Urban Infrastructure-to-Vehicle Traffic Data Dissemination Using UEP Rateless Codes

Čedomir Stefanović, Student Member, IEEE, Dejan Vukobratović, Member, IEEE, Francesco Chiti, Member, IEEE, Lorenzo Niccolai, Vladimir Crnojević, Member, IEEE, Romano Fantacci, Fellow, IEEE

Abstract—In this paper we propose an end-to-end solution for urban infrastructure-to-vehicle traffic data delivery based on a class of unequal error protection (UEP) rateless codes called expanding window fountain (EWF) codes. The proposed solution relies on attractive features that rateless codes introduce to networks with unpredictable dynamics: the universal capacity approaching property which is wellmatched to time-varying behavior of wireless links, and the innovative nature of each encoded packet which makes both time-consuming retransmission and content-reconciliation mechanisms unnecessary. Furthermore, usage of EWF codes allows separation of delivered data in importance classes with different error protection and recovery time guarantees, enabling mobile users to retrieve more important information more reliably and in shorter time span, thus making the proposed solution suitable for time-critical services. The addressed urban communication scenario consists of large number of sensors that sample and relay traffic flow information to network of Access Points (APs). APs use the existing underlying communication infrastructure, such as metropolitan area networks (MANs), to exchange traffic flow data, encode it using EWF coding principles, and finally disseminate it to roaming vehicles that join the network service in an ad-hoc manner in order to retrieve information regarding the surrounding environment. The proposed approach is suitable for real-time applications, such as frequent periodic reporting of urban traffic conditions, that could be used by on-board computers to provide improved navigation for end-users.

Index Terms—infrastructure-to-vehicle communication, data dissemination, EWF codes, rateless codes, IEEE 802.11

I. INTRODUCTION AND MOTIVATION

INTELLIGENT Transport Systems (ITSs) represent a promising research area for real-time traffic reporting and alerting, allowing remote operation management and self-configuration of traffic flows, as well as specific information delivering to vehicles concerning, for instance, traffic congestion or the presence of accidents. ITS services availability relies on the presence of an infrastructure usually comprising fixed devices interconnected by an underlying network, either wired or wireless. Data exchange toward or among mobile terminals is inherently wireless, since information should directly reach the drivers through their smart phones, personal digital assistants (PDAs) or on-board transceivers; in evidence, IEEE 802 committee has activated 11p Task Group to define a Wi-Fi extension for Wireless Access in Vehicular Environments (WAVE) [1]. Moreover, wireless connections can be also used for data gathering, according to the wireless sensor network paradigm, comprising large number of devices that sense and relay information to the core network [2].

Within the above scenario, several communications paradigms are possible. The case in which fixed Access Points (APs) allow mobile nodes to join the network is referred to as infrastructure-to-vehicle (I2V) communications and can support advanced applications such as web surfing, multimedia streaming, remote vehicle diagnostics, real time navigation, to name a few; on the other side, vehicle-to-vehicle (V2V) communications represent the option in which mobile nodes can directly communicate to each other without any need of infrastructure. Although V2V and I2V communications are both prominent research fields, this paper is focused on the latter, as it aims to efficiently exchange short amounts of data, collected and aggregated by an in-field deployed sensor network, to nomadic users, while keeping the complexity of on-board circuitry as low as possible. It is worth noticing that a reliable I2V scheme is extremely valuable even for V2V communications since, whenever a direct link among vehicles is not available, message exchange can leverage on the infrastructure instead of being successively relayed by few low-reliable mobile nodes, as addressed in [3].

The urban environment is usually composed of a large number of mobile users that are likely to quickly change their reference APs. Due to frequent disconnection and reconnection procedures, it may not be viable to deliver the total amount of required data to a mobile user within a single session. Moreover, the urban channel is affected by long and short term fading that introduces additional delays for data retransmissions (in the case of TCP traffic) or sensibly lowers the data reliability (in the case of UDP traffic); these issues are addressed in details in [4] and [5], providing a practical case study involving IEEE 802.11b. As the proposed application scenario is concerned with fast and efficient information retrieval, these drawbacks could be faced by introducing an appropriate data dissemination algorithm, enhancing the infor-
mation delivery throughout the network without an excessive overload in terms of total packet transmissions.

