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Semantic V2X Communications for Image Transmission in 6G Systems

Jose Manuel Gimenez-Guzman, Israel Leyva-Mayorga, and Petar Popovski

Abstract

The success of future Intelligent Transportation Systems (ITS) heavily relies on the availability of wireless communications technologies that are able to fulfil the strict requirements imposed by applications such as autonomous driving. However, due to the scarce spectrum allocated to ITS, current vehicle-to-everything (V2X) networks experience a severe capacity bottleneck. In this paper, we consider a typical ITS application where images are periodically captured and transmitted by the vehicles. Using an open dataset of real video frames captured by vehicles, we show that the current bandwidth allocated to ITS is insufficient, requiring the vehicles to transmit the video at only a small portion of the frame rate at which it can be captured by the sensors. Furthermore, we show that semantic communications (SemCom) using semantic segmentation are essential to solve this problem, since the receivers are not interested in receiving high definition images but a semantic interpretation that assesses the importance of the elements in it. Our results show that, although the benefits of SemCom in terms of energy consumption are limited to algorithms with a low computational complexity, SemCom are able to greatly improve the performance in terms of maximum supported load and latency, making SemCom essential to make future ITS over 6G viable.

Introduction

Future Intelligent Transportation Systems (ITS) will result in highly dynamic and complex network topologies due to the highly diverse communication flows and network elements involved: vehicles, infrastructure, pedestrians, roadside barriers, among others. Moreover, these network elements must coexist and interact with other moving elements that are not connected, so the network must be able to perceive and react to the environment in a coordinated manner. Such level of coordination among network elements requires the dissemination of sensory data with high reliability and low latency.

From the regulation and standardization points of view, there are two decisive milestones that have led ITS to be a key 5G application. First, the possibility of direct communications was included by the 3GPP since Release 14 of its 4G cellular network standards in 2017. Second, in 2021, the decision of the US Federal Communications Commission (FCC) to use the 5.9 GHz frequency band (the one reserved for ITS) by C-V2X (Cellular Vehicle-to-Everything), instead of Dedicated Short Range Communications (DSRC). Hence, although DSRC networks were initially envisioned to support V2X communications, their unbounded channel access delay and, specially, limited coverage, has boosted the use of C-V2X.

Despite these milestones, the ability of 5G to support Ultra Reliable and Low Latency Communication (URLLC) ITS is limited since spectrum regulations have led to a bandwidth shortage for ITS. Specifically, the FCC reduced the bandwidth allocated for ITS in the US to 30 MHz in 2021. Consequently, fulfilling the large set of strict and oftentimes conflicting requirements for ITS is an open problem for the scientific community and for the design of the sixth generation of mobile networks (6G), whose foundational design can be guided towards fulfilling the specific requirements of ITS applications.

In addition to fulfilling the essential application requirements, energy efficiency is another Key Performance Indicator (KPI) that must be considered to develop sustainable 6G networks. Notwithstanding, the evolution of well-known research areas, including antenna design, adaptive modulation and coding, and waveforms for ITS, will not be sufficient to develop efficient 6G-based V2X networks, so we will also require to develop disruptive and revolutionary technologies, including semantic communications (SemCom). SemCom constitute a revolutionary new architecture that integrates the meaning of information in data processing and communication. Due to the high number of resource-hungry applications and limited bandwidth, it is expected that SemCom becomes the key enabler to make future ITS feasible [1].

The original ideas of SemCom can be found in the work by Shannon and Weaver as the second-level problem in the area of communications, in addition to the well-known technical problem tackled by Claude Shannon to reliably transmit data. Although the ideas of SemCom are not new, the recent interest in SemCom is motivated by the advent of machine learning and artificial intelligence (ML/AI) for communications, which play a key role by providing the tools to extract the

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semantic information from the data. Shannon and Weaver also identified a third-level problem that lays the foundations for pragmatic communications [2], namely the effectiveness problem, that makes the emphasis in the action that is expected from the receiver after receiving data.

