CoRoute: A New Cognitive Anypath Vehicular Routing Protocol

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***Abstract*—Vehicular communications promise to bring us safer driving and better traffic control. Dedicated Short Range Communications (DSRC) and IEEE 802.11p are now well established standards for the inter-vehicle and vehicle-to-road side unit (RSU) communication. These channels, however, are of limited capacity and are not sufficient to support the broad range of services envisioned in VANETs. Thus, vehicles will utilize WiFi (802.11 a/b/g) and unlicensed ISM band to acquire more capacity. Unfortunately, the WiFi channels in urban area are already heavily subscribed by residential customers. In this paper, we propose CoVanet, a cognitive vehicular ad hoc network architecture that allows vehicles opportunistic access to WiFi channels. CoVanet is the first approach to use cognitive radios in a VANET. It differs from conventional cognitive radio strategies in that it uses unlicensed band and operates in an ad hoc, multihop mode. In CoVanet, network topology and channel environment change frequently due to high node mobility. The main contribution of this work is a Cognitive Ad hoc Vehicular Routing Protocol (CoRoute) that utilizes geographical location and sensed channel information. Simulation results demonstrate CoRoute efficiency and robustness to mobility and external interference.**

***Index Terms*—Vehicular Networks, routing protocol, Cognitive Networks**

I. Introduction

Vehicular ad hoc networks (VANETs) have attracted attention in the support of safe driving, intelligent navigation, and emergency and entertainment applications. Dedicated short range communication (DSRC) [1] has been standardized and exploited in vehicular testbeds, but it has only limited number of channels and it is basically reserved to safety purposes. Thus, VANETs must use WiFi for non safety applications.

Unfortunately, WiFi channels suffer from scarcity of available spectrum due to heavy interference from residential users, as well as various wireless devices in the ISM bands (e.g. 2.4GHz or 5GHz). Cognitive Radios, proposed by J. Mitola [2], are one of the solutions for spectrum scarcity in wireless networks. The cognitive radios opportunistically utilize spectrum holes in licensed bands without interrupting the licensed users (e.g., primary nodes (PN)). Cognitive radios are typically used in centralized, base stations, such as in IEEE 802.22 WRAN (Wireless Regional Area Network)[3] standard. However, cognitive radio implementations in ad hoc mobile environments still face a challenge due to the complexity of primary user detection and spectrum access scheduling.

In this paper, we introduce CoVanet, a new cognitive VANET model operated on unlicensed bands instead of licensed bands. It exploits multiple channels to increase network capacity and scalability while allowing a cognitive node (CN) to coexist with a PN in the same channel. Say, in CoVanet, residential 802.11a/b/g access points near roadside are PNs and vehicles are CNs. Based on this environment, we develop Cognitive Ad hoc Vehicular Routing Protocol (CoRoute), an anypath vehicular routing protocol that exploits channel and geo-location information. Vehicles periodically sense multiple channels in order to estimate channel workload and share the sensed channel information with each other. Each vehicle selects its own channel based on the measured channel information.

Existing routing protocols for cognitive radios allocate channels along the routing path using well established metrics such as shortest expected transmission time (ETT) [4][5][6]. However, they fail to establish an optimal path in rapidly changing channel condition and workload. Some proactive routing protocols (SAMER) [7] utilize overall network link-state information (including channel and spectrum conditions) to dynamically calculate alternate paths. However, link-state routing protocols produce too much overhead to follow rapidly changing channel condition. Geographic based routing protocols, such as GPSR [8], GPCR [9] and GPSRJ+ [10], are more suitable to support robust connectivity with relatively low overhead even in high vehicle mobility. They, however, do not account for spectrum limitations and for interference and conflicts. CoRoute is the first attempt to VANET routing with cognitive radios accounting for both high mobility and spectrum scarcity.

The remainder of this work is structured as follows: Section II describes our *CoVanet* architecture along with spectrum sensing and channel assignment algorithms. Section III gives an overview on the design of CoRoute. And simulation results about CoRoute performance are shown in Section IV. Section V reviews related works. The paper concludes in section VI.

