some historical information about previous behaviors; every mobile phone owner has its personal agent PA (informally, a guardian angel PA);
- a *lighting agent* LA, that maintains a single and special area which requires special attention, for example sharp curves, schools, and others, c.f. Fig. 4;
- a *BTS agent* BTS-A for every base transceiver station BTS, that, for every personal agent PA that came into the BTS area at the same time slot, creates a temporary *coordination agent* CA which stamps the time of the entry to an area and try to characterize every PA's behaviour in the following way:

  1. if a jump among (at least three) regions is slow, then walking,
  2. if a jump among (at least three) regions is medium, then private car or public transportation,
  3. if a jump among (at least three) regions is fast, then private car;

  the speed (slow, medium, fast) is determined by taking into account speeds observed in the considered area; every agent CA is removed/killed when its reasoning process, initiated by an agent BTS-A for a list of jumping PA agents passed to CA is finished;
- a *public transportation manager agent* PTM that tries to recognize and represent the group of personal agents PAs that move in the same line;
- a *lighting prediction agent* LP that analyse information gathered in the system, predicts upcoming events that require the intervention in the lighting system, see Fig. 4, in other words maintaining all lighting agents LAs.

The following are rules for the CA agent creation algorithm:

- for every pair of neighboring BTS regions the BTS generates a list of PA agents which passed/jumped between two regions in a given time slot;
- the CA agent is created and the list of jumping agents PAs constitute its input; CA gathers information about the trace of previous travel and creates a *travel graph* for all PA agents considered by CA.

Let us consider a graph $G = \langle V, E \rangle$, c.f. [16], where vertices V are parts of the BTS state which maintains the collection of PA agents that jump to this BTS from other BTS at a certain time, and E shows the movement between nodes, i.e. $(v, w) \in E$. Nodes in the travel tree represent the BTS in time t, so we will describe it as a pair (BTS_{ID}, t) – such node will be called node at level t. Initially, at time t, there is only one node for which the CA agent has been created. At level $t-1$, there are nodes from which an object jumps to nodes at level t. Edges show from which node at level $t-1$ an object is moved to a node at level t. Each edge is labelled by the name of the moving object.

Let us notice that the travel graph is a multi-edge graph, which means that more than one edge can exist between two nodes. Next we will designate the object using a recursive algorithm; at level $t-1$ we initially assume that with node $x = (id, t-1)$ there are associated all objects that will jump from x to any node at the higher level. For each object Q associated with node x, agent CA retrieves the information about the previous traversal of Q from agent PA_Q; It should be noticed that:

- the number of associated object can grow, because agent PA_Q can remember that at time $t-1$, Q was in id_{BTS} with other objects;
- this travel enriches the travel graph at levels lower then $t-1$.

When we gather all the information about the route of the object from level $t-1$, we will update the information about the nodes at level $t-2$ and the following ones. Time is an attribute of the edge. The following rules should be fulfilled in the travel graph:

- $\forall v, w \in V : (w, PA_Q) \in E \Rightarrow time(v) + 1 = time(w)$;
- $y_v = x_w$;
- and agent PA_Q moves from w to v.

The travel graph is a multi-graph, which means that more than one edge can exist between the same two graphs nodes. They are differentiated by a label that identifies the PA agent. This graph might constitute a base for reasoning.

The decision made by the CA agent is supported by the information from the PTM agent that can verify if the route traveled by a PA agent can be covered using public transportation. Let us note that we still have a problem with differentiation of the two situations:

1. traveling by a bus,
2. traveling in a column of a few/column cars.

In such case, historical data is used to make a decision with the most probability. Let us note that in next steps we can determine the type of transportation because either it is not possible to find a bus travel in this destination or the column of cars has been split. A sample travel graph is shown in Figure 6, where two arrows from one node to another (if any) symbolize that more than one edge exists between two nodes, (i.e. there are two or more edges). Analysis of the graph shows that agents from 51 to 71 are traveling together using the public transport system. Agent 14 travels by car.

The agent system can be extended by two more types of agents:

- a *historical data maintainer agent* HDM, i.e. an agent that maintains the historical data of personal agents;
- a *data mining agent* DM, that takes the trace of route traveled by a personal agent and processes it into some interesting historical behavior; for example:

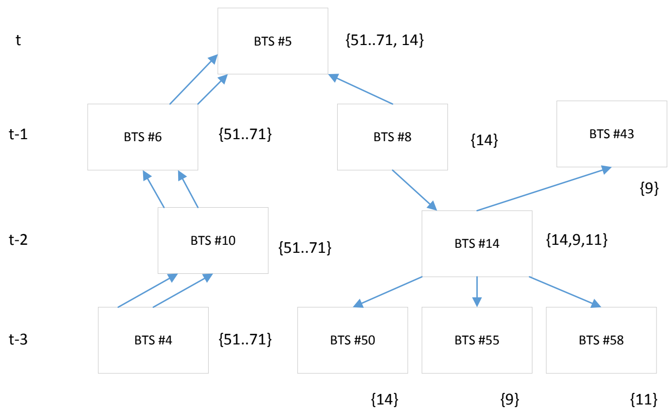

Figure 6. A screen shot of a sample travel graph

* routes that are covered by walking, via public or private transportation,
* public agents which usually travel together,
* a schedule of routes that are executed periodically.

A personal agent PA returns the information to the DM agent (after finishing the travel) and takes it from HDM before starting a new travel.

Historical data maintained by some agents open an interesting issue that supplements the approach presented here. The historical behaviors are encoded into logical specifications, and can be later analyzed for satisfiability, c.f. works [17], or [18,19,20], supporting the current reasoning process and behavior recognition.

Common agents	Lighting agents	Transport agents
HDM, DM	LA, LP	PA, BTS-A, CA, PTM

Table 2. Agents operating in the proposed ecosystem

Summing up, all agents proposed in this paper constitute a digital ecosystem. *Ecosystem* is a distributed, self-organized and open system gathering knowledge about (selected aspect of) smart city environment. It constitutes a community of digital devices and their environment functioning as a whole (hardware, software, services). Table 2 gathers all agents operating in the proposed solution for managing lighting and public transportations system. This system might be extended considering other aspects of smart city, for example urban pollutions, fire and emergency systems, water and sanitation, energy, etc.

6. Conclusions

In this paper, the problem of sensing inhabitant behaviors in a smart city is considered. The classification of behaviors observed using the BTS networks is proposed. A lighting as well as public transportation cases are discussed, and a multi-agent system is proposed. This work opens a research area which is of crucial importance for smart cities.

Future works may include the implementation of the reasoning engine. It should result in a CASE software, which could be a first step involved in creating industrial-proof tools.

Acknowledgements

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