Addressing the Unbounded Latency of Best-Effort Device-to-Device Communication with Low Earth Orbit Satellite Support

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***Abstract*—We propose SAMAC, a Device-to-Device (D2D) communication scheme that can exploit Low Earth Orbit (LEO) satellites as temporarily-available infrastructure with intermediate round-trip-times for supporting D2D medium access of highly mobile ground nodes such as vehicles. We demonstrate how such a scheme can be kept backwards-compatible to, e.g., IEEE 802.11p and we demonstrate analytically and in computer simulations that, compared to unassisted D2D communication or relaying, in situations where a LEO satellite is available it can improve performance in terms of all of throughput, latency bounds, and reliability.**

I. Introduction

With ever-increasing demands of modern systems on network throughput and latency and with ever-increasing levels of end device mobility, the Device-to-Device (D2D) communication paradigm is experiencing a renaissance. Multiple established standards have seen the introduction of new features like the *Outside the Context of a BSS (OCB)* mode introduced in the IEEE 802.11p WLAN amendment or *sidelink communication* introduced for 4G in the last decade – and D2D communication is a major pillar of ongoing standardization work on 6G.

An often-mentioned drawback of contention-based D2D communication, which is also exhibited by the aforementioned standards, is that of unbounded latency [1], [2]: Because no access guarantees can be given, frames may sit in transmit queues for arbitrarily-long times if the protocol was designed to neither drop frames after a given time nor to transmit them via a *busy* channel that would likely just drop them as well.

This problem can easily be worked around by central control and, indeed, this is what many modern communication systems such as 4G/5G systems opt for in their basestation-assisted sidelink operation modes. Naturally, though, such approaches require pre-deployed infrastructure, so mobile systems can only enjoy universal guarantees once global coverage with infrastructure is achieved.

To work around this problem, researchers have looked at concepts like aerial base stations, such that basestations can be deployed in regions with little to no infrastructure at all, though these suffer from limited coverage per system, thus high deployment and operation costs.

An alternative to increasing coverage all the way to global coverage has always been to rely on satellite networks [3]. In the past, these relied mostly on Geostationary Earth Orbit (GEO) satellites because of the high cost per satellite and per launch. However, as the resulting small constellation sizes meant low total network capacity and high orbits meant excessive propagation delays, this has led to satellites being widely disregarded as a potential solution.

In recent years, however, reduced hardware cost and new launch vehicles have introduced Low Earth Orbit (LEO) satellites as an alternative: Because of their low orbit these satellites offer low-latency communication (in the region of 5 ms) and cheap launch costs (in the region of 1400 US$/kg with 2.5 US$/kg being cited as a future possibility [4]), which also affords large constellations that, in turn, offer high total network capacity.

Combining these trends, it appears that a salient combination of features might be an approach that can provide some channel coordination for (formerly) best-effort D2D communication based on LEO satellites.

In this paper we therefore discuss a medium access scheme that can exploit LEO satellites for D2D communication in highly mobile networks which we call Satellite Assisted Medium Access Control (SAMAC); we show how such a scheme can be kept backwards compatible to legacy medium access schemes (here: to IEEE 802.11p), thus all devices can still communicate with each other even when a subset of devices has no possibility to communicate with LEO satellites; and we investigate its performance in a proof-of-concept simulation, meaning a subset of SAMAC is simulated in order to obtain easy to follow simulation results. We compare its performance against simpler access control schemes, traditional D2D, and approaches that employ uplink/downlink instead of sidelink communication.

II. Related Work

Facilitating D2D communication in larger networking scenarios can be accomplished using techniques from the area of data forwarding/relaying or by offloading coordination tasks by taking advantage of infrastructure/satellites/drones. In the

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following we discuss advantages and disadvantages of these methodologies which serve as motivation for our proposed LEO satellite assisted medium access scheme to support D2D communication in a distributed and highly mobile network.

Early works in the area of improving information dissemination in vehicular ad-hoc networks use satellites as relays [5] to transmit information in sparse networking situations, e.g., at nighttime. Although information dissemination can heavily benefit from additional satellite uplinks, the latency for communication (e.g., propagation delay due to geostationary satellites) as well as scalability (limited uplink/downlink capacity of satellites) limit the applicability of these approaches in dense networking scenarios with dependability on low latency communication.

