Cluster-based Transmit Power Control in Heterogeneous Vehicular Networks

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***Abstract*—Heterogeneous vehicular networks combine the advantages of multiple access technologies like LTE and DSRC. Such heterogeneous networks are often combined with clustering, which helps to aggregate information locally before sharing it in a wide area, thus reducing channel load. Another mechanism to reduce channel load is to reduce transmit power, but this requires accurate information or good heuristics. Otherwise, too low transmit power may cause increased packet loss, thus wasted channel capacity and overall reduced system performance. We present an approach that combines centrally managed clustering with transmit power control in a heterogeneous vehicular network. Here, centrally available knowledge can be relied on for transmit power control decisions. Based on computer simulation, we show that such a system can free up to 50 % of channel capacity with no more than a 1 % drop in system performance.**

I. Introduction and Motivation

In general, Wireless LAN (WLAN) technologies have been considered as the main access technology for Inter-Vehicle Communication (IVC), leading to the development of IEEE 802.11p-based standards such as IEEE WAVE in the U.S. and ETSI ITS-G5 in Europe. However, these technologies, called Dedicated Short-Range Communication (DSRC), have some weaknesses owing to their distributed nature and they will show poor performance at low market penetration [1]. Alternatively, one could use the existing cellular infrastructure for IVC [2]. But, when using cellular technologies, other problems may arise, such as scalability [3]. This led to a new concept, known as *heterogeneous vehicular networks*, where different types of communication technologies are used so they complement each other. Recently, heterogeneous vehicular networks have attracted attention in the field of vehicular networking and are being investigated for use in IVC applications.

IVC enables a range of different applications, many of which rely on information gathered from the periodic broadcast of messages by vehicles – a concept known as *beaconing* in vehicular networking. Being the fundamental block of many IVC applications, beaconing approaches have been studied extensively, especially in the context of safety applications [4]. These applications have strict latency and reliability requirements giving rise to the problem of channel overload due to the frequent broadcasts.

To mitigate this issue, many approaches have suggested the adaptation of beaconing parameters, such as the transmission interval or the transmission power. By tuning those parameters, the application requirements can be satisfied while the channel utilization remains below a given threshold. However, doing so in a distributed fashion has often proven to be either error-prone or requiring additional communication overhead.

In this paper, we investigate the feasibility of performing adaptive transmission power control in a heterogeneous vehicular network, piggybacking on centralized clustering. We added the adaptive transmit power control feature to LTE4V2X [5], a centralized clustering approach for heterogeneous vehicular networks. The outcome represents a novel approach where a central entity adapts the DSRC transmission power of the nodes, based on the span of the cluster they belong to.

Our cluster-based transmit power control mechanism, to the best of our knowledge, represents the first such approach in a heterogeneous vehicular network. Our results show that, by dynamically adjusting the transmission power of the nodes based on centrally available information, we could halve the channel load while minimally sacrificing application performance.

II. Related work

Cooperative Awareness Message (CAM) is a standardized form of beaconing, which is part of the *cooperative awareness* application envisioned by ETSI ITS-G5 [6]. The U.S. equivalent of CAM is called Basic Safety Message (BSM). These applications foresee that all participants in a road traffic scenario should become fully aware of each others' mobility and positioning parameters by periodic broadcast of CAMs. However, the frequent transmission of beacons in highly dynamic and dense scenarios can quickly overload the communication channel.

As a countermeasure, Torrent-Moreno et al. [7] show that tuning the transmit power of the nodes to achieve fair distribution of channel capacity among vehicles can avoid overload conditions. For the power adaption, based on local knowledge, each vehicle computes a common power value – for itself and the nodes within its transmission range – such that the cumulative power does not surpass the threshold. Then, a distributed strategy is used to fine-tune the power level computation: each vehicle broadcasts a packet containing the result of its computation. This newly obtained information is used by a vehicle to compute the final transmit power level. Adaptive selection of the transmit power has also been adopted by ETSI ITS-G5 [6], though Tielert et al. [8] note that, without being able to optimize for a certain node density or distance to cover, the impact of purely reactive approaches is limited. In the following we show a different approach, which pro-actively adapts the transmit power based on application data.

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Besides using adaptivity to achieve better channel conditions, another strategy would be distributing the channel load between the networks in a heterogeneous vehicular networking scenario based on clustering. A real-world project based on this idea was the *CoCarX* project, where Long Term Evolution (LTE) cellular technology was combined with IEEE 802.11p DSRC [9]. In this system, vehicles exchange CAMs which are aggregated at a cluster head before being sent to the neighboring vehicles via LTE. The performance of the system was satisfactory for low beaconing frequencies, but it was not able to cope with the frequent transmission of CAMs.