II. *CoVanet*: Cognitive vehicular ad hoc networks

This section overviews *CoVanet*, a novel multi-radio multi-channel cross-layer architecture based on principles of cognitive radio system.

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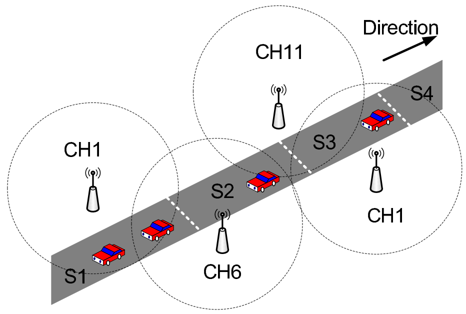


Fig. 1: Model of Urban Wireless Mesh Networks

A. CoVanet network architecture

Figure 1 illustrates a simple CoVanet architecture. Residential APs are located near roadside (actually inside building) using various channels as shown in Figure 1. Due to the transmission power and shadowing, AP's radio coverage and interference range are different so that each segment of road has different interference channel and interference signal power level. For example, in Figure 1, channel 1 and 6 have interference signals from APs in the road segment S1 while only channel 1 suffers from interference in road segment S4. Furthermore, some portion of S1 has interference channel 1, but other portion of S1 has interference channel 1 and 6. Therefore, vehicles experience dynamic channel environments while they are driving on the road.

Vehicles in CoVanet are equipped with two radios (i.e. R1 and R2) for data and a radio for the common control channel (CCC). Vehicles are able to transmit and receive packets simultaneously via both R1 and R2 radios. For example, R1 is tuned to the receiving channel while R2 is transmitting. Typically, the channel with lowest interference is selected for R1. R1 slowly changes as the vehicle travels through the urban grid, but R2 is dynamically switched among current neighbors' receiving channels. In the current platforms, switching delay is assumed to be approximately $100\mu s$ while packet transmission time is around $5-6ms$ in 2Mpbs data rate radio. Such a hybrid multi-radio approach achieves adaptive channel diversity while maintaining stable connectivity (without time synchronization or deafness problem).

B. Spectrum Sensing and Channel Assignment

Instead of sensing multiple channels, a CN in CoVanet monitors only its receiving channel and shares monitored information with neighbor nodes. In order to monitor PN's traffic load and pattern, CoVanet employs a quiet period during which all CN nodes stop data transmission and hear PN's traffic. The quiet period is for example $20ms$ every second. For the quiet period, time synchronization can be realized by the GPS system installed on each vehicle. The CN node senses PN's radio states: busy or idle state. Therefore, monitored channel is described by a two-state semi-Markov model. The duration of expected busy, T_{busy}, and idle, T_{idle} times are expressed by exponential distribution which rates are λ and μ, [11] and thus their Cumulative Distribution Functions (CDFs) are,

$$P(T_{idle} < t) = 1 - e^{-\lambda t}$$
$$P(T_{busy} < t) = 1 - e^{-\mu t} \quad (1)$$

Now *channel workload* (ω) can be estimated by monitored information.

$$\omega = \frac{T_{busy}}{T_{busy} + T_{idle}} \quad (2)$$

Using the measured workload of channel ω and the physical data rate R_0 (e.g. 11 Mbps), expected capacity R_i for channel i is calculated:

$$R_i = R_0 \cdot (1 - \omega) \quad (3)$$

Then, each CN approximates the channel capacity per-node R'_i as follows:

$$R'_i = \frac{R_i}{N(i)} \quad (4)$$

where $N(i)$ is the number of CNs nodes selecting the channel i within radio range. A node finds out $N(i)$ value via control packet exchanging over CCC and a CN selects the receiving channel, j, among multiple channel as following:

$$j = arg \max_i R'_i \quad (5)$$

Then, it tunes its receiving interface R1 to channel j and this selected channel is noticed to other CNs using a control message, called Hello packet. The Hello packet is flooded every second after it monitored the channel. It includes monitored channel information, selected channel, neighbor information, and own activity (whether it has a flows to transmit) and current geo-location information. To avoid collision, random jitter is inserted before sending out.