In general, content distribution through overlay networks is more efficient when compared to traditional solutions using multiple unicasts. In order to achieve higher throughput and failure resilience, parallel downloading from multiple overlay nodes represents a typical approach in recent proposals [6]. However, the same content may be unnecessarily supplied by multiple nodes, rising the problem of the content reconciliation, which is usually a time and bandwidth consuming operation [7]. This can be avoided by applying rateless codes [8] for data dissemination in vehicular networks, as proposed in [9]. Potentially infinite number of encoded rateless packets can be created and delivered from any AP to connecting vehicles, where each encoded packet is an independent, novel and innovative representation of the data, thus decreasing conflict and duplicate occurrences in parallel downloading.

In this paper we present a solution for data dissemination based on expanding window fountain (EWF) codes [10], which are a class of rateless codes with unequal error protection (UEP) property. In the proposed setup, EWF coding is applied over the sensor data in a distributed and network-wide encoding process performed by APs. The usage of EWF codes allows the separation of disseminated data into importance classes with unequal error protection and, which is more significant for the proposed scenario, with unequal recovery times, enabling faster retrieval of time-critical information. In brief, EWF codes provide an efficient solution for the content reconciliation problem, adaptation to the changing link behavior and timely and reliable delivery of important data.

The rest of the paper is organized as follows. In the next section a background on rateless and EWF codes is provided, as well as an overview of related work. Section III gives the detailed system description. Simulation results are presented in Section IV, while conclusions are given in Section V.

II. BACKGROUND

A. Unequal Error Protection (UEP) Rateless Codes

Rateless (or digital fountain) codes are a recently introduced class of forward error correction codes with universally capacity-approaching behavior over erasure channels with arbitrary erasure statistics. The first practical capacity-approaching version of rateless codes are LT codes [11]. Using LT codes, a transmitter can generate potentially infinite amount of encoded symbols from $k$ information packets of a source block. LT encoding is a simple process where, for each encoded packet, a degree $d$ is sampled from a degree distribution $\Omega(d)$, and $d$ out of $k$ information packets from the source message are uniformly selected and bit-wise XOR-ed to produce the encoded packet (Fig. 1). The design of the degree distribution $\Omega(d)$ that will enable source message recovery from any slightly more than $k$ received encoded symbols using the iterative Belief-Propagation (BP) decoding algorithm is fundamental to the LT code design. This problem is solved in [11], where it is shown that using so called robust soliton degree distribution, it is possible to recover the source message from any $k'$ encoded symbols, where $k' \to k$ asymptotically, with encoding/decoding complexity of the order $O(k \cdot \log k)$.

To obtain linear encoding-decoding complexity with capacity-approaching performance, a reduced complexity inner LT code can be concatenated with an outer high-rate LDPC pre-code, resulting in a class of rateless codes called Raptor codes [12].

LT and Raptor codes are equal error protection codes. EWF codes are a simple extension to LT codes that provide unequal error protection [10]. In EWF codes, the set of $r$ expanding windows are defined over the source block using polynomial $\Pi(x) = \sum_{i=1}^{r} \Pi_i x^i$, where $\Pi_i = \frac{k_i - k_{i-1}}{k_i}$ and $k_i$ is the $i$-th window size (Fig. 2). The set of expanding windows is characterized by a window selection probability distribution described by polynomial $\Gamma(x) = \sum_{i=1}^{r} \Gamma_i x^i$, where $\Gamma_i$ is the probability of selecting the $i$-th window. Finally, a degree distribution $\Omega^{(j)}(x) = \sum_{i=1}^{k_j} \Omega^{(j)}_i x^i$ is associated with the $j$-th expanding window, $1 \leq j \leq r$. EWF encoding proceeds in a slightly different fashion than the usual LT encoding. To create a new EWF encoded symbol, first one of the windows is randomly selected with respect to the window selection probability distribution $\Gamma(x)$. Then a new encoded symbol is determined with an LT code described by the selected window degree distribution as if encoding were performed only on the input symbols from the selected window. This procedure is repeated for each encoded symbol. As the windowing scheme is not relevant for the decoding process, EWF decoding is the same iterative BP decoder applied in LT decoding.
B. Related Work

