Automotive IoT: Connected Vehicles

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1 Introduction

The Internet of Things (IoT) is a huge buzzword today in the communications industry, and for good reason; it represents the pinnacle of wireless communications, a dynamic network of interconnected devices able to communicate and diffuse information amongst incredible amounts of devices, all within the same network. Many different industries have found applications for the Internet of Things, from home automation to industrial settings to the healthcare industry. In this paper we will propose the network design for a new IoT network, focusing on the application of the IoT in automobiles.

2 Model and Problem Statement

During the past decade, many papers discussed the potentials and chgallenges of the Internet of Things (IoT) from a theoretical and practical viewpoint [8] [16] [27] [10] [18]. Based on different applications, the network architecture and protocol differ drastically [18]. In active road safety applications, which aims to decrease the probability of accidents and their damage, the network should be reliable enough to warn drivers of warnings efficiently, for example, Intersection collision warnings and pre-crash warnings [23] [25]. In traffic efficiency and management, which aims to improve the traffic flow and assistance, the network needs to scale well with the information flow [15]. Another application is infotainment that which deals with communities, services and ITS station life cycle [7].

In this report, we focus on the problem of how to design the architecture and protocols of a network which can support the traffic efficiency and management applications. We emphasize two types: speed management and co-operative navigation. Speed management is one key part of road safety and encompasses a range of measures aimed at balancing safety and efficiency of vehicle speeds on a road network [19]. The co-operative navigation can increase traffic efficiency by managing the cooperation between vehicles and vehicles with roadside units.

3 Architecture and Communication Links

Connected vehicles is one of many promising applications for the Internet of Things. However, due to the high mobility of vehicles, the rapid dynamic topology changes of Vehicular Ad hoc Networks and the frequent network disconnections, there is a challenge in implementing traditional Ad Hoc methods. Also, there is difficulty in providing Intelligent Transportation System services using only a single wireless network. We present a framework for HetVNET that integrates LTE and DSRC as wireless access networks. We compare the later two in terms of performance for Vehicular to Vehicular communication (V2V) and Vehicular to Infrastructure communication (V2I).

Heterogeneous Vehicular Networks (HetVNETs) are composed of a Radio Access Network (RAN) a Core Network (CN) and a Service Center (SC) [31] as seen in Figure 1. For this problem we will focus on the RAN. Within the RAN there are two main communication links to be considered. The first is the Vehicle to Infrastructure link (V2I). This aims to connect the vehicles to the infrastructure represented by the base stations (BS) on the the roadside. For our network we will consider either using LTE networks that are already deployed for cellular communication or DSRC. The other communication link to consider is the Vehicle to Vehicle (V2V). This refers to direct communication between vehicles. The interconnectedness of vehicles ensures efficient traffic flow in terms of congestion and also accident minimization. We will compare the same two techniques, LTE and DSRC, and choose one for our V2V communication in this HetVNET.

In choosing a technique for our V2I communication in our network, we first introduce the advantages and disadvantages of the two techniques that are considered, the LTE and DSRC. For LTE, it is shown in [31] that it could provide up link data rates of up to 50 Mbps and down link data rates up to 100 Mbps, and could support a maximum mobile speed of 350 km/h. This is very important for our networks since the problem of high vehicle mobility could be resolved using this technique. Also, LTE networks are able to provide wide coverage and high capacity while maintaining a low link delay [31]. Experiments showed that LTE could provide a robust mechanism for mobility management, and is able to provide a data rate of 10 Mbps at a speed of 140 km/h. In [31], the authors show how the LTE system can support the demand of 1500 transmitting cooperative awareness messages (CAMs) per second per cell. This shows that LTE could provide a reliable multi cast and broadcasts

