Topology Control in VANET and Capacity Estimation

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Abstract—Some safety applications using VANET ex-
change a large amount of data, and consequently require
an important network capacity. In this paper, we focus on
extended perception map applications, that use information
from local and distant sensors to offer driving assistance
(autonomous driving, collision warning, etc). Extended
perception requires a high bandwidth that might not be
available in practice in classical IEEE 802.11p ad hoc
networks. Therefore, we propose an adaptive power control
algorithm optimized for this particular application. We
show through an analytical model and a large set of
simulations that the network capacity is then significantly
increased.

I. INTRODUCTION

Perception map consists for a vehicle in collecting
data through a set of embedded sensors measuring the
surrounding environment. It gives both a local represen-
tation and modeling of the information resources used
by the vehicle applications like ACC (Adaptive Cruise
Control), Stop and Go, road departure avoidance, colli-
sion mitigation, etc. With the VANET, perception maps
may be broadcasted to the adjacent vehicles allowing a
node to extend its local vision. The so-called "extended
perception" may improve the safety applications as it
offers a better risk assessment, a better anticipation of
dangerous situation, and may provide information for
autonomous driving applications.

But, information from sensors needs to be exchanged
at a high rate (up to 100 packets per second) to be
pertinent. Therefore, extended perception may generate
an important amount of data that must be efficiently
carried by the network. The fundamental and natural
question that arises is thus to know if the VANET
can offer such a capacity. If not, we need to propose

mechanisms offering enough bandwidth to support these
essential applications.

In a near future, VANET should be based on the recent
IEEE 802.11p [2] standard for its communication. The
capacity of IEEE 802.11p based ad hoc networks is
mainly limited by the spatial reuse, due to the CSMA/CA
mechanism. Indeed, a node in a CSMA/CA network
can access to the share wireless medium only if the
medium is detected idle. To determine this idleness, the
CSMA/CA uses a sub-mechanism named CCA (Clear
Channel Assessment). It may report a busy medium upon
detecting any energy above an Energy Detection thresh-
old (CCA mode 1). In this case, the channel occupancy is
related to the total interference level. Or, it may report a
busy medium if it detects a signal compliant with its own
standard (CCA mode 2), i.e. same physical layer (PHY)
characteristics, such as modulation or spreading. Also,
the wireless interface may use a logical combination
(e.g. AND or OR) of the two previous mode (CCA
mode 3). Obviously, these CCA mechanisms ensure that
only nodes sufficiently far from the transmitting node
can access the medium and limit interference between
concurrent transmissions. But, it also limits the number
of simultaneous transmitters, the number of frames that
the network can carry per second, and consequently the
VANET capacity.

A natural way to improve this capacity is to increase
the spatial reuse by using an adaptive transmission power
control algorithm. It is particularly pertinent in this con-
text as the perception map application send information
to the neighborhood in a sub-radio scope (around 100
meters) and not in the whole 802.11p radio range. A
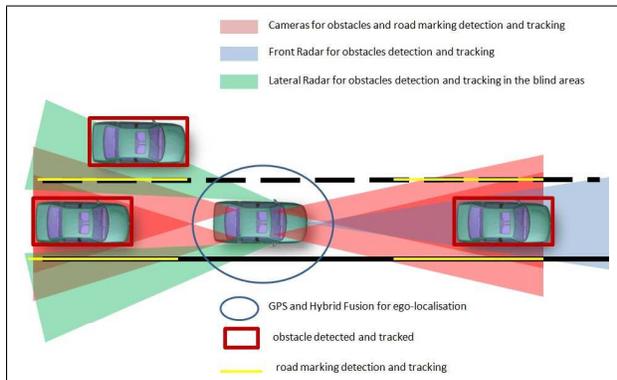certain number of power control algorithm designed for

Fig. 1. Attributes of a perception local map.

Neighbor ID	Up-link	Down-link	local time out
192.168.0.1	-75 dBm	-54 dBm	$timeout_1$
192.168.0.3	-60 dBm	-59 dBm	$timeout_2$
...	...	...	...

TABLE I
EXAMPLE OF A *LocalNeighborsList*.

VANET have been recently proposed [5], [16], [13], [4], [12], but they cannot be applied to the perception map application due to its specific constraints.

