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Efficient resource management in direct and indirect transmission in V2X communications

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ABSTRACT

Autonomous driving systems consist of vehicles that are able to communicate not only with other vehicles but also with entities in their environment, forming vehicle-to-everything (V2X) communication. However, the V2X applications have intense requirements posing a significant challenge to the telecommunication infrastructure. In this work, we consider two types of transmission, i.e. direct and indirect, and we utilize analytical traffic-engineering models with a view to conduct a performance analysis of a vehicular network that enables V2X communication. We additionally propose two resource management strategies in order to decrease the request rejection probability and consequently ensure enhanced communication conditions. The results reveal that the proposed resource management strategies constitute a strong asset for improving the system's service provisioning capability.

1. Introduction

The emergence of vehicle-to-everything (V2X) communication technologies is anticipated to catalyze the transformation of the current vehicular systems and to serve as the stepping stone towards the realization of autonomous driving. The automotive industry focuses on designing vehicles that are equipped with highly developed systems and sensors, such as cameras, radars and LiDARs, aiming to assist the vehicles to have a continuous view of the surrounding environment and to efficiently adapt to environmental changes. Towards fulfilling the concept of fully autonomous driving, each individual vehicle is challenged to interact and communicate not only with other autonomous and partially automated vehicles but also with other network entities, such as the road infrastructure, the core network and the pedestrians. The main target of the V2X technologies is to leverage the interconnection between the vehicles and the other network entities in order to offer improved safety and higher levels of vehicle automation, as well as to reduce road traffic congestion and emissions in an eco-friendly way [1].

A contributing factor towards the complete transformation of vehicular networks constitutes the design and development of the upcoming 6^{th} generation (6G) of telecommunication systems. The designing procedure of the 6G networks has as its main pillars the provision of high data rates, low latency, and improved reliability, while it comprises the key enabler for realizing the concept of machine-to-machine (M2M) communication [2,3]. Therefore, the deployment of 6G networks will set the ground for providing the necessary conditions in order for the V2X systems to flourish. However, the V2X applications and services mandate a number of requirements to be met concurrently, like high data-rate, security, low latency, etc., and for this reason, accurate performance evaluation is of the utmost level of importance to ensure a sufficient quality of service (QoS) [1]. At the same time, the amount of system resources is finite while the applications' requirements increase at a rapid pace; thus, a necessity for developing efficient resource management schemes is emerging.

The development of efficient resource management strategies in vehicular networks and the performance evaluation of these systems constitute an issue that concerns academia [4–9]. In more detail, the authors in [4,5] propose efficient resource management schemes applied in challenging V2X scenarios, such as the indirect

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communication between the vehicle and the main network in [4] or the enablement of V2X communication in intersections in [5]. To address these issues, [4,5] utilize the simulation method in order to evaluate the performance of the system under study, which constitutes a realistic solution, but it is time-consuming. On the other hand, the authors in [6–9] utilize analytical queuing models from the teletraffic theory in order to evaluate the performance of the V2X systems and propose techniques for the system's service provisioning capability improvement in different challenging V2X cases. However, the works in [6–9] focus on evaluating the performance of vehicular systems that serve applications and services with similar features and requirements. To address these issues, in this work, we aim to estimate the performance of a V2X system that supports different types of applications and services with diverse requirements as in [10] and to additionally propose two efficient resource management techniques that improve the system's service provisioning capability. In particular, in Section 2 we present our system under study that consists of vehicles requiring service from Next-Generation Node Bs (gNBs) in the area. The transmission of the request can be conducted in two ways: a) directly (i.e. a vehicle sends directly its request to the gNB) and b) indirectly (i.e. a vehicle exploits other vehicles on the road to forward its request to the gNB). Next, in Section 3, we move toward utilizing multi-rate loss models from the teletraffic theory in order to calculate the probability that a request for service is rejected due to unavailability of resources. Next, in Section 3.2.1, we propose two resource management strategies, denoted as "resource reservation strategy" and "load split strategy" with a view to decreasing the probability that a request for service cannot allocate the required resources in order to be served. To demonstrate the efficiency of the teletraffic theory models in the performance evaluation of V2X systems, Section 4 benchmarks the proposed framework against numerical simulation. It is shown that features related to the system infrastructure, such as the links' capacity or the distance between the vehicles and the gNBs, significantly affect the request rejection probability. However, the employment of the proposed resource management strategies, i.e. the resource reservation strategy and the load split strategy, constitutes a powerful countermeasure towards improving the system's service provisioning capability. Finally, our work concludes in Section 5.