III. Cluster-based Transmit Power Control

In contrast to the approaches considered above, where adaptive transmit power control and clustering are used separately to solve the same problem – that of an overloaded communication channel – we consider these concepts together and propose a cluster-based transmit power control scheme for heterogeneous vehicular networks.

We base our work on the LTE4V2X approach by Rémy et al. [5], a centralized clustering approach for heterogeneous vehicular networks. It assumes a scenario where all vehicles are equipped with two network interfaces: one ad-hoc and one cellular. LTE4V2X takes advantage of LTE's wide coverage by assigning the complex task of cluster formation and coordination to a central entity, the *server* (which, without loss of generality, we treat as synonymous to the eNodeB). Vehicles use DSRC to communicate with each other, and LTE to communicate with the server.

After a short initialization step, LTE4V2X executes a round-based protocol; each 1 s protocol round consists of four protocol phases. In the first phase (LTE downlink), the server updates the clusters and elects their Cluster Heads (CHs) based on the most recent CAM messages. Then, it informs the CHs about the updated cluster configuration. From this point onwards each CH acts as gateway that receives information from the server and provides that to the vehicles in the Vehicular Ad Hoc Network (VANET) and vice-versa. In the second phase (DSRC downlink) each CH broadcasts a message which contains the IDs of corresponding Cluster Members (CMs). A vehicle which finds its own ID in this message becomes a CM of the broadcasting CH. In the third phase (DSRC uplink), CMs send their CAM messages to their CH using DSRC. The CH collects these CAM messages and combines them into an aggregated CAM (called floating car data). In the fourth phase (LTE uplink), CHs send aggregated CAMs to the server. After this phase, protocol operation starts the next round.

As [5] does not clearly indicate which car to chose as a CH, we decided to select the vehicle with the minimum distance to the eNodeB. This is to keep the communicating parties as close as possible since distance has nontrivial impact on the quality of a wireless channel.

In addition, we extended LTE4V2X in three respects: First, we are varying the maximum cluster span, whereas the original LTE4V2X set the upper bound to an assumed "range" of DSRC of 300 m. This is also necessary for incorporating the transmit power control into the protocol. Second, we configured the clustering algorithm to consider the current road, current heading, and current speed of vehicles for determining cluster membership. Finally, we extended LTE4V2X with our Cluster-based Transmit Power Control (C-TPC) approach as follows.

In a traditional LTE4V2X scenario the CHs and CMs use the default transmission power when communicating via DSRC. This means that in a dense scenario there is a high probability that the nodes lose packets due to interference and collisions. As a solution, we propose a novel approach which allows centralized transmit power control in VANETs.

The main enabling factor for adaptive transmit power in LTE4V2X is its *centrality*. That is, the existence of the server which represents a single point of knowledge and decision making. By exploiting this property of LTE4V2X we extended it to also perform adaptive transmission power control. This means that the server, besides coordinating the clusters, can also dictate the output power of vehicles' DSRC radios.

The transmit power control mechanism was designed such that it can make use of the knowledge available for clustering. Previously, we mentioned that to calculate the clusters the server requires positional data about the vehicles. As a result, while calculating the clusters it can infer the distance between a CH and all of its CMs. In turn, this information can be used to perform adaptive transmit power control. Such an adaptive transmit power control mechanism does not require extra coordination: The selected power levels are embedded in regular LTE4V2X frames and announced following the usual communication hierarchy: server to CH, CH to CMs.

In the simplest case, one could dynamically adjust the transmit power of DSRC as a function of the distance between the CH and its farthest CM. Once the clusters are calculated the server checks the distance between the CH and the farthest CM for each cluster. Then, it sets the power levels for all CMs according to that distance.

Of course, based on the information available at the central server, better approaches (in particular for avoiding inter-cluster interference) could be imagined; we leave such investigations as future work.

IV. Simulation Scenario and Parameters

To evaluate LTE4V2X and the newly integrated adaptive power control mechanism we used *Veins LTE*, the LTE extension [10] of the well known *Veins* Open Source vehicular network simulation framework.