ITSs represent a novel and widely addressed application field for data dissemination algorithms, potentially involving hundreds of nodes which handle a large amount of heterogeneous information. A system supporting traffic alert dissemination and visualization is described in [13], with the aim to provide the drivers with continuous updates about traffic conditions. It resorts to direct V2V communications while adopting three different dissemination algorithms to reduce the network overloading and minimize message broadcasting. Concerning I2V communications, the adoption of IEEE 802.11 has been investigated in [14], with the aim of managing the session state information of vehicles via a distributed proxy; an application to secure payment protocol is pointed out in [15], while [16] provides a platform for advanced emergency call in order to reduce recovery time after accidents. Further, [17] focuses on a realistic urban environment to investigate whether communications between vehicles could benefit from a pre-existing infrastructure in the presence of user mobility. It is highlighted that an opportunistic deployment of the APs is strongly advisable, given an accurate mobility model.

An application of rateless codes to data dissemination within a vehicular networks adopting both I2V and V2V, as well as I2V2V\(^1\) schemes, is addressed in [9]; it employs an efficient coding scheme already adopted in wired P2P networks, properly modified to increase the dissemination speed. The same authors applied a similar data dissemination protocol in [18], enhanced by a simple content reconciliation procedure that makes it suitable for e-commerce and e-advertising applications. The focus of the work presented in [9] and [18] is on I2V2V scenario and in particular, on the problem of designing an efficient scheme for sharing downloaded encoded packets among vehicles while ensuring that only innovative encoded packets are exchanged. On the other hand, our proposal investigates I2V scenario and focuses on designing efficient EWF coding in multi-source scenario distributed over network of APs. The proposed solution is dimensioned to allow the separation of disseminated data into importance classes with unequal recovery times, thus providing an elegant, simple and flexible solution to match heterogeneous network traffics with different quality of service constraints.

III. DISTRIBUTED UEP RATELESS CODING

A. System Model

The application scenario envisioned in this paper is derived from a real world case study, inspired by the Tuscany region project “Metropolitan Mobility Agency Supporting Tools” (SSAMM), devoted to enhance the quality of urban transportation system introducing innovative paradigms. The addressed urban communications scenario is modeled as a two-level network, as illustrated in Fig. 3. In particular, the lower level is composed of a large number of Sensor Nodes (SNs), positioned in such way that suitable and effective sampling of the road traffic is achieved within the area of interest [19]. Whenever possible, SNs are deployed in correspondence with road infrastructures such as posts, lamps and traffic lights, typically arranged in a square grid fashion. Their purpose is to collect traffic flow information (such as average crossroad waiting times, presence of roadworks or accidents, etc.) and relay it to the higher layer AP network consisting of interconnected APs, where a subset of SNs is connected in a star-wise or tree topology to an AP. The proposed topology might be compared with a classical 3G oriented architecture; in this case APs would be replaced by Base Stations (BSs) additionally endowed with a Wireless Personal Area Network (WPAN) interface in order to be connected with SNs. However, a limited number of BSs could require multihop routing procedures to deliver data with a consequent throughput reduction, while a higher number of BSs might dramatically affect the overall complexity.

Upon reception of SN data, APs exchange and encode data packets and broadcast the encoded data to Mobile Users (MUs). MUs join the network without need of association with a specific AP by adopting a passive operation mode and continuously collecting information regarding the surrounding environment broadcasted by APs. MUs are not involved in the data dissemination algorithm, as they operate only in receiving mode in order to lower the implementation complexity and cost of the mobile equipment, minimize the downloading time avoiding access contentions and complex handover procedures. As a consequence, inter-vehicle communications are not hereafter considered. Finally, we assume that MUs have on-board capabilities to process the downloaded data in order to interpret current traffic information. Specifically, the collected real-time data provide opportunity for on-board computer to perform optimal route calculation, delay estimates and display visual map representation of critical locations.

Data processing is implemented in an automatic (i.e., peri-

\(^1\)In I2V2V scenario, mobile nodes re-disseminate information obtained from the infrastructure.
Fig. 4. Data refreshment period of the proposed application, encompassing gathering, exchange, encoding and download phases.