2. System under study

The different kinds of V2X communications that are enabled by vehicular networks are vehicle-to-vehicle (V2V) communication (information exchange between the vehicles), vehicle-to-network (V2N) communication (information exchange between the vehicles and the core network), vehicle-to-infrastructure (V2I) communication (information exchange between the vehicles and the system fixed infrastructure) and vehicle-to-pedestrian (V2P) communication (information exchange between the vehicles and the smart devices of the pedestrians) [1]. In this work, we emphasize the most common communication types, which are the V2V and V2N, as they accommodate the requests of the majority of vehicular-related applications and services. The V2N communication is mainly used for serving applications that request access to the Internet, e.g., for the users' infotainment or for traffic efficiency management. On the other hand, V2V communication is especially used for exchanging necessary information such as location, speed, accident prevention/detection, etc. This kind of information is critical for safety-related V2X use cases, such as platooning and cooperative driving.

To estimate the performance of the abovementioned system, we define a vehicular network as a directed and connected graph $G(V,L)$, where the gNBs and the vehicles are represented by the graph's nodes V and the wireless links between them constitute the graph's edges L. Each edge l is defined by two specific features [6]: a) the edge's capacity C_l and b) the cost w_l of sending a packet over the edge. In our case, a node can be either a gNB or a vehicle, and we study two different types of communications. Thus we denote the capacity of an edge l as C_{ml} where $m = 1{,}2$ while $m = 1$ stands for the V2N communication and $m = 2$ for the V2V communication. For simplification purposes, we assume that all the edges have the same cost denoted by w.

In the system under study, the applications and services hosted by the vehicles require access to the Internet; thus, their requests should be transmitted over the wireless links to the gNBs in order to be served. A request for service can be transmitted to the gNB either directly (or via single-hop) or indirectly (or via multi-hops). In the single-hop transmission, the vehicle requesting for service communicates directly with the gNB conducting V2N communication (e.g. the V2N link between vehicle "A" and gNB1 in Fig. 1). However, when the gNB-receiver is not within the vehicle's coverage area, the vehicle-sender transmits its request through its V2V link to the neighboring vehicle in order to forward it to the gNB. If the neighboring vehicle does not communicate directly with the gNB, it transmits the request to its neighboring vehicle and this process continues until the request is transmitted to the gNB. Therefore, in the multi-hop transmission, the intervening vehicles between the sender (i.e., the vehicle) and the receiver (i.e., the gNB) are leveraged as relays, and they do not have an active role in the transmission. In particular, as it is illustrated in the inset in Fig. 1, the link interconnections between the vehicle-sender, the vehicle-relays and the gNB-receiver form an end-to-end path between the vehicle-sender and the gNB-receiver, where the resources are exclusively allocated for transmitting the requests generated by the vehicle-sender. Since each edge is associated with a cost w and a specific capacity C_{ml}, finding the shortest path (i.e. combination of links) between the vehicle-sender and the gNB-receiver constitutes the most cost-effective solution in order for a request to be served. As the system under study is described as a graph, finding the best route can be dealt with as a shortest path problem (SPP) whose objective is to find the path with the minimum number of possible hops. However, the links that constitute the path between the vehicle-sender and the gNB-receiver have a finite capacity; thus, their bandwidth resources may not suffice to transmit the request.

In more detail, we consider that both types of the communication links, i.e. the V2N link and the V2V link, have a fixed capacity equal to C_{1l} and C_{2l} bandwidth units (b.u.), respectively. The applications and services hosted by the moving vehicles can be categorized into K different service-classes where each service-class k ($k = 1,\ldots, K$) has its specific features and resource requirement. In particular, a request for service arrives at the system according to a Poisson process and the arrival rate has a mean value λ_k. The time that a request of a service-class k spends in the system after its acceptance is exponentially distributed with mean value μ_k^{-1} and therefore, the traffic load of this service-class is $a_k = \lambda_k/\mu_k$ erl [11]. An arriving request of a service-class k needs b_k b.u. in order to be served; otherwise, the request is rejected. With a view to evaluate the system's service provisioning capability to the vehicles, we utilize traffic-engineering analytical models, as described in Section 3, in