At the same time, popular D2D communication techniques, e.g., IEEE 802.11p standardized for vehicular communications and using carrier sense multiple access with collision avoidance (CSMA/CA), suffer from unbounded latency for channel access due to lack of a central coordinator or infrastructure. These shortcomings of decentralized and distributed channel access methods have already been revealed long time ago [6] and approaches have been studied and developed to build self adapting time division multiple access methods for highly mobile networks. Although such approaches like Self-Organizing Time Division Multiple Access (STDMA) [7], [8] can improve networking performance in mobile scenarios, they rely on detailed position information of network members where nodes still can select the same time slot for transmission suffering from interference and thus are interference limited. Especially in highly congested scenarios, when control packets are lost or cannot be decoded, due to, e.g., interference or hidden terminal situations, STDMA performance drops way below CSMA/CA [8].

In our approach we target exactly this problem by taking advantage of an additional control channel (via LEO satellites) to accomplish coordination tasks, i.e., medium access control, while the actual data exchange happens directly between participating stations on the ground. Consequently, in our approach we have the ability to provide bounded latency for data communication for participating nodes based on detailed scheduling decisions (by an external coordinator).

Addressing the issue of unbounded latency due to channel access can also be accomplished by adding infrastructure to the ground network, e.g., by using cellular networks and deploying static 5G basestations in a traditional way. However, this is often unsuitable in areas with highly dynamic traffic densities as those basestations require infrastructure (power, connectivity). First concepts using geostationary satellites in conjunction with medium [9] or low earth orbit satellite systems [10] to support 5G communication have been studied in several projects, e.g., the Horizon 2020 project SaT5G.

Consequently, also drone-assisted relaying concepts [11] to support vehicular networks or even tethered drones [12] addressing energy related aspects of drones in the context of 6G networks have been studied in the past. Particularly, multi-tiered Space-Air-Ground Architectures [13] targeting specific vehicular networking scenarios outline resource allocation as an important research aspect to improve satellite- and air-assisted communication paradigms.

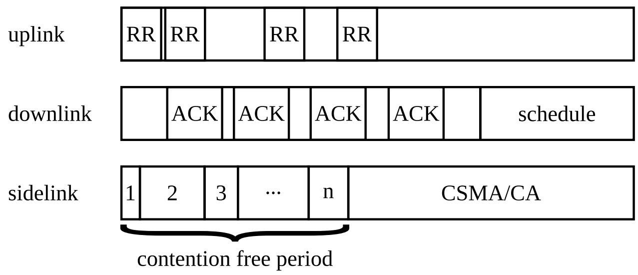

Figure 1. Required communication channels and their allocation of a single interval for SAMAC.

In summary, it is our understanding that the provision of 5G basestations on satellites or low altitude platforms will not solve the problems of scalability and limited networking capacity when they are used for relaying data which also could have been transmitted directly between stations on the ground. More severe, by using such systems for relaying data traffic, the negative effect of additional latency induced by propagation delays due to large distances between ground stations and satellites meets degraded networking performance due to congested communication channels. On the other hand, outsourcing necessary coordination tasks – thus medium access – to optimize networking performance can be envisioned to result in performance optimization in multiple dimensions: low latency like CSMA/CA, bounded latency like TDMA, and exploiting networking capacity and spatial reuse due to scheduling at a central coordinator with the benefits of keeping coordination overhead and energy consumption low. Yet, to the best of our knowledge, detailed investigations how popular and widely-used ad-hoc communication systems like IEEE 802.11 can benefit from LEO satellite support are still missing – a gap which we fill with this paper.

III. SAMAC: Satellite Assisted Medium Access Control

The guiding use case for the construction of SAMAC is the local dissemination of Awareness Messages (AMs), transmitted semi-periodically by vehicles on the ground and to be received by those in the immediate vicinity of the transmitter. This use case captures the needs of a wide variety of protocols, such as the SAE J2945/8 Cooperative Perception System (CPS) using, e.g., Cellular Vehicle-to-Everything (C-V2X) or the ETSI ITS-G5 Cooperative Awareness Message (CAM) service for vehicles, but can be generalized to many use cases of communication between highly mobile systems on the ground.