The system application, residing in APs, periodically performs the following four procedures: (i) data gathering from SNs, (ii) data exchange with other APs, (iii) encoding and (iv) disseminating encoded data to MUs. We refer to these four stages as upload, exchange, encoding and download phase, respectively, and the period encompassing all of them as data refreshment period. According to the IEEE 802.11 standard, the link time in every AP coverage zone is divided into superframes [20], and the data refreshment period in each zone is aligned with superframe boundaries (Fig. 4).

During the upload phase, every AP polls all SN in its domain and collects the most recent measurements. As typically foreseen by most of the IEEE 802.11 standards [20], superframes are divided into the Contention-Free Period (CFP) and Contention-Based Period (CBP), where the former is used to avoid MAC collisions and deliver prioritized information. The polling phase can be accomplished within the CFP part of a typical frame. In particular, it starts after an AP beacon containing a field dedicated to delivery traffic information map. As a consequence, the stations (i.e., SNs in our case) associated with AP become aware of CFP beginning and avoid entering a contention for a time interval equal to CFP duration. Then, AP individually polls each station with a poll message and waits for responding data and acknowledgment messages [20]. We assume that APs are globally synchronized over the AP network, so the upload takes place in the first superframe period following the start of the data refreshment period. Each SN uploads its measurements within a single data packet of length $L$ bits. Since SNs and APs form an infrastructured network, we assume that SNs have been deployed in line-of-sight fashion in order to optimize link quality; however possible packet losses are managed by means of Automatic Repeat reQuest (ARQ) scheme, so that from an application point of view, data delivery could be considered reliable. To match the constraint of polling completion within the first superframe, a maximum ARQ retransmission persistence is set to $N_A$ attempts, where this parameter is selected in order to yield a negligible residual packet error probability.

After the upload phase, each AP stores and uniquely indexes each received data packet, where the indexing scheme is known to all APs. The total number of stored data packets in APs network per data refreshment period is $k$. The $k$ data packets represent a single data generation upon which the UEP rateless coding is performed. The differentiation among data generations can be achieved using an appropriate field in the packet header, allowing MUs to maintain global time-references. The data generation is distributed over all APs in the network and each AP contains only a subset of packets of the data generation. Therefore, prior to the encoding phase, each AP has to collect missing parts of the data generation.
from other APs, which is done during the exchange phase.

Ideally, during the exchange phase, each AP exchanges its own part of the global data generation with other APs. However, for large AP network, this may present a sizable communication burden on the infrastructure MAN. Therefore, for large AP networks, a separation into AP regions is possible where each AP would frequently exchange its data with the APs within the region it belongs to, and less frequently with the remote regions of the AP network. The details of such network organization are omitted and in the following we assume that at the beginning of each refreshment period all APs exchange their data among each other.

After the exchange phase, the system application in each AP in the network performs EWF encoding over the data packets of a single generation (i.e., coding is performed at the application level). Prior to encoding, each AP defines the set of data importance classes by introducing the set of expanding windows over the data block to be transmitted. In addition, AP selects parameters of the EWF code to be applied: window selection distribution $\Gamma(x)$ and the set of degree distributions $\Omega^{(i)}(x)$ for each of $r$ windows. The division of the data block into importance classes (windows) may be defined for each AP in advance. For example, an AP may select all the data exchanged with its neighboring APs (including its own) as the most important data, and the data gathered from the remaining (non-neighboring) APs as the least important data.

Following the appropriate EWF code design, each AP independently produces $k_{AP}$ EWF encoded packets, where the actual value of $k_{AP}$ is chosen such that it is sufficient for successful data recovery of all data importance classes by majority of MUs with high probability (w.h.p.). Specifically,

$$k_{AP} \geq \left( 1 + \frac{\epsilon^{(\text{max}}}{1 - P_{PL}} \right) \cdot k$$

(1)

where $\epsilon^{(\text{max}}$ is the reception overhead that allows for decoding of the complete data generation w.h.p. and depends on the properties of applied EWF codes, while $P_{PL}$ is the estimated worst-case link-layer packet loss probability. Clearly, the reception overhead required to recover the subset of more important data within the data generation could be considerably lower than $\epsilon^{(\text{max}}$ and EWF code design should enable MUs to recover at least the most important data.