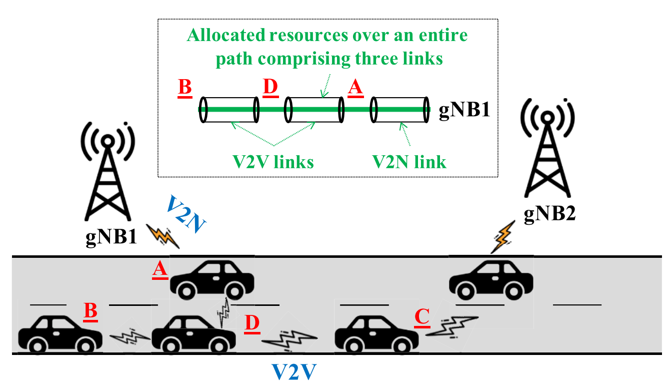

Fig. 1. The system under study. The inset illustrates the resource allocation conducted over the entire path between vehicle "B" and gNB1 exploiting three links (i.e. two V2V links and one V2N link).

order to calculate the probability that a request is blocked due to resource unavailability.

3. Description of the performance evaluation methods

3.1. Single-hop transmission

As illustrated in Fig. 1, we consider a single-hop transmission where a vehicle communicates directly with the gNB, forming a V2N communication. To evaluate the system's performance, we calculate the probability that a request for service from a service-class k is denied due to resource unavailability. The resource allocation is performed according to the complete sharing (CS) policy, where the resource assignment to the service-classes is conducted on a first-come-first-served basis without considering any other priority among them. To this end, we calculate the system's resource occupancy distribution $q(j)$, where j denotes the total occupied resources of the V2N link. The unnormalized values of the $q(j)$'s are obtained by utilizing the classical Kaufman-Roberts recursive formula [12,13] as follows:

$$q(j) = \begin{cases} 1, & \text{for } j = 0 \\ \frac{1}{j}\sum_{k=1}^{K} a_k b_k q(j-b_k), & j = 1,\dots,C_{ml} \\ 0, & \text{otherwise} \end{cases} \quad (1)$$

where $l = 1,\dots,L$, and $m = 1$ since, in the system under study, the communication in the single-hop transmission is always V2N. The probability that a request for service generated by a service-class k is blocked, Pb_k, is given by:

$$Pb_k = \sum_{j=C_{ml}-b_k+1}^{C_{ml}} \frac{q(j)}{G} \quad (2)$$

where G is the normalization constant determined as $G = \sum_{j=0}^{C_{ml}} q(j)$.

3.2. Multi-hop transmission

In the multi-hop transmission, the path between the vehicle-sender and the gNB-receiver consists of one V2N link and at least one V2V link. Therefore, an end-to-end connection establishment between the transmitting vehicle and the receiving gNB is considered successful if the required resources are available not only in the V2N link but also in all V2V links that form the path. In more detail, the system illustrated in Fig. 1 can be modeled as a fixed routing network R that consists of L links and each link supports K service-classes. When a request for service of a service-class k generated by a vehicle is transmitted to a gNB through multi-hop transmission, then a path of links, R_k, is created, so $R_k \subseteq \{1,\dots, R\}$. In this path R_k, the bandwidth resources of b_k b.u. must be available in each link in order for the transmission to be regarded as successful; otherwise, the request is rejected. To estimate the performance of this use case, we utilize the reduced load approximation (RLA) method [14] in the direction of calculating the probability that a request of a service-class k is end-to-end rejected due to the unavailability of resources. As stated in the RLA method, the links belonging to the path may have different capacities, so calculating the blocking probability of a request of a service-class k in link l is not representative of the performance of the whole path R_k. For this reason, it is assumed that the offered traffic load of a service-class k to a link l is actually reduced when it traverses through the sequence of links. Therefore, with respect to a service-class k, the offered traffic-load a_k is reduced to $a_k\prod_{i\in R_k-\{l\}}(1-V_{ik})$ and the emerging approximated blocking probability of a request of this service-class in a specific link l is defined as:

$$V_{lk} = B_{lk}[C_{ml}; a_k \prod_{i\in R_k-\{l\}}(1-V_{ik}), k\in K] = \sum_{j=C_{ml}-b_k+1}^{C_{ml}} G^{-1}q(j) \quad (3)$$

where C_{ml} denotes the capacity of a system link l ($l = 1,\dots,L$), $m = 1, 2$ and G is the normalization constant while $q(j)$ is the resource occupancy distribution of link l determined via the Kaufman-Roberts formula of (1). The total blocking probability of a service-class k in the path R_k due to lack of resources is determined by:

$$Pb_k \approx 1 - \prod_{l\in R_k}(1-V_{lk}), k = 1\dots K \quad (4)$$

3.2.1. Resource management strategies

In the multi-hop transmission, successfully serving the requests of a service-class k strongly depends on finding available the required resources in all links in path R_k. This can be challenging, resulting in increased request rejection probability and consequently, degradation of the QoS. With a view to improve the system's service provisioning capability, we aim to efficiently manage the system's available resources and we propose the following two strategies: a) the resource reservation strategy and b) the load split strategy, which are analyzed in the following sub-sections.