In this work we focus on the semantic problem, where the transmitter aims to convey the semantic meaning of the data. In this setting, a question arises: how is SemCom expected to operate in future V2X networks? Of course, this is not a question that can be answered with precision currently. However, there are some clear issues and design guidelines for future SemCom V2X networks. First, as semantics has a strong dependence on the type and source of the information, it is not expected to have a unique SemCom algorithm operating in the V2X network ecosystem, but a plethora of them depending on the application. For example, the SemCom algorithm used for an application devoted to increasing driving efficiency may be different from the one for an application devoted to increase traffic security. Furthermore, the semantics of the information provided by a sensor camera will be radically different to the one provided by a wheel pressure sensor or the sensors that identify the engine or battery status. Second, to enable a flexible development of SemCom techniques, they should not take part of the network design itself. However, the network should help providing the computational needs of SemCom algorithms. In this sense, it is expected that edge computing can highly contribute to alleviate the computational efforts from vehicles. Third, due to the heterogeneous nature of services transported over V2X networks and to contribute to enrich the scope and transmission range of the source data and its semantics, it will also be mandatory to consider more flexible network deployments. In this sense, it is interesting to highlight the recent efforts to include Low Earth Orbit satellites or Unmanned Aerial Vehicles (UAV) [3] to assist cellular V2X communications, so 6G networks must be ready to support this kind of deployments to contribute to richer SemCom deployments.

In our previous work [4], we characterized the limitations in the amount of data that can be generated and transmitted by the vehicles in general V2X environments, and observed that employing lossless compression techniques is greatly inefficient, motivating the need for semantic or goal-oriented communications in important ITS scenarios. In this manuscript we analyze the benefits and drawbacks of using SemCom in the context of V2X networks by considering algorithms that have been trained for the specific application goal and, hence, assume that these perform an effective semantic extraction. The focus is on the specific case of image transmission, showing again the inability for sending raw images as they are generated from a very well-known dataset, so we compare the performance of using lossy image compression techniques with SemCom.

The major contributions of the work are:

1. We study the problem of image transmission over vehicular networks showing the impossibility of transmitting raw images from a real-life dataset [5].
2. We study the benefits of lossy image compression techniques to tackle the problem.
3. We study how the use of SemCom can improve the performance with respect to lossy image compression in terms of latency, supported load and energy consumption, simultaneously.
4. We compare the performance of some very recent semantic segmentation techniques to perform SemCom in ITS environments.

> In addition to fulfilling the essential application requirements, energy efficiency is another Key Performance Indicator (KPI) that must be considered to develop sustainable 6G networks.

The rest of the article is structured as follows. In the next section, we describe the case study of interest, namely, the transmission of images obtained by sensors installed in vehicles, including the motivation for the necessity of incorporating some form of data reduction technique (either compression or SemCom). Next, we describe the role of SemCom in data transmission over V2X networks and we propose a communications architecture to facilitate the integration and development of SemCom in future V2X networks over 6G technology. Later, we present a performance analysis of SemCom and finally, we summarize the main conclusions of the article.

Case Study: Image Transmission in ITS

One of the most bandwidth consuming data in V2X networks is the transmission of visual information. At the same time, this type of data is necessary for a number of services in ITS, such as those oriented to traffic safety, so being able to efficiently transport it is of utmost importance. In Fig. 1 we present a simple but meaningful scenario where image transmission is necessary to increase traffic safety. In this example, a vehicle informs nearby vehicles with a limited vision about an obstacle in the road to avoid a possible collision. Thus, by having vehicles send images they capture, it is possible to extend the awareness of other nearby vehicles, having a clear positive impact in safety. However, and even in this simple setting, we can notice a clear problem: the required bandwidth to transmit the images can be larger than the available one. Under these circumstances, we can take one of the following four options. First, we can do nothing, and simply accept that, if network capacity is not enough to transmit the sequences of frames, some of these must be dropped. We will use this scenario as a baseline, although we cannot recommend it if the network is overloaded, as the lost video frames or parts of frames can have important information for the safety point of view and also, the received information may have experienced an unacceptable latency. Second, we can deal with the sequence of images as a video and use video inter frame compression techniques. However, we discard this option as V2X networks are very dynamic, so the duration of communications between nearby vehicles can be very short, and video compressions where frame codings depend on previous frames would only be valid when sensing cameras refresh rates are high to have a fast response time. Third, we can compress the images using a well-known and efficient lossy