III. CoRoute: Cognitive Anypath Vehicular Routing Protocol

Existing VANET routing protocols focus on having a robust connection while at the same time controlling the overhead caused by high vehicle mobility. In dense urban areas, however, heavy channel interference is another critical factor that must be considered for routing. This paper proposes a new routing protocol for urban areas, CoRoute, which increases network throughput by selecting low interference channels and exploiting alternate paths. The following aspects have been considered in CoRoute design:

- *Connectivity between vehicles:* Due to prevailed multiple paths, network connectivity becomes robust as node density increases in VANETs. In urban channel environment, the connectivity changes frequently because of many obstacles. Connections can be lost, for example, if larger portion of neighbor nodes are blocked by buildings. To maintain connectivity, nodes periodically broadcast Hello messages to neighbors in order to detect topology and neighbor nodes change.
- *Channel robustness of each road segment:* Channel robustness in CoVanet is decided by many factors. The urban environment because of buildings, structures, and hills invokes multi-path fading with diffraction and scattering. Mobility, particularly speed of vehicles, causes

Doppler spread. In addition, PN interference from residential APs decreases channel robustness. Thus, each node must select a next hop and a route that has robust channel.

- *Congestion free road:* High vehicle density for robust connectivity does not guarantee better throughput since high network congestion and overhead. Each vehicle must consider network congestion generated by PNs and CNs.

ETT [12] is Expected Transmission Time and ETX [13] is Expected Transmission count which are the typical route metrics used in wireless ad hoc networks. In this study, we adopt ETT value as a metric to express link quality, as it reflects indirectly packet loss and channel bandwidth. We also adopt cumulated ETT to indicate path quality including hop count.

A. ETX estimation

Expected transmission count (ETX) is the average number of transmissions required to deliver a packet across a link. It can be measured by broadcasting probing packets at very slow rate during a predefined window. Let p_f and p_r be packet loss probabilities in forward and reverse transmission, respectively. Then, probability of transmission failure and ETX are,

$$p = 1 - (1-p_f)(1-p_r)$$

$$ETX = \sum_{k=1}^{\infty} kp^{k-1}(1-p) \; = \; \frac{1}{1-p} \tag{6}$$

The probing or data packets to measure ETX probably imposes considerable overhead or inaccurate in CoVanets since each node must send packets on multiple channels. In CoRoute, ETX is derived probabilistically by estimated PN workload and distance between a sender and a receiver. ETX is then used for ETT computation, see equation Eq.(9). It is assumed all vehicles in CoVanet know their location via GPS. First, loss probability is investigated under fixed data rate between a pair of vehicles both using the same transmission power and modulation.

First, the probability of successfully receiving a packet based on distance d is notated by $P_d(d,k)$ with data rate is k. The k is achievable when the current signal to noise ratio (SNR) is above the threshold Ψ_k as follow:

$$P_d(d,k) = Pr(\frac{A^2}{\eta} > \Psi_k) = 1 - \frac{\gamma(m, \frac{m}{\Omega}\Psi_k)}{\Gamma(m)}$$

,where η is thermal noise and γ is incomplete gamma function. A is the random variable that represents the amplitude of the received signal in a vehicular environment modeled by the Nakagami distribution [14]. The amplitude of the signal follows the probability distribution function (pdf):

$$p(r;m,\Omega) = \frac{2m^m}{\Gamma(m)\Omega^m} r^{2m-1} \cdot exp(-\frac{m}{\Omega}r^2)$$

,where Γ is the Gamma function and m is the fading intensity. Note that m depends on the environment and the distance between the transmitter and the receiver and can be varied to multi-path fading distributions (e.g.,Ricean and

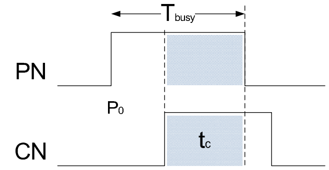


Fig. 2: Collision between PN and CN

Rayleigh distribution). Ω is the received power derived from two-ray path loss model as follow:

$$\Omega = \frac{P_t G_t G_r h_t^2 h_r^2}{d^\theta L} \; = \; c \cdot d^{-\theta}$$

,where P_t is the transmit power, G_t and G_r are antenna gains of transmitter and receiver, respectively, h_t and h_r are antenna heights of the transmitter and the receiver. d is the distance between the transmitter and the receiver, θ is the path loss exponent, and L is the system loss. Assumed that the all parameters except d are fixed, Ω can be simply denoted by the product of the fixed coefficient c and distance with path loss exponent.