3.2.1.1. Resource reservation strategy. To favor some particular service-classes, we apply the bandwidth reservation (BR) policy, according to which some resources are reserved in order to exclusively serve these service-classes [11]. At greater length, in the BR policy, a request of a service-class k is accepted to be served in the system only if, after its acceptance, there exist available at least t_k b.u. to serve requests of other service-classes. By properly selecting the values of parameters t_k, some service-classes can be served with higher priority compared to other classes. In particular, a high value of t_k indicates a high number of reserved resources available for the other service-classes. Therefore, service-class k with the lowest t_k value can be considered as the service-class with the highest priority and vice versa. In multi-hop transmission, these resources should be reserved in all links in the path between the vehicle and the gNB. To calculate the requested blocking probability in multi-hop transmission under the BR policy, we modify the RLA procedure described in Section 3.2 in order to incorporate the BR policy. In particular, the approximated blocking probability of a request of this service-class in a specific link l is determined as:

$$V_{lk} = B_{lk}[C_{ml}; a_k \prod_{i\in R_k-\{l\}}(1-V_{ik}), k\in K] = \sum_{j=C_{ml}-b_k-t_k+1}^{C_{ml}} G^{-1}q(j) \quad (5)$$

where the resource occupancy distribution values $q(j)$ are calculated by [11,15]:

$$q(j) = \begin{cases} 1, & \text{for } j = 0 \\ \frac{1}{j}\sum_{k=1}^{K} a_k D_k(j-b_k) q(j-b_k), & j = 1,\dots,C_{ml}, k = 1,..,K \\ 0, & \text{otherwise} \end{cases} \quad (6)$$

and the term $D_k(j-b_k)$ is given by: $D_k(j-b_k) = \begin{cases} b_k, & \text{for } j \le C_{ml} - t_k \\ 0, & \text{for } j > C_{ml} - t_k \end{cases}$.

Accordingly, the total blocking probability of a service-class k in the path R_k is calculated by (4).

3.2.1.2. Load split strategy. In the direction of providing better QoS to the applications and services hosted by the vehicles, we aim to exploit the multi-hop transmission procedure in order to transmit the requests for service to multiple gNBs instead of a single gNB. Extending the case described in Section 3.2, we introduce the concept that the vehicle is able to transmit its requests to the P nearest gNBs in order to be served. Accordingly, we apply the SPP algorithm in order to find the P end-to-end shortest paths that lead to the corresponding gNBs, defined as $R_{k,p}$ ($p = 1,\ldots,P$). The traffic generated by the transmitting vehicles is divided and equally transmitted to the p nearest gNBs and the traffic load traversing each path $R_{k,p}$ can be estimated:

$$a_{k,p} = \frac{1}{P} a_k \tag{7}$$

The probability that a request of a service-class k is blocked in all P paths should incorporate the particular probabilities that a request is rejected in all individual end-to-end paths; thus, the total averaged blocking probability is given by:

$$Pb_k = \sum_{p=1}^{P} \frac{1}{P} Pb_{Rk,p} \tag{8}$$

where $Pb_{Rk,p}$ is the probability that a request for service of a service-class k is blocked in path $R_{k,p}$. To calculate the probability $Pb_{Rk,p}$ in a single path $R_{k,p}$, we calculate the load on this path via (7) and we utilize the RLA method described in Sections 3.2 for the CS policy and in Section 3.2.1.1 for the BR policy.

