Hybrid Context-aware Message Flooding for Dead Spot Mitigation in V2I Communication

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***Abstract*—An often overlooked practical problem in Intelligent Transportation Systems (ITS) is the presence of areas without cellular network connectivity, so-called *dead spots*, which aggravates the communication between vehicles and the external infrastructure. In our previous work, we suggested to mitigate this problem by using a hybrid data dissemination protocol that combines cellular network communication with ad-hoc networks between vehicles. If the vehicles in such ad-hoc networks are in a dead spot but have a good estimation about the time they will leave it again, messages can be forwarded to the vehicle that is supposed to regain cellular network coverage first. Since this vehicle may transmit the stored messages immediately after having left the dead spot, the delivery time is improved. In this paper, we first analyze the behavior of the aforementioned data dissemination protocol in larger dead spots in which a message may be carried by several vehicles before being delivered via the cellular network. The analysis reveals that messages are not always delivered in the fastest possible time. To address this concern, a new protocol variant named *context-aware message flooding protocol* is introduced. This protocol, indeed, guarantees the fastest possible forwarding of messages to their recipients. This is achieved at the cost of delivering duplicates that, however, are only produced when the delivery of a message is sped up.**

***Index Terms*—Cellular Network Access, Dead Spot, Ad-hoc Networking, Context-aware Message Flooding Protocol, Minimization of Transmission Time, Reduction of Duplicates.**

I. Introduction

In Intelligent Transportation Systems (ITS), the coordination between vehicles and their external environment is named Vehicle-to-Infrastructure (V2I) communication which nowadays is mostly realized using cellular networks [1]. In contrast, data transfer between the vehicles is called Vehicle-to-Vehicle (V2V) communication. The vehicles often connect directly, but, with the proliferation of 5G, also here cellular networks will be applied more frequently thanks to the high bandwidth and good reliability of the Ultra-Reliable Low-Latency Communication (URLLC) technology in 5G [2]. In consequence, many ITS solutions depend on the provision of a good cellular network coverage.

In practice, however, we cannot expect sufficient cellular network access everywhere. To illustrate this, we recommend a look on the coverage maps for several countries and their major cellular network carriers provided in [3]. These maps reveal that in many countries significant areas without cellular network coverage, so-called *dead spots*, exist. That is particularly true for rural areas since the cell tower infrastructure usually depends on the number of people living in a region [4]. Especially, in large sparsely populated areas like the Australian Outback, where cellular network coverage can be found only around the far-flung settlements, the size of a dead spot can easily extend 100 kilometers (see [5]). Dead spots can further be found in mountainous terrain since heights deteriorate the radio signal reception as a result of echoes [6].

On the other hand, modern ITS technology may be most helpful when crossing wide sparsely inhabited areas where, e.g., breakdown support or information about the condition of unpaved roads can be vital. To alleviate the impact of dead spots for the transmission of messages from vehicles to their external environment, we developed a *data dissemination protocol* [5], [7]. It combines cellular network communication with ephemeral ad-hoc networks between vehicles. Using this hybrid technology, e.g., a vehicle veh_s that wants to transmit a message m to the external infrastructure but recently entered a larger dead spot, may build an ad-hoc connection with another vehicle veh_o approaching from the opposite direction. Then, veh_s hands m over to veh_o which stores and transmits it via the cellular network as soon as it regains coverage. Since veh_o leaves the dead spot much earlier than veh_s, which just entered it, the transmission of m is accelerated.

In [5] and [7], we present two variants of the data dissemination protocol that use different methods to find out which vehicle will likely leave a dead spot first. In both papers, however, we just devised the solitary collaboration of vehicles in single ad-hoc networks but did not look into the general flows of messages that may be carried by several vehicles until being delivered to their recipients via the cellular network. In this article, we catch up with this by analyzing the protocol. Particularly, we demonstrate that the time needed to deliver messages to the infrastructure, is not always minimal.

To avoid this weakness, we further introduce the *context-aware message flooding protocol* which is the main contribution of this paper. Like the original protocol but unlike most other existing vehicular protocols, it considers spatiotemporal aspects like the positions, directions, and speeds of vehicles in a dead spot to decide how to route messages in order to minimize the time needed to deliver them to the infrastructure. In contrast to the original protocol, it introduces duplicates but their number is kept to the minimum necessary to guarantee the fastest delivery of the messages.

The article is structured as follows. After a look on related work in Sect. II, we present the existing protocol in Sect. III and its analysis in Sect. IV. The context-aware message flooding protocol is proposed in Sect. V. In Sect. VI, we outline the proof that it minimizes the delivery time and keeps the number of duplicates low. The article is completed by some concluding remarks and an outlook in Sect. VII.

II. Related Work

Several works suggest the use of *opportunistic networks*, to which also our approach can be attributed, for areas where cellular networks are absent, e.g., due to disasters. For instance, in [8] the prompt and reliable delivery of messages originated within those areas to the outer and connected world has been examined. The authors introduce and evaluate *epidemic routing*, i.e., a pair-wise random exchange of messages among mobile peers. In [9], a modified version of epidemic routing is introduced, which is implemented on smart phones with short-range wireless communication capabilities. This approach adopts the one-to-many paradigm on disseminating messages instead of utilizing the pair-wise pattern.