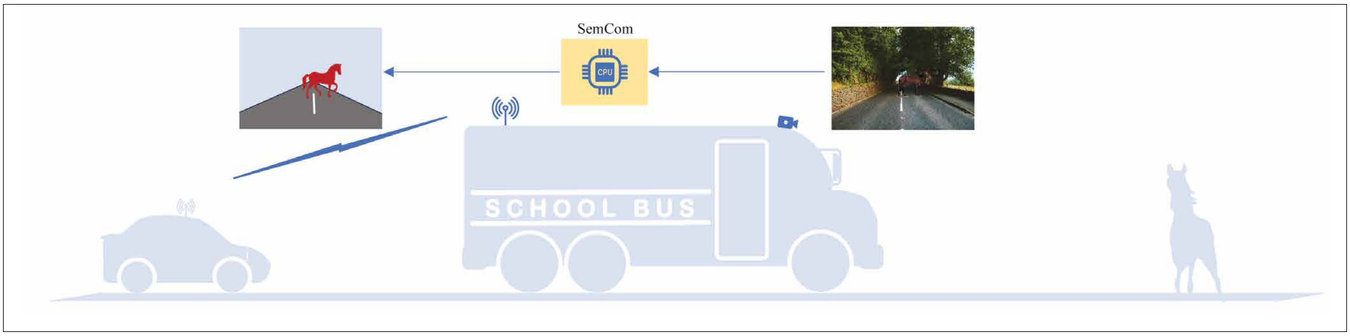

FIGURE 1. Example of the use of SemCom for image transmission in V2X networks.

Semantic Communications emerge as one of the key technologies for making future ITS over 6G networks viable.

image compression algorithm, such as JPEG or the more recent intra-frame coders defined in H.265/HEVC and H.266/VVC. Fourth, and last, we can resort to SemCom. This last choice is specially suited to the problem under study because the receiver is not interested in having a high definition image but only an interpretation of that image.

It could be argued that the third and fourth approaches are somewhat similar and, yet, fundamentally different. While both focus on reducing the amount of data to transmit, directly applying a classical compression algorithm does not take into account what is the important information contained in the image. For instance, in an extreme case, MJPEG could be used to obtain and transmit a very low definition image. However, this is not an option, as it can hinder the identification of a specific road hazard at the receiver, which might need to run an algorithm to detect this hazard. On the contrary, SemCom focuses on transmitting the important aspects contained in the images with a much smaller number of bits. Differently to proprietary systems running pre-defined algorithms, SemCom exploits the programmability and function virtualization capabilities to implement the algorithms to extract such important aspects in software. Then, these can be updated and optimized taking into account the use of computational and communication resources, which can be reflected by the overall energy consumption. In Fig. 1 we show an example of such situation, where the sensing vehicle does not send raw images, but a simplified semantic version of them, whose size is much lower and, at the same time, it highlights the road hazard.

At this point, it is also necessary to make a brief discussion about computation costs, as the size reduction obtained by image compression or SemCom may require a high computation cost. Unfortunately, edge or cloud computing approaches are not valid under this setting, because if we want to avoid the transmission of a raw image to its real destination, we also cannot transmit it for an edge computing approach.

To account for real sensing data, we have made use of the Cityscapes dataset [5]. This dataset includes several hundreds of thousands of video frames (and annotations of 25k of them) captured primarily in Germany with a stereo camera using CMOS 2 megapixels sensors capturing at 17 Hz equipped in a station wagon. Then, each frame consists of a 8 -bit PNG-lossless compressed image with size 2048×1024 pixels.

