Space-Orthogonal Frequency-Time Medium Access Control (SOFT MAC) for VANET

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Abstract
The IEEE is working on a MAC standard (802.11p) for VANET based on 802.11e. Although the access function of 802.11e supports QoS by using different backoff counters and inter-frame spaces for different QoS requirements, this reduces to a best effort service and low performance when the number of vehicles increases. Some applications of VANET, particularly safety related, have strict QoS requirements that cannot be guaranteed by 802.11p especially in heavy traffic conditions. To resolve these issues, we propose Space-Orthogonal Frequency-Time medium access control (SOFT MAC) protocol that can support QoS requirements and is compatible with 802.11 standard. The proposed MAC allocates guaranteed transmission slots via reservation and also has a random access period for best effort service. Reservations are allocated in a distributed manner without the need for a basestation or a cluster head. In this paper we analyse and discuss in details the rules and algorithms that govern SOFT MAC protocol and also explain its implementation using 802.11. The analysis of SOFT MAC proves it achieves higher saturation throughput than 802.11.

Keywords—802.11, DCF, CSMA, FDMA, MAC, OFDMA, PCF, SDMA, TDMA

I. INTRODUCTION

Vehicle Ad-hoc Networks (VANET) aim at reducing the number of accidents in the road by exchanging safety and road condition information and, at the same time, provide commercial applications. The IEEE is working on a Medium Access Control (MAC) standard known as IEEE 802.11p. The standard is based on the previous 802.11e which uses an Enhanced Distributed Co-ordination Function (EDCF), an extension of the Distributed Co-ordination Function (DCF), to organise channel access. DCF is a random access mechanism based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), it has an unreliable broadcasting service, achieves low throughput as the number of devices increases and has little support for Quality of Service (QoS) [1-4]. A request-to-send / clear-to-send (RTS/CTS) handshake, supported in DCF, can be used to improve the performance of point-to-point transfers but is not applicable to broadcast messages. Since a large number of applications in VANET is broadcasting by nature (e.g. safety messages, location messages, traffic condition messages … etc), the RTS/CTS handshake cannot be used with these applications. Moreover the number of vehicles (nodes) varies with time and location, and peaks in congested areas leading to severe degradation in DCF performance [1-4]. EDCF provides some QoS by using different queues and counters for each QoS requirement, but still packets contend for the channel and may collide with packets having the same QoS requirements (e.g. safety messages from different vehicles). We propose a MAC protocol which is a combination of Space, Orthogonal Frequency and Time Division Multiple Access called SOFT MAC protocol [5]. In SOFT MAC the space (road) is divided into cells and a portion of the available subcarriers is assigned to each cell. These subcarriers are then shared between nodes within the cell via a TDMA protocol.

The rest of the paper is organised as follows: some related work is reviewed in the next section. Section III describes the new protocol. Section IV explains the implementation of the protocol using 802.11 standard. In section V the saturation throughput is theoretically analysed. The results of the analysis are presented and discussed in section VI then the paper is concluded.

II. RELATED WORK

Several MAC protocols for VANET considering different approaches were proposed [6-12]. In [8, 9, 11] a Time Division Multiple Access (TDMA) access mechanism was used, Space Division Multiple Access (SDMA) in [6, 7, 10] and a combination of Frequency Division Multiple Access (FDMA) and Code Division Multiple Access (CDMA) in [12]. In [9] cluster based MAC (CBMAC) was introduced where nodes form clusters and a cluster head is elected to organise access to the channel. Issues of cluster head election, clusters merging and loss of connection to cluster head are usually of concern in this and all cluster-based protocols in addition to the large signalling overhead. In an attempt to avoid the cluster head issues, ADHOC MAC was developed for VANET [8, 13]. In ADHOC MAC time is divided into frames and each frame is divided into a fixed number of slots. Nodes using ADHOC MAC exchange information about the status of each time slot (BUSY/IDLE) as each node senses it. With this information, the nodes are aware of which slots are free and attempt to reserve only free slots. The main drawbacks of ADHOC MAC are the large overhead and fixed number of slots. The status of each slot in the frame must be transmitted along with the ID of the node transmitting in the slot. Under high traffic this

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overhead is justifiable but under low traffic and/or small packets the large overhead makes the protocol inefficient. Moreover since the number of slots is fixed, the number of nodes that can access the channel is limited to the number of slots.

The SDMA scheme was addressed in [6, 7, 10]. The basic principal is to divide the area into small cells, each cell is big enough to occupy only one node and assign a time slot, frequency band or code for each cell. The scheme is very reliable and simple but it has poor efficiency since most of the time a large percentage of these cells will not be occupied by nodes and therefore the slots are wasted. Another limitation in these SDMA schemes is that location errors may result in collisions.