In the past years, the research community has shown increasing interest in utilizing Delay/Disruption Tolerant Networks (DTNs) to overcome the disruptions in end-to-end connectivity [10]. The aforementioned works based on the epidemic routing protocol are examples of the store-carry-forward paradigm, which forms the basis of the DTN architecture (see [11]). In these types of networks, the mobility of peers and their ability to establish ad-hoc networks are exploited when they are within the communication range of each other. However, as stated in [12], epidemic routing could lead to an increased contention of network resources between peers and additional traffic in the network. Moreover, the intensive exchange of messages imposes additional overhead on mobile phone battery usage as well. Several researchers have investigated and evaluated different techniques to alleviate the supplementary overhead introduced by *flooding-based* data dissemination protocols [12], [13], [14], [15], [16]. A representative example of the mobile store-carry-forward type of communication networks is the Vehicular Ad-hoc Network (VANET). It is also the principal network structure used in our work.

Another category of works is based on communication switching between phone-to-phone and phone to a cellular/wireless network. In [17], an optimized communication mechanism is proposed to strategically enable phone-to-phone and/or phone-to-WiFi AP communications by optimally toggling the phone between the normal client and hotspot modes. In [18], an energy-efficient phone-to-phone communication method to schedule the phone's switching between these modes is proposed based on WiFi Hotspots (EPCWH). To increase the packet delivery ratio, and also to reduce the dead spot in VANET-cellular network, in [19] a Simplified Gateway Selection (SGS) scheme for multi-hop relay is proposed. To support safety-critical applications, the authors of [20] propose a hybrid V2X system in which the service discovery of the ad-hoc network technology WiFi-Direct [21] is sped up and the overall connectivity is strengthened. For that, a cloud-based server is accessed via a cellular network. Similarly, to improve reliability of multi-hop broadcast in urban areas, [22] proposes a protocol that makes restricting the forwarding and acknowledging of broadcast packets to only one vehicle possible. For that, the road portion inside the transmission range is divided into segments. Then, the protocol chooses the vehicle in the furthest non-empty segment without utilizing a priori topology information. In contrast to our approach, the above works do not explicitly consider locations and speeds of the peers to decide on the routing of messages.

III. Original Data Dissemination Protocol

As mentioned in the introduction, we created two variants of our data dissemination protocol that use different ways to find out which vehicle in an ad-hoc network is supposed to leave a dead spot first. In [5], we assume that most dead spots are on smallish rural and often mountainous roads which limits the average speed of a vehicle. In consequence, the vehicles in a certain road section use similar speeds such that the time needed to cross a dead spot is around the same for all of them. Then, the vehicle in an ad-hoc network that entered the dead spot first, will likely be the one leaving it first as well. Therefore, it receives all the messages from its peers. This approach is easy to realize but sometimes imprecise since it assumes that all vehicles use the same route through the dead spot. Further, it does not consider speed differences, e.g., between passenger cars and trucks that are slow at steep slopes.

The approach presented in [7] utilizes *connectivity maps* [23] showing the extensions of dead spots in a certain area. The maps are generated by a central server that aggregates local coverage data sensed by various vehicles and sends the maps back to the vehicles. By considering the downloaded connectivity maps, a vehicle can find the border of the dead spot, it is currently in. Then, from its own speed and the condition of the road ahead, the vehicle calculates the time it will leave the dead spot. The expected path of a vehicle can be taken from its route guidance system. Of course, the expenses for the server infrastructure and the transmission of the sensor data between vehicles and servers (e.g., 3.4 petabytes per year in Norway [7]) make this approach more costly than the other one. However, since several patents [24], [25], [26] indicate significant interest of the industry in connectivity maps, there is a fair chance that such an infrastructure will be built up. Our protocol could then be used on top of the provided facilities.

The functionality of our data dissemination protocol is depicted by the flow graph in Fig. 1. The graph is executed whenever a vehicle veh_s intends to send a message m to the external infrastructure via the cellular network. As shown by the uppermost choice node, veh_s first checks if it has sufficient cellular network coverage. In this case, m is immediately transmitted via the cellular network (flow A in Fig. 1). If veh_s is in a dead spot, it checks if it is already a member of an ad-hoc network with other vehicles as pointed out by the second choice node. If that is not the case, veh_s cannot do anything but keep the message and wait for either regaining cellular