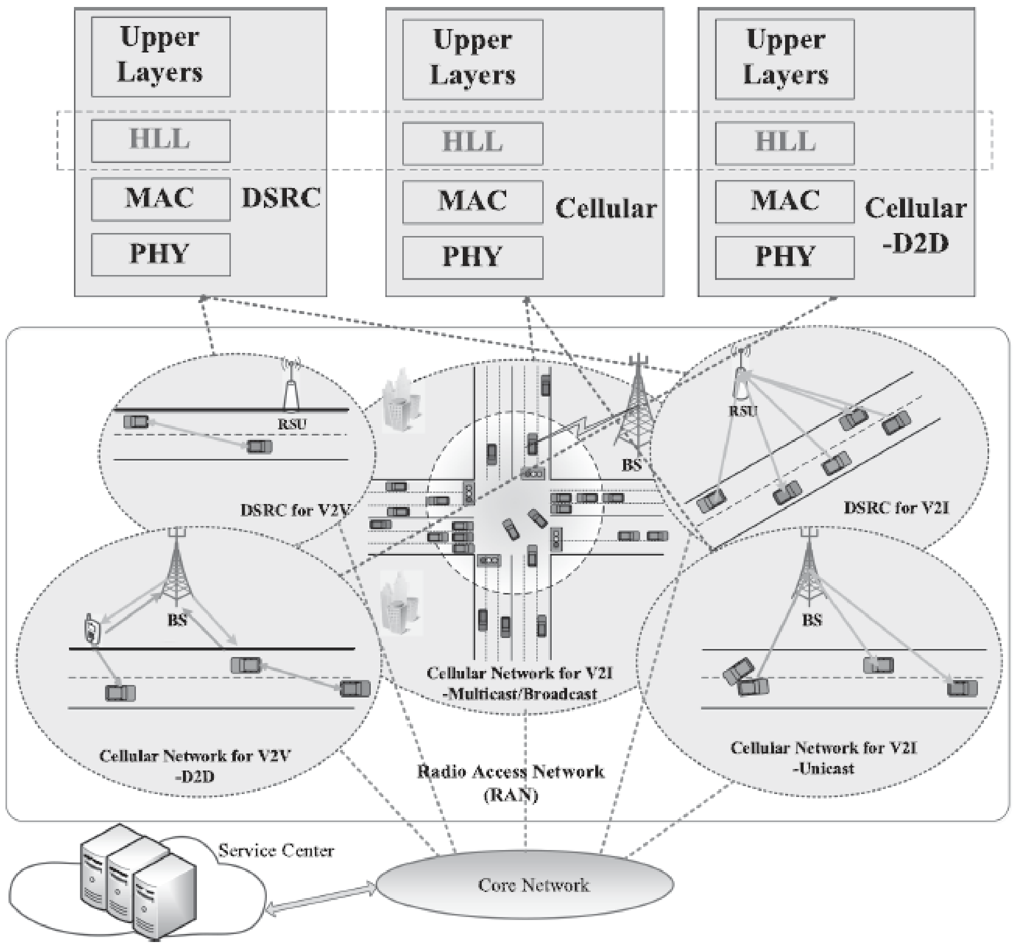


Figure 1: HetVNET Model

service in highly dense vehicle situations. On the down side, LTE lacks an efficient scheduling scheme for ITS services and the users with no mobility cause a delay in disseminating message [31].

As for Dedicated Short Range Communications (DSRC), this option provides a an easy and low deployment cost, that is suitable for local message dissemination, for example: traffic light signals, parking information. However this network model will not be suitable for our application for several reasons. Since the V2I environment is very dynamic, high multi path delay and high mobility result in a highly time-frequency selective vehicular communication channel [31]. It is found in [31] that the typical transmission period in DSRC is 0.5 ms, which is much larger that expected coherence time of 0.2 ms in a typical application scenario. This will therefore be insufficient in estimating the channel state information. Other downsides of DSRC as mentioned in [31] are: channel will become congested with large number of vehicles, hidden node problems and unbalanced links. For these reasons, its clear that LTE is much more suitable for the dynamic environment of V2I communication.

Vehicle to Vehicle (V2V) communication deals with the direct connection of vehicles. Th reason we are implementing this feature in our network is to provide efficient traffic control. By that, we hope to decrease drastically accidents caused by vehicles, decrease congestion and improving traffic flow. This is done by exchanging relevant data between neighboring vehicles such as acceleration, speed, and vehicle status [31]. We discuss the same two techniques for V2V communication.

In LTE systems, Device to Device communication (D2D) has been proposed as a way to exploit the physical proximity of communication devices. However, it faces a few challenges, D2D communication share the same radio resources as other links with the LTE network [31], this gives rise to a major problem, which is interference.

Also, most D2D devices used to communicate in LTE are of low speed mobility. This is not the case with our application of connected vehicles. The problem rises when two vehicles want to communicate, first they need to find each other and set up a connection. In D2d this might take up to 10s. Since this is longer than the expected availability time for two vehicles to connect, the D2D mechanism fails to ensure quality of service (QoS) requirements, and could be dangerous to implement.

On the other hand, DSRC has been shown to be a reliable and safe service for V2V communication. Since V2V communication requires a decentralized approach, DSRC is autonomous and requires no previous infrastructure. Also, V2V communication using DSRC does not interfere with cellular networks since it uses a different frequency band [31]. Since both entities are the same, vehicle to vehicle, the problem of unbalanced links will not be an issue. For these reasons, DSRC is chosen to be implemented for V2V communication.

4 LTE and DSRC

Because of the advantages of LTE, we decide to use LTE network for V2I communication in project. Long-term evolution is a standard for high-speed wireless communication for mobile devices and data terminals [6]. LTE network has high speed, which can up to 250km/h, large coverage and low latency which is less than 100ms in the radio access [6], which is perfect for our project. As shown in Figure 2, the structure of LTE can be divided into two big parts: access network and core network. The access network is composed of eNodesBs which are hardwares connected to the mobile network. The eNodesBs are designed to manage radio resources and handover events. The core network has three main parts: the mobility management entity(MME), the serving gateway(SGW) and the packet data network gateway(PGW). The MME part is responsible for control process and authentication or security part. The SGW part is designed for routing and data forwarding. In addition, by using the PCRF can finish charging part. The PGW part allows communications with IP and circuit switch networks [5].