This paper aims to propose and evaluate an adaptive Transmission Power Control (TPC) algorithm designed for perception map applications. This application is presented in Section II. The first contribution is thus a power control algorithm presented in Section III. In Section IV, we propose an analytical model allowing us to evaluate the performance of our algorithm in term of capacity. Simulations and analytical results are compared in Section V, and we conclude in Section VI.

II. PERCEPTION MAP APPLICATION

Recently, it is become very important to extend the perception range in order to anticipate the hazardous situation (risk assessment) and to provide information for autonomous driving applications (copilot application with path planning and navigation functionalities) [14]. The extended map modeling is both a spatial and temporal representation of a specific extended situation (limited in the local map by sensor ranges) allowed by communication means. An illustration of embedded sensors that can be equipped on a vehicle for building the perception map is depicted in Figure 1. By using communications within a range of less than 50-100 meters, we can send information to the other vehicles moving both in front and in the rear of our position. This local information can also be used in order to inform vehicles far away from the ego-vehicle (in rear position) to have enough information to assess a risk indication. Such an application has been already tested in [7], [6] and prove its efficiency to reduce the global risk point of view. In these papers, the authors compare the performance of a cooperative risk assessment using an extended map against a non-cooperative approach based on local-perception only. The results of this study

show a systematic improvement of forward warning time for most vehicles in a platoon scenario when using the extended-map-based risk assessment.

But, data quality heavily depends on both the quality of the local algorithms used to perceive the environment, and the communication capability to send an amount of data in a short time and in a dense traffic configuration. The more delay the communications have, the more uncertainties on the data (especially the position, speed, and heading) will be degraded and unusable. With the required frequency of exchanged between vehicles (up to 100 Hz), and the expected radio range of the IEEE 802.11p technology (up to 1km), such application may not be supported due to the lack of network capacity [8]. The work presented in this paper is dedicated to this problem and try to give a first answer in order to improve the network capacity for a better extended perception.

III. ADAPTIVE TPC ALGORITHM

A. Motivation

Our power control algorithm is dedicated to the extended map application, i.e. transmission power changes apply only to this application packets. As described earlier, the perception map application have the following properties: each vehicle/node broadcasts information at a high frequency, information contained in these packets are pertinent in the vicinity of the nodes (50-100 meters), and the application does not require a fully reliable delivery of the broadcasted packets so it tolerates a few losses. Therefore, the proposed power control algorithm aims to ensure a good reception rate of broadcast packets for receivers lying less than a certain distance (denoted d_{ref} in the following), and with the smallest possible transmission power. We do not assume any particular radio environment, path-loss, etc. The algorithm is thus adaptive, i.e. transmission power is tuned only with regard to measures made locally on each node. Basically, the algorithm has three tasks: update a list of nodes at distance less than d_{ref}, spy the reception qualities for these nodes, and increase/decrease the transmission power according to these information.

B. Algorithm details

The algorithm and the application assume that all involved nodes are equipped with GPS receiver or any

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Parameters	Values
Application packet frequency	Varying
HELLO_INTERVAL	1 second
LOCAL_TIMEOUT	$3\times$ Packet frequency (0.3 sec)
GLOBAL_TIMEOUT	$3\times$ HELLO_INTERVAL (3.0 sec)
P_{max}	33
θ	-90 dBm
d_{ref}	50 meters
Δ	1 dBm

TABLE II

DEFAULT VALUES OF THE POWER CONTROL ALGORITHM.

Fig. 2. Random packing model example.

devices allowing a node to know its location. Our algorithm manages two lists of neighbors.

The first list relies on a link sensing mechanism using HELLO packets. These HELLOs are sent periodically, at a low frequency denoted HELLO_INTERVAL (about 1 or 2 seconds), at the maximum transmission power, and include the sender location. It allows each node to keep a global neighbors list, with ID and locations of the neighbors. An entry/neighbor is removed from this list if no HELLO is received for a GLOBAL_TIMEOUT period. This algorithm being very classical, we do not present the details.