In addition, the probability of successfully receiving packets depends on PN interference. Here the probability (i.e.Packet error rate (PER)) is determined by collision duration between PN and CN packets and by SNR (i.e. bit error rate) discussed in the previous paragraph. The collision duration in CoRoute is approximated using the two-state PN traffic model introduced in section II.

In Figure 2, T_c is the collision duration and T_{busy} is average busy duration (i.e. E[t] = 1/μ in Eq.(1)). P_0 is a probability that the busy period of both nodes starts at same time; P_0 is a value multiplied by two $T_{bit}/(T_{busy} + T_{idle})$ of each PN and CN where T_{bit} is bit duration(i.e., 1/2 Mbps = 0.5 usec). At the P_0, T_c has maximum collision duration with fully overlapped two T_{busy}. On the other hand, T_c can be zero at P_n. Average collision duration (E[T_c]) can be calculated in discrete time domain since time less than bit-duration is not meaningful to BER.

$$E[t] = P_0 \cdot T_m + \sum_{t=1}^{T_m} (1 - \prod_{n=0}^{t-1} P_n)(T_m - t)$$

where t is the number of unit times(i.e., T_{bit}) as a random variable and T_m is the maximum overlapped time, $\frac{\min(T_{busy}(PN), T_{busy}(CN))}{T_{bit}}$.

The error rate of received packets with data rate $= k$ (i.e., modulation type) and collision duration $= t$ is denoted by $P_c(t,k)$. Eq.(7) indicates BER, P_b if for $k = 1$ Mbps (i.e., 802.11b with binary phase shift keying (BPSK)) and zero PN interference. Received SNR (E_s/N_0) should be replaced by SINR ($E_s/(N_0 + N_i)$) if the collision duration $t > 0$ due to PN interference during packet transmission. The approximated $P_c(t,k)$ with the P_b is shown in eq.(8).

$$P_b = \frac{1}{2} erfc(\sqrt{\frac{E_b}{N_0}}) \tag{7}$$

$$P_c(t,k) = 1 - (1-P_b)^n, \quad n = \frac{E[t]}{T_{bit}} \tag{8}$$

From the $P_d(d,k)$ and $P_c(t,k)$, the error probability of forward and reversed transmission can be calculated as p_f or p_r = 1-($P_d(d,k)$·(1-$P_c(t,k)$)) in a receiver node for MAC or ACK frame in case of unicast. The ETX value might not be exact due to other channel effects. Nonetheless, it is valuable as a routing metric that targets wireless link quality.

B. ETT estimation

Expected transmission time (ETT) is the transmission time to deliver a packet with size S and data rate R over a link with the ETX. Namely:

$$ETT = ETX \cdot \frac{S}{R} \tag{9}$$

where S is packet size and R is data rate. As discussed in Section II, the available data rate from PN workload (ω) is $R = R_0 \cdot (1-\omega)$ when both PNs and CNs can share channel bandwidth by avoiding mutual collision using 802.11 MAC protocol collision avoidance. Collisions occurred by detection error or hidden terminal situations can be factored in ETX. As a result, a route with heavy PN traffic will result to have more congestion and more retransmissions.

C. Anypath routing

In CoRoute, vehicles select a route instantaneously among multiple candidates based on estimated channel conditions. Namely, CoRoute uses opportunistic anypath routing following the forwarding set technique introduced in [15]. In [15] vehicles in the forwarding set transmit packets if they do not hear packet transmission from higher priority neighbor nodes. Otherwise, they discard the packets to suppress duplicated forwarding. The packet transmission priority is determined by the end to end, Expected Anypath Transmission Time EATT to a properly defined node. In [15], such node is the final destination. In CoVanet, initially the node in question is the node 2-hops away that offers best progress to destination. This choice greatly simplifies the computation yet preserving the multipath robustness of the solution. EATT in this case applies to the 2-hop path as shown in Figure 3. This choice is motivated by the fact that anypath routing guarantees the minimum EATT from a source to a destination [15]. It should be noted that initially our algorithm minimizes EATT to the 2-hop neighbor. However, as packets reach destination, the EATT values are propagated from destination back to the source through periodic Hello messages. After that happens, a generic intermediate node j will, like in [15], send packets on the path that minimizes EATT estimate to destination