The authors in [12] proposed each node to use two transceivers. Nodes form clusters to exchange safety and non-safety messages. An elected cluster head (CH) organises the access to the channels and relays safety messages between clusters. One of the transceivers in the CH is tuned to the safety and control channel within the cluster and is used to exchange safety and data channel reservation requests from cluster members and organise channel access using TDMA. The other transceiver is used to communicate with other clusters and exchange safety messages using 802.11 MAC. For cluster members one of the transceivers is used to communicate with the CH while the other is used to transmit non-safety data in the channels assigned by the CH. To reduce interference between clusters, each cluster uses a different CDMA code. This system has a high cost due to the use of two transceivers. Moreover CDMA has the near-far problem and power control is hard to implement in ad hoc networks since different destinations experience different path losses. Another limitation of this protocol is the fact that the CH cannot transmit non-safety data since both transceivers are used to communicate safety messages either with cluster members or with other CHs.

DCF and EDCF use CSMA for channel access. Under heavy load, the performance of TDMA is superior to CSMA, however under light traffic CSMA shows better performance. An attempt to combine the two protocols was introduced in [14]. The nodes use CSMA as long as the traffic is below a certain threshold. Once the traffic exceeds the threshold, nodes switch to TDMA and do not switch back to CSMA unless the traffic drops below the threshold. However different nodes will have different traffic conditions, therefore some will prefer TDMA while for the others CSMA will be the best choice. The Point Coordination Function (PCF) of 802.11 uses a combination of TDMA and CSMA. The basestation announces a contention free period (CFP) in which it polls node for data (TDMA). After the polling finishes or the maximum CFP period has elapsed, the basestation announces the end of the CFP and a contention period (CP) starts in which nodes use DCF [15-17].

The Dedicated Short Range Communications (DSRC) standard specifies seven communication channels. Channel 178 has been declared as a safety and control channel while the rest of the channels were left unspecified. The draft of the Wireless Access in Vehicular Environment (WAVE) IEEE standard solves the multi-channel access by dividing time into frames of 100ms interval. All nodes must switch to the control channel for 50ms every frame and may switch to any of the other channels for the other 50ms [18]. The MAC protocol we introduce in the next section is to share a single channel between available nodes. When integrated with WAVE, each channel will be independent from the others and has its own frame, subcarriers, and reservations. As nodes switch between channels every 50ms, they keep records of the frame information of the control channel and any other channel(s) they switch to.

III. SOFT MAC

Our MAC uses a combination of SDMA, OFDMA and TDMA. Instead of defining the cells in SDMA to occupy only one node as in [6, 7, 10], a cell in our proposal usually contains several nodes. Each cell is assigned a number of subcarriers and nodes within the cell share these subcarriers in time. Time is divided into frames and each frame is divided into slots. However unlike Reservation ALOHA (R-ALOHA) [11, 19] and ADHOC MAC, SOFT MAC has two types of slots or periods, namely reserved transmission slots (TS slots) and reservation (RS) slots/period. TS slots cannot be accessed without prior reservation while the RS period is accessed via a random access scheme (e.g. DCF or slotted ALOHA). The number of TS slots varies with the number of reservations as will be explained and the RS slots occupy the rest of the frame. Under low traffic most of the frame will be RS period. At high traffic most of the nodes will have a large amount of data and reserve TS slots. Therefore most of the frame will be TS slots and hence the performance will approximate that of TDMA systems. Thus the protocol should provide the performance of random access methods under low traffic and TDMA performance under heavy traffic.

A. SDMA-OFDMA in SOFT MAC

We assume the system uses N subcarriers, each node knows its location and the network is time and frequency synchronised possibly via GPS. In our SDMA scheme the roads are divided into cells of radius R and a portion N_c of the subcarriers is allocated to each cell as shown in Fig. 1. Maps identifying which subcarriers are allocated to each portion of the road are pre-installed at the nodes. The radius of the cells and the number of subcarriers per cell are design parameters. At the physical layer, using more subcarriers per cell means higher data rates but shorter reuse distance since the number of subcarriers is limited whereas using a large radius means longer reuse distance since higher power is required and hence the interference will be higher in adjacent cells. The radius also has a major impact on MAC layer performance. By increasing the radius we decrease the number of handoff processes when nodes move between cells; however a larger radius also means more nodes within the cell and, therefore more traffic and contention. We expect a larger radius will improve efficiency in low traffic conditions but cause more collisions in high traffic. There should be an optimum radius for a given traffic density. We can, therefore, optimise the cell radii to provide the best performance for the expected traffic density at a given time. A set of allocation maps can then be used with each map optimised for the expected traffic density. For instance the city centre at peak hours will use small radius cells, while the highway at night will have a large radius cell. Using this scheme we can improve the efficiency of SDMA in a distributed manner with small hardware complexity.

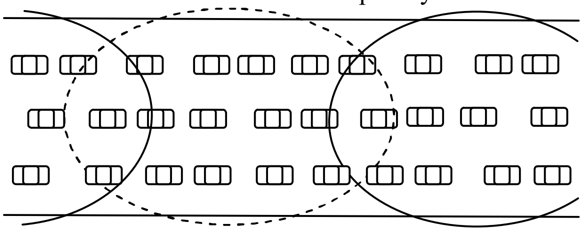

Figure 1. Illustration of Cells in SOFT MAC

An important advantage of OFDMA over frequency division multiplexing (FDMA) is that nodes belonging to two cells can transmit/receive at both cells with a single transceiver whereas in FDMA this is not possible since the node must tune to one of the frequencies used in the cells. Fig. 2 shows an example of how the subcarriers are assigned to cells assuming four unique sets of subcarriers (S1 to S4). Nodes in the intersection of two cells may transmit using the subcarriers of either or both cells.