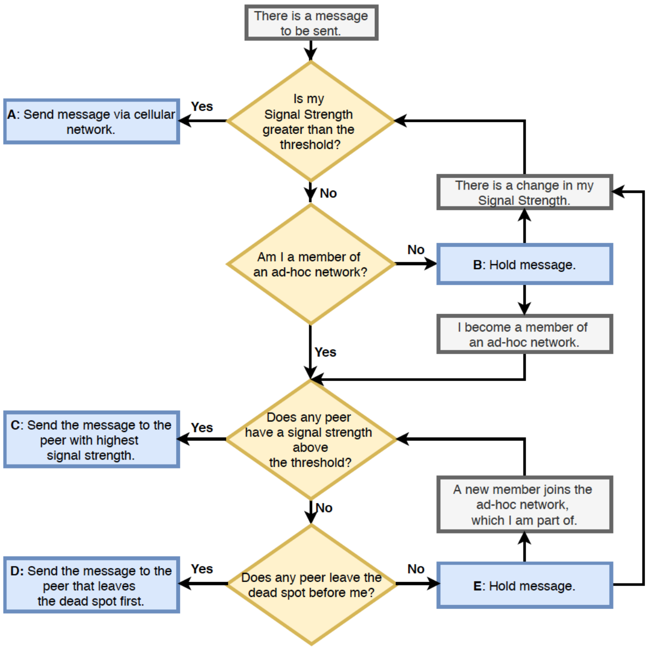


Fig. 1: Original data dissemination protocol.

network connectivity or building up an ad-hoc network with other vehicles (flow B).

If veh_s is a member of an ad-hoc network, it checks, whether there are peers that still have cellular network connectivity (third choice node). That can be the case if veh_s is close to the edge of the dead spot or any of the other ad-hoc network peers use another mobile carrier which has a better coverage on that road section. If such a vehicle veh_c exists, it receives message m from veh_s and transmits it immediately via the cellular network (flow C).

If none of the other peers in the ad-hoc network has cellular network access, veh_s compares its own predicted time to leave the dead spot with those of the other vehicles using one of the two techniques discussed above. This is depicted by the fourth choice node in Fig. 1. If another vehicle veh_f is supposed to leave the dead spot earlier than veh_s, m is transmitted from veh_s to veh_f (flow D). Now, veh_f overtakes the full responsibility to deliver m later. If veh_s, however, leaves the dead spot earlier than any of its peers, it keeps m since transferring it to another vehicle would not promise any expedition of the transmission (flow E).

The flow graph is rerun if an ad-hoc network is extended by new vehicles joining it. It also handles unexpected stops of a vehicle since, in this case, the leaving time will jump to "infinite" and the stored messages are handed over to other vehicles as soon as it joins a new ad-hoc network. For that, we assume that parked vehicles keep running the protocol until they do not carry any messages anymore.

We created a demonstrator of the first protocol variant based on the technology WiFiDirect [21] which is realized on most mobile devices. Our tests showed that, in spite of the relative short range coverage of 200 meters guaranteed by WiFiDirect, this protocol works nicely for opposing traffic with each of the vehicles running with 80 km/h, see [5]. Even with a speed of 110 km/h, around 71% of all message handovers were successful such that nearly all messages can be transferred within the first three attempts.

IV. Analysis of the Original Protocol

Particularly in larger dead spots, the vehicles can participate in several ad-hoc networks over time and messages may be carried by various vehicles until finally being transmitted via the cellular network. An advantage of the original protocol is that it avoids the transmission of message duplicates to the recipient. The flow graph in Fig. 1 reveals that this property holds since a message is either sent via the cellular network (flows A and C), kept in the vehicle carrying it (flows B and E), or transferred to exactly one other vehicle (flow D). Thus, only one vehicle will deliver the message to its recipient via the cellular network.

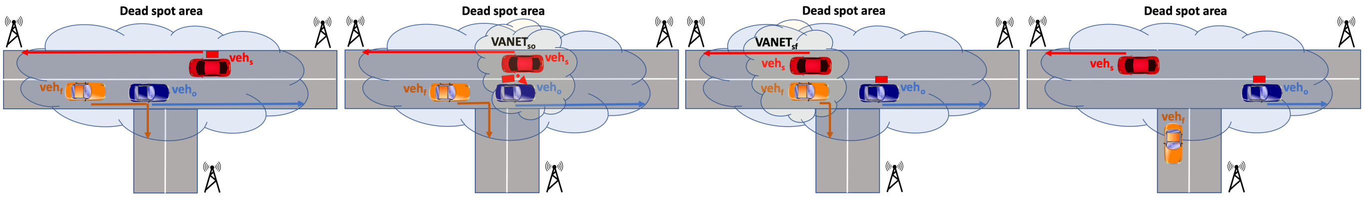
A property that, especially in larger dead spots, is more relevant, is *minimization of transmission time*, i.e., a message is transferred between connected vehicles in a way that it can be sent via the cellular network in the minimal amount of time possible. The data dissemination protocol does not always fulfill this property which can be shown using a single counterexample, e.g., the scenario depicted in Fig. 2. Here, a large dead spot covers a road junction where a side road joins a main road. In both directions of the main road, the distances from the junction to the dead spot border are quite long. In contrast, when taking the side road, cellular network connectivity can be regained relatively fast. Further, we assume that the variant based on connectivity maps [7] is used such that the vehicles know the planned route when calculating the times that they are supposed to leave the dead spot.