The wireless V2X channel considered is a block Rayleigh fading channel, so channel power gain remains constant during the transmission of an image but vary with time because of multipath fading and shadowing. When the received signal to noise ratio (SNR) is below a threshold, bits cannot be correctly decoded and we incur in an outage. Therefore, the outage probability is the probability that the received SNR is below that threshold. As the power gain in Rayleigh channels for each image is exponentially distributed, outage probability is also exponentially distributed and then the number of transmissions needed for successfully sending a packet is geometrically distributed. From the outage probability, the transmission rate, and the image size we can easily compute the required time to transmit an image over the wireless link.

Previous to the transmission latency and due to the stochastic nature of data traffic, images will also incur in an additional waiting latency. Of course, this latency increases monotonically with load. To model this latency, we have considered the wireless link to be a D/G/1 queue (following Kendall notation), guided by the deterministic nature of the image arrival rate to the queue, i.e. the generation rate of images by the sensing camera. As the size of PNG images is not deterministic, transmission time for each image is stochastic with a general statistical distribution. To compute the mean waiting time, we make use of the Alleen-Cunneen approximation for the more general G/G/1 queue, so we are able to obtain an upper bound for the mean waiting time depending on the system load, the service time and the coefficient of variation of both arrival and service processes.

Under these realistic settings, we have measured the average latency to send a frame over the V2X wireless channel with a refresh rate equal to the one produced by the dataset (17 Hz) and operating in the 5.9 GHz frequency band with a transmitting power of 26 dBm over 20 MHz channels, a distance from the transmitter to the receiver of 20 meters and an outage probability of 1%. However, under this configuration the system load is higher than one, so the queueing delay is not bounded. In fact, as it can be seen in Fig. 2, the queueing delay tends to infinity when the refresh rate is above 1.6 Hz, which is less than 10% of the 17 Hz refresh rate used in the Cityscapes dataset. With these results, we can easily conclude that V2X networks are, in its naivest operation mode, far from being able to transport the huge amount of data expected in future ITS, so it is mandatory to deal with the challenge of making them feasible. In fact, we have observed this behavior even with just one high-quality image sensor, while future deployments are expected to have a larger bunch of sensors. In this manuscript we study how SemCom can efficiently solve this issue. In fact, we will show that SemCom can become a powerful tool not to only make future ITS feasible, but also to increase the performance in terms of latency and energy consumption.

SemCom for Image Transmission Over V2X Networks

The integration of SemCom in V2X networks is essential to overcome the limitations described in the previous section. Our proposal for such integration is to place SemCom modules within the application layer of the ITS communications architecture defined in ETSI EN 302665 [6] and ISO 21217 [7] as shown in Fig. 3. Including SemCom in the application layer makes its use transparent to the ITS network infrastructure, so it does not affect the deployment of current and future standardized communication networks. The SemCom modules are accompanied by a SemCom management plane that sets up and adjusts the parameters of the algorithms and evaluates the data generated by the applications. The SemCom management plane also selects the SemCom algorithm to use for each data traffic flow, which allows different use cases or applications to use and share the same V2X message, as considered in 5G V2X standards [8]. These functionalities facilitate the use of different SemCom algorithms operating together in the same ITS network empowering the research and applicability of new computer vision techniques.

The benefits of using SemCom are based on its very high summarization capacity. A clear example of this capacity is shown in the Cityscapes dataset [5]. For example, if we encode each pixel with 24 bits, each image of the perspective camera would have a size of 6 Mbytes, as its number of pixels is 2048×1024. In the dataset, where the images are in PNG format using a lossless compression, each of these images has a size of about 2413 kbytes. However, the dataset also includes a semantic interpretation of each image, being its average size around 30.5 kbytes. With these data, we observe that the summarization capacity of SemCom is about 201:1 with respect to the uncompressed images and 79:1 with respect to the PNG images. Naturally, such high values for summarization capacity can lead to a drastic reduction in transmission time. However, the extraction of semantic information may have a high computational cost and we have to consider the additional execution time of the algorithms to evaluate the usefulness of SemCom for image transmission in V2X networks.