The second list contains only nodes at a distance less than d_{ref} (pertinent distance from the application point of view). To manage this list, we use the packets of the perception map application that periodically broadcasted packets at a high frequency. The power control algorithm applies to these packets. The corresponding list of nodes is denoted *LocalNeighborsList*. It contains the neighbor IDs, up-link and down-link quality, and a local time out as shown in Table I. The initial local timeout is set according to the constant LOCAL_TIMEOUT. This timeout aims to update/remove an entry of the local neighbor list when there are several consecutive missed packets from this neighbor. The up-link and down-link qualities may be the received signal strength, SNR, SINR or any quantity reflecting the link quality. In our simulations, we considered the received signal strength since it is available, but for a real implementation the RSSI (Radio Signal Strength Indicator) could be considered instead. The down-link quality is updated at the reception of a probe/application packet. When sending a probe packet (an application packet using this algorithm is called a probe packet), the sender piggybacks its own location and its *LocalNeighborList*. These information allows the receiver to update the location/distance and the up-link quality for this neighbor.

The algorithm includes 3 sub-procedures. The three procedures are detailed in Table 1, 2 and 3. Each node
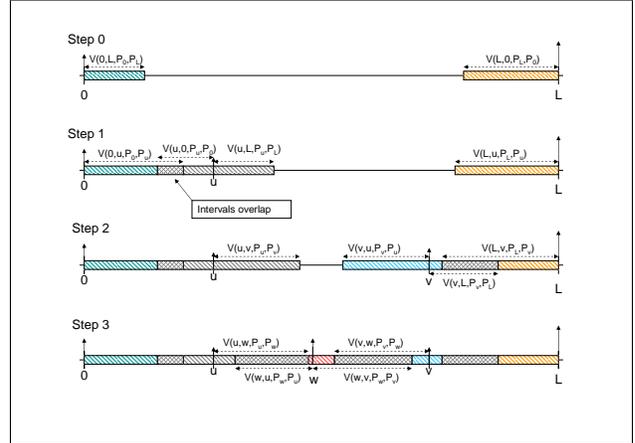
has a global variable TxPower that sets the transmission power of the probe packets. When a node R receives a probe packet from a node E, it calls the Reception() procedure. R updates the *LocalNeighborsList*, and increases the transmission power if R is not in *LocalNeighborsList* of E who sent this probe (meaning that the transmission power of R is not sufficiently high to reach its neighbor E). When a node wants to transmit its probe, it calls the Transmission() procedure. It checks if the *LocalNeighborsList* contains all nodes at distance less than d_{ref}. If not, it increases its transmission power. Also, it checks if all neighbors at distance less than d_{ref} received its probes with a minimum quality (denoted θ in the algorithm). If yes, it decreases the transmission power. The procedure LocalTimeoutExpiration(), called at the local time out expiration, aims to update the *LocalNeighborList* when a node is at distance greater than d_{ref}. The defaults values of the different parameters involved in our algorithm are given in Table II.

IV. RANDOM PACKING MODEL

A. *The model*

We propose in this Section a random packing model to evaluate the network capacity when using a power control algorithm. Packing model consists in placing points in a given space under some constraints until the space is completely filled. The considered space is $\mathbb{R}^+$, representing a road or a highway. In our context, points will represent the transmitter locations. We deduce the mean number of simultaneous transmitters, hence the mean number of transmitted frames and the capacity.

Most of the packing problem [9], [15] associate to each point an interval of fixed or random size. The next points are kept if and only if it does not lie in one of

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Algorithm 1: Procedure called at the reception of a probe packet

---

```
void Reception()
```
begin

    Extract from the received packet, the *LocalNeighborsList* and the transmitter Location;

    Update the sender location in the global neighbors list;

    if $distance(transmitter, receiver) > d_{ref}$ **then**

        ```/* This transmitter is too far with regard to the application   */```

        Discard this packet;

        Remove the transmitter from the receiver *LocalNeighborsList* if present;

    else

        if *the transmitter ID is in the receiver LocalNeighborsList* **then**

            if *the local node ID is not in the transmitter LocalNeighborsList* **then**

                ```/* The local node is not in the list of this neighbor: add Δ dBm```

                ```*/```

                TxPower += Δ;

        else

            ```/* This transmitter is a new neighbor   */```

            Add to the receiver *LocalNeighborsList* a new entry with the ID of this transmitter;

            Update this entry with up-link quality extracted from the transmitter *LocalNeighborsList* if present;