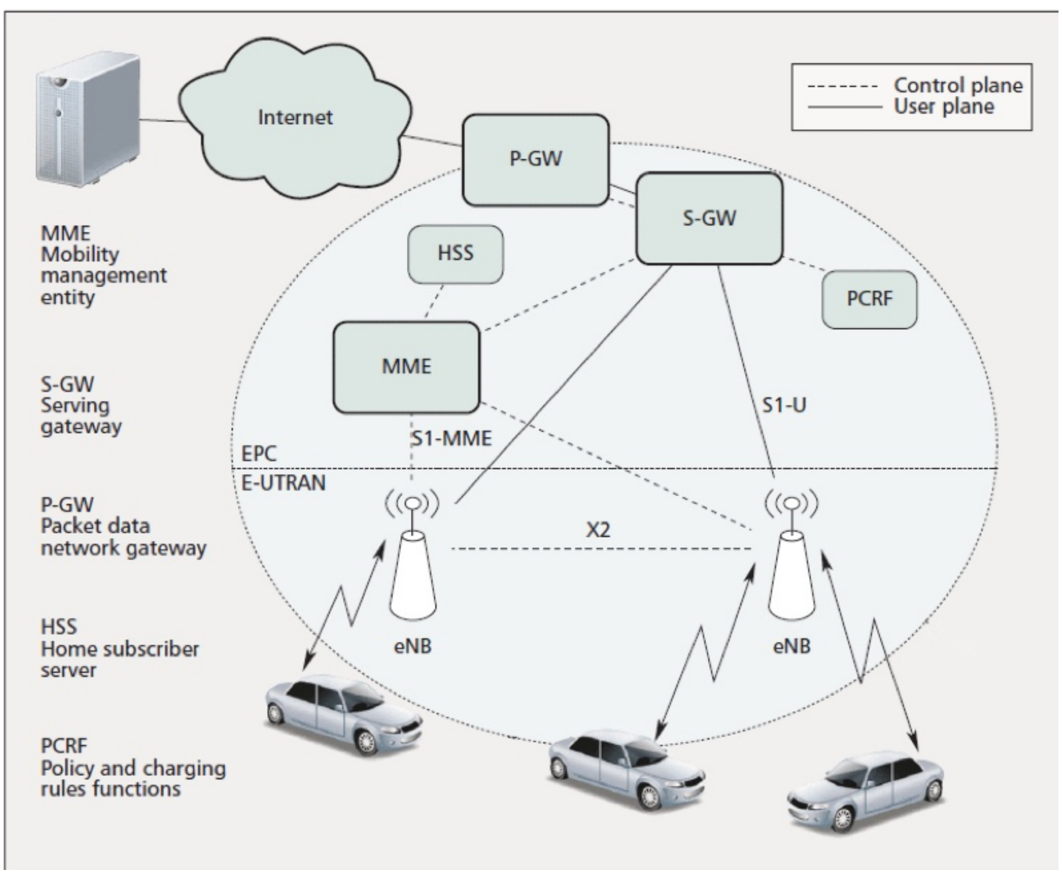


Figure 2: LTE architecture.

As for the V2V communication, we use dedicated short-range communication(DSRC). It is a two-way short to medium range high data transmission [2]. The DSRC is based on the wireless access in vehicular environments (WAVE) that standardized by the IEEE protocols. Figure 3 shows the corresponding layers [20]. The IEEE 802.11p, typically uses channels at 5.9 GHz band with 10Mhz bandwidth, is a nationwide network that offer communications between vehicles and vehicles as well as vehicles to roadside units. 802.11p also defines the Physical Layer Management Entity and MAC Layer Management Entity. Another protocol, IEEE 1609.4, can provide multi-channel operations to IEEE 802.11 p when construct MAC SubLayer. Building logical link control layer as an upper part of data layer, it needs IEEE 802.2 protocol to add control information to the message [11]. IEEE 1609.3 protocol provides routing and addressing service for network layer. IEEE 1609.2 protocol focuses on security to ensure the safety message changing. IEEE 1609.1 protocol is used to build upper layer which allows the interactions.

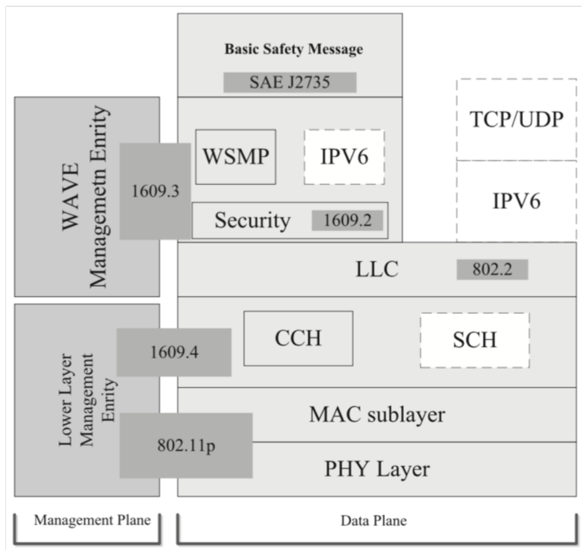


Figure 3: WAVE protocol stack of DSRC networks.

5 Frequency and Channel Allocation

Frequency and channel allocation are very important parts of IoT networks, due to the number of devices that will be connected to the network. Frequency allocation is controlled by governmental agencies, The National Telecommunications and Information Administration for the United States [1].

5.1 Frequency Options

Before the team had decided on using DSRC and LTE for the communication protocols, several options for frequency were investigated. The team looked into using both the ISM 915 MHz and ISM 2.4 GHz bands; however, these bands are filled with millions of devices and interference would need to be handled appropriately. The team decided on using LTE and DSRC for the communication protocols, which already have Frequency allocated to them. DSRC has 75 MHz of bandwidth available in the 5.9 GHz band, and LTE has 10 bands available between 800 MHz and 2500 MHz.