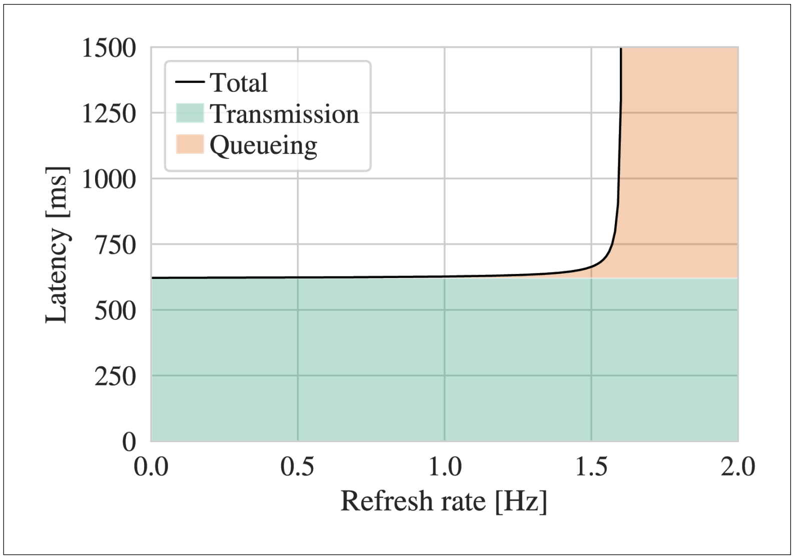

FIGURE 2. Latency as a function of the image refresh rate with raw data transmission. The maximum refresh rate before the latency increases towards infinity corresponds to the maximum supported load.

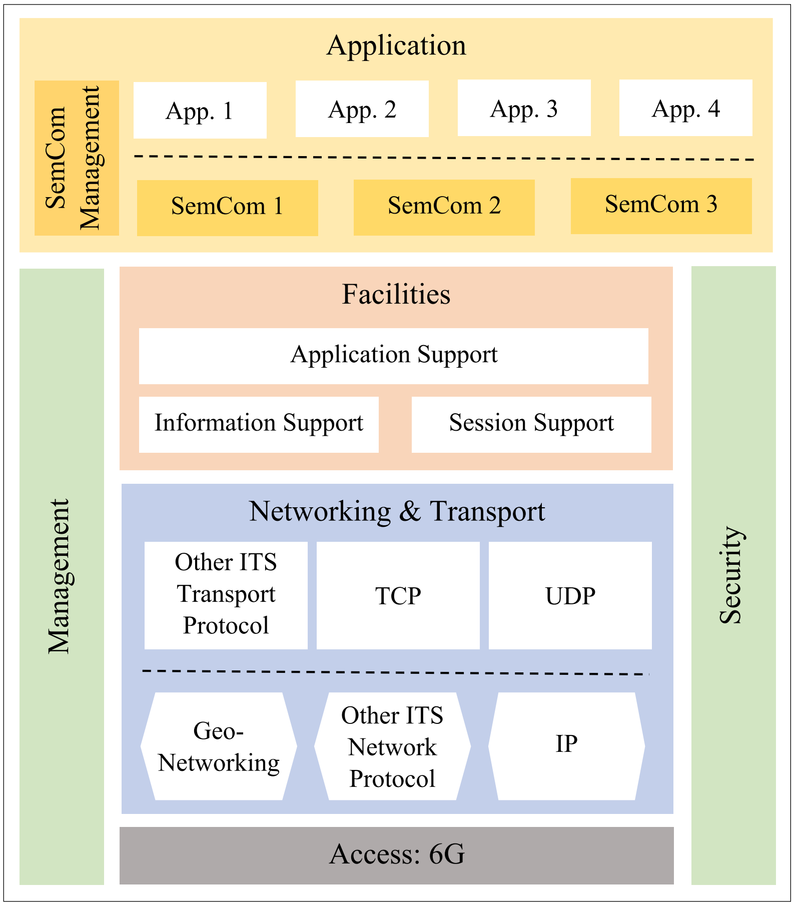

FIGURE 3. Proposed communications architecture.