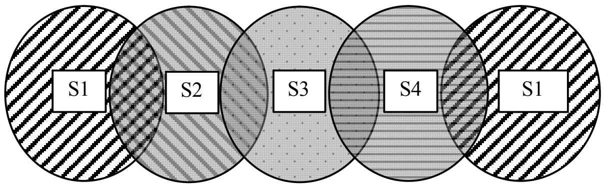

Figure 2. Subcarrier assignment to cells

A node wishing to transmit has to identify which subcarriers it may use. First the node determines its position using GPS and then uses this position to find the subcarriers allocated for its position using the pre-installed maps. However since more than one node may exist within the same cell, the nodes must co-operate to share the available subcarriers. This is done through the TDMA protocol discussed in the next section. To avoid collisions due to the hidden terminal problem at least four sets of subcarriers are needed to ensure the same subcarriers are not used for a distance of two hops, which is the necessary condition to avoid collisions [20].

B. TDMA in SOFT MAC

TDMA has been the most popular medium access for several link access protocols. Its reliability and ease of implementation makes it a very attractive option. TDMA provides efficient, delay constraint access to the medium and therefore has been adopted for voice traffic standards, such as GSM as well as for data traffic in the Point Co-ordination Function (PCF) of the IEEE 802.11 standard. Under heavy traffic TDMA shows superior performance in terms of throughput, delay, fairness and efficiency compared to the Carrier Sense Multiple Access (CSMA) that is used in the DCF of IEEE 802.11. However in light traffic situations TDMA has longer delays and larger overhead compared to CSMA since a node can only transmit at its designated slots thus incorporating unnecessary delay. Additionally, TDMA needs a central node, typically a basestation, to assign slots to the nodes and provide time synchronisation. To overcome these problems we propose a flexible, distributed TDMA method that combines the benefits of TDMA and random access techniques.

The proposed TDMA frame consists of two periods, a reservation (RS) period of duration d_R and a transmission period of N_{TS} transmission slots (TS). Fig. 3 shows the TS and RS periods and the frame structure of SOFT MAC. For simplicity, we assume constant TS slot duration and total frame duration. We also assume the reservation period has a minimum duration ($d_{R,min}$). The RS period is used by the nodes to reserve one or more of the TS slots and to transmit short messages.

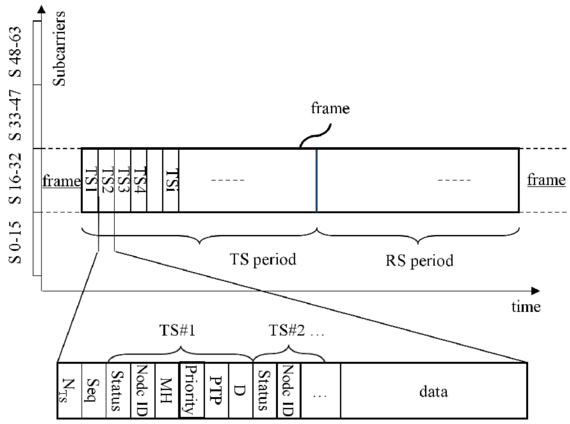

Figure 3. SOFT MAC Frame Structure

Access to the RS period is accomplished via a random access technique such as DCF, CSMA or slotted ALOHA (S-ALOHA) while access to the TS period is granted only via reservation. Next we explain how the reservation and transmission processes are performed in SOFT MAC.

A node wishing to transmit has two options depending on the amount of its queued data, either to transmit a short message in the RS period, using random access techniques or attempt to reserve a transmission slot to transmit a larger amount of data in the reserved TS depending on some or all of the following parameters:

- The amount of queued data to be transmitted,
- QoS requirements of queued data,
- A request for a connection from higher layers

Initially the RS period occupies the whole frame with no TS slots. As reservation requests are sent, the number of TS slots increases till the maximum number of TS slots is reached. The number of TS slots (N_{TS}) is announced in all transmissions in TS as well as in RS. Transmissions in TS slots, additionally, contain information about the status of each TS slot, BUSY or IDLE, and IDs of the nodes transmitting in BUSY slots. This is known as frame information (FI). A node sets the status of a slot to BUSY in its FI if it can correctly decode a message transmitted in that slot and sets it to IDLE otherwise. A node wishing to reserve a TS slot checks the number of TS slots in the current frame and initiates a reservation request (Res-Req). Each TS slot has a unique sequence number (Seq). If the maximum number of TS slots is reached, all nodes cease from sending reservation requests for new TS slots but reservations for existing TS slots (e.g. IDLE slots) can still be sent. Nodes with no reserved slots access the channel in the RS period. When a node powers up it sets its TS to zero, starts a listening timer and listens for transmission. There are three possible scenarios:

- The node receives a packet in TS or RS containing the number of TS slots. It then modifies its TS to the new value and may reserve or transmit in the RS period as required.
- A timeout occurred without receiving any messages. In this case the node assumes the maximum number of TS slots and transmits in the RS period a Hello-New message. Then it sets another counter for repeating this process *r* times before it gives up.
- The node receives a Hello-New message. In this case the node assumes N_{TS} is zero. If it has data, it may either transmit in the RS period or send a Res-Req. If it does not have data, it sends a Re-Hello-New packet which contains the FI, node ID, position, speed, etc. Other nodes use the FI in these packets to update their FIs.