5.2 Channel Allocation Algorithms

Within the ad-hoc network, a mobility-aware channel allocation strategy would be needed in order to provide optimum reliability and throughput on the network [24]. As outlined within [24], the Mobility-aware Channel Allocation (MobiCA) algorithm would be effective to be used for the IoT traffic management network due to its throughput, low delay, and mobility.

Figures 4 and 5 compare the MObiCA channel allocation algorithm to a centralized channel allocation algorithm (TABU), a random channel allocation algorithm, and largest spectral distance algorithm.

Figure 4(a) compares the throughput of the algorithms. This figure shows the strength of the MobiCA algorithm as it is only 5.41% lower than TABU, which is considered the upper performance limit. Figure 4(b) compares the overhead of the algorithms. This shows the weakness of the TABU algorithm, with its high overhead costs and exemplifies another strength of the MobiCA algorithm as it is within error of the rest of the algorithms. Figure 4(c) compares the spectral distance of the algorithms as the number of channels; however, as throughput is not directly correlated to spectral distance, this is not particularly useful information.

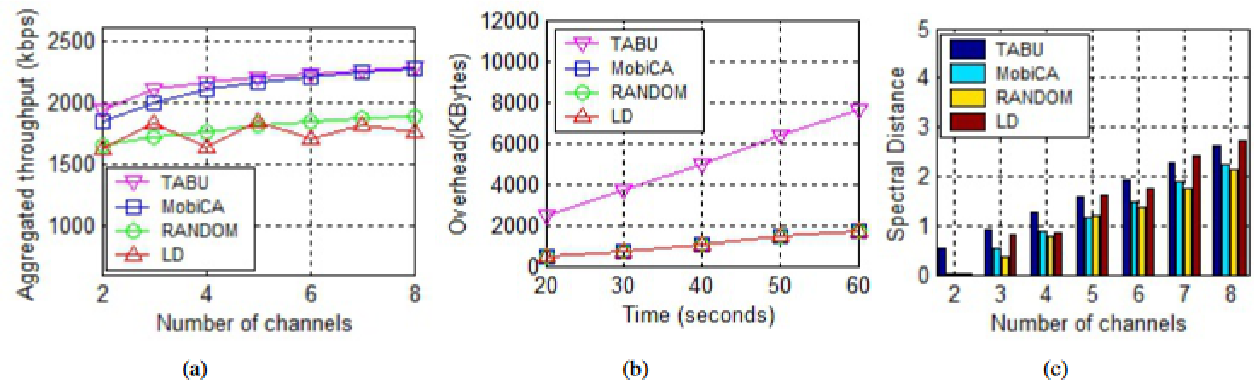


Figure 4: (a) Aggregated throughput, (b) overhead, (c) spectral distance [24]

Figure 5(a) compares the delivery rate of a packet between the channel allocation algorithms as the number of channels increases. MobiCA had a packet delivery rate of 50.8%, directly behind the leader (TABU). Figure 5(b) illustrates the end-to-end delay of the algorithms. This factor is very important for traffic management as messages need to be passed between devices quickly in order to maintain the safety of the users. The MobiCA algorithm demonstrates that its delay is close to the ideal delay (TABU). Finally, Figure 5(c) shows the throughput as velocity (mobility) is increased. This is very important with traffic management as many of the devices on the network will be mobile and will still need to connect while mobile. This figure shows that the MobiCA algorithm has higher throughput than the other algorithms even as velocity increases.

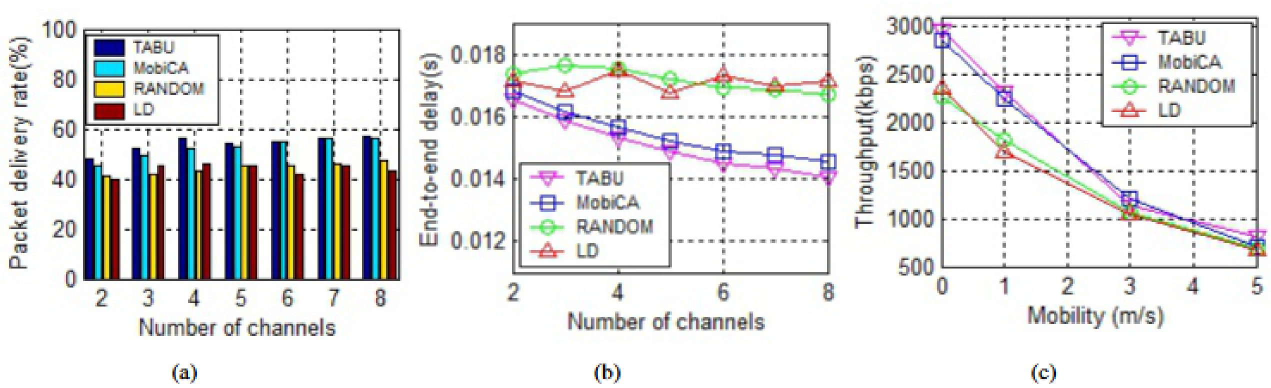


Figure 5: (a) Packet delivery rate, (b) end-to-end delay, (c) mobility [24]

6 Mobility and Handoff

The implementation of a Smart vehicle system through the Internet of Things is not possible without an optimal implementation of mobility management. Considering that there may be hundreds of thousands of ‘things’ in a given city network that may be comprised of several cells, communication between these nodes must be seamless. Mobile nodes must be able to communicate with each other seamlessly. Considering that a large part of what the network will work on is moving and ongoing traffic, mobility management where the location of various users is determined is absolutely key. This section will take a glance at various mobility schemes and attempt to determine the best implementation within the given ad hoc network.