In the final, download phase, each AP disseminates EWF encoded packets by simply broadcasting them to mobile users currently located in its coverage area. This approach has been adopted in order to minimize the complexity and the power consumption of MU receiver by always keeping it in a receiving mode. The dissemination starts in the first superframe that follows the encoding phase, and lasts until the next data collection phase (i.e., the next data refreshment period). For the purpose of broadcasting, a natural choice is to use CFP part of the superframe, as it guarantees delivery of traffic-info updates to all MUs within the service area. While traveling within the service area, each MU performs a channel sensing at periodic intervals (say $\theta$) and dynamically selects the best carrier while transparently roaming among adjacent APs. MU continuously downloads EWF encoded packets from each AP it is associated to, until it collects enough for data recovery using the iterative BP algorithm. It is important to note that the decoding algorithm needs not be aware of the importance structure imposed by each AP over the data generation, as long as all the APs, which provide MUs with encoded data, perform EWF encoding over the same data generation (i.e., over the identical source message).

As the reception of packets and decoding progresses, a MU will sequentially recover data from consecutive importance classes, starting with the most important class. The average number of excessive encoded packets needed for recovering the $k_i$ data packets contained in the $i$-th window is measured by the reception overhead $\epsilon'_i$. For successful recovery of the first $i$ importance classes, MU needs on average $k'_i = (1 + \epsilon'_i) \cdot k_i$ encoded packets, where $\epsilon'_i$ should be as small as possible positive number. However, as differences among various $k_i$ can be significant, the number of received packets needed to recover the corresponding class will be also different. A small $k_i$ will cause small $k'_i$ and therefore, short recovery time. Apart from the values of $k_i$, the differences in recovery times of importance classes are affected by the choice of window selection distribution $\Gamma(x)$ and corresponding degree distributions $\Omega^{(i)}(x)$.

Finally, since each encoded packet is an innovative representation of the original data, any subset of $k' = (1 + \epsilon') \cdot k$ received encoded packets allows for restoration of the whole original data. Therefore, EWF codes, as a class of rateless codes, are suitable candidate to be used at the application level for content delivery in vehicular networks, as packet losses caused by the varying link characteristics are compensated simply by reception of the new packets without need for time-consuming TCP-like acknowledgment-retransmission mechanisms. Moreover, packets losses caused by receiver deafness during the selection of a different AP do not impact the data dissemination scheme, as MU continues downloading data without any need for (de/re)association, session management or content reconciliation. Finally, the division of data into importance classes by spatial criteria means that the importance classes of neighboring APs significantly overlap. When entering a new AP coverage zone, partially reconstructed data
from the previous zone should preserve retrieval times of the importance classes in the new zone.

The flowchart presented in Fig. 5 illustrates the above described process of data gathering, encoding and dissemination.

C. Delay Analysis

We denote the number of APs in the system by $N_{AP}$, the number of SNs by $k$ and we assume that number of sensor nodes per AP is $N_{SN} = k/N_{AP}$. Every AP divides the time in its service area in superframes of duration $T_{SF}$, equal to the beacon period needed to maintain the synchronization within each domain, while superframe time references in different AP domains are independent and not necessarily aligned. We assume that the transmission rate between AP and MUs is fixed and equal to $R$ bits/s.

1) Upload Delay Estimate: Typical sensor readings and the corresponding data packets contain small amount of data (up to few hundred bytes). The number of SNs per AP is expected to be in the order of tens, which means that the polling of all the SNs in the AP zone and the following upload of data packets can be performed within a single superframe; in other words, the total upload delay is $T_{UL} \leq T_{SF}^2$.

2) Exchange and Encoding Delay Estimate: As described, every AP produces $k_{AP}$ encoded packets by XOR-ing randomly selected data packets which are initially stored in different APs. In order to perform encoding, an AP requests missing data packets from the APs where these are stored, using the known indexing/storage location association. We assume that missing data packets are requested from respective APs collectively (i.e., in a single request per AP) and the requested data packets are sent collectively in the response packets. Therefore, the total encoding delay is:

$$\tau_{EE} \leq T_{req} + T_{resp} + \tau_{max}^{RTT} + \tau_{proc} \tag{2}$$

where $T_{req}$ and $T_{resp}$ are times needed to transmit the request and response packet(s) during the exchange phase, $\tau_{max}^{RTT}$ is the maximum round-trip time in the MAN and $\tau_{proc}$ is the processing delay required for the encoding of $k_{AP}$ packets. If we assume a typical gigabit Ethernet MAN interconnection between APs and consider realistic values for inter-AP ranges, all the delays introduced above could easily fit within the remaining part of the same superframe period in which SN data was polled; thus the exchange and encoding delay $\tau_{EE}$ can be considered negligible.