To reserve a TS slot, the node broadcasts in the RS a reservation request (Res-Req) packet to reserve the slot that has the sequence number:

$$Seq = Max\begin{pmatrix} N_{TS} + winning\ Res\_Req\ received, \\ Seq\ requested\ in\ Res\_Req\ received \end{pmatrix} + 1 \ldots (1)$$

The term “winning Res-Req” will be clarified later. For now assume all Res-Req are winning Res-Req. After the transmission of the Res-Req, the node waits for one frame after the frame it initiated the reservation in. The reservation is assumed successful if the slot is assigned as reserved for the node in succeeding received FIs, the reservation is also assumed successful if Seq = 1 and no FI was received during the waiting period. The reservation is assumed to have failed otherwise. A node may also request a slot which has been marked as IDLE in all received FIs for *k* consecutive frames. All Res-Req packets contain an FI of current and new successfully reserved TS slots within the same frame.

A node belonging to two cells and having a TS slot in cell 1 may reserve a TS slot in cell 2 and keep the reserved slot in cell 1 if the new slot satisfies one or more of the following conditions:

- It has the same sequence number as its reserved TS
- The TS slot in the frame of cell 1 is marked as point-to-point (PTP) and this node is not the destination
- It is in the RS period of cell 1

If a TS slot is free, even if a reservation request has been sent for it by another node, or BUSY but a must-have (MH) flag is not set, a node may send a reservation request for this slot with the MH flag set. This is used only by nodes belonging to two cells. The slot is then allocated to one of the nodes that have set the MH flag on a first come first serve basis and the MH status of the slot in the FI is set. Nodes which have requested the slot and set the MH flag but failed the first come first serve process are not allocated a slot. These are ‘failing’ Res-Req and all the others are ‘winning’ Res-Req.

If a node correctly decodes a packet in a TS slot, it announces this slot as reserved for the transmitting node. Otherwise it announces the slot as IDLE. A broadcast transmission is assumed successful if all the frame information (FI) received by the source indicate the slot is reserved for it. If this is not true, a collision is assumed. The slot is then released and a new reservation is started.

A node modifies its FI information to include any new TS slots if it receives an FI with the new slot(s) allocated to certain destination(s). This is a case when a node cannot sense the reservation but another node within the cell can. This is an example of hidden terminal problem.

In the FI each TS slot has a delete (*D*) flag. An active node broadcasts a delete request by setting in its FI the *D* flag of a slot to delete the assignment of that unused TS slot to an inactive node if for *q* consecutive frames ($q > k$) the slot was sensed idle and declared IDLE in all received frame information (FI). Each node checks its own FI to determine the slots it can occupy in the frame and broadcasts this in its own transmission. A node declares it can occupy a slot if it is IDLE in all received FI and on its own FI. The active node that broadcasted the delete request rearranges the allocation of slots to nodes so that last TS slot becomes IDLE and broadcasts the new slot assignment to the active nodes in the next frame. The number of TS slots is reduced for each unassigned TS slot while the RS period increases i.e. the last TS slot(s) becomes part of the RS period. If a node declares it cannot occupy a slot (e.g. because a neighbour indicates slot is BUSY) then the slot cannot be re-assigned to it but can be re-assigned to another node that can occupy it. If a slot cannot be re-assigned, the delete counter is reset to *q*.

An active node with no reserved TS sets its timer if it detects two successful reserve requests for the same TS slot (at least the second request has the MH flag unset, which may be generated by a hidden node). Let's call this case *double reservation*. The node reduces the timer (Gateway counter) to half its current value for each additional successfully detected reserve request for the same slot. If the Gateway counter expires, the node sends a message (Gateway-Hello). In the Gateway-Hello message the number of TS slots is set to:

$$N_T = Max\left(N_{TS}\ in\ Res\_Req, N_T\ in\ node\right) + \\ No\ \ of\ \ received\ double\ Reservations.....(2)$$

The FI field in the Gateway-Hello message arranges the assignment of the slots to nodes based on a first come first served basis. If the Gateway already has a reserved slot it can defer the transmission and transmit in its TS slot. The node resets its Gateway counter and does not transmit a Gateway-Hello message if there are no more free TS slots or if all the following conditions became true:

1. A Gateway-Hello message or FI sent from another node is received
2. The received Gateway-Hello or FI has equal or greater N_{TS}
3. The received Gateway-Hello or FI assigned slots to all the nodes requesting new reservations

C. Point-to-Point Transmission in SOFT MAC

For point-to-point (PTP) communications we adapt the approach proposed in [8] to work with our proposal. A Point-to-Point (PTP) flag is used to differentiate between a broadcast transmission and a PTP transmission. A node sets the PTP flag for a TS slot in its own FI to 1 if:

1. The packet received in that slot is a broadcast packet or
2. It is the destination of this packet

The PTP flag is set to 0 otherwise. If the destination does not have a reserved slot it replies with an ACK packet (explicit ACK) in the same TS slot otherwise the PTP flag is sufficient (implicit ACK).