4. Performance evaluation and discussion

In this section, we aim to evaluate the performance of the system of Fig. 1 by utilizing the analytical methods described in Section 3 and their quantitative comparison is portrayed in Figs. 2-4. At greater length, our study is two-fold: First, we assess in Section 4.1 the impact of the single-hop and the multi-hop transmission on the service provisioning to the vehicles. Second, in Section 4.2, we focus on the multi-hop transmission as it is more challenging compared to the single-hop transmission, and we aim to improve the service provisioning to the vehicles by employing the strategies detailed in Section 3.2. To start with, we consider the system of Fig. 1 which consists of two gNBs and moving vehicles requesting for service from the gNBs. The vehicles transmit their requests for service to the gNBs either single-hop (or direct) over one V2N link or via multi-hops (or indirect) over one V2N link and at least one V2V link. All V2N links are identical with a capacity equal to $C_1 = 40$ b.u.. In accordance, all V2V links are identical with capacity equal to C_2 b.u.. Both the V2N and V2V links accommodate requests of $K = 2$ service-classes generated by the moving vehicles. In respect to the requests of the 1st service-class, they arrive at the system with an arrival rate $\lambda_1 = 1$ packet/s, the service rate is equal to $\mu_1 = 1$ packet/s and they require $b_1 = 3$ b.u. in order to be served. Apropos the requests of the 2nd service-class, the requests' arrival rate is $\lambda_2 = 2$ packets/s, the service-rate is $\mu_2 = 1$ packet/s and $b_2 = 4$ b.u. should be allocated in order to serve this request.

In the direction of conducting a solid analysis of the performance of the system under study, we evaluate its performance for three different capacities of V2V links: $C_2 = 30$, 40, and 100 b.u.. Next, we assess the impact of the traffic volume on the system's service provisioning capability by evaluating its performance for an increasing number of offered traffic loads. The increment in the offered traffic load is expressed in Figs. 2-4 by traffic points that are increased by 0.5 erl for both service-classes. Hence, point 1 represents the values $a_1 = 1$ erl and $a_2 = 2$ erl, while point 10 corresponds to the traffic load values: $a_1 = 5.5$ erl and $a_2 = 6.5$ erl. In addition, we validate the analysis conducted via analytical models with simulation results obtained via the Simscript III simulation language [16] and the corresponding results are presented in Figs. 2-4. It is important to clarify that the Kaufman-Roberts utilized in Section 3.1 is an exact formula and consequently no simulation is required in order to validate its accuracy and the corresponding results are not demonstrated in Fig. 2. Regarding the other employed methods, it is observed that the absolute relative error between the analytical and simulation results is less than 12 % which verifies that the teletraffic theory models constitute a valuable method for estimating the performance of V2X systems.

4.1. Performance estimation of direct and indirect transmission

With a view to evaluating the impact of the single-hop and the multi-hop transmission on the service provided to the users, we investigate three different scenarios: First, we consider a single-hop transmission case where a vehicle (i.e. vehicle "A" in Fig. 1) requests direct service from the gNB (i.e. the gNB1). Second, we focus on vehicle "B," which cannot communicate directly with a gNB, as no gNB exists within the vehicle's coverage area. By employing the SPP algorithm, it is observed that the nearest gNB is gNB1, so the requests of vehicle "B" are indirectly transmitted to gNB1 and $N = 2$ neighboring vehicles are utilized for the transmission. A significant prerequisite is that $N = 2$ vehicles do exist in the network in order to be leveraged as relays. According to the parameters defined in field trials, the number of vehicles on the road can exceed the 100 vehicles [17], so there is a significant possibility that the neighboring vehicles suffice in order to conduct a successful multi-hop transmission. Last but not least, in the third case, we focus on vehicle "C" that cannot directly request service from a gNB; thus it leverages the multi-hop transmission process in order to transmit indirectly its request to the nearest gNB. In contrast to vehicle "B" in the second case, vehicle "C" exploits $N = 1$ neighboring vehicles in order to send its request to the nearest gNB, i.e., gNB2. For the system's performance evaluation in the abovementioned three cases, we calculate the probability that a request