The core idea of SAMAC is using LEO satellites which coordinate the medium access of the vehicles' transmissions. For this, three dedicated communication channels, which do not interfere with each other, are assumed, as shown in Figure 1: an *uplink* channel for communication towards the satellite, a *downlink* channel for communication towards the vehicles, and a *sidelink* channel for the D2D communication between vehicles on the ground. Since uplink and downlink are commonly separate radio channels which do not interfere with each other, full duplex communication between LEO satellites and vehicles is possible.

Coordinating channel access of the sidelink channel is based on a Time-Division Multiple Access (TDMA) scheme. For this we assume that vehicles can receive Global Positioning System (GPS) precision time stamps (in addition to communicating with satellites and other vehicles).

Time is divided into *superframes*, predefined intervals of duration t_{int}. According to this interval a LEO satellite broadcasts a schedule via the downlink channel to coordinate channel access on the sidelink. In order to cope with time variant propagation delays t_{lat} (distance varies depending on their relative position to a vehicle, from local zenith to disappearing behind the horizon) between vehicles and LEO satellites, the schedule begins after a short guard time t_{guard} with respect to the beginning of an interval. The guard time t_{guard} must be longer than the largest communication latency between any vehicle and the LEO satellite, that is, $t_{\text{guard}} > \max t_{\text{lat}}$. Each schedule is subdivided into slots whose duration depends on the size of the packet to be sent.

Upon receiving a schedule, vehicles perform two tasks:

First, they aim at reserving a slot for the next schedule by sending a Reservation Request (RR) via the satellite uplink.

If the LEO satellite successfully receives an RR, the LEO satellite either allocates the requested radio resources to the sending vehicle and transmits an acknowledgment (ACK) of the RR, or it responds with a Negative Acknowledge (NACK) indicating that all slots for the next schedule are already occupied. The LEO satellite can allocate the sidelink channel's radio resources such that space diversity is optimally utilized, i.e., as many vehicles as possible can transmit at the same time limiting the probability of creating frame collisions at receivers – a technique also called spatial reuse. This can be achieved, e.g., by the RRs piggybacking a report of when the sidelink was sensed as busy in the last interval. Based on the received reports the LEO satellite can create a graph indicating all neighborhood relations between the vehicles. By solving the graph coloring problem of the neighborhood graph, the LEO satellite can then determine which vehicles may transmit simultaneously and thus benefit from spatial reuse.

Vehicles stop transmitting RRs for the next schedule once they received either ACK or NACK and the load on the uplink is reduced. If a vehicle receives neither ACK nor NACK, it will stop transmitting RRs for the next schedule when the remaining time of the current interval is smaller than the Round Trip Time (RTT) $t_{\text{rtt}} > 2t_{\text{lat}}$. Otherwise, there is too little time for the vehicle to receive either an ACK or a NACK.

Second, the vehicles schedule their transmissions according to their assigned slot announced in the newly received schedule. At the beginning of its slot, each vehicle transmits a Clear-To-Send (CTS) packet indicating the duration for which the sidelink channel is reserved for itself. Thereby vehicles which did not receive the schedule are aware of the reserved slots and will defer channel access, e.g., by adding the announced time of CTS frames to an IEEE 802.11 Network Allocation Vector (NAV). Directly after transmitting the CTS packet, the same vehicle transmits its data packet.

If a vehicle does not have a reserved slot on the sidelink, it will fall back to CSMA/CA after all reserved slots of the current schedule are passed and until the next schedule starts. If such a vehicle could not get channel access via CSMA/CA until the next schedule starts, it simply drops the packet and informs the application. Then, higher layer protocols can take care of re-transmissions.

As we have a dedicated central controller (i.e., the LEO satellite), we can enforce and guarantee an upper bound of communication latency. Further, schedule information is also available to the application running on the vehicle, thus serves as additional source of information to be able to control message generation intervals.