A TS slot can be accessed for PTP communication if the following conditions are satisfied:

1. The PTP flag in set to 0 in all received FIs
2. The FI received from the intended destination declares the slot as IDLE
3. An ACK cannot be sensed in the specified slot.

The first and third conditions ensure that the ongoing communication in the slot is PTP and the destination of this transmission is not within the range of the transmitter. The second condition ensures the new destination is not within the range of the transmitter or the receiver of the original transmission. The transmission is considered successful if the slot is set to BUSY with the correct node ID and PTP set in the FI of the destination terminal or if an ACK was received; otherwise it is assumed that the transmission has failed.

D. Priority in SOFT MAC

We adapt the 2-bits priority field of the IEEE 802.11e standard to identify the type of traffic in a given TS slot [16, 17]. Nodes use this field, along with the MH flag, to request TS slots occupied by lower priority traffic. Slots with lower priorities can be overtaken by Res-Req of higher priority traffic. Table I shows the proposed priority scheme in descending order.

TABLE I. PRIORITY IN SOFT MAC

MH flag	Priority	Type of Traffic
1	X	Handoff
0	3	Safety
0	2	Road Traffic data
0	1	Multimedia
0	0	Best Effort

IV. IMPLEMENTATION OF SOFT MAC USING 802.11

The 802.11 standard has two modes of operation, the Distributed Co-ordination Function (DCF) and the Point Co-ordination Function (PCF). PCF is implemented using an Access Point (AP). In PCF there are two intervals, Contention Period (CP) and Contention Free Period (CFP). During the CP, nodes access the channel using the DCF in a distributed manner without the intervention of the AP. In the CFP, the AP polls the nodes for data. A node must register itself with the AP to enter the polling list [15-17]. The frame structure is shown in Fig. 4 [17].

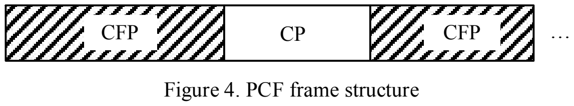

Figure 4. PCF frame structure

There are four basic time units in 802.11, the slot time (σ), Short Inter Frame Space (SIFS), Priority Inter Frame Space (PIFS) and Distributed Inter Frame Space (DIFS). The slot time is the time unit used for the back-off counters. SIFS is used between a transmission and its acknowledgement as well as in between RTS/CTS handshakes (RTS-CTS-data-

ACK). PIFS (=SIFS+σ) is used only by the AP while the DIFS (=SIFS+2σ) is used by all nodes [15].

In PCF the AP waits for the channel to be idle for a PIFS before broadcasting a beacon packet. This beacon indicates the start of the CFP period and announces the channel will be busy for the maximum CFP period. All nodes then update their Network Allocation Vector (NAV) to indicate the channel busy duration specified in the beacon. During this period no node will attempt to access the channel unless the AP polls it for data. After the AP finishes polling (even if the maximum CFP is not reached), it broadcasts another beacon that terminates the CFP (starts the CP). The nodes then reset their NAV and contend for the channel using the DCF [17].

SOFT MAC can be easily implemented using the PCF features. When the TS period starts, the node that reserved TS 1 waits for a PIFS before transmission. This will ensure the node gains access to the channel before any other nodes. Subsequent nodes follow the same strategy to access their TS slots. All nodes transmitting in the TS will broadcast the time left in the TS period, number of TS slots and sequence number of current slot. This will be used by nodes unaware of the number of slots to update their NAV as well as number of TS slots and hence do not attempt to access the channel during the TS period. After the TS period, all nodes must wait for a DIFS before attempting to access the channel. Although the PCF mode is optional, the 802.11 standard specifies that all nodes must be able to co-operate with the PCF function even if they do not support the polling service of the AP [17]. This ensures that SOFT MAC can coexist with 802.11. Fig. 5 shows this access scheme. In the next section we derive the saturation throughput of this implementation.

TS 1	PIFS	TS 2	PIFS	TS 3	DIFS	RS Period

Figure 5. SOFT MAC implementation using 802.11

V. Throughput Analysis of SOFT MAC

In this section we theoretically analyse the performance of the TDMA protocol of SOFT MAC for one cell and compare it to the basic access mode of 802.11 standard. The following assumptions will be used in our analysis:

- Both SOFT MAC and 802.11 have the same bandwidth (20MHz), number of subcarriers (64) per cell and data rate (6Mbps).
- Nodes share a single channel
- SOFT MAC is implemented using 802.11 as described in the previous section
- We adopt the specifications for 802.11a (5.8GHz), since 802.11p is based on 802.11a
- The frame duration is fixed (T_{frame} = 100ms)
- All transmissions start and finish within a frame (no transmission extends between two frames)
- All TS slots have been reserved
- Implicit ACK is used
- The nodes always have data to transmit (saturation throughput)
- No hidden terminals