    ```/* Update information for this neighbor in the receiver```

    ```LocalNeighborsList   */```

    Update local timeout for this transmitter;

    Update the down-link quality according to the reception power for this transmitter;

Algorithm 2: Transmit sub-procedure

```
void Transmission()
```
begin

    if *Some nodes in the global neighbor list lie at distance $< d_{ref}$ but are not present in the LocalNeighborsList* **then**

        TxPower += Δ;

    else

        if *All of the up-link quality in LocalNeighborsList $\geq \theta$* **then**

            TxPower -= Δ;

    Insert location and *LocalNeighborsList* of the local node into the probe packet;

    Transmit the packet;

Algorithm 3: Function called at a local time out expiration

```
void LocalTimeoutExpiration()
```
begin

    if *the neighbor for which the timer expires is at a distance less than d_{ref} according to the global neighbor list* **then**

        TxPower += Δ ;

        Update the local timeout for this neighbor;

    else

        remove the neighbor for which the timer has expired from the *LocalNeighborsList*;

---

these interval, and so on. These processes can model the CCA mode 2, where the medium is set as busy when a signal compliant with the IEEE 802.11 standard is detected. Indeed, if we assume that a transmission/signal is detected at a certain distance, the interval of the car packing model represents the region around the transmitter where its signal is detected. But with the CCA mode 1, a medium is sensed as busy or idle according to the interference signal strength. It does not correspond to the signal from the closest transmitter, but as the sum of the signals of the current transmissions. Extensions of the classical packing model have been proposed to model this mode [8], but they assume a constant transmission power. We propose here, a packing process modeling mode 1 with heterogeneous transmission power.

With CCA mode 1, the medium is busy if this interference level is above a pre-defined threshold denoted γ. We assume that radio environment can be modeled by a path-loss function, denoted $l(.)$. It gives the received signal strength according to the distance from the transmitter when the transmitting power is 1 (mW or W). $l(.)$, defined in $\mathbb{R}^+$, is assumed positive, continuous, decreasing with $\lim_{x \to +\infty} l(x) = 0$.

Due to the fact that radio signals attenuate quickly with the distance, interference is mainly composed of the closest interferers. Therefore, our model takes into account the interference that is generated by the two closest transmitting nodes, from the left and from the right. Interference at location x is thus formally described as:

$$I(x) = P_{le}l(x - le) + P_{ri}l(x + ri) \qquad (1)$$

where le and ri are the locations of the two closest interferers on left and right hand sides of x. P_{le} (resp. P_{ri}) is the transmitting power from node at le (resp. ri). P_y is thus a random variable describing the transmission power for a node at location y. Transmitting powers are assumed i.i.d., and greater than γ almost surely (the transmitting power is greater than the CCA detection threshold).

Our model is built as follows. We consider an interval $[0, L]$ with $L \in \mathbb{R}^+$. We assume that there are two points/nodes at 0 and L. For L sufficiently great, there are two sub-intervals denoted $[0, v(0, L, P_0, P_L)]$ and $[0, v(L, 0, P_L, P_0)]$ (represented in Figure 2) where the interference level is greater than γ. These busy intervals cannot host new transmitters as they will detect a busy medium. Their formal definitions are described below. If these two subinterval does not overlap, there is an idle interval where a new transmitter/point can be added. It is uniformly distributed in this interval. It corresponds to the step 1 in Figure 2. This new point, located at u

in our example, generates two busy intervals of lengths $v(u, 0, P_u, P_0)$ and $v(u, L, P_u, P_L)$ respectively. Also, the lengths of the busy intervals at 0 and L increase since the interferer at u is closer. The intervals become $v(0, u, P_0, P_u)$ and $v(L, u, P_L, P_u)$. Then, a new point is added in the idle interval (at v in step 2), and so on. We repeat this process until there is no idle interval in $[0, L]$.

The busy intervals $v(., ., ., .)$ are defined as follows. $v(loc_1, loc_2, power_1, power_2)$ represents the length of the busy interval around location loc_1 when interferers are located at distance loc_1 and loc_2 with transmitting powers $power_1$ and $power_2$. This interval is located on the right hand side of loc_1 when $loc_2 > loc_1$ and on the left hand side otherwise. It is formally defined as the solution of $I(loc_1 + v(loc_1, loc_2, power_1, power_2)) = \gamma$ when $loc_2 > loc_1$ and $I(loc_1 - v(loc_1, loc_2, power_1, power_2)) = \gamma$ otherwise.