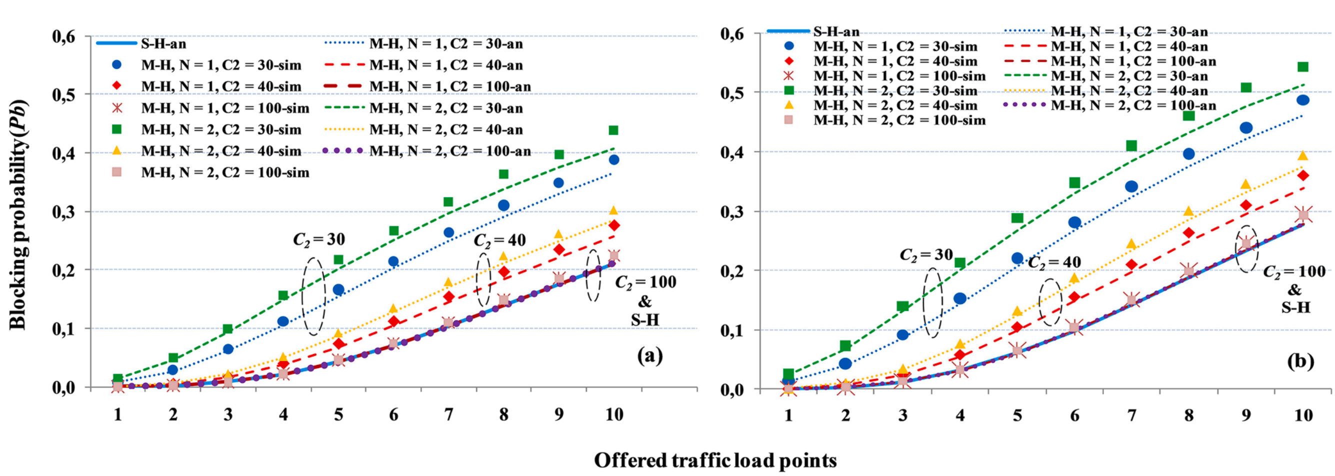

Fig. 2. The impact of the offered traffic load on a) the request blocking probability of the 1st service-class (Pb_1) and b) the request blocking probability of the 2nd service-class (Pb_2).

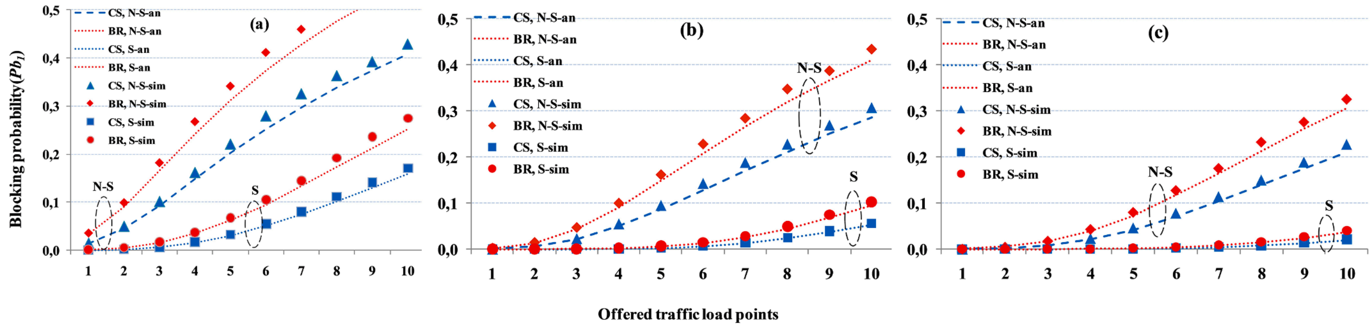

Fig. 3. Blocking probability of the 1st service-class in the multi-hop transmission for V2V capacity equal to: a) $C_2 = 30$, b) $C_2 = 40$ and c) $C_2 = 100$.

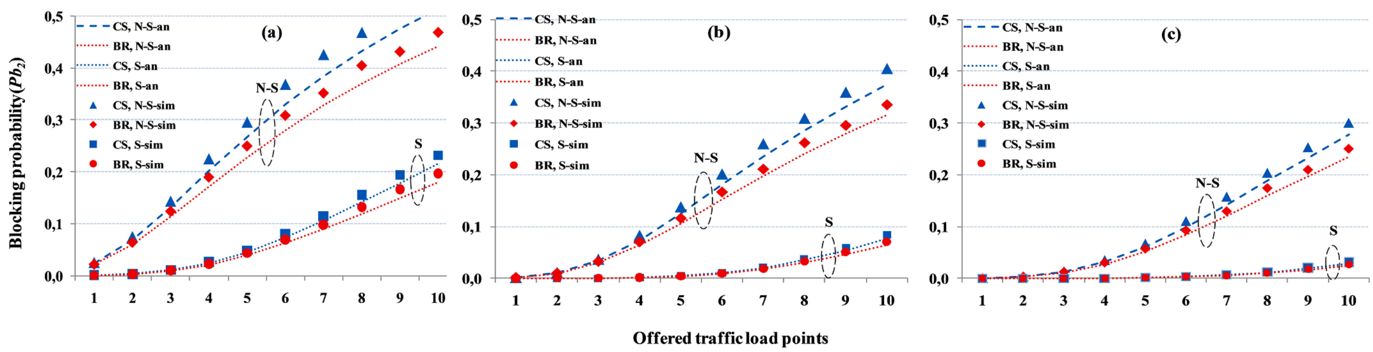

Fig. 4. Blocking probability of the 2nd service-class in the multi-hop transmission for V2V capacity equal to: a) $C_2 = 30$, b) $C_2 = 40$ and c) $C_2 = 100$.