Figure 3 illustrates how ETT values(d_j) and success transmission probability (p_j = 1/ETX) in parenthesis for each link are used to calculate EATT, i.e. D_i based on Bellman equation(i.e. D_i = $d_{i,J}$ + D_J) across Forwarding set J. Here since the d_j is proportional to number of transmissions, d_j is determined by 1/p_j. More precisely:

$$d_{i,J} = \frac{1}{1-\prod_{j\in J}(1-p_j)} \cdot \frac{S}{R_j} \tag{10}$$

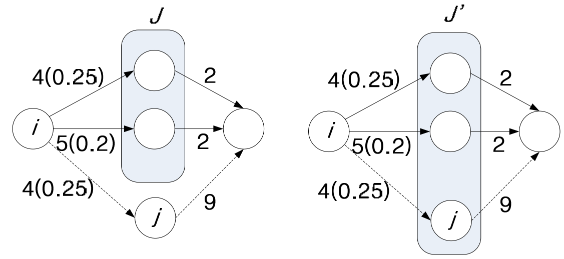


Fig. 3: Forwarding set of anypath routing

where R_j is defined in Eq.(3). D_J is calculated as weighted sum of each contribution across the forwarding set .

$$D_J = \sum_{j\in J} \omega_j D_j, \quad where \sum_{j\in J} \omega_j = 1 \tag{11}$$

where ω_j is the probability that forwarder j is successfully used, and is given by:

$$\omega_j = \frac{p_j \prod_{k=1}^{j-1}(1-p_k)}{1-\prod_{j\in J}(1-p_j)} \tag{12}$$

As an illustration, in Figure 3 using the above formula we find that the forwarding set J has average 4.5 EATT(=$\frac{1}{1-(3/4)(4/5)}$ + $\frac{2/4+(3/4)(1/5)\cdot 2}{1-(3/4)(4/5)}$) assuming average bit duration S/R= 1. As per definition in [15] the forwarding set consists of the minimum number of forwarders that creates the lowest EATT based on Eq.(11) and (12). The forward set J' in the right figure has EATT = 5.7, which implies that the additional forwarder j increases EATT and thus should not be included in the set based on the forwarding set definition in [15]. The D_i is updated as Hellos convey fresh information from the destination. Thus, the forwarding set changes dynamically.

It should be pointed out that the original forwarding model in [15] was based on a single channel configuration. In our case the model was modified to multiple channels. In particular, instead of a single broadcast like in [15], multiple broadcasts on different frequencies are required for different subsets of nodes. Due to multiple broadcasts, the EATT optimality claimed in [15] is not longer guaranteed.

D. Forward set implementation

In CoRoute, each vehicle via Hello messages on the Common Control Channel (CCC), propagates to all neighbors its sensed channel information and geographical location. This information is used by each node to select the least congested receive channel to listen too. It is also used to select the forwarding set. Namely, based on the neighbor table, each vehicle selects vehicles geographically close to the destination to form the forwarding set J.

A node transmits the packet to the forwarding set J using multiple broadcasts. To avoid unnecessary duplicate forwarding, each node in J has a priority in relaying the received packet based on its EATT. Namely, the time out is proportional to EATT. To suppress superfluous multiple transmissions, a top priority node broadcasts a "notification" message on CCC to the sender and all forwarders in J. Note that CCC is used because forwarders and a sender can be on different channels.