6.1 Selected Model

The selected model for the network will have to be a synthetic mobility model, and more specifically, a Constrained Topology based model [4]. This is the better option due to the fact that the network is Heterogenous, implementing LTE and DSRC. Additionally, a constrained topology based model includes partial randomness not full randomness, which is closer to the real life scenario of cars moving within a city. The mobility Vector model is possibly the best fitting model for a city trying to implement a smart vehicle network. The main difference between the Vector and the waypoint model is that the vector model allows for more realistic movement whereas in the waypoint model, mobile nodes make sudden stops and sharp turns [4]. This may seem like a very subtle difference but considering that a large reason for the implementation of this network is tracking accidents and collisions, sudden stops and turns could strongly skew the data. The implementation of this model in an Ad hoc network is called the Ad Hoc On-Demand Distance Vector Protocol (AODV).

6.2 Evaluation and Simulation

In the vector model, the velocity of a mobile host (mobile vector, M) can be written as: $M = B + V$, where B is the base vector, is the acceleration factor, and V is the deviation vector [4]. The deviation vector is defined by the deviation from the base Vector. Therefore the base vector can be defined as the movement of the entire group whereas the deviation vector is the movement of each individual host, which aligns perfectly with the real life Smart City model when moving vehicles are trying to be represented as mobile hosts. Figure 6 shows two histograms which are simulations comparing the Random Walk (Vector model) and the Random Waypoint model:

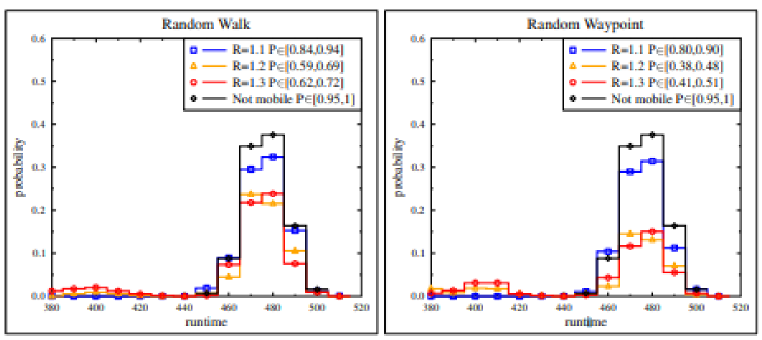


Figure 6: Comparing Probability of Packet Delivery [4]

R is representing three different transmission ranges, P is the probability of a route being established. When comparing all three ranges, we can clearly see that a Random Walk method has a higher probability of successfully establishing a connection between mobile nodes.

7 Medium Access Control

Medium Access Control(MAC) is a vital part of any network, especially one that communicates safety critical applications. Although this network is using both LTE and DSRC, we are only exploring MAC protocols for DSRC. This is due to LTE having a well-established foundation that does not require any changes. The MAC protocol for DSRC needs to maintain a low latency and high signal reliability for safety critical applications. While there may not always be safety critical situations, these need to be taken into account so that when they do occur, a critical failure does not occur because the information was not transferred in the correct time frame. Low latency could result in safety information being relayed to a car too late, causing the vehicle to not have enough time to assess the situation and may lead to a critical failure. Poor signal reliability [29] could also cause failure in safety applications, this could also simply lead to a poor performance in efficiency of the system as a whole.

7.1 Choice of Protocol

With the VANET, there is a high chance of transmission failure if packets are constantly being transmitted from to one car and a backup may be a result of this. Furthermore, to ensure that the data makes it through the other systems, repetition of packets should be implemented. This repetition can resolve dropped packets, and will have a specific timeout period that is uniquely defined by physical characteristics of the network. While repetition will be useful, there is a point where it causes more negative effects than positive effects [28]. Taking these conditions into account, the potential protocols [21] were a mix of Asynchronous, Synchronous, Fixed Repetition, P-persistent repetition, and Carrier Sensing.

After evaluating these choices it is observed that synchronizing the generation or transmission of packets would be beneficial. However, due to the physical parameters of this V-V network, that would be difficult to do. The other consideration to be taken into account is the type of repetition that each protocol uses. P-persistent repetition may be unreliable when adding or removing users from the VANET and different rates of repetition are used throughout the system uptime. This variability will lead to a network that is not as efficient as it could be, so we want to go with a fixed repetition protocol. This fixed repetition will allow the design to use the optimal amount of repetitions before timeout occurs. Simulations for probability of reception failure vs number of transmissions were done [21] for two of the protocols. From this simulation it is seen that SPR and APR have the best performance at 15 repetitions and 7 repetitions respectively. This simulation however was not the most realistic due to packets being allowed to overwrite packets that collided in previous messages. A more realistic simulation is shown below, for all protocols. As shown in the figure below, asynchronous fixed repetition with carrier sensing has the lowest chance of failure. After this result, channel busy time was also evaluated [21]. The channel busy time for this protocol was consistently 10 percent less than the other protocols explored.