3) Download Delay Estimate: Download delay depends on the amount of downloaded data, download speed (i.e., bit-rate), mobility pattern and the allocated fraction of the superframe reserved for the broadcast of service traffic from APs to MUs.

We assume that an MU is able to decode the entire data generated w.h.p. once it downloads $(1 + \epsilon_{max})/(1 - P_{PL}) \cdot k \cdot L$ bits of data. The amount of data each vehicular user gets from an AP within a single superframe is $T_{SF}^{BC} \cdot R$, where $T_{SF}^{BC}$ is the duration of the fraction of the superframe reserved for AP broadcasting service and $R$ is the bit-rate. The number of superframes $N_{DL}^{(BC)}$ needed for successful completion of the service stems from the following inequality:

$$N_{DL}^{(BC)} \cdot T_{SF}^{(BC)} \cdot R > \frac{1 + \epsilon_{max}}{1 - P_{PL}} \cdot k \cdot L \tag{3}$$

where $N_{DL}^{(BC)}$ is obtained as the smallest integer satisfying the above inequality. The download delay estimate is:

$$\tau_{DL}^{(BC)} = N_{DL}^{(BC)} \cdot T_{SF} + \left(\frac{N_{DL}^{(BC)}}{N_{SF}}\right) \cdot \theta/2 \tag{4}$$

where $\theta/2$ is the expected waiting time until the correct carrier has been sensed, and $N_{SF}$ is the average number of superframes MU spends in a single AP zone. Note that by replacing $\epsilon_{max}$ with $\epsilon_i$ and $k$ with $k_i$ in the above equations, we can obtain delay estimates of recovering the first $i$ importance classes.

IV. Simulation Results

The simulation setup assumes that the urban area is covered by an irregular Voronoi polygon lattice (Fig. 6). Voronoi polygon lattice is commonly used in wireless communications to model the division of the urban service area in coverage zones, where each polygon represents the coverage zone of a single AP. MUs move throughout the lattice using the rectangular grid that models urban road-infrastructure, associating with the nearest AP. The overlay Voronoi polygon lattice is independent and arbitrarily aligned with the underlying rectangular road-grid. We assume that the simulation area is torus; when a MU reaches area boundary, it reappears on the same street on the opposite side. The MUs move according to the recently introduced cellular automata based model of urban traffic [22]. This is a discrete space and discrete time mobility model that has three major components: cellular road structure, vehicle movement and traffic light control. At each time step, vehicles move on a regular grid consisting of horizontal and vertical (bidirectional) streets divided into discrete cells; speed and
motion of the each vehicle is influenced by the motion of the closest vehicle traveling in front, it’s turning decision and the current state of the traffic light on the next intersection. Control of the traffic lights is coordinated at all intersections and updated at each time step. Further details on the used mobility model can be found in [22] and [23].

In the simulations we employed EWF codes with two windows, where the first window contains the traffic data of higher importance (i.e., immediate neighborhood) and the second window encompasses traffic data both of higher and lower importance. We will refer to data contained in the first window as the more important data (MID), and to the remaining data as less important data (LID). Both data blocks (i.e., windows) are encoded using LT codes with robust soliton degree distribution [11]. The purpose of the simulations is to estimate the duration of the download phase, both for MID and LID, as this is by far the lengthiest phase within the data refreshment period. In each simulation run, while moving on the road grid, the MU starts receiving the encoded data from the AP in whose coverage zone it is currently located. The reception of the encoded packets continues until the MU collects enough to successfully decode both MID and LID. If during this process, MU happens to move to another AP zone, it simply associates to a new local AP and starts to receive its encoded packets (MID window slightly shifts accordingly). Upon reception of sufficient amount of encoded packets, MU starts the iterative BP decoding algorithm for LT codes [11], whose iterations advance as the reception of encoded packets continues. The simulation run ends when the decoding of both MID and LID is finished and all the original data packets are retrieved. All the presented results are obtained by performing 1000 simulation runs for each set of parameters.