IV. Evaluation

A. Simulation setup

We implemented CoRoute and compared it with other routing schemes using Qualnet 3.9.5. The simulation platform runs IEEE 802.11b with 2 Mbps data rate and 11 orthogonal channels having Rayleigh fading. The mobility traces for the simulations were generated using VanetMobiSim. Both macro and micro mobility are accounted for in the vehicular environment so as to reproduce a realistic urban motion pattern. A 1500m x 1500m Manhattan grid with 300m road segments was used. All roads have a speed limit of 15 m/s (54 km/h). The micro-mobility is controlled by the Intelligent Driver Model (IDM- IM). Mobility traces were collected for a variable number of vehicles ranging from 60 to 120.

The number of primary interfering nodes PNs (ie, residential Access Points) ranges from 10 to 200. These PNs are placed randomly in the urban grid. We compare CoRoute with a georouting scheme called Route which is identical to CoRoute except for using only one radio tuned to one channel. We also develop CoAODV and compare with AODV. CoAODV is identical to AODV, except that it runs on a Cog Radio and exploits multiple channels. CoAODV achieves local optimization by selecting not only feasible local channels. It also achieves overall path optimization using cumulative ETT. Since the channel environment changes dynamically, the source floods the route request (RREQ) message periodically to refresh the path and channels without Hello like CoRoute. In this simulation, the period is set as 5 seconds to minimize control overhead. In the sequel, CoAODV will be compared to conventional AODV and to CoRoute.

All simulations were run with a fixed source-destination connection with a 64 Kbps UDP data traffic transfer.

B. Simulation results

The first experiment features CoRoute. It evaluated CoRoute for different numbers of interfering primary stations characterized by different utilization factors.

Figure 4 shows CoRoute average delivery ratio for variable number of PNs and for 3 levels of PN loads (i.e. 20, 40 and 70%). There are varying number of vehicles in the grid. The primary nodes are added incrementally reflecting a monotonic increase from 10 to 200 PNs. The source-destination pair is randomly chosen, and is the same for the entire set of experiments. The confidence interval is 95%. As expected, delivery ratio decreases monotonically. The degradation is higher for higher primary occupancy.

The second set of experiments compares CoRoute with Route. Delivery ratios are shown in Figure 5.

As before, there is a single source destination pair and it is the same in all the runs. PNs are loaded by 70% and are added incrementally. The delivery ratio decreases monotonically as the PN interference becomes larger. CoRoute outperforms Route in all scenarios due to benefit of multi-channel diversity. The diversity gain however decreases as the number of PNs increases. It is remarkable how much better CoRoute performs than Route for high vehicular density since the collisions occur more in the Route that is operated on a single channel.

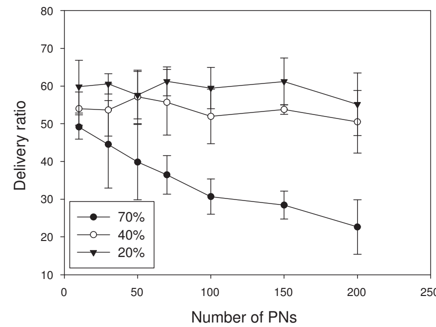
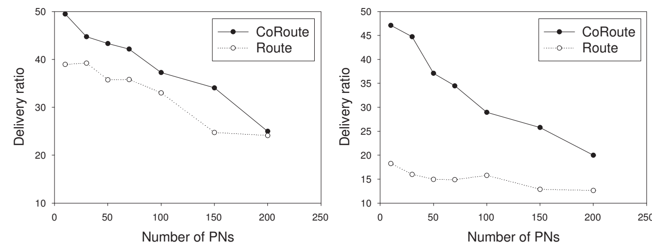


Fig. 4: Delivery ratio with varying PN workloads

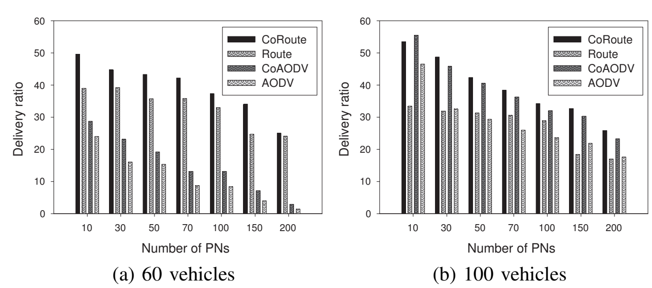


(a) 60 vehicles (b) 120 vehicles

Fig. 5: performance comparison between CoRoute and Route

Next, CoAODV, CoRoute, Route and AODV are compared (see Figure 6). The delivery ratio is evaluated for two different vehicle populations, 60 and 100 vehicles. CoRoute and Route easily outperform CoAODV and AODV with 60 vehicles. However, with 100 vehicles CoRoute and CoAODV exhibit about the same performance.