Computer vision techniques are the key algorithms to extract semantic information from images. More specifically, computer vision algorithms are able to accomplish the following goals: image classification, object detection and semantic segmentation, among others. Image classification is oriented to discover the main content of an image, while object detection is able to

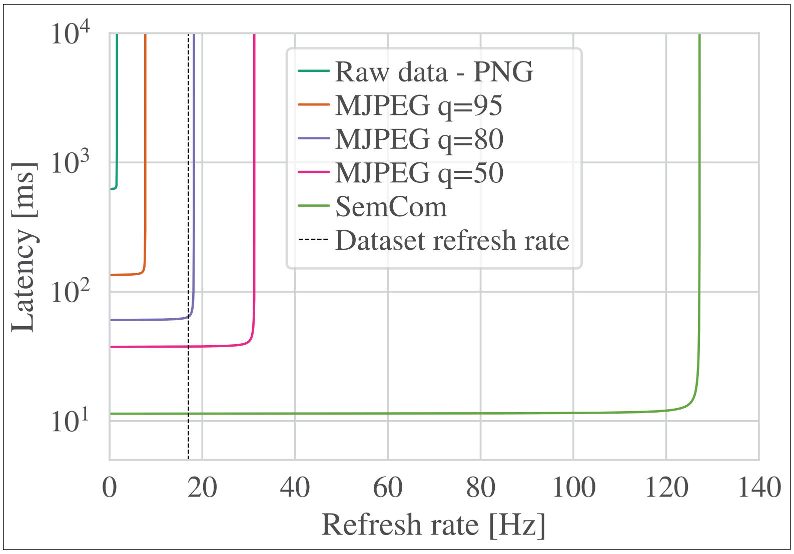

FIGURE 4. Latency as a function of the image refresh rate. The maximum refresh rate before the latency increases towards infinity corresponds to the maximum supported load.

locate the position and types of objects appearing in an image. However, and following our interest in semantics, we focus on semantic segmentation, whose objective is to classify the category to which each pixel of an image belongs. Then, in ITS environments, it would identify vehicles, trucks, pedestrians, obstacles, pavements, traffic signs and so on. Since semantic segmentation is a processing task, it requires a certain computational effort, expressed in floating-point operations (FLOPs). Naturally, the execution time of the algorithms is inversely proportional to the CPU clock frequency and to the number of CPU cores available at the processor (assuming that the algorithms can be efficiently run in parallel). As latency and energy are the main KPIs we are focused on, we are interested in lightweight semantic segmentation techniques, which are specially tailored for computations at mobile or edge nodes, as in our use case. More specifically, we have considered RealtimeSeg [9] as the technique to perform SemCom in our evaluations, as it has been shown to be very efficient for semantic segmentation in ITS, although in the latter section of results we also evaluate other semantic segmentation techniques.

Performance Analysis

In this section we evaluate the benefits and possible drawbacks of using SemCom in future ITS deployments. More specifically, we study to which extent SemCom can become the key enabler for 6G-based ITS. Naturally, SemCom is not the only potential candidate to solve this challenge. In fact, as it has been mentioned, a simple alternative is the use of lossy image compression to reduce the amount of data to be transported by the wireless network. MJPEG is a well-known lossy video compression standard that has been profusely used for video streaming in current wired and wireless networks. For that reason, we will compare the performance of SemCom not only with the naive approach of transmitting the raw data generated by sensing cameras in PNG format, but also with MJPEG compression. Based on the wavelet discrete transform applied to the YCbCr components of the JPEG lossy compression, MJPEG is able to greatly reduce image size while keeping an acceptable mean square error. The compression ratio will depend on a configuration parameter, called quality and denoted as q, for the JPEG compression. More specifically, we have considered three different qualities to account for high, medium and low quality ($q = 95$, $q = 80$ and $q = 50$, respectively). An important feature of JPEG compression is that its computation complexity does not depend on the compression ratio, as it is usual in typical lossless data compressors like Lempel-Ziv (LZ) source coders. To account for the computational effort for compressing Cityscapes video frames into a MJPEG stream, we have compressed 267 video frames captured in Frankfurt from the Cityscapes dataset using the Python Pillow library, measuring a computational effort of 1129 FLOPs to convert each pixel of each video frame.