As shown in Fig. 2a, a vehicle veh_s that is running on the main road and supposed to leave the dead spot at 16:00, creates a message m at 15:00. Five minutes later, veh_s meets a vehicle veh_o approaching from the opposite direction which is supposed to regain cellular network connectivity at 15:45 (see Fig. 2b). We depict in Fig. 2c that at 15:10, shortly after having passed the road junction, veh_s meets a third vehicle veh_f which intends to join the side road and therefore probably leaves the dead spot already at 15:15 (see Fig. 2d).

In theory, the fastest way would have been, that veh_s keeps its message until meeting veh_f since that one leaves the dead spot much earlier than the other two vehicles. However, not knowing about veh_f at 15:05, veh_s takes the opportunity of an ad-hoc network connection with veh_o to hand the message over to this vehicle in order to gain an improved delivery time of around 15 minutes. In consequence, the message will be delivered half an hour later than possible.

V. Context-Aware Message Flooding Protocol

The scenario in Fig. 2 provides also an informative basis for how one can adapt the data dissemination protocol to guarantee minimization of transmission time if one is willing to sacrifice the prevention of duplicates. When vehicle veh_s



(a) Time: 15:00. (b) Time: 15:05. (c) Time: 15:10. (d) Time: 15:15.

Fig. 2: Counterexample showing that minimization of transmission time is not guaranteed.

meets veh_o at 15:05, it cannot know that this encounter does not pose the best opportunity to shorten the delivery time of message m since, e.g., veh_o might be the last vehicle that veh_s passes while being in the dead spot. Therefore, it is definitely useful to hand m over to veh_o for transmission and take it out of its own *transmission buffer*, i.e., the buffer storing messages to be sent via the cellular network.

However, veh_s should also keep a copy of m in a second storage that we call *opportunity buffer*. Moreover, it should tag this copy with a time indicator marking the time at which it will be earliest sent according to veh_s's context knowledge. In our scenario, after meeting with veh_o at 15:05, the tag for m will be 15:45. The copy of m in the opportunity buffer of veh_s can be utilized when the possibility of a faster delivery happens. In our scenario, that is at 15:10 when veh_s meets veh_f. By comparing the supposed leaving time of veh_f, i.e., 15:15, with m's tag in the opportunity buffer of veh_s, the two vehicles find out that handing over the message to veh_f for transmission improves the delivery significantly. Thus, veh_f adds message m into its transmission buffer while veh_s adjusts m's tag in the opportunity buffer to 15:15 since that is now the earliest delivery time in the context of veh_s. In consequence, m will be delivered by veh_f at 15:15 guaranteeing the minimization of transmission time property but again at 15:45 by veh_o since this vehicle cannot be informed about the better opportunity that arose later.

We call this variant *context-aware message flooding protocol* since, on the one hand, messages are flooded through all vehicles in a dead spot. On the other hand, duplicates are only sent when this, in the local context of the peers of an ad-hoc network, leads to an acceleration of the message delivery.

In contrast to the original protocol, several copies of a message can be stored in the transmission and opportunity buffers of various vehicles at the same time. To avoid synchronization issues resulting from the existence of different copies, we assume that the creator of a message provides it with a unique identifier such that the vehicles connected via an ad-hoc network can easily determine if they refer to different copies of the same message or to different messages.

The data dissemination protocol was developed in view of delivering shorter text messages, for instance, emergency information, from vehicles to their environment and not, e.g., video streams. Thus, due to the storage capacity of modern smart-phones, we do not see any problems caused by buffer overflow as long as all messages are deleted after being sent via the cellular network. We just need to determine if a message still needs to be stored in an opportunity buffer or if it can be removed. To achieve that, the creator veh_c of a new message provides it with an *expiry date* which is shortly after its own supposed leaving time, e.g., 16:01 for message m in our scenario. The protocol guarantees that messages are only forwarded to other vehicles for transmission if these leave the dead spot earlier than veh_c. Therefore, each message m will latest be delivered to its recipient via the cellular network when veh_c leaves the dead spot. In consequence, when the expiry date of m passes, it is already delivered and the vehicles can remove it from their opportunity buffers to avoid overflow.

The process of the context-aware message flooding protocol is depicted in Fig. 3. As shown in the first choice node, the protocol checks if a vehicle veh_s has a message m in its transmission buffer. If that is not the case, the protocol flow exits. Otherwise, the protocol tests if veh_s has sufficient cellular network coverage (second choice node). If that is the case, the message m is sent via the cellular network (flow A). Moreover, m is removed from the transmission buffer but added to the opportunity buffer tagged with the current time. Thus, the information about the transmission of m is kept and, in forthcoming ad-hoc networks, can be shared with other peers holding m in their respective buffers.

Similar to the original protocol, veh_s checks whether it is a member of an ad-hoc network with other vehicles, if it has not sufficient cellular network coverage (third choice node). If that is not the case, there are no other possibilities than waiting until the vehicle regains cellular network access or joins an ad-hoc network (flow B).