The worst case scenario regarding sidelink transmission latency is the following: Packet generation at the exact point in time when a vehicle stops transmitting RRs because of the remaining time of the current interval being smaller than RTT. In this rare worst case, a vehicle would have to wait $t_{\text{rtt}} + t_{\text{int}} + t_{\text{guard}}$ until the next schedule begins. If, then, its transmission is scheduled to the last slot of this schedule, the transmission will be finished after an additional duration of t_{int}. Thus, the overall worst case delay for sidelink transmissions is

$$t_{\text{wc}} = \max\{t_{\text{rtt}}\} + 2t_{\text{int}} + t_{\text{guard}}. \quad (1)$$

IV. Evaluation

To show the effectiveness of our approach, we compare the performance of SAMAC for coordinating sidelink channel access with three alternative approaches.

As the first baseline, IEEE 802.11p is considered as it is a popular standard for uncoordinated D2D communication in vehicular networks (cf. Figure 2a) which is using CSMA/CA for contention based medium access.

As the second baseline – called *random slots* – we consider a simplified and un-coordinated version of SAMAC without a satellite coordinating medium access. Instead, vehicles randomly select slots for transmissions according to a uniform random distribution.

As a third baseline, we consider using satellites as *relays* (cf. Figure 2b): Here, the vehicles can request to use the satellite as a relay and the satellite transmits a schedule of when which vehicle can use the satellite as relay. As this scheme is very similar to our SAMAC approach, we provide simple analytical results showing the performance of this approach: We start by considering Equation (1), the worst case delay for a transmission. Additionally, the propagation time t_{sat} of a packet traveling from earth to LEO satellite and back, the RTT, has to be taken into account for the end-to-end latency, $t_{\text{sat}} = t_{\text{rtt}}$. Thus, the worst case end-to-end latency for a relaying approach (cf. Figure 2b) can be obtained as

$$t_{\text{relayed}} = t_{\text{wc}} + t_{\text{sat}}. \quad (2)$$

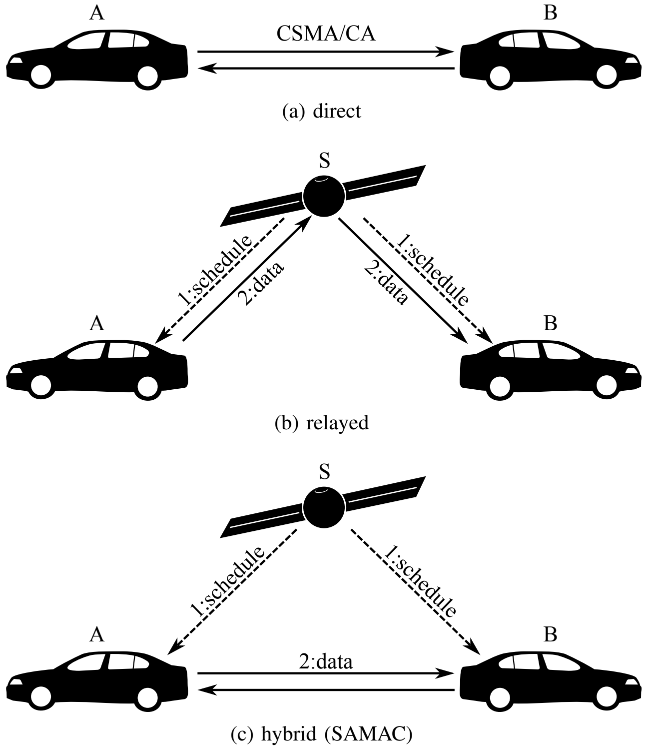

Figure 2. Different communication topologies considered in the evaluation.

The worst case end-to-end latency of our SAMAC approach (cf. Figure 2c) can be calculated as

$$t_{\text{hybrid}} = t_{\text{wc}} + t_{\text{D2D}}, \tag{3}$$

where, in contrast to relaying packets via the satellite, the propagation time of D2D packet transmissions t_{D2D} is only in the order of hundreds of µs (as compared to ms).

Due to the large distance difference between a signal being relayed via a LEO satellite and a signal traveling from one ground device to another ground device, one can always assume $t_{\text{sat}} > t_{\text{D2D}}$, which would make the relaying approach appear inferior in all important networking metrics: consumed networking capacity, robustness, and latency.