Figure 1 shows our scenario, a single intersection road network where four roads meet at an intersection. The eNodeB is located close to this intersection. To accommodate a maximum density of 100 veh/km the roads are 550 m long. Each road consists of a single lane in each direction. There are no buildings in the scenario, so we configure a free space path loss model. Vehicles are exponentially distributed on roads at fixed average densities, depending on the scenario. All of the vehicles move with a static speed of 50 km/h, reflecting the urban speed limits in Europe. The penetration rate for LTE and DSRC is set at 100 % as required by LTE4V2X. We assume

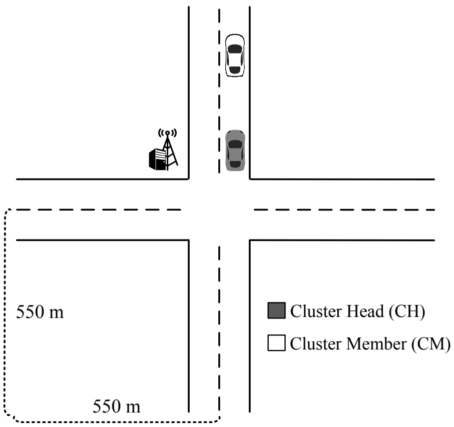

Figure 1. The simulated road network topology.

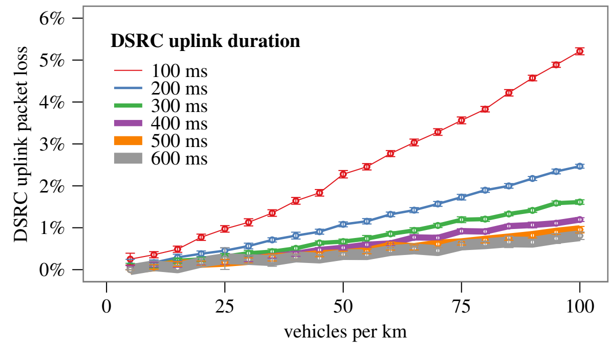

Figure 2. DSRC uplink packet loss for different node densities and interval durations.

there is no additional LTE or DSRC traffic in the scenario. The boundaries of the scenario represent also the boundaries of the LTE cell. Simulations are run for 60 s, prefixed by 80 s warm up time to stabilize. All simulations are repeated 10 times with independent random number seeds to show a 95 % confidence interval of the mean for each considered metric. We consider three metrics to evaluate the performance of our approach:

- Packet loss: the fraction of packets sent towards a destination but not reaching it. The packet loss metric is used to assess the channel quality for individual transmissions in a LTE4V2X periodic round. We distinguish packet loss in the LTE downlink (from the server to the CHs), in the DSRC downlink (from the CH to its CMs), or *mutatis mutandis* for the uplink.
- CAM loss: the fraction of vehicles in the scenario that do not receive CAM messages. We use the CAM Loss application metric to get an holistic assessment of the application performance, regardless of the losses in each transmission.
- MAC busy time: the fraction of time a vehicle observes the DSRC channel as busy over its lifetime. We use this metric to evaluate the impact of C-TPC on the utilization of the DSRC channel. After decreasing the DSRC transmit power, this metric should reflect whether the nodes observe less of a busy channel due to lowered interference from transmitting neighbors.

V. Results and Discussion

In an initial set of experiments, we set DSRC to use a fixed transmit power of 20 mW and set the clustering distance to 300 m. First, we configure the duration of the individual protocol phases. We start with the LTE downlink and the DSRC downlink, which we set to 100 ms each. Even for this short duration, we observed negligible results for the packet loss. We have an almost perfect transmission from the server towards the CHs regardless of the node density. With 100 Resource Blocks available – which is the equivalent of a 20 MHz channel – the eNodeB can easily handle the unicast traffic towards the relatively low number of CHs elected by the clustering decision. Similarly, the DSRC downlink channel is stable too, with the packet loss remaining below 2 % even at highest density.

More interesting is the DSRC uplink phase. Figure 2 highlights that packet loss in this phase is not just dependent on the vehicle density, but just as well on the allocated duration of the phase. As discussed, the DSRC uplink transmission phase is when the CMs send CAM messages to their CH. The figure shows that the packet loss gets worse as the number of the vehicles increases, especially for shorter uplink intervals. This happens because when there are more CMs, the CH needs more time to receive the CAM messages from all of them. Note that the DSRC uplink, used by the CMs, is a broadcast channel. This means that packets can be lost due to interference and collisions from the neighboring nodes. In the following, we configured the duration of the DSRC uplink phase to be 300 ms to leave enough room in a 1 s round duration for other protocol phases.

The LTE uplink phase is the most important one, because that is when the data of a cluster is transmitted from the CH to the server. If the packet from a CH is lost, a whole set of aggregated CAMs are lost and the whole cluster is not considered for the clustering decisions of the next round, hence not losing those packets has a higher priority. After an extensive parameter study (omitted here for the sake of brevity), we set 400 ms as the LTE uplink phase duration, leaving 100 ms as a guard interval before the next round starts.