generated by a vehicle is blocked due to a lack of resources. The quantitative analysis of these three scenarios is demonstrated in Fig. 2a and 2b for the 1st and the 2nd service-class, respectively. In particular, in the first scenario (denoted as S-H in Fig. 2), the request transmission is performed via a single hop transmission, so the blocking probability calculation is conducted according to the method presented in Section 3.1. In the same manner, in the latter two scenarios (denoted as M−H in Fig. 2), the request transmission is performed via multi-hop transmission; thus, we employ the method described in Section 3.2 for the request blocking probability calculation. However, since the number of the utilized neighboring vehicles differs in the latter two scenarios, we use in Fig. 2 the notion of the number of the intervening vehicles N in order to differentiate them (i.e., $N = 2$ stands for the second scenario and $N = 1$ denotes the third scenario). It is significant to clarify that in these two scenarios, the resource allocation is carried out according to the CS policy, and no load split strategy is applied. In respect to the quantitative analysis portrayed in Fig. 2, it is shown that both kinds of transmission (i.e. single-hop or multi-hop) and the V2V link capacity significantly affect the request blocking probability of the two service-classes and consequently the system's service provisioning capability. At greater length, it is shown that the lowest blocking probability for both service-classes is observed either in the single-hop transmission or when the V2V link capacity in the multi-hop transmission is high. On the opposite, the highest blocking probability values are noticed for both service-classes in the indirect transmission when V2V link capacity is low (i.e. when $C_2 = 30$) and the number of exploited vehicles is high (i.e. when $N = 2$). A slight improvement in the system's service provisioning is observed when the number of hops in multi-hop transmission is reduced to $N = 1$. However, a noticeable impact on improving the system's performance is performed when the C_2 value increases i.e. when $C_2 = 40$ and $C_2 = 100$. This outcome is justified by the fact that when the V2V link capacity is low then the arriving request cannot find the necessary resources to be forwarded to the gNB. This becomes even worse as the number of hops increases since the necessary resources should be available in all V2V links in order for the request to be successfully forwarded to the gNB. On the other hand, when the V2V link capacity is high, then the multi-hop transmission does not affect the QoS provided to the users since the bandwidth resources suffice to forward the requests to the gNB-receiver.

Apropos the impact of the number of intervening vehicles, it is observed that when the V2V link capacity is high, i.e. when $C_2 = 100$, the number of hops between the vehicle-sender and the gNB-receiver does not affect the request blocking probability. This outcome is reasonable since the required resources do exist in all hops in order to forward the request to the gNB. Therefore, it is shown that when the V2V link capacity is high, the multi-hop transmission system operates the same way as in the single-hop transmission. Last but not least, it is noticed that an increase in the offered traffic load causes an increase in the blocking probability values of both service-classes. The rationale behind this lies in the fact that an increase in the offered traffic load is interpreted as more arriving requests for service that compete for the same resources, so the probability that the available resources may not be sufficient increases.

4.2. Evaluation of the resource management strategies in multi-hop transmission

In this subsection, we aim to evaluate the system's performance when the resource management strategies in multi-hop transmission are employed. For this purpose, we investigate the system's capability to deal with the requirements of the two service-classes in four different scenarios and the corresponding quantitative comparison is illustrated in Figs. 3-4. At greater length, in the first scenario, we consider that vehicle "B" transmits its request to gNB1 in order to be served and it exploits $N = 2$ vehicles as a way to achieve its purpose. The first scenario is denoted as "CS, N-S" in Figs. 3-4 due to the fact that the resources are allocated according to the CS policy and no load split strategy is adopted. Similar to the first case, in the second scenario, vehicle "B" transmits its request for service to gNB1, but the resources are assigned to the vehicle according to the BR policy. Since the requests are forwarded only to gNB1 and no split strategy is employed, the second scenario is denoted as "BR, N-S" in Figs. 3-4. In the third scenario, denoted as "CS, S" in Figs. 3-4, we consider that vehicle "B" utilizes the load split strategy in order to transmit its request to more than one gNB. In particular, as it is observed in Fig. 1, vehicle "B" is able to request service from $p = 2$ gNBs, i.e., gNB1 and gNB2. For this reason, it sends 50 % of its requests for service to gNB1 and 50 % of its requests to gNB2by exploiting $N = 2$ and $N = 3$ vehicles, respectively. In this case, the resource allocation is conducted according to the CS policy. Finally, in the last but equally significant case, vehicle "B" transmits requests for service to both gNB1 and gNB2 according to the procedure described in the third case, but the BR policy is adopted (denoted as "BR, S" in Figs. 3-4). It is significant to mention that when the BR policy is adopted (i.e. in the 2nd and 4th scenarios), we consider that the requests for service of the 2nd service-class should be served with higher priority. For this reason, we determine the t_k parameters as $t_1 = 2$ b.u. and $t_2 = 0$ b.u. for the 1st and the 2nd service-class, respectively.