For a more detailed investigation we compare the performance of the two D2D (direct) baselines to that of our SAMAC approach in a detailed and realistic simulation study. In this study the implementation of SAMAC is simplified in order to get better insights into the core functionality of the protocol. This proof-of-concept version implements a fixed slot length, no spatial reuse, and no vehicles without a satellite communication interface. Further, the values of t_{int}, t_{slot}, and t_{guard} are chosen such that the evaluation of the simulation is easy to follow.

A. Simulation Setup

In our computer simulations, two scenarios with low and high vehicle density are investigated. Either 10 or 100 vehicles are driving on a three-by-three Manhattan grid located at *Null Island* (i.e., at location 0.0°N, 0.0°E). Its overall size is $750\,\text{m} \times 750\,\text{m}$. The vehicles' mobility model is provided by the well known and established road traffic simulator *Simulation of Urban MObility (SUMO)* 1.11.0 [14] which is integrated into the simulation by Veins_INET which is part of *Vehicles in Network Simulation (Veins)* 5.2 [15], one of the state-of-the art simulation frameworks for realistic vehicular communication simulations. LEO satellites are integrated by the help of space_-Veins [16], an extension for Veins which relies on the Simplified General Perturbations 4 (SGP4) model for calculating orbits of LEO satellites. As input to model the satellite mobility, the SGP4 model expects NASA/NORAD Two-line Element Sets (TLEs) [17] which contain measurements enabling the calculation of such orbits. In order to be independent from any existing LEO satellite constellation, an artificial satellite corresponding to a TLE of

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space_Veins-1
1 51472U 22010S   22053.00000000  .00000000  00000+0  00000-0 0  9995
2 51472  70.0000 000.0000 0000000  00.0000 000.0000 15.73209361  2401
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is used. Further, the space_Veins version used in this evaluation depends on INET 4.2.1 for modeling the uplink and downlink channels. For simplicity, these channels are realized by INET's unit disk model which is parameterized such that full duplex communication is possible – an assumption which holds in realistic satellite communication systems where different frequency bands for uplink and downlink communication are used simultaneously. For the sidelink channel, the INET IEEE 802.11 model is used and parameterized with a Free Space path loss model, a background noise of −98 dBm, a sensitivity of −98 dBm, an energy detection threshold of −65 dBm, BPSK-1/2 modulation, a transmit power of 20 dBm, and an EDCA category of *VO* (see Table I).

Every 100 ms, each vehicle generates a 669 Byte message carrying 600 Byte of payload information – a size which is suitable to carry, e.g., a rather large CAM [18]. Consequently, the total offered load for the sidelink channel in our configuration is 0.535 Mbit/s or 5.352 Mbit/s for low and high vehicle density, respectively. In our simulation, the vehicles' configured Modulation and Coding Scheme (MCS) for the sidelink channel corresponds to a bit rate of 6 Mbit/s. As a result, the offered load is equal to 8.92 % and 89.2 % (depending on the vehicle density) of the sidelink channel's total channel capacity. Thus, the simulation study considers two scenarios: in one scenario the sidelink channel is heavily used and in the other scenario it is rarely used. Each simulation scenario is run 168 times for the sake of statistical validity.

For SAMAC we set $t_{\text{int}} = 100\,\text{ms}$, $t_{\text{slot}} = 1\,\text{ms}$, $t_{\text{guard}} = 5\,\text{ms}$, as well as uplink/downlink bit rates of 100 Mbit/s, in order to reduce the evaluation's complexity. As shown by Equation (1), t_{wc} mainly depends on t_{int}. In this simulation study worst case transmission latency was measured as 204 ms which is rather high compared to IEEE 802.11p, but – crucially – below the analytically calculated bound of $t_{\text{wc}} = 209.6\,\text{ms}$. We point out that reducing t_{int} would definitely result in a lower worst case transmission latency compared to the results in this simulation study, but parameter optimization is considered as future work. Further, the main goal of SAMAC is not to reduce latency, but rather to improve predictability by guaranteeing latency bounds and radio resources to registered vehicles.