If veh_s is part of an ad-hoc network, it is checked if any peer veh_c has cellular network connectivity (fourth choice node). In this case, veh_c sends all messages that are either in the transmission buffers of its peers or in their opportunity buffers tagged with a time in the future (flow C). Of course, all peers remove the messages, sent by veh_c, from their transmission buffers. For the reasons mentioned above, the peers store copies of the sent messages tagged with the current time in their opportunity buffers.

The flows D and E cover the case that no peer in the ad-hoc network has cellular network coverage. As expressed by the last choice node, for each message m, any of the peers carry, the time tags of m in their opportunity buffers with

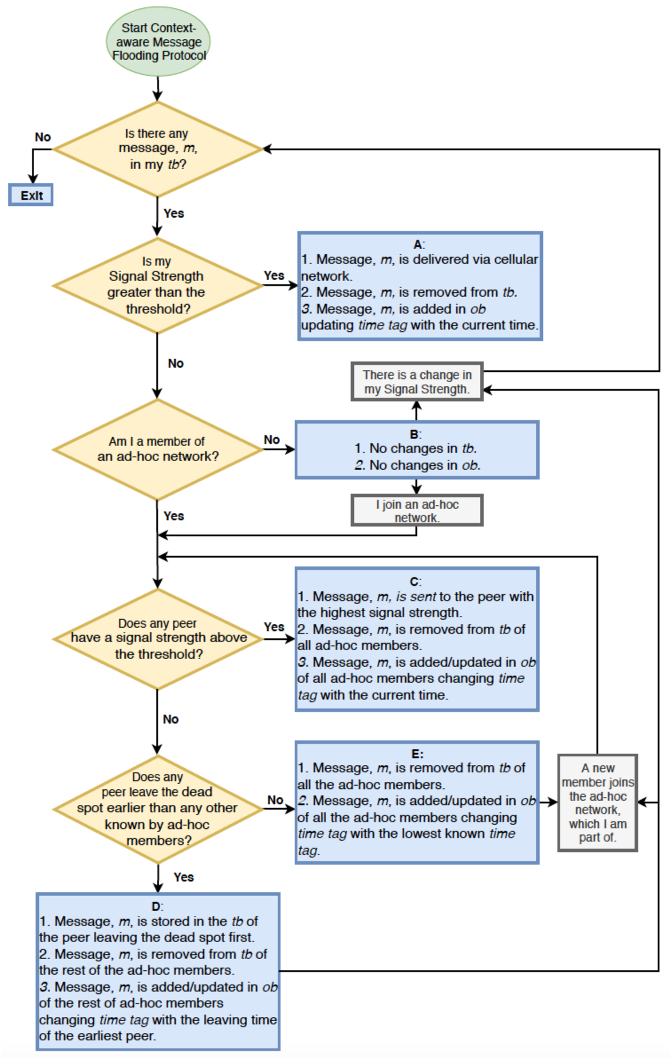


Fig. 3: Context-aware message flooding protocol.

the supposed leaving times of the vehicles are compared. Let veh_{fl} be the vehicle in the ad-hoc network that is supposed to leave the dead spot first. Then, we possibly[1] get an improved delivery time if veh_{fl} regains cellular network access earlier than the lowest *time tag* in the opportunity buffers or when m is only stored in transmission buffers but not any opportunity buffers. If one of these two conditions hold, veh_{fl} stores m in its transmission buffer for later delivery via the cellular network. All other peers store m in their opportunity buffers and tag it with the leaving time of veh_{fl} (flow D). In our scenario, this happens, e.g., at 15:05 between veh_s and veh_o.

Flow E describes the case that the earliest tag t_m for message m in the opportunity buffers of the peers is earlier than the supposed leaving time of veh_{fl}, i.e., one of the peers was connected with another vehicle in a previous ad-hoc network that can deliver m earlier than all the members of the current one. Then no peer of the ad-hoc network needs to deliver m since that would not speed the delivery time up. Therefore, all peers remove m from their transmission buffers but store it in their opportunity buffers. They tag their opportunity buffer entries with t_m.

[1] A non-member in the ad-hoc network leaving the dead spot earlier than veh_{fl} may exist without being referred to in a tag in an opportunity buffer, e.g., if in our scenario veh_o meets another vehicle at 15:12.

VI. Analysis of the Context-Aware Protocol

The raison d'être of the new protocol is to guarantee the transmission time property, i.e., to deliver messages produced in a dead spot to its recipient in the fastest possible way. This is shown below. Further, we sketch that the number of duplicates sent to the message recipients, is kept to a minimum.

A. Minimization of Transmission Time

To verify this property, we conducted an invariant proof using the Temporal Logic of Actions (TLA) [27]. Due to the space limit, we do not show the TLA specification and verification here but give just an outline of the proof.

The formula, that we prove to be a system invariant, states that for each message m that was created by a vehicle veh_c but not yet delivered to its recipient via the cellular network, the following two properties hold:

1) The vehicle veh_c has a copy of m. Further, each vehicle that has been connected with a carrier of a copy of m via an ad-hoc network, will carry a copy of m itself.
2) Of all vehicles carrying a copy of m, the one veh_f that is supposed to leave the dead spot first, has m in its transmission buffer such that m is immediately delivered after veh_f has left the dead spot.