Table I summarizes the values for the communication and mobility model parameters used in simulations. The number of APs is chosen such that it provides a coverage area which is approximately equal to a medium-sized city area. Number of SNs per AP is selected to allow effective traffic sampling in the service area and, at the same time, to satisfy upload delay constraints, as elaborated in Section III-C. The data packet length is estimated in such way that is sufficient to accommodate single sensor readings and additional headers (i.e., IEEE 802.11 MAC and LLC, network and transport layer). The values for bit-rate and superframe duration are selected as suggested in [24] and [25], and service time is chosen such that it leaves enough superframe time for other AP services. Pessimistic assumption on packet-loss rate was taken from [4], while the mobility model parameters were taken from [23]. We performed simulations using sparse, moderate and dense vehicle traffic assumptions [23], however, there were no significant differences among the obtained results. Here we present the results only for the sparse traffic, as they represent the worst-case performance scenario (in this case the movements of MUs from one to another coverage zone are the most frequent).

![Fig. 7. Probability of successful recovery $P_{SR}$ for MID and LID, $R = 6$ Mbit/s.](image-url)

Fig. 7 presents the probability $P_{SR}$ that the MU successfully recovers MID and LID as a function of time, for the download rate $R = 6$ Mbit/s and MID window selection probability $\Gamma_1$ equal to 0.1, 0.25 and 0.5, respectively. As it can be observed, the choice of $\Gamma_1$ significantly influences the recovery time both for MID and LID. For $\Gamma_1 = 0.1$, the difference between MID and LID recovery time is negligible, meaning that the division of data into different importance classes has almost no effect. However, with the increase of $\Gamma_1$ the difference between MID and LID recovery times becomes apparent, as the former decreases and the latter increases. Appropriate choice of $\Gamma_1$ can yield short recovery times for MID and longer (but tolerable) recovery times for LID. For example, for $\Gamma_1 = 0.5$ the data refreshment period needs to be of the order of 30 seconds to allow the retrieval of LID data w.h.p., while MID is retrieved w.h.p already after 5 seconds. As the MID represents traffic
information with currently highest spatial importance for the MU, its fast retrieval allows timely decisions, sufficient for the period until next update is retrieved. Moreover, longer data refreshment period means infrequent data exchange among APs and lower communication burden for the AP network.

Figs. 8(a) and 8(b) show\( P_{SD}(R) \) for \( R = 12 \text{ Mbit/s} \) and \( 24 \text{ Mbit/s} \), respectively. The impact of \( \Gamma_{1} \) on the MID and LID recovery time is the same as in the previous case - the increase of \( \Gamma_{1} \) lowers MID and raises LID recovery time. However, the increase in the data rate decreases both decoding times (as compared to \( R = 6 \text{ Mbit/s} \)), which are now of the order of several seconds.

V. CONCLUSIONS

In this paper, we presented a low-complexity end-to-end solution for I2V data dissemination based on a class of UEP rateless codes called EWF codes. The problem of heterogeneous connection durations and link qualities of different MUs retrieving traffic information updates is solved by a careful EWF code design. Improved error protection and short recovery times facilitate reception of more important traf- fic by majority of MUs within a strict service delay-constraints and increased reliability, providing simple and elegant solution to achieving different qualities of service. In other words, with appropriate EWF code design, MUs with good reception conditions will receive complete traffic updates, whereas MUs with severe connection impairments will be able to recover at least the most important traffic data. Furthermore, EWF codes preserve all the benefits of standard rateless codes as each encoded packet created by APs is an representation of the original data. While roaming through the network, MUs simply collect the encoded data in receiving mode only, avoiding time-consuming TCP-like reliability mechanisms, and, while changing reference APs, MUs straightforwardly continue with data download without need for the content reconciliation phase.