Table I
SIMULATION PARAMETERS

Number of vehicles	{10, 100}
Uplink/downlink channel model	INET UnitDiskModel
Sidelink channel model	INET IEEE 802.11
Sidelink path loss model	INET Free Space path loss
Background noise	−98 dBm
Sensitivity	−98 dBm
Energy detection threshold	−65 dBm
Channel bandwidth	20 MHz
Modulation	BPSK-1/2
Sidelink transmit power	20 dBm
EDCA category	VO
Packet size	669 Byte
t_{int}	100 ms
t_{slot}	1 ms
t_{guard}	5 ms
t_{rtt} (depending on satellite position)	2.3 ms to 4.6 ms

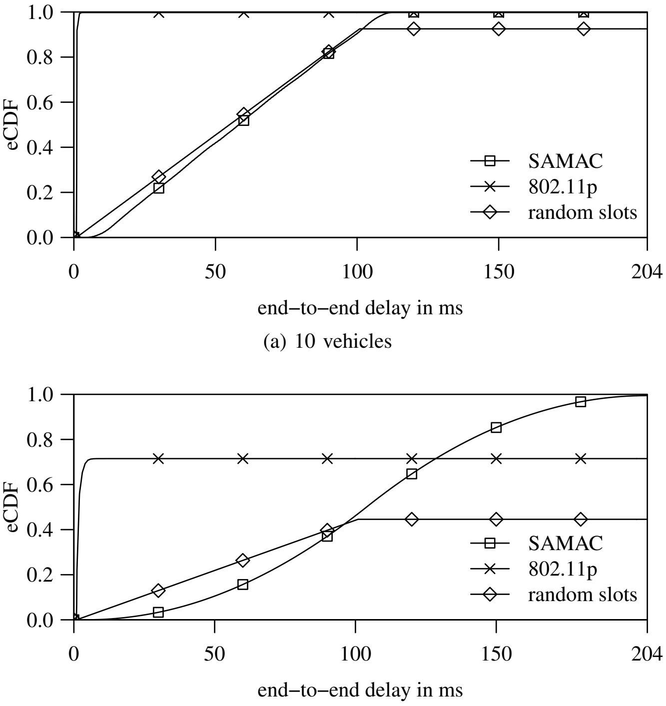
As channel access protocols we implement the baseline D2D approaches described in Section IV (direct communication without coordinated channel access as well as the random slots approach) as well as the proof of concept version of SAMAC: In particular, we use ALOHA for transmitting RRs to the satellite; more sophisticated channel access schemes for satellite communications are available in the literature which, e.g., employ sophisticated multiplexing schemes and/or successive interference cancellation, but a study of such improvements are out of scope of this paper. Additionally, the schedule is built according to the order of received RRs, i.e., the first come first serve principle is applied; here, more sophisticated scheduling strategies could add QoS principles for resource allocation to vehicles. Lastly, if a vehicle has not been able to reserve a slot, the implemented proof of concept version of SAMAC simply selects a random un-allocated slot in the active schedule.

B. Performance

We employ three performance metrics: end-to-end latency, Packet Delivery Ratio (PDR), and relative average goodput.

In Figure 3 we show the end-to-end latency as well as the PDR. Particularly, we present the results in form of three empirical Cumulative Distribution Functions (eCDFs) of the measured end-to-end delays, one for each simulated sidelink channel access approach. We consider as end-to-end latency the time from generating an AM up until when it has been successfully received at the receivers' application layer, thus, including the propagation delay. An eCDF takes into account all transmitted packets; packets which could not be successfully decoded are assigned an infinite end-to-end latency. This way, the PDRs are visible as the maxima of the eCDFs, illustrating to which degree an approach can support reliable data communication.

Regarding the *random slots* approach, one can clearly see that the end-to-end latency is bounded because the highest measured end-to-end latency corresponds to the configured interval $t_{\text{int}} = 100\,\text{ms}$ for both scenarios. However, approximately 92.5 % and only 45 % of all decoding attempts succeed depending on the number of simulated vehicles. Consequently, the remaining



(a) 10 vehicles

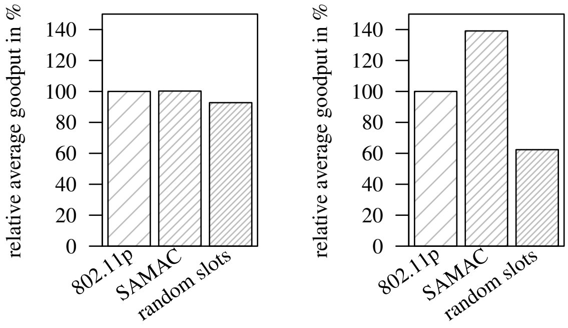
(b) 100 vehicles

Figure 3. End-to-end delay measurements.