The first property states that amongst others, the vehicle veh_f leaving the dead spot first, has a copy of m. The second one guarantees that veh_f will send m as soon as it leaves the dead spot. Together, the two properties ensure the minimization of transmission time aspect.

Invariant proofs are carried out by verifying that (a) the invariant holds at system start and (b) no system step falsifies it if it is true before executing the step. The verification of (a) is trivial since, in the beginning, no messages are created yet.

It is also easy to verify that the creation of a new message m in vehicle veh_c preserves the invariant. After producing m but before carrying out the context-aware protocol, veh_c is the only vehicle carrying a copy of m. Since m was not, yet, involved in an ad-hoc network connection, the first invariant property is trivially true. Further, as veh_c stores m in its transmission buffer, the second property holds as well.

Other system steps describe the five flows of the protocol that are listed in Fig. 3. The proofs that the steps A, B, and C do not falsify the invariant, are also quite simple. The flows A and C model the transmission of m to its recipient via the cellular network. After having carried out one of these steps, m will be delivered such that the invariant is true according to its definition. Flow B is a so-called stuttering step in which the system state does not change at all. Thus, if the invariant holds before passing this flow, it is valid afterwards as well.

The proofs of the flows D and E, that model the message handling in ad-hoc networks between vehicles without cellular network access, are a little more subtle. In both flows, all messages m that are in a transmission or opportunity buffer of at least one peer, are forwarded to all the other peers. Thus, the first property of the invariant is preserved by the two flows.

We assume that veh_{fl} is again the peer in an ad-hoc network that is supposed to leave the dead spot first. Flow D is carried out if none of the peers is aware of a carrier of a message m that is not in the ad-hoc network but leaves the dead spot earlier than veh_{fl}. If such a carrier exists, flow D does not change its state since only the states of network peers are altered. This preserves the second invariant property trivially.

If no carrier of m out of the ad-hoc network leaves the dead spot earlier than veh_{fl}, after completing flow D, veh_{fl} is the carrier of m regaining cellular network coverage first. Since m is stored in the transmission buffer of veh_{fl}, the second invariant property is also guaranteed in this case.

Flow E handles the case that a peer in the ad-hoc network is aware of a non-member that will leave the dead spot earlier than veh_{fl}. Since the flow only influences peers of the ad-hoc network, it trivially preserves the second invariant property.

Finally, we look on the mechanism of removing a message m from an opportunity buffer if its expiry date has passed. By proving an extended invariant, we can easily show that all vehicles carrying m in their transmission buffers, leave the dead spot earlier than the expiry date. That holds particularly for vehicle veh_f which exists according to the second property of our invariant. In consequence, when the expiry date elapses, veh_f has already transmitted m via the cellular network making the invariant trivially true.

By verifying that the context-aware message flooding protocol fulfills our invariant, we proved that it, indeed, guarantees the minimization of transmission time property.

B. Context-dependent Reduction of Duplicates

Our scenario from Fig. 2 shows clearly that the new protocol does not prevent the delivery of duplicates to message recipients since both veh_f and veh_o are sending copies of the message m via the cellular network. Nevertheless, it is interesting to check if our protocol keeps the number of duplicates to a minimum. For that, we consider the sets of vehicles that have the same *context* of a message m, i.e., identical knowledge about the carrier of m that leaves the dead spot first. To exemplify this, let us look again at the scenario depicted in Fig. 2. When veh_s creates message m at 15:00, it is the sole vehicle having a context about m supposing to deliver the message at 16:00. During the encounter at 15:05, veh_s forms a common context with veh_o, both assuming that veh_o will deliver m at 15:45. A split into two different contexts happens with the meeting between veh_s and veh_f at 15:10. From then, veh_o keeps thinking that it will deliver m at 15:45 while both veh_s and veh_f assume that veh_f will send m via the cellular network at 15:15.

The development of contexts over time can be described as follows: When a vehicle veh_c creates a new message, it is the only unit having a context of it. If an ad-hoc network is built and one of the three flows C, D, E (see Fig. 3) is executed, the peers of this network are removed from the existing contexts since they learn something new and therefore get different contextual knowledge. The newly gained information is expressed as a new context consisting of the peers of the ad-hoc network which commonly share the novel knowledge.

We can use the context information to describe that the minimum of duplicates is reached if at most one of the vehicles sharing a common context about a message m, has m in its transmission buffer for later delivery via the cellular network. Since, except ad-hoc networks, we do not have a method to align vehicles with different contexts in a dead spot, this is the minimum number of duplicates we have to accept in order to guarantee the minimization of transmission time property.