For the computations required by MJPEG compression and SemCom coding, we have considered that the vehicle is equipped with a microprocessor with 8 cores, with each processor able to run 16 FLOPs per CPU cycle (as it is in processors supporting the Advanced Vector Extensions 2, AVX2) and that can operate up to a maximum clock frequency of $f_{CPU} = 3.36$ GHz.

Latency and Supported Load

In a first step, we analyse how SemCom is able to greatly increase the maximum supported load of wireless links with respect to the use of raw PNG data and also with MJPEG compression considering three different JPEG qualities: $q = 95$, $q = 80$ and $q = 50$. The maximum number of frames per second that allows to operate in real time for raw PNG data, MJPEG q=95, MJPEG q = 80, MJPEG q = 50 and SemCom are 1.50, 7.23, 17.03, 29.26 and 118.94, respectively. Note that this number represents the maximum number of frames per second that allows the frames to be processed and transmitted before the arrival of the next frame. These results show that only MJPEG $q = 80$ and $q = 50$ and SemCom are able to send frames with the dataset rate, being 17 Hz, with SemCom clearly overcoming MJPEG. On the other hand, Fig. 4 shows the latency as a function of the image refresh rate. As it can be seen, SemCom is not only able to greatly increase the maximum supported load (i.e., the maximum refresh rate with finite latency) with respect to the rest of proposals but also to greatly reduce the total latency. These results show that the use of SemCom can be very beneficial for future ITS deployments.

Energy Consumption Perspective

After illustrating the advantage of using SemCom in terms of supported load and latency, we now evaluate the impact of SemCom also in terms of energy consumption. To compute the energy consumption of the different proposals, we have considered both i) the energy required for communications, which depends on the time the vehicle is transmitting the frame, and ii) the energy required for the MJPEG compression and SemCom coding, consumed by the processor to perform the computation tasks. For this last component, we have considered the model used in [10], that considers that energy consumption is proportional to the square of the operating frequency of the CPU denoted as $f_r \leq f_{CPU}$. In Fig. 5 we show the mean energy required to perform the required computation and transmission of a Cityscapes dataset frame for different CPU clock operating factors, defined as the ratio of the operating to maximum CPU frequency, and being equal to 1 when the CPU operates at its maximum clock frequency f_{CPU} = 3.36 GHz. Note that we restrict the results to MJPEG q = 80 and q = 50 and SemCom because, when operating at the frame rate defined by the Cityscapes dataset, latency is unbounded for MJPEG q = 95 and for raw PNG frames. As it can be shown from Fig. 5, we can obtain lower energy consumptions for lower CPU operating clock frequencies. However, as there is a tradeoff between latency and energy consumption, we also show in Fig. 5 the latency for the different operating frequencies of the CPU. From this figure, we can mainly conclude that: i) CPU clock can be tuned to emphasize either latency or energy and ii) SemCom clearly outperforms MJPEG not only in terms of latency but also in terms of energy consumption, simultaneously.

Evaluation of Other Semantic Segmentation Techniques

In the previous subsection we have shown how the very recently proposed RealtimeSeg [9] is able to make SemCom to become the key enabler for future V2X communications. Notwithstanding, and also recently, there have been other proposals in the area of lightweight semantic segmentation, as it is of paramount importance that these techniques operate in real-time in mobile edge nodes. Table 1 shows a comparison between MJPEG, RealtimeSeg and other lightweight semantic segmentation techniques: NDNet [11], SeaFormer-S [12] and SGCPNet [13]. We also include in the comparison some recent lossy compression techniques. More specifically, we have considered the intra-frame coders H.265/HEVC and H.266/VVC. To perform a fair comparison, we have considered pictures with an equivalent quality to those of MJPEG q=80 using the Bjøntegaard Delta (BD) bit rate defined in [14] and [15].