A. Throughput of the TS period

Since the TS period is contention free, the throughput (S_{TS}) is given by:

$$S_{TS} = \frac{Data/rate}{(Header + Data)/rate + Wait\_time} \quad \text{.............}(3)$$

Where *Data* is the total transmitted data, *rate* is the data rate, *Header* is the total header (control bits) and *Wait_time* is the total channel idle time (PIFS). The header in each TS slot is calculated as:

$$H_{TS} = N_{TS}(status + PTP + MH\_P + NodeID + D) + No_{TS} + Seq + FrCON + FrDU + DestID \quad ..(4)$$

N_{TS} is the number of TS slots. The other parameters (based on 802.11 standard [15]) are listed in Table II.

TABLE II. Fields of TS Header

Field	Use	Number per TS slot	Size (bits)
status	TS slot status (BUSY/IDLE)	N_{TS}	1
PTP	Point-To-Point flag	N_{TS}	1
MH_P	MH/Priority of each slot	N_{TS}	1+2
D	Delete flag	N_{TS}	1
NodeID	MAC Address of node transmitting in a TS slot	N_{TS}	48
No_{TS}	Announces current number of TS slots	1	8
Seq	Sequence No. of current TS slot	1	8
FrCON	Frame Control	1	16
FrDU	Frame Duration (Time left in TS period)	1	16
DestID	MAC address of the destination of the slot	1	48

Since there are N_{TS} slots per frame, the parameters of equation (3) are given by:

$$Header = N_{TS} \times H_{TS}$$
$$Data = N_{TS} \times P_{TS} \quad \text{...}(5)$$
$$Wait\_time = N_{TS} \times PIFS$$

Where P_{TS} is the average payload size per TS slot.
The TS period duration (T_{TS}) should satisfy:

$$T_{frame} \geq T_{TS} \geq \frac{(Header + Data)}{rate} + Wait\_time \quad \text{.......}(6)$$

After the TS period all nodes wait for a DIFS before attempting to access the channel. Therefore the RS period duration (T_{RS}) is given by:

$$T_{RS} = T_{frame} - T_{TS} - DIFS \quad \text{.................................}(7)$$

Nodes access the RS period via the DCF. Equations (4) to (7) are the key to the design of the frame as they specify the possible number of TS slots for a specific frame duration, TS duration and packet size. As the packet size increases, the possible number of TS slots decreases while improving the throughput since less header and wait time is needed. On the other hand a smaller number of TS slots means less nodes can reserve TS slots.

B. Throughput of the RS period

The theoretical saturation throughput (S_{RS}) of the RS period is the throughput of the DCF. This has been analysed in [1] and closed form expressions were obtained as:

$$\tau = \frac{2(1-2p)}{(1-2p)(W+1)+pW\left(1-(2p)^m\right)} \quad (8)$$

$$p = 1-(1-\tau)^{n-1} \quad (9)$$

$$P_{tr} = 1-(1-\tau)^n \quad (10)$$

$$P_s = \frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^n} \quad (11)$$

$$S_{RS} = \frac{P_s.P_{tr}.E[P]}{(1-P_{tr})\sigma + P_{tr}.P_s.T_s + P_{tr}(1-P_s)T_c} \quad (12)$$

$$T_s = H + E[P] + SIFS + \delta + ACK + DIFS + \delta \quad (13)$$

$$T_c = H + E[P^*] + DIFS + \delta \quad (14)$$

Where τ is the probability that a node transmits in a randomly chosen slot time, p is the probability of collision. These are found by solving equations (8) and (9). W is the window size, m defines the maximum window size, n is the number of nodes, P_{tr} is the probability of at least one transmission in the considered slot time, P_s is the probability of successful transmission, σ is the duration of a slot, T_s is the average channel busy time due to successful transmission, T_c is the average channel busy time due to collision, H is the packet header, $E[P]$ and $E[P^*]$ are the average packet lengths for successful transmission and collision respectively and δ is the propagation delay [1]. Combining the throughput of the TS with the throughput of the RS, the total throughput of the frame is then given by:

$$S = \frac{S_{TS} \times T_{TS} + S_{RS} \times T_{RS}}{T_{frame}} \quad (15)$$

Note that if the RS period is smaller than the time required to transmit a packet and its ACK, we set the throughput of the RS period to zero.

VI. RESULTS

In this section we analyse the protocol and compare its performance to the basic access method of DCF. Fig (6) shows the slot efficiency (data ÷ packet size) and number of TS slots versus payload size for $T_{TS} = T_{frame}$. As the payload size increases the number of possible TS slots drops thus reducing the overhead and wait time but improving efficiency. However, the number of nodes that can access the channel becomes smaller. Therefore there is a trade-off between efficiency and number of TS slots.