With 60 nodes, the network is sparse and connectivity is weak in AODV and CoAODV due to mobility, interference and obstacles. The path tends to break easily and cannot be repaired because of poor connectivity. AODV and CoAODV flood RREQ packets in search for new path. This has dramatic effect on AODV/CoAODV throughput. On the other hands, CoRoute does well with 60. This is because CoRoute is a georouting protocol and is much more robust to path breakage.



(a) 60 vehicles (b) 100 vehicles

Fig. 6: performance comparison between CoRoute and CoAODV

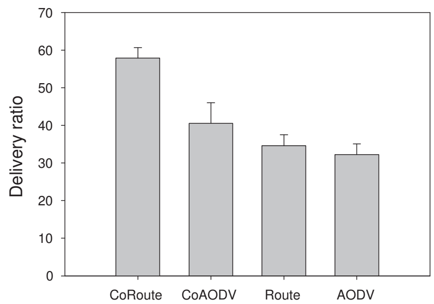


Fig. 7: Aggregated average delivery ratio

It automatically finds another path since it maintains periodically connectivity based on Hello and exploit the forwarding set.

With 100 Nodes, delivery ratio dramatically improves for AODV/CoAODV. There are enough alternate paths for AODV to fall back to if the path breaks or interference has become intolerable, without having to initialize a new flood search. At 100 nodes, the delivery ratio is comparable to CoRoute.

Figure 7 shows aggregated delivery ratio of all protocols with varying PNs from 10 to 200, 40% workloads, randomly picked communication pairs and varying number of vehicles in the range from 60 to 120. Here again CoRoute outperforms all other approaches firmly establishing its superiority in congested spectrum environments.

V. Related Work on Cognitive VANET routing

Many routing protocols have been proposed for VANETs including the broad family of protocols originally developed for MANET. As GPS navigators have becomes popular, geographic routing protocols inspired by GPSR [8] have become prevalent in the VANET literature. Several improvements have been proposed. GPCR [9] improves GPSR by using map knowledge in real urban environments and avoiding the planarization problem. GpsrJ+[10] further improves performance by relaxing the dependency on junction nodes required by GPCR. Many routing protocols have recently been proposed also for cognitive radios. They have considered delay stemming from channel sensing and switching as a the routing metric to minimize. G.Cheng [4] proposed an AODV like protocol that accounts for channel switching and backoff delay at each node to select the minimum delay path. In SPEAR [6], channel assignment on each link is computed by destination upon receiving multiple RREQs, using ETX, ETT and WCETT criteria. Most routing protocols of cognitive radio [4][5][6] jointly allocate channels for each node usually by RREQ/RREP. However, they are not efficient to confront rapidly varying channel conditions. There are different approaches to solve the problem[7][16][17]. SEARCH [17] finds a detour route (before changing the channel) to avoid PUs in geographic way when an intermediate node detects PNs. STARP [16] uses a new path stability metric based on for channel usage statistics at each node. SAMER [7] is a link state routing protocol managing local spectrum availability as a metric. SAMER however needs global link states to build a candidate forwarding mesh.

VI. Conclusion

We have proposed a novel routing scheme, CoRoute, for cognitive VANETs. CoRoute achieves two goals. It makes best use of the available WiFi bandwidth and it causes minimum disruption on residential users CoRoute is inspired to state of the art VANET routing protocols. It is based on georouting, the most popular scheme in VANETs. Moreover, it follows the on demand principle of most existing Mesh based cognitive routing schemes. CoRoute consistently outperforms conventional geo-routing as well as other cognitive routing schemes such as CoAODV, yielding up to 100% throughput improvement. Future work will optimize CoRoute features such as Hello and multiple unicasts to further improve its performance.

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