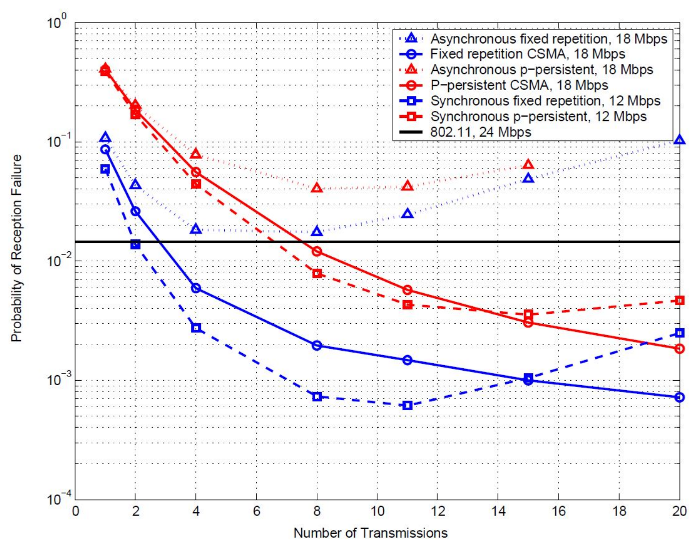


Figure 7: Probability of Reception Failure [21]

8 Scalability

Scalability is necessary in an IoT wireless network in order to ensure that large numbers of devices can connect and transmit information. Without handling scalability well, multi-hop traffic and overhead requirements could result in large amounts of traffic, potentially slowing the throughput of the network to a crawl. Particularly in our implementation, scalability is necessary to ensure the MANET used for V2V communication is able to handle the throughput necessary for the network to fulfill its goal. One of the ways we can ensure our MANET is able to handle the amounts of traffic we will encounter at each node is by utilizing node clustering. Clustering is the action of creating groups of nodes that function as small substructures that can take away some of the traffic load from nodes. The Cluster Head, a node designated to store routing and topology information [22], can coordinate actions of the nodes in it cluster and send information through gateway nodes to other clusters. Cluster Gateways are the nodes at the edge of the cluster, with a connection to gateways in other clusters. Nodes which are neither heads nor gateways are simply called members. The cluster structure enables the network to strategically control data flow from the Cluster Heads and eliminate overhead and traffic at the cluster members. Through utilizing cluster architecture, studies have shown that we can decrease packet delay and control overhead in our network [14]. There are two main types of clustering algorithms, active and reactive clustering, that focus on either actively forming clusters ahead of time, or reactively creating clusters as traffic flows through the network. For a network such as ours requiring a solution with high capability for mobility, we had to investigate algorithms of the two types in order to determine which type would be best to maintain connections for as long as possible with the numerous nodes connected to the network. We eventually chose reactive clustering, specifically the On-Demand Group Mobility-Based Clustering (ODGMBC) developed by a group of researchers in Germany [13]. In ODGMBC, the member nodes know their Cluster Head, but the Cluster Head does not know the member nodes, eliminating control packet flow and focusing entirely on routing decisions. Nodes determine Cluster Heads by default; if a node detects another node, it waits for a random time interval, at the end of which it determines if there is already a Cluster Head in range. If not, it declares itself the Cluster Head, and other nodes within range can recognize this and become cluster members. In this way, any node can become a Cluster Head whenever the situation arises. The advantages of a reactive method such as ODGMBC is that control traffic on the network is limited, and the network is flexible to topography changes by the nodes. By allowing nodes the flexibility to roam and join and drop from different clusters at will, reactive algorithms enable the network to be fluid as locations change. In addition, by limiting the amount of overhead traffic generated by forming and maintaining routing tables at each node, we can increase throughput at each node. In particular, when compared in testing against an active clustering algorithm [13], the ODGMBC algorithm performed better in Bytes per second and packets per period, as shown in Figure 8. These results confirm that the use of a reactive algorithm such as ODGMBC can help to increase the scalability of our network.

Configuration	Leader Changes [1/s]	Cluster Changes [1/s]	Leader Stability [s]	Cluster Sojourn Time [s]	Byte/s	Packets/Period
ODGMBC, 5 s	0.21	1.42	46.07	100.47	38.96	3.88
ODGMBC, 60 s	0.07	1.07	70.75	181.71	5.80	9.10
GMBC, 5 s	1.54	7.21	14.53	28.96	6.55	1.93
GMBC, 30 s	0.36	1.79	40.26	89.94	5.90	10.40

Figure 8: Simulation Results: Stability and Overhead [13]

One of the other ways we can ensure the scalability of our network is to use IPv6 as our addressing scheme. IPv6 has up to 3.4 x 1038 addresses for nodes, allowing us to add massive amounts of nodes to the network and still be able to address them properly.

9 Routing and Scheduling

Routing and Scheduling It is critical to achieve efficient routing and scheduling procedures in a large scale IoT network such as the one required for vehicle to vehicle communication through an ad hoc network. Vehicle to vehicle communication contains critical time sensitive information. This data must be delivered quickly in order to fulfill the safety requirements for driving. Because this information is being transmitted and received by devices powered by vehicles, data throughput is prioritized over energy efficiency.