The minimal use of duplicates can be expressed by a logical formula according to which, of all vehicles having the same context about a message m, at most one vehicle veh_{cs} has m in its transmission buffer while the other members carry m only in their opportunity buffers. We can verify this formula as an invariant proof as well. Since, initially no messages were created, the formula holds at system start. After the generation of a message, its creator will be the only one in a context keeping the formula. When due to carrying out one of the flows C, D, or E vehicles are removed from existing contexts, the invariant is preserved. The trivial reason is that if, in a certain set of vehicles, at most one vehicle has m in its transmission buffer, this also holds for any subset. Finally, if a new context consisting of the peers in an ad-hoc network is created, only one (flow D) resp. none (flows C and E) stores m in its transmission buffer such that the formula is kept as well. All the other system steps do not change the contexts such that the context-aware message flooding protocol guarantees the context-dependent reduction of duplicates.

VII. Concluding Remarks

We started the paper by discussing the use of our original data dissemination protocol [5], [7] in larger dead spots in which a message may be carried by several vehicles. An important result was that this protocol does not always guarantee the fastest possible delivery of a message to its recipient. To avoid this weakness, we developed the context-aware message flooding protocol. We outlined a formal proof that this variant, indeed, assures message delivery as fast as possible but at the expense of potentially sending message duplicates. To mitigate this flooding effect, the protocol, however, considers the contexts of the various vehicles in a dead spot and creates additional copies of a message only if that improves the delivery time. Thus, the number of delivered copies is kept to a minimum which could also be formally verified.

We are currently implementing the modified protocol based on WiFiDirect [21] that was already used for the original version [5]. WiFiDirect is hierarchical, i.e., one of the peers in an ad-hoc network acts as the *Group Owner* (*GO*) which manages the temporary connection. Since the *GO* is the only peer that has the full connection data, it is predestined to conduct the message coordination as well. Thus, all peers in the ad-hoc network send their signal strengths and the supposed leaving times together with all messages in their transmission and opportunity buffers, as well as the time tags to the GO. Following the flows modeled in Fig. 3, the GO then computes how each message has to be handled. The result of this computation is then sent together with the messages from the GO to all other peers that update their buffers accordingly.

We expect that the performance tests for the new protocol render results that are similar to those for the original variants discussed in [5]. On the one side, an effect of the flooding will be that, on average, more messages have to be exchanged in an ad-hoc network than in the original versions. On the other side, this will be mitigated by the more central coordination using the GO since the additional exchange of IP addresses between the other peers can, in contrast to the original protocol, be avoided. Moreover, since the detection of peers and the forming of an ad-hoc network are the most time-critical events in WiFiDirect, we expect that the context-aware message flooding protocol will reliably work for opposing traffic until the speed of 80 km/h and mostly also for faster traffic until 110 km/h. Using more modern VANET technologies that have a reachability of much more than 200 meters, the performance of the context-aware message flooding protocol for dead spot mitigation will work for even faster traffic.

Unexpected events like vehicles that stop surprisingly or deviate from their route guidance systems, may violate the minimization of transmission time property in practice. One can attenuate this by letting more than just one vehicle with a common context deliver messages. We are currently developing a simulator that will allow us to try several strategies in order to find a preferably good balance between delivering messages fast and avoiding many duplicates even if some vehicles deviate from the expectations. We plan to report about these results in a later publication.

REFERENCES

[1] J. E. Siegel, D. C. Erb, and S. E. Sarma, "A Survey of the Connected Vehicle Landscape — Architectures, Enabling Technologies, Applications, and Development Areas," *IEEE Transactions on Intelligent Transportation Systems*, 2017.

[2] S. Mumtaz, K. M. S. Huq, and J. Rodriguez, "Direct Mobile-to-Mobile Communication: Paradigm for 5G," *IEEE Wireless Communications*, vol. 21, Oct. 2014.

[3] NPerf, "3G / 4G / 5G Coverage Map," https://www.nperf.com/, 2020, accessed: 2020-01-24.

[4] C. F. Mecklenbräuker, A. F. Molisch, J. Karedal, F. Tufvesson, A. Paier, L. Bernado, T. Zemen, O. Klemp, and N. Czink, "Vehicular Channel Characterization and Its Implications for Wireless System Design and Performance," *Proceedings of the IEEE*, vol. 99, no. 7, pp. 1189–1212, 2011.

[5] E. Puka and P. Herrmann, "Data Dissemination for Vehicles in Temporary Cellular Network Dead Spots," *International Journal of Cyber-Physical Systems (IJCPS)*, vol. 1, no. 2, pp. 38–55, 2019.

[6] P. E. Driesen, "Prediction of Multipath Delay Profiles in Mountainous Terrain," *IEEE Journal on Selected Areas in Communications*, vol. 8, no. 3, pp. 336–346, 2000.

[7] J. A. E. Meyer, E. Puka, and P. Herrmann, "Utilizing Connectivity Maps to Accelerate V2I Communication in Cellular Network Dead Spots," in

[8] A. Vahdat and D. Becker, "Epidemic Routing for Partially-Connected Ad Hoc Networks," Duke University, Durham, NC, USA, Tech. Rep., Jun. 2000.

6th International Conerence on Internet of Vehicles (IOV), no. LNCS 11894. Kaohsiung, Taiwan: Springer-Verlag, 2019, pp. 76–87.