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Cedomir Stefanović (S04) received the Dipl.-Ing. degree and Mr.-Ing. degree in electrical engineering from the University of Novi Sad, Novi Sad, Serbia. Since 2006, he has been a Teaching Assistant and a PhD student at the Department of Power, Electronics and Communication Engineering, University of Novi Sad. His research interests include distributed coding for wireless ad-hoc and sensor networks, frame synchronization and synchronization sequence design.

Dejan Vukobratović (S02-M08) received the Dipl.-Ing. degree in electrical engineering and the Dr.-Ing. degree in electrical engineering from the University of Novi Sad, Novi Sad, Serbia, in 2001 and 2008, respectively. Since 2008, he has been an Assistant Professor with the Department of Power, Electronics and Communication Engineering, University of Novi Sad. From June 2009, he is on leave as Marie Curie Postdoctoral Research Fellow at the University of Strathclyde, Glasgow, U.K. His research interests include sparse-graph codes, iterative decoding and network coding with applications in multimedia communications and wireless sensor networks.

Francesco Chiti (M01) received the degree in Telecommunications Engineering and the PhD degrees in Informatics and Telecommunications Engineering from the University of Florence in 2000 and 2004, respectively. His current research topics are devoted to Link and Network layers protocols design as well as resource management schemes for Ad Hoc and sensor networks. He took part in several European research projects as REGPOT AgroSense, IP GoodFood, STREP DustBot, NoEs NEWCOM and CRUISE, GJU TWIST, ETSI STF179 and COST 289 action.

Lorenzo Nicolai was born in Pistoia in 1982 and received his Master Degree in Telecommunication Engineering in 2007 from the University of Florence. His main research topics are ranging and localization procedures for wireless networks, H-ARQ schemes for digital communications and routing protocols for Mobile Ad hoc Networks. He took part in several European research projects such as REGPOT AgroSense, STREP DustBot and CRUISE.

Vladimir Crnojević received the Diploma degree, M.Sc. degree, and PhD degree in electrical engineering from the University of Novi Sad, Serbia, in 1995, 1999, and 2004 respectively. From 1995 he worked as teaching and research assistant with Communications and Signal Processing group at the Department of Electrical Engineering, University of Novi Sad. From 2004 he works as an assistant professor at the same Department. Vladimir Crnojevic is the director of BioSense center devoted to deployment of state-of-the-art ICT solutions in agriculture, forestry and environment. He is also the leader of the URSUS group doing research in computer vision and intelligent surveillance systems. He authored or co-authored more than 50 conference and journal papers. He is the coordinator of two FP7 projects, two EUREKA! projects, one national project of technology development, as well as participant in several other FP7, COST and national research projects. His research interests include image processing, pattern recognition, computer vision, evolutionary algorithms and wireless sensor networks.

Romano Fantacci (M84, SM90, F05), born in Pistoia, Italy, graduated from the Engineering School of the University of Florence, Florence, Italy, with a degree in electronics in 1982. He received his Ph.D. degree in telecommunications in 1987. After joining the Electronics and Telecommunications Department of the University of Florence as an assistant professor, he was appointed associate professor in 1991 and full professor in 1999. Romano has been involved as responsible in several European Space Agency (ESA) and European Union research projects. He is the author of more than 300 papers published in prestigious communication science journal and holds some patents. Romano was funder of the Information Communication technology Consortium (TICOM), a joint venture between the University of Florence and Selex Comms, SpA, a Finmeccanica Company and appointed as president since May 2010. He guest edited special issues in IEEE Journals and magazines and served as symposium chair of several IEEE conferences, including VTC, ICC and Globecom. Actually, he is involved in PIRMC10, Istanbul, Turkey, as Wireless Communications symposium chair. He has had an active role in IEEE and ComSoc for several years. In 2004, Romano was involved in the proposal of the IEEE/ComSoc Technical Committee on Ad-Hoc Sensor Networks and IEEE/ComSoc Technical Committee on Power Line Communications; since then he has been serving as its Vice-Chair. He received the AEI/IEEE Renato Mariani Award in 1982, IEEE IERE Benefactor premium in 1990 and IEEE COMSOC Award Distinguished Contributions to Satellite Communications in 2002. Romano was Associate Editor for Telecommunication Systems, International J. Commun. Systems, IEEE Trans. Commun and funder Area Editor for IEEE Transactions on Wireless Communications. Since 2005 he is an IEEE Fellow.