9.1 Routing Protocols

The first decision in determining the routing and scheduling algorithms must be determining the type of routing protocol used. The MANET will be very dynamic as vehicles will change physical locations relative to each other very quickly. The network itself becomes dynamic as connections are constantly changing as vehicles move towards and away from each other. Because of this, a reactive scheme would work much more naturally for this application. The proactive scheme would have to quickly and constantly update all routes. This would flood the network with transmissions regarding routes and take away transmission time from data communications. A Destination-Sequenced Distance Vector approach in proactive routing limits the scalability of the network as overhead grows by $O(n^2)$. The solution of reactive routing is much more attractive as routes are only formed when needed and unnecessary routes are not constantly being found only to be unavailable moments later. Further, the Ad-hoc On-demand Distance-Vector approach becomes more attractive than Dynamic Source Routing. AODV has two inherent traits that make it more suitable for this application than DSR. Firstly, there is lower overhead than DSR; low overhead results in more data transmission which creates a safer experience for the vehicles. Secondly, AODV is much more scalable, an important feature in this application. AODV also works naturally with node clustering. There are two types of routing in this mechanism: intra-cluster routing and inter-cluster routing. Intra-cluster routing if for routing within a cluster. Every node has routing information regarding its cluster. When a node needs a route to a destination in the cluster, it sends a Local Route Request (LRREQ). Inter-cluster routing is for routing between clusters. When a node needs to transmit outside of its cluster, the cluster head sends a Route Request (RREQ). To reduce overhead, only cluster heads and gateways can send or forward the RREQ. Ordinary nodes do not deal with RREQ packets. This results in a higher packet delivery ratio (PDR) that gets better than regular AODV with more nodes added [26]. This can be observed below in Figure 9, 10, and 11.

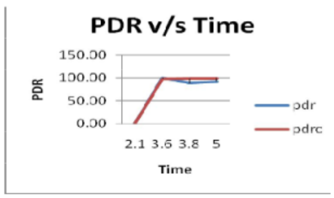


Figure 9: PDR for 10 nodes using AODC and Cluster-AODV

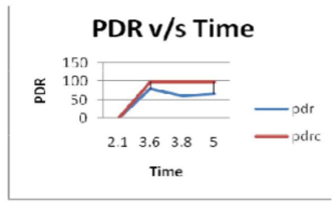


Figure 10: PDR for 20 nodes using AODC and Cluster-AODV

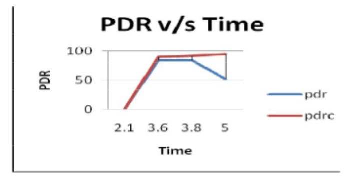


Figure 11: PDR for 30 nodes using AODC and Cluster-AODV

9.2 Route Scheduling

While this clustering AODV efficiently routes data in the ad hoc network, there should be an extra step taken to avoid congestion in high traffic environments, like rush hour in a city. Queue scheduling can help alleviate this. Energy and Bandwidth based Fair Queue Scheduling (EBFQS) focuses on lowering energy and bandwidth requirements in MANETs and provides a good solution to this issue. To do this, EBFQS tries to route more data through nodes with lower traffic. Even though data may have to experience an extra number of hops, the packets should wait in queues for shorter amounts of time. To achieve this, different scheduling policies must be adopted by nodes when they have different queue loads. A node can be categorized with a light, medium, or heavy load. This is done my measuring the load capacity of the queue. Two thresholds can be defined as Minth and Maxth. Nodes with remaining queue length less than Minth are considered heavy. Nodes between Minth and Maxth are medium. Nodes with remaining queue length greater than Maxth are considered light. Different scheduling policies are adopted for each load level. Lightly loaded nodes give priority to all RREQ and RREP routing messages. The node has enough buffer left in the queue to hold these messages so it should be able to assist in helping route discovery quickly. Nodes with a medium load balance the priority for route messaging packets and data packets. Medium loaded nodes operate at steady state. Heavily loaded nodes give priority to data packets over RREQ and RREP packets. The node focuses on delivering data packets instead of assisting in as much route discovery. All arriving RREQ messages are dropped. RREP messages carry important route information and will still be given priority with data packets. RERR messages are always given priority because successful transmissions and prevent misdirected packets from arriving later. This has benefit over standard fair queue scheduling as packets are directed in traffic and have reduced delay in complete transmission [3]. The relevant benefits can be observed below.

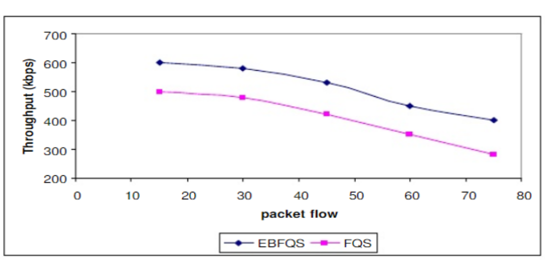


Figure 12: Throughput relative to the inflow of packets at one node

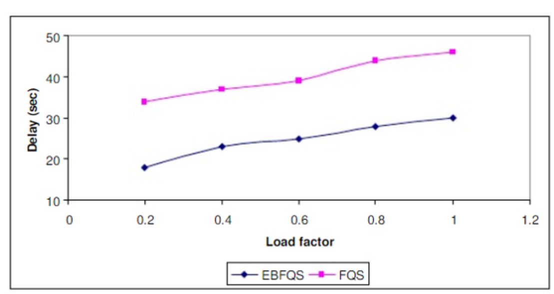


Figure 13: Packet delivery delay relative to the load on the network

10 Power Management

The choice of power level fundamentally affects the signal quality and the range of transmission, power control becomes a key to performance measures such as throughput and energy consumption[9]. In view of this, this report will be focusing on design a energy-efficient wireless network.