[9] X. Wu, M. Mazurowski, Z. Chen, and N. Meratnia, "Emergency Message Dissemination System for Smartphones during Natural Disasters," in *11th International Conference on ITS Telecommunications*, Aug. 2011, pp. 258–263.

[10] K. Fall and S. Farrell, "DTN: an architectural retrospective," *IEEE Journal on Selected Areas in Communications*, vol. 26, no. 5, pp. 828–836, Jun. 2008.

[11] M. J. Khabbaz, C. M. Assi, and W. F. Fawaz, "Disruption-Tolerant Networking: A Comprehensive Survey on Recent Developments and Persisting Challenges," *IEEE Communications Surveys Tutorials*, vol. 14, no. 2, pp. 607–640, Feb. 2012.

[12] S. C. Nelson, M. Bakht, and R. Kravets, "Encounter-Based Routing in DTNs," in *28th IEEE International Conference on Computer Communications (INFOCOM)*, Apr. 2009, pp. 846–854.

[13] A. Balasubramanian, B. Levine, and A. Venkataramani, "DTN Routing as a Resource Allocation Problem," in *PConference on Applications, Technologies, Architectures, and Protocols for Computer Communications (SIGCOMM*. Kyoto, Japan: ACM, 2007, pp. 373—-384.

[14] J. Burgess, B. Gallagher, D. Jensen, and B. N. Levine, "MaxProp: Routing for Vehicle-Based Disruption-Tolerant Networks," in *25th IEEE International Conference on Computer Communications (INFOCOM)*, Apr. 2006, pp. 1–11.

[15] V. Erramilli and M. Crovella, "Forwarding in Opportunistic Networks with Resource Constraints," in *3rd ACM Workshop on Challenged Networks*. San Francisco, CA, USA: ACM, 2008, pp. 41—48.

[16] R. Ramanathan, R. Hansen, P. Basu, R. Rosales-Hain, and R. Krishnan, "Prioritized Epidemic Routing for Opportunistic Networks," in *Proceedings of the 1st International MobiSys Workshop on Mobile Opportunistic Networking*. San Juan, PR, USA: ACM, 2007, pp. 62—-66.

[17] S. Hu, H. Liu, L. Su, H. Wang, T. F. Abdelzaher, P. Hui, W. Zheng, Z. Xie, and J. A. Stankovic, "Towards Automatic Phone-to-Phone Communication for Vehicular Networking Applications," in *IEEE Conference on Computer Communications (INFOCOM)*. Toronto, ON, Canada: IEEE, 2014, pp. 1752–1760.

[18] E. Wang, Y. Yang, J. Wu, and W. Liu, "Phone-to-Phone Communication Utilizing WiFi Hotspot in Energy-Constrained Pocket Switched Networks," *IEEE Transactions on Vehicular Technology*, vol. 65, no. 10, pp. 8578–8590, Oct. 2016.

[19] A. A. Eltahir, R. A. Saeed, A. Mukherjee, and M. K. Hasan, "Evaluation and Analysis of an Enhanced Hybrid Wireless Mesh Protocol for Vehicular Ad Hoc Network," *EURASIP Journal on Wireless Communications and Networking*, no. 169, 2016.

[20] S. Jeong, Y. Baek, and S. H. Son, "A Hybrid V2X System for Safety-Critical Applications in VANET," in *IEEE 4th International Conference on Cyber-Physical Systems, Networks, and Applications (CPSNA)*, Nagoya, Japan, 2016, pp. 13–18.

[21] Wi-Fi Alliance, P2P Technical Group, "Wi-Fi Peer-to-Peer (P2P) Technical Specification v1.7," 2016.

[22] G. Korkmaz, E. Ekici, F. Özgüner, and Ü. Özgüner, "Urban Multi-Hop Broadcast Protocol for Inter-Vehicle Communication Systems," in *1st ACM international workshop on Vehicular ad hoc networks (VANET)*. ACM, 2004, pp. 76–85.

[23] F. F. Tseng, D. P. Filev, and I. H. Makki, "Vehicular Connectivity Map," U.S. Patent 9 775 128 B2, Sep. 26, 2017, U.S. Patent 9 775 128 B2.

[24] V. Jain, B. Raghunathan, and V. Kone, "Dead Spot Prediction Method for Wireless Vehicular Applications," U.S. Patent 8 494 563, Jul. 23, 2013, U.S. Patent 8 494 563.

[25] F. F. Tseng, D. P. Filev, I. H. Makki, K. O. Prakah-Asante, and H. Yang, "Crowd Enhenced Connectivity Map for Data Transfer Intermittency Mitigation," U.S. Patent 2015/028 190, Oct. 1, 2015, U.S. Patent 2015/028 190.

[26] L. S. DeLuca, G. T. Lakshmanan, D. L. Price, and S. D. Smith, "Mitigating Service Disruptions using Mobile Prefetching based on Predicted Dead Spots," U.S. Patent 9 860 336, Jan. 2, 2018, U.S. Patent 9 860 336.

[27] L. Lamport, *Specifying Systems: The TLA+ Language and Tools for Hardware and Software Engineers*. Addison-Wesley, 2003.