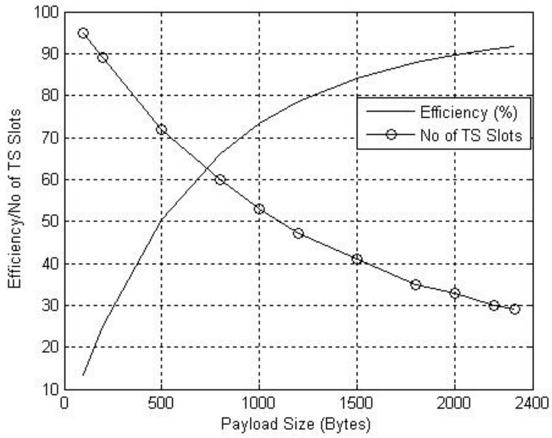

Figure 6. Slot Efficiency and No. of TS slots vs. Payload Size

Fig. 7 shows the performance of SOFT MAC versus the number of nodes for TS durations starting from 0 (pure DCF) to the maximum possible slots in T_{frame} duration (pure TDMA). The payload size is 2312 bytes which is the maximum payload in 802.11 [15]. The performance of SOFT MAC improves as the TS duration increases reaching approximately 90% for pure TDMA but then only 29 nodes can access the channel. Reducing the payload to 1000 bytes increases the maximum number of slots to 53 but the maximum achievable throughput is less than 75% as shown in Fig. 8.

Finally Fig. 9 shows the performance of SOFT MAC versus the payload size for a network of 50 nodes. For a small payload size the number of slots is high and, thus, the header becomes a considerable percentage of the packet and the throughput drops. As the payload increases, the throughput increases but the possible number of TS slots decreases. A payload size of approximately 500 bytes is the threshold for SOFT MAC to perform better than 802.11.

VII. CONCLUSION

In this paper we introduced and analysed a new MAC protocol for VANET known as SOFT MAC. The protocol divides the roads into cells and allocates each cell a group of subcarriers. Within the cell, the nodes share the available subcarriers using a combined TDMA-CSMA protocol. Time is split into frames and each frame has two periods. The first period consists of transmission slots (TS period) and is accessed after reservation. The second period is the reservation (RS) period and is accessed using a random access technique (DCF). The RS period is used to send reservation requests as well as data. A mathematical analysis of the saturation throughput was derived and used to analyse the protocol. Compared to 802.11 basic access, SOFT MAC shows improvement in throughput as long as the payload size exceeds 500 bytes. As the TS period increases the performance improves but the number of nodes that can access the channel is reduced.

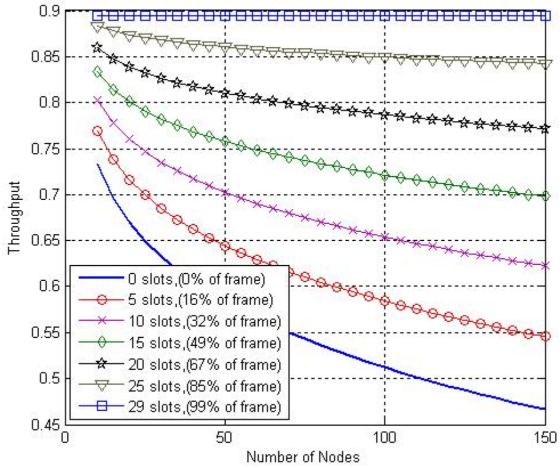

Figure 7. Throughput vs. No of Nodes (Payload size = 2312B)

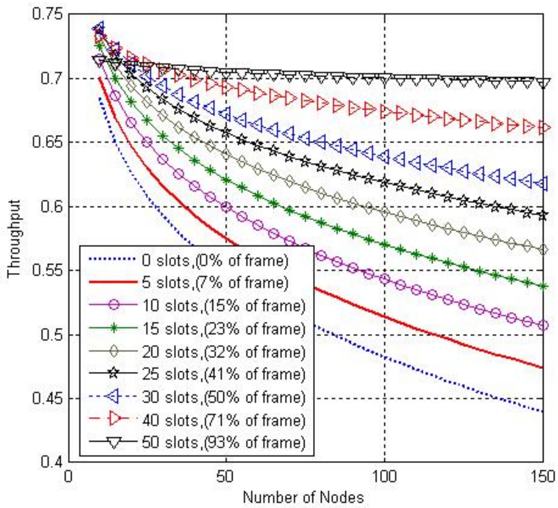

Figure 8. Throughput vs. No of Nodes (Payload size = 1000B)

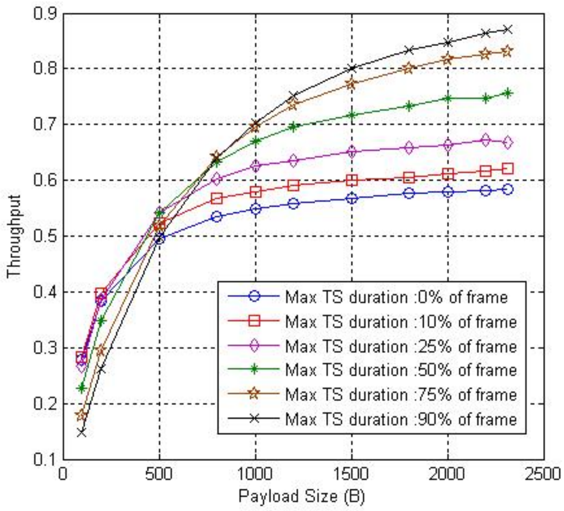

Figure 9. Throughput vs. Payload Size (50 Nodes)

REFERENCES

[1] G. Bianchi, "Performance Analysis of the IEEE 802.11 Distributed Coordination Function," *IEEE Journal on Areas in Communications,* vol. 18, pp. 535-547, March 2000.