Proposition 1: Let $m(L)$ be the mean number of points in the interval $(0, L)$ (we do not count the two points at 0 and L) for the process defined above, then:

$$\lim_{L \to \infty} \frac{m(L)}{L} = \beta \qquad (2)$$

where β is a positive constant.

By lack of place, we give only the sketch of the proof. We can observe that $m(L)$ is a super-additive function, i.e. $m(L) \geq m(s) + m(L - s)$. According to the Fekete's lemma, $\frac{m(L)}{L}$ converges to a finite constant or diverges to infinity. To conclude it suffices to show that there exists a constant A such that $m(L) < A \cdot L$ for all L. It is straightforward since there is a minimal distance between the points. $\frac{m(L)}{L}$ is thus bound, and converges to a finite limit.

B. Capacity estimation

The positive constant β can be used to estimate the mean number of simultaneous transmitters over a road with length L at a given time. We denote T the mean time to transmit a 802.11p frame. It takes into account the different times used in the 802.11p protocol (DIFS, SIFS, etc.). We do not consider acknowledgment as our application generates only broadcast traffic. The average number of frames that a network with length L can transmit per second can be expressed as:

$$Capacity(L) = \frac{\beta L}{T} \qquad (3)$$

According to equation (3), estimation of the capacity boils down to the computation of the limit β. We propose an estimation that allows us to compute this constant
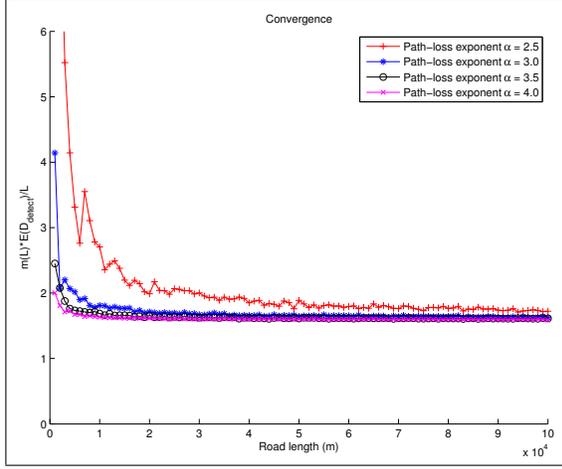
Fig. 3. Convergence of $\frac{m(L)\mathbb{E}[D_{detect}]}{L}$ for different path-loss function parameters.

from the path-loss function and the distribution of the transmission power. Since the adaptive TPC algorithm leads to the use of different transmission powers, we represent it as a random variable P_{tx}. We collected more than $120,000$ samples of transmission powers from simulations (described in a next section). The best fit among the classical distributions of the empirical distribution of $P_{tx} - P_{max}$, where P_{max} is the maximum transmission power, was the exponential law. Therefore, we express the transmission power distribution as a shifted exponential random variable truncated on the interval $[0, P_{max}]$. Its p.d.f. is given by:

$$f_{P_{tx}}(x) = \frac{\lambda}{1 - exp^{-\lambda P_{max}}} \exp^{-\lambda(P_{max} - x)} \quad (4)$$

λ has been inferred from the samples. In order to estimate β, we consider the mean detection distance denoted D_{detect}. It corresponds to the distance at which a node detects a transmission when there is no other sources of interference. D_{detect} is the solution of $P_{tx}l(D_{detect}) = \gamma$. We get:

$$D_{detect} = l^{-1}\left(\frac{\gamma}{P_{tx}}\right) \quad (5)$$

In Figure 3, we plotted the quantity $\frac{m(L)2\mathbb{E}[D_{detect}]}{L}$ when L increases ($\mathbb{E}[D_{detect}]$ is the expectation of D_{detect}). Each point is the average of 100 samples and is shown with a confidence interval at 95%. The considered path-loss function is the classical log distance path-loss [11]: $l(d) = min(c, c/d^{\alpha})$. The values of the parameters are given in Table III. We observe that all curves converge to the same constant, approximately equal to 1.70. This result is not surprising as it holds
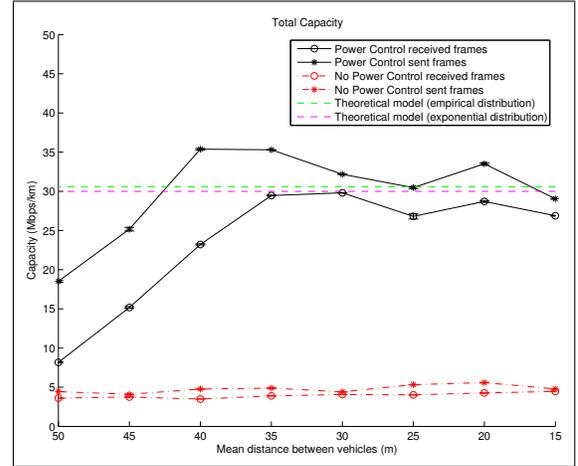
for other packing problems in one or two-dimensional spaces (see [9] or [3] for instance). This convergence to a universal constant allows us to estimate the limit β of Proposition 1 as follows:

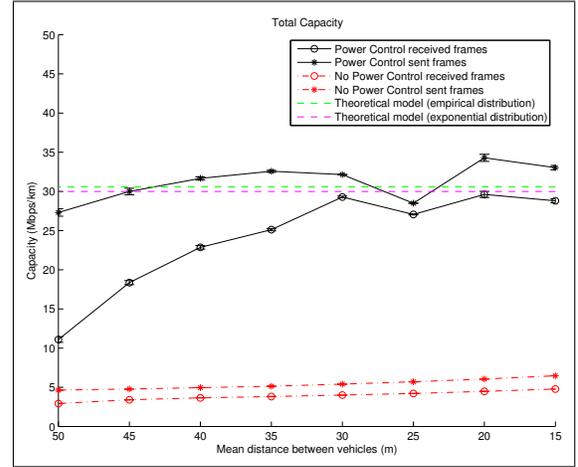$$\lim_{L \to +\infty} \frac{m(L)}{L} = \frac{1.70}{\mathbb{E}[D_{detect}]} \quad (6)$$

Therefore, the final capacity can be expressed as:

$$Capacity(L) = \frac{1.70L}{\mathbb{E}[D_{detect}]T} \quad (7)$$

V. NS-3 Simulation results

(a) Constant Total Capacity

(b) Mobile Total Capacity

Fig. 4. Total capacity for constant and mobile case in pure broadcast scenarios.

In order to validate our theoretical model and study the performance of our algorithm, we implemented our algorithm in NS-3 [1]. In these simulations, nodes were

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Theoretical and NS-3 Parameters	Numerical Values	Theoretical and NS-3 Parameters	Numerical Values
IEEE 802.11std	802.11p - CCH channel	Path-loss function	$l(d) = P_t \cdot min\left(1, \frac{10^{-4.5677}}{d^3}\right)$
CCA mode	CCA mode 1	CCA ED Threshold (γ)	-99 dBm
Road length (L)	15 km	Number of samples per point	100
Length of the packet	1024 bytes	Duration of the simulation	3 sec
DIFS (DCF Interframe Space)	34 μs	SIFS (Short Interframe Space)	16 μs

TABLE III

SIMULATION PARAMETERS.
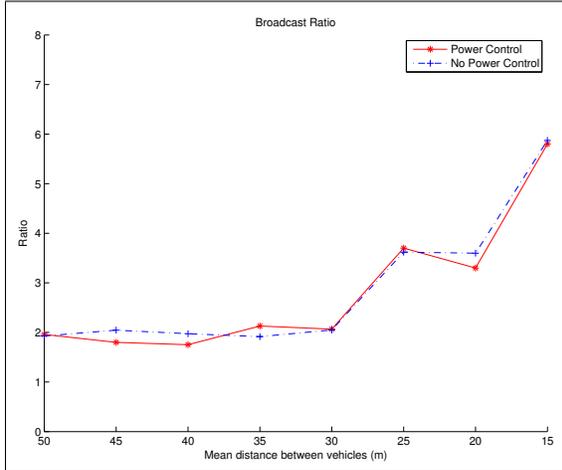
(a) Constant broadcast ratio
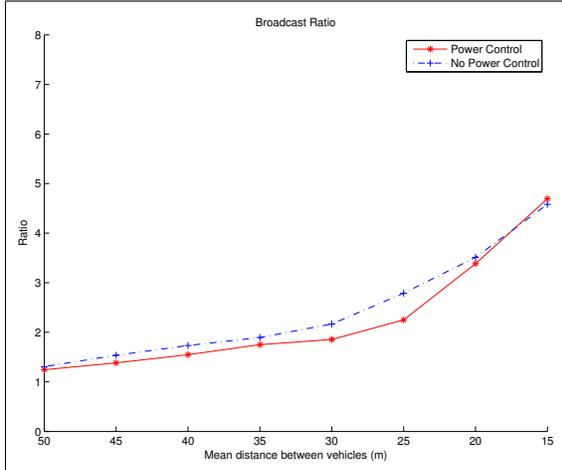
(b) Mobile broadcast ratio