As it is demonstrated in Figs. 3-4, the service management strategies have a strong impact on the system's performance in multi-hop transmission. In particular, in the cases that the system performs under the CS policy (i.e. in the 1st and in the 3rd case), it is observed that the blocking probability values of the 1st service-class are lower compared to the corresponding values of the 2nd service-class. This is justified by the fact that the 1st service-class requires less bandwidth resources for the request transmission and consequently, it is easier to find them available and fulfill its demand. However, when the system's resource allocation is conducted according to BR policy, then the resource reservation that is applied to prioritize the 2nd service-class has a negative impact on the requests of the 1st service-class. In particular, it is observed that the blocking probability values of the 1st service-class under the BR policy are increased compared to the corresponding values under CS policy. On the contrary, the blocking probability values of the 2nd service-class under the BR policy are decreased compared to the corresponding values under CS policy because the BR policy is adopted in order to prioritize them.

With respect to the load split strategy, it is observed that the blocking probability values of both service-classes are highly improved in both case studies in which this strategy is employed (i.e. the 3rd and 4th scenarios). In particular, in the 1st service-class, the lowest blocking probability values are observed when the resource allocation is performed according to CS policy and the load split strategy is applied. On the contrary, the highest blocking probability values are observed when the BR policy is applied and the traffic load is forwarded only to gNB1 in order to be served. An interesting outcome of the analysis presented in Fig. 3 is that when the load split strategy is applied, the QoS provided to the requests of the 1st service-class is significantly improved compared to the cases where no split strategy is considered, even in the case where the BR policy is adopted. Regarding the 2nd service-class, it is observed that it is endorsed by both the adoption of the BR policy and the application of the load split strategy. This is justified by the fact that the highest blocking probability values for the 2nd service-class are marked in the 1st scenario (i.e. when the CS policy is adopted and the no-load split strategy is applied), whilst the lowest blocking probability values are demonstrated in the 4th scenario (i.e. when both the BR policy and the load split strategy are considered). Another interesting outcome that emerges from these case studies is that when the load split strategy is applied, the requests forwarded to gNB2 are transmitted via a longer path compared to the requests that are sent to gNB1. However, the total blocking probability values in these scenarios (i.e. the 3rd and the 4th) are lower compared to the blocking probability values in the former two scenarios, where all the requests are transmitted over the shortest path. The justification for this outcome lies in the fact that when the load split strategy is applied, the traffic load is equally distributed over multiple paths, resulting in no congestion on the resources of a single path. As a consequence, the competition in occupying the available resources is lessened, and it is easier for a request for service to allocate the required resources in order to be served.

5. Conclusion

In this work, we proposed two resource management strategies that improve the performance of a vehicular network that includes V2X communication. The system under study consists of moving vehicles that request service from the gNBs and the request transmission to the gNB can be either single-hop or multi-hop. We presented a traffic-engineering framework in order to assess the performance of the applied resource management strategies. It was shown that when no resource management strategy is applied, both the links' capacity and the number of hops have a strong impact on the blocking probability and consequently, on the overall QoS. However, the application of resource management strategies alleviates the negative impact of these features and it significantly improves the system's service provisioning. Since vehicular networks are characterized by intense requirements, the development of novel and efficient resource management strategies constitutes an indispensable factor in the designing process of these networks. In future work, we aim to expand the abovementioned analysis to incorporate the issue of link unavailability due to bad channel conditions.

CRediT authorship contribution statement

I. Keramidi: Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **D. Uzunidis:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Conceptualization. **I. Moscholios:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **K. Yiannopoulos:** Writing – review & editing, Supervision, Project administration, Conceptualization. **N. Sagias:** Writing – review & editing, Supervision, Project administration, Conceptualization. **P. Sarigiannidis:** Writing – review & editing, Supervision, Project administration, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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