In the next set of experiments, we investigate the impact of clustering distance. Figure 3 illustrates that the distance of a CH to the eNodeB has a major impact on packet loss. Consequently, because larger clusters mean more freedom to pick a CH that is close to the eNodeB, larger clusters will lead to better system performance as long as the LTE channel is not overloaded. However, larger clusters offer less potential for optimizing DSRC transmit power, as we will see in the following.

We now enable our C-TPC approach, allowing the server to inform CHs (which, in turn, inform their CMs) about the desired transmit power. We also investigate different maximum clustering distances, ranging from 100 m to 400 m. As discussed, we implemented a simple mechanism which bases transmit power on the true, centrally known cluster size.

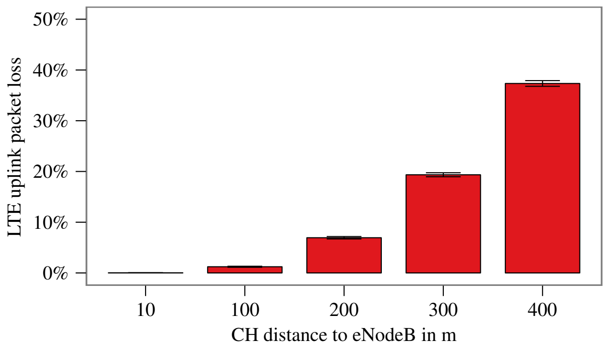

Figure 3. LTE uplink packet loss as a function of the distance between the Cluster Heads (CHs) and the eNodeB.

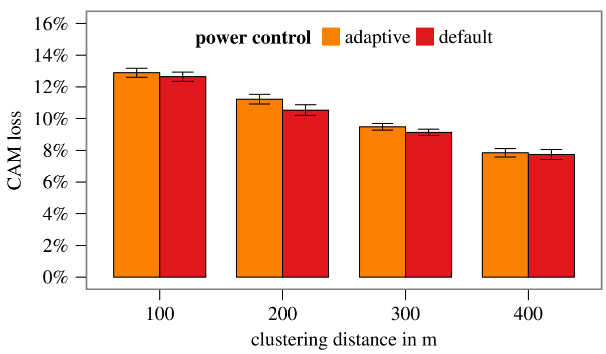

Figure 4. CAM Loss for adapted transmit power vs. default transmit power.

For a cluster size of up to 100, 200, 300, and 400 m, the cluster is instructed to use 5, 5, 10, and 15 mW as DSRC transmit power, respectively, instead of the full 20 mW. The thresholds are based on an extensive simulation study to ensure that, if for a given cluster span the transmission power was lowered the loss in application performance would be miniscule.

Figure 4 compares CAM loss for clusters with and without adapted transmit power. In all of the cases the application performance is reduced by no more than approx. 1 %. Thus, transmit power control is (at least) not harmful the protocol performance, which only leaves its impact on channel utilization to be investigated. Figure 5 illustrates the DSRC channel

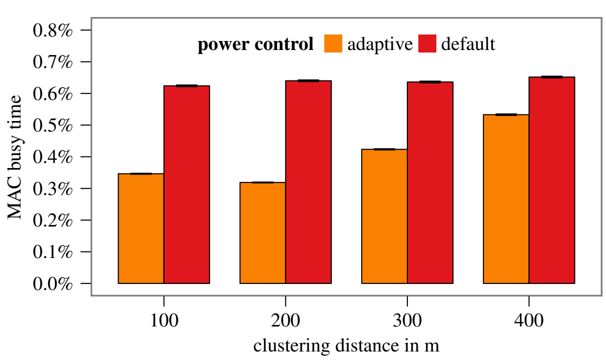

Figure 5. DSRC channel utilization for adapted transmit power vs. default transmit power.

utilization for the different cluster sizes when using adapted transmit power and default transmit power. We can see that whenever adaptive transmit power control was used, the nodes observed the channel as busy for shorter amounts of time. That is because by tuning the DSRC transmit power to the cluster span, we ensure that the nodes within a cluster can reliably communicate with their CH, while interfering as little as possible with other clusters. This occurrence is most evident for the clusters spanning up to 200 m where the channel becomes half as busy since the transmit power was decreased for 75 %. Similar effects can be observed for the 300 m and 400 m but there the difference between the two approaches is smaller, because DSRC transmit power was decreased to a lesser extent.

VI. Conclusion

We presented an approach that combines centrally managed clustering with transmit power control in a heterogeneous vehicular network. Here, centrally available knowledge can be relied on for transmit power control decisions. Based on computer simulations we were able to show that, with minimal sacrifice of application performance, it is possible to free up to 50 % of the DSRC channel, which enables its utilization by other IVC applications. This builds the basis for investigations of more involved centralized transmission power adaptation schemes, e.g., taking into account the environment or inter-cluster coordination.

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