Fig. 5. Broadcast ratio for constant and mobile case in pure broadcast scenarios.

equipped with IEEE 802.11p interfaces. The parameters are given in Table III. Vehicles were located along a line modeling a highway of $15km$. Vehicles periodically broadcast probe packets using the TPC algorithm as defined in Section III. These simulations aim to estimate the maximum rate reachable by our TPC algorithm. In order to estimate this maximum capacity we had to consider two different application rates. Indeed, as we increase the number of vehicles, a constant rate led to significant contention and a poor throughput when the traffic density became high. To keep a reasonable delivery rate, the number of packets per second generated by the perception map application was 125 packets/sec for inter-vehicle distances from 50 to 25 meters. For lower inter-distances, the application rate was 58 packets/sec.

Each point in the different figures are computed as the mean of 100 simulations and are presented with a confidence interval at 95%. We considered 2 mobility scenarios: "constant mobility" where vehicles have a 104 km/h constant velocity, and "Gaussian mobility" where the vehicle speeds follow a Gaussian distribution with mean 104 km/h and variance 43. These values have been set according to vehicle speeds collected on Canadian highways [10].

In order to evaluate the benefit of our TPC algorithm, we perform the same simulations with and without power control. The first quantity we considered is the broadcast ratio defined as the ratio of received frames over the number of sent frames. The number of received frames is the sum of the successful receptions for vehicles at distance less than d_{ref} from the transmitter. This quantity is thus greater than one, and increases with the vehicles density. In Figure 5, we plotted the broadcast ratio for the two mobility models. It shows that the delivery rate is almost the same with and without the power control algorithm. It means that our mechanism decreases the transmission power while keeping the targeted neighbors in its radio range. We have only a few losses with the Gaussian mobility model when the traffic becomes dense. These losses are mainly due to new neighbors entering within the pertinent area (distance

$< d_{ref}$), that are not taken into account by our algorithm instantaneously.

The second quantity that we estimated is the spatial capacity. It is computed as the mean number of sent/received bits per second and per kilometer. When we consider the sent bits, we just count what is transmitted by the nodes. For the reception, we take into account bits of a broadcasted frame only once (even if there are several receptions), and only if it has been properly received by at least one node. The capacity improvement is shown in Figure 4. We observe a huge improvement of capacity (almost 10 times in some points). The fluctuation that appears when the inter-distance is equal to 25 meters is due to the change of our application rate explained earlier. The two horizontal lines correspond to the theoretical evaluation. We considered an exponential distribution of the transmission powers, and the empirical distribution obtained from the simulation samples. The bound from the exponential distribution is very close to the empirical one, and has the benefit to be easily and analytically computable. The two bounds are very accurate. For some points, the number of sent bits is greater than the theoretical bounds, but it is due to collisions, i.e. when a transmission does not respect the CCA rules (mainly due to the draw of the same back-off by two nodes). But, when we are looking at the number of received bits, our bounds are not reached and clearly offer very good estimates.

VI. Conclusion

In this paper, we propose an adaptive TPC algorithm dedicated to extended perception map building. It is based on signal strength measurements of the packets generated by the application. It is worth noting that without power control, the perception map application is likely unusable by lack of capacity. We have shown through simulations and a theoretical model that this algorithm may improve the network capacity up to 10 times. It offers an extended bandwidth while keeping a good transmission reliability.

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