The results show that the semantic segmentation techniques outperform MPEG, HEVC, and VVC, in terms of maximum refresh rate. In comparison, HEVC and VVC are the worst alternatives, since the high computational cost of HEVC requires a near-maximum use of the CPU to avoid increasing the latency indefinitely and does not compensate for its savings in image size, whereas VVC is not able to operate in real time. Table 1 also shows that, from the studied semantic segmentation techniques, only RealTimeSeg is able to decrease the energy consumption with respect to the use of MJPEG compression, as it is the semantic segmentation technique with the lowest computation complexity among all those evaluated.

Conclusion and Future Perspectives

Vehicle-to-Everything (V2X) networks will radically change the way we conceive future transportation systems. A huge amount of communication will take place over these networks to provide advanced services like autonomous driving, among many other possibilities. However, to fulfil the strict service requirements that all those data flows will require poses a great challenge to the scientific community, specially due to the bandwidth shortage devoted to Intelligent Transportation Systems (ITS). Semantic Communications (SemCom) emerge as one of the key technologies for making future ITS over 6G networks viable. In this work we evaluate the utility of SemCom in V2X networks with the study of a paradigmatic use case that requires a very high bandwidth: image transmission. The use of SemCom, by means of semantic segmentation, totally fits within this use case, as receivers are not interested in receiving detailed images but a semantic interpretation of what images mean for the receiver. Results show how SemCom are not only useful for this purpose, but also are necessary, because transmitting raw images is not feasible.

Vehicle-to-Everything (V2X) networks will radically change the way we conceive future transportation systems.

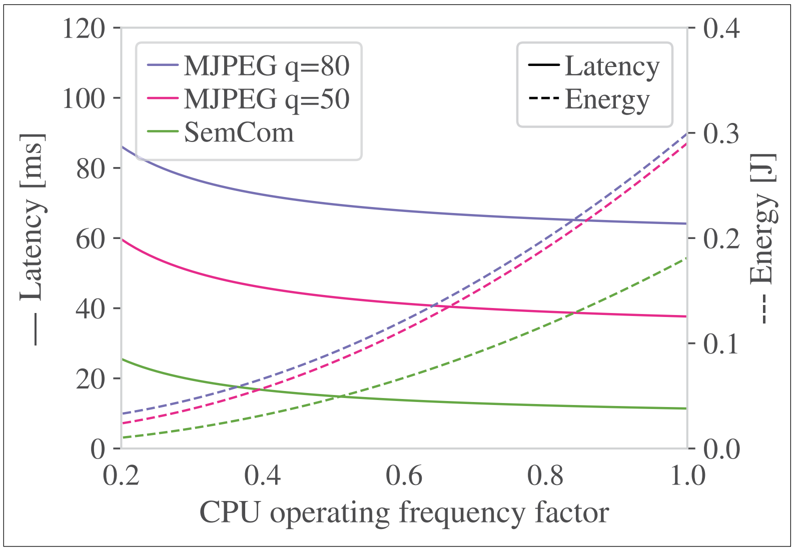

FIGURE 5. Latency and energy consumption for different CPU clock frequencies.

	Latency [ms]	Energy [J]	Maximum refresh rate [Hz]
Raw data - PNG	-	-	1.50
MJPEG q=95	-	-	7.23
MJPEG q=80	64.12	0.299	17.03
MJPEG q=50	37.64	0.290	29.26
HEVC	85.19	2.74	18.49
VVC	-	-	0.72
NDNet	40.42	1.644	30.72
SeaFormer-S	26.47	0.941	53.76
SGCPNet	18.33	0.530	95.57
RealTimeSeg	11.40	0.181	118.94

TABLE 1. Comparison among different semantic segmentation techniques, HEVC and VVC for the transmission of 2048×1024 video frames of the Cityscapes dataset.

SemCom leads to a dramatic increase in the network supported load and to a sharp decrease in latency, which are crucial key performance indicators in vehicular environments. On the other hand, in terms of energy consumption, SemCom only outperforms other alternatives when its computation cost is low, as it is the case of RealTimeSeg semantic segmentation technique.

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