7.5 % and 55 % (for low and high vehicle density, respectively) of all transmitted packets have an end-to-end latency set to infinity since they could never be received by any vehicle. The main reason for packets not being decodable is packet collision due to at least two nearby vehicles selecting the same slot. With a higher number of simulated vehicles, and thus a higher offered channel load, the packet collision probability increases leading to more packets being dropped by the sidelink channel.

IEEE 802.11p demonstrates better performance in both aspects. Here, the maximum measured end-to-end latency is approximately 12 ms, but due to the nature of IEEE 802.11p it cannot be considered as theoretical upper bound. Moreover, approximately 99.8 % and only 70 % (for low and high vehicle density, respectively) of all decoding attempts are successful. This can be explained by considering the IEEE 802.11p Hybrid Coordination Function (HCF). All AMs are categorized according to the highest access category in this simulation. This means the shortest Contention Window (CW) is used for randomly selecting transmit backoff slots. As a result, the end-to-end delay is decreased at the cost of a higher probability for two vehicles selecting the same number of backoff slots which often results in a packet collision, especially when the offered load is as high as configured in one of the simulation scenarios. In contrast to that, when the offered load for the sidelink channel is low, IEEE 802.11p manages to achieve a high PDR as well as short latency mainly because there are more radio resources available than required.

SAMAC's end-to-end latency is successfully upper bounded to the calculated $t_{\text{wc}} = 209.6\,\text{ms}$ in both simulation scenarios:



(a) 10 vehicles (b) 100 vehicles

Figure 4. Relative average goodput.

the highest observed latency is 204 ms. More importantly, SAMAC outperforms both baselines with a PDR of 99.99 % and 99.5 % for low and high vehicle density. This is because only vehicles which could not reserve a slot in the schedule due to packet collisions on the uplink channel select a random slot (and we emphasize that this is due to the simplistic proof of concept implementation used, which relies on ALOHA and random slot selection instead of implementing advanced methods here) and only if two vehicles randomly select the same slot there is a possibility for a collision. As a result, SAMAC achieves very high PDRs independent from the offered channel loads, but at a cost of increased latency. However, as stated earlier, SAMAC's main goal is to improve predictability in terms of latency bounds and the allocation of radio resources. The simulation study demonstrated that SAMAC fulfills both goals for low and high vehicle densities. Further, due to the backwards compatibility vehicles are not forced to use SAMAC. Thus, they can always fall back to pure IEEE 802.11p, e.g., in case they sense the sidelink channel is only rarely busy.

As a third performance metric, the relative average goodput, visualized by Figure 4, is evaluated. Goodput only considers the payload of successfully received packets. Specifically, the relative average goodput is defined as the average goodput per vehicle over a whole simulation run divided by the average goodput of IEEE 802.11p. Consequently, the relative average goodput of IEEE 802.11p is 100 %. The random slots approach achieves a relative average goodput of 93 % and 62 % for low and high vehicle density, respectively. The SAMAC approach achieves 100.2 % and 139 % for low and high vehicle density, respectively. This underlines that SAMAC can not only successfully deliver more packets and can do so below a tolerable latency bound, but also achieves a higher goodput meaning that more data is actually successfully transmitted in high load situations.

V. Conclusion

In this paper, we proposed Satellite Assisted Medium Access Control (SAMAC), a Device-to-Device (D2D) communication scheme that can exploit Low Earth Orbit (LEO) satellites as temporarily-available infrastructure with intermediate round-trip-times for supporting D2D medium access.

We also explained how such a scheme can be kept backwards-compatible to, e.g., IEEE 802.11p and we demonstrated analytically and in computer simulations that (in situations where a LEO satellite is available) it can improve performance in terms of all of throughput, latency bounds, and reliability when compared to unassisted D2D communication or relaying.

Future work will encompass: studying the performance of SAMAC in mixed and legacy deployments; developing the SAMAC mechanism into a protocol draft; and investigating the benefits of feedback from SAMAC to application layer protocols and vice versa.

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