[2] H. Fattah, "Analysis of the Channel Access Mechanism in IEEE 802.11 Wireless Local Area Networks," in *IEEE Pacific Rim Conference on Communication, Computing and Signal Processing*, Aug 2007, pp. 74-77.

[3] L. Kleinrock and F. A. Tobagi, "Packet Switching in Radio Channels: Part I-Carrier Sense Multiple-Access Modes and Their Throughput-Delay Characteristics," *IEEE Transactions on Communications,* vol. COM-23, pp. 1400-1416, Dec 1975.

[4] L. Kleinrock and F. A. Tobagi, "Packet Switching in Radio Channels: Part II-Carrier Sense Multiple-Access Modes and Their Throughput-Delay Characteristics," *IEEE Transactions on Communications,* vol. COM-23, pp. 1417-1433, Dec 1975.

[5] M. A. Abu-Rgheff, G. M. T. Abdalla, and S.-M. Senouci, "Space-Orthogonal Frequency-Time Medium Access Control (SOFT MAC) for VANET," French patent, pending.

[6] S. V. Bana and P. Varaiya, "Space Division Multiple Access (SDMA) for Robust Ad hoc Vehicle Communication Networks," in *IEEE Intelligent Transportation Systems Conference*, Oakland (CA) USA, 25-29 Aug 2001, pp. 962-967.

[7] J. J. Blum and A. Eskandarian, "A Reliable Link-Layer Protocol for Robust and Scalable Intervehicle Communications," *IEEE Transactions on Intelligent Transportation Systems,* vol. 8, pp. 4-13, March 2007.

[8] F. Borgonovo, A. Capone, M. Cesana, and L. Fratta, "ADHOC MAC: New MAC Architecture for Ad Hoc Networks Providing Efficient and Reliable Point-to-Point and Broadcast Services," *Wireless Networks,* vol. 10, pp. 359-366, 2004.

[9] Y. Gunter, B. Wiegel, and H. P. Grossmann, "Cluster-based Medium Access Scheme for VANETs," in *IEEE Intelligent Transportation Systems Conference*, Seattle, USA, Oct 2007, pp. 343-348.

[10] S. Katragadda, C. N. S. Ganesh Murthy, M. S. Ranga Rao, S. Mohan Kumar, and R. Sachin, "A decentralized location-based channel access protocol for inter-vehicle communication," in *The 57th IEEE Semiannual Vehicular Technology Conference, 2003. VTC 2003-Spring*, 22-25 April 2003, pp. 1831-1835.

[11] T.-K. Liu, J. A. Silvester, and A. Polydoros, "Performance Evaluation of R-ALOHA in Distributed Packet Radio Networks with Hard Real-time Communications," in *IEEE 45th Vehicular Technology Conference*. vol. 2, 1995.

[12] X. Zhang, H. Su, and H.-H. Chen, "Cluster-Based Multi-Channel Communications protocol in Vehicle Ad Hoc Networks," in *IEEE Wireless Communications*, Oct 2006, pp. 44-51.

[13] F. Borgonovo, A. Capone, M. Cesana, and L. Fratta, "ADHOC MAC: a new, flexible and reliable MAC architecture for ad-hoc networks," in *IEEE Wireless Communications and Networking*, 2003, pp. 965-970 vol.2.

[14] C. Chih-Min, S. Jang-Ping, and I. C. Chou, "A load awareness medium access control protocol for wireless ad hoc network," in *IEEE International Conference on Communications*, 2003, pp. 438-442.

[15] B. O'Hara and A. Petrick, *IEEE 802.11 Handbook A Designer's Companion*. New York: Institute of Electrical and Electronics Engineers Inc., 1999.

[16] N. Reid and R. Seide, *802.11 (Wi-Fi) Networking Handbook*. USA: McGraw-Hill, 2003.

[17] J. Larocca and R. Larocca, *802.11 Demystified*. USA: McGraw-Hill, 2002.

[18] Y. Zang, L. Stibor, B. Walke, H. J. Reumerman, and A. Barroso, "A Novel MAC Protocol for Throughput Sensitive Applications in Vehicular Environments," in *IEEE Vehicular Technology Conference*, 22-25 April 2007, pp. 2580-2584.

[19] X. Ma, P. Hrubik, H. Refai, and S. Yang, "Capture Effect on R-ALOHA Protocol for Inter-Vehicle Communications," in *IEEE 62nd Vehicular Technology Conference*. vol. 4, 25-28 Sept 2005.

[20] F. Borgonovo, L. Campelli, M. Cesana, and L. Fratta, "Impact of User Mobility on the Broadcast Service Efficiency of the ADHOC MAC protocol," in *IEEE 61st Vehicular Technology Conference*, 30 May -1 June 2005, pp. 2310-2314.