10.1 Model and Problem Statement

Consider a multi-in-multi-out system with N_t transmitters, N_r receivers. Then the inputs and outputs are related as follows:

$$Y_{N_r \times 1} = \sum H_{N_r \times N_t} X_{N_t \times 1} + N_{N_r \times 1} \tag{1}$$

where, **Y** is the received signal, **H** is the channel matrix, **X** is transimitted signal and **N** is the additive white Gaussian noise(AWGN) vector.

Assume Rayleigh flat fading channel with average power varied with the path loss and unit bandwidth, the energy efficiency under this model can be represented as

$$\eta_{EE} = \frac{W \times log_2|I + \frac{P_t}{WN_tN_0} HH^H|}{\frac{1}{\eta_{pa}} \cdot P_t + N_t \cdot P_{ct} + N_r \cdot P_{cr} + P_{c0}} \tag{2}$$

where P denotes the overall power consumption, W denotes the system bandwidth and N_0 stands for the power spectral density of AWGN, P_t is the transmission power and the total power consumption, $P(s_i)$ denotes the transmitting power level of a sender s_i, the d_{ii}^{α} denotes the path loss with path-loss exponent $\alpha > 2$, $\frac{P(s_j)}{d_{ji}^{\alpha}}$ denotes the interference from other signals and N denotes the noise.

To maximize the energy efficiency, the exhaustive research and the Delkinbach Method are used to solve the problem stated below

$$\begin{aligned} {P_t}^* = \arg\max_{P_t} \quad & \eta_{EE} \\ s.t. \begin{cases} R \geq R_{\min} \\ 0 < P_t \leq P_t^{\max} \end{cases} \end{aligned} \tag{3}$$

10.2 Methods

1. Exhaustive Search(a.k.a. Brute-fore Method)
   Exhaustive search enumerates all possible candidates and checks the solutions to find the candidate which satisfies the statement most. Therefore, the exhaustive search provides the optimal solution to this problem.

2. The Dinkelbach Method
   The Dinkelbach method provides an iterative method to solve the nonlinear fractional problem.[30]

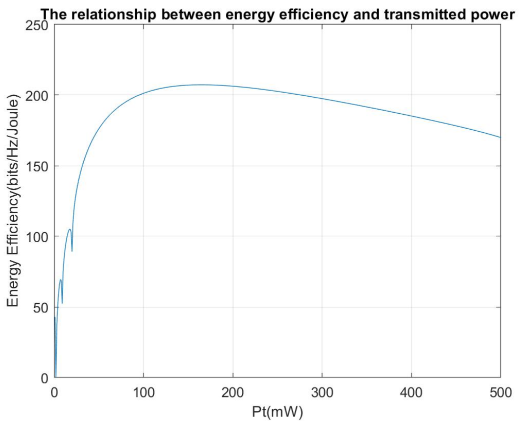
10.3 Simulation and Evaluation

In this section, the result of simulation is shown below. As we can see in Figure 1, the energy efficiency generally increases and then decreases as the transmitted power increases given the fixed number of inputs & outputs($N_t = N_r = 8$), minimum instantaneous capacity of the channel($R_{min} = 5(bits/s/Hz)$) which are adopted from[32]. The other parameters are set as $P_{ct} = 120mW, P_{c0} = 85mW, \eta_{pa} = 35\%$ [12]. The Figure 2 shows the iteration of transmitted power approaching to the optimal power using the Dinkelbach method. As long as the optimality tolerance is as small as possible, the approximated optimal transmitted power is close to the optimal value within an acceptable boundary of error.

10.4 Computational Complexity Analysis

In this problem, the Exhaustive Search search provides the optimal solution for the problem statement. As we can see the results shown in next section, the Dinkelbach methods approaches the optimal solution within several times of iteration.

However, the computational complexity of optimal exhaustive search increases exponentially as a function of search size, while the computational complexity of the Dinkelbach method is determined by the number



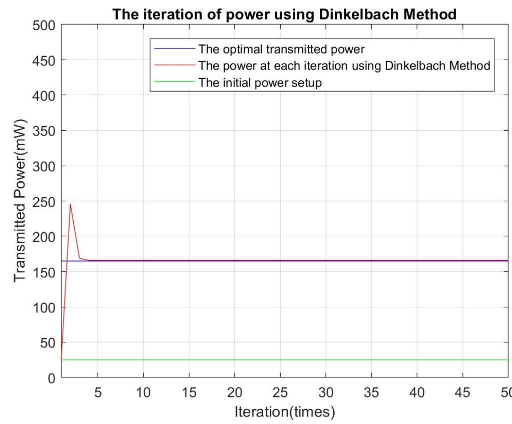


Figure 14: Energy efficiency & the Transmitted power Figure 15: The power iteration using the Dinkelbach method

of iterations and the complexity of the auxiliary problems. For the system with large size, the computational complexity of Dinkelbach method is bounded and much less complex than the exhaustive method [17]. Therefore, the Dinkelbach method is preferred for the large and complex optimization problem.

11 Conclusion

The design outlined in this report would be sufficient to create an IoT network specifically designed for vehicular usage. V2V and V2H communications have been outlined, in addition to how handoff between the two would take place. Network scalability and routing have been looked into in order to enable the network to scale to large numbers of cars. A power management plan has been developed in order to ensure our network communications do not drain the batteries of a typical automotive vehicle. With all of the specifics outlined in this report, an IoT network would successfully be able to fulfill the needs of communication between automobiles.

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