WirelessAcrossRoad: RF based Road Traffic Congestion Detection

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Abstract

Road congestion is a common problem worldwide. Intelligent Transport Systems (ITS) seek to alleviate this problem using technology. But most ITS techniques, currently used in developed countries, are inapplicable in developing regions due to high cost and assumptions of orderly traffic. Efforts in developing regions have been few. In this paper, we seek to develop a low-cost ITS technique to detect congestion in disorderly road conditions. We take Indian traffic conditions as an example for our analysis. But we believe that most of our claims and experimental results can be extended to other developing countries too.

Our technique is based on exploiting the variation in wireless link characteristics when line of sight conditions between a wireless sender and receiver vary. Our system comprises of a wireless sender-receiver pair across a road. The sender continuously sends packets. The receiver measures metrics like signal strength, link quality and packet reception. These metrics show a marked change in values depending on whether the road in between has free-flowing or congested traffic. We have experimented with off-the-shelf IEEE 802.15.4 compliant CROSSBOW Telosb motes. From about 15 hours of experimental data on two different roads in Mumbai, we show that we can classify traffic states as free-flowing and congested using a decision tree based classifier with 97% accuracy.

I. Introduction

The average number of vehicles on Indian roads is growing at an enormous rate — 10.16% annually since the last five years [1]. Mumbai, a metropolitan city, has over 590 vehicles per km of road. Bangalore, another metropolitan city, has about 5 million vehicles plying on a road network of barely 3000 kms [2], [3]. This is leading to increasing levels of road congestion, longer and unpredictable travel times and wastage of time and fuel for commuters. Growth in infrastructure has been slow due to various reasons such as high cost, lack of space, bureaucracy, etc.

We define traffic on a road to be *free-flowing*, if each vehicle moves at the desired speed of its driver, bounded by the speed limit of the road. Any situation other than this, where drivers have to slow down vehicles or stop and go, because of presence of several other vehicles on road, is considered *congested*. Automated congestion detection can help in traffic management by making traffic signal timings more efficient. Secondly, if some roads or junctions show regular trends of becoming congested, this knowledge can be used to plan new infrastructure such as flyovers and freeways. Thirdly, this can be used to design interesting mobile applications for on road commuters. Which congested routes should be avoided? What is the travel time along a congested route? Applications that can answer such questions will certainly make traveling on roads less cumbersome.

Many congestion detection techniques [4], [5], [6], [7], [8], [9] are already being used in developed countries. But unlike traffic in developed countries, traffic on Indian city-roads is characterized by high variability in size and speed of vehicles [10], [11]. The same road is shared by buses, trucks, cars, vans, auto rickshaws, motor-bikes, bicycles, and pedestrians. Traffic is often chaotic, with no semblance of a lane-system common in developed countries [12]. Thus, as we discuss in Section II, the various congestion detection techniques used in developed countries will not be directly applicable in an Indian context. This is a possible reason behind the fact that the *Traffic* component of *Google Maps*, that shows roads in red, yellow and green, according to decreasing congestion level, does not display traffic conditions on Indian roads.

In a different field of work, in the area of wireless networks, prior literature [13], [14], [15] shows that wireless link behavior suffers in absence of clear line of sight between the sender and receiver. In this paper, we exploit this prior knowledge and design a new congestion detection technique that can handle chaotic traffic. Our technique comprises of a wireless sender-receiver pair across a road. The sender continuously sends packets. The receiver measures metrics like signal strength, link quality and packet reception. We show that these metrics show strong correlation

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with free-flowing or congested traffic states of the road. Our technique gives 97% traffic classification accuracy on 15 hours of data collected from two different roads in Mumbai. The initial cost analysis shows that our system will need about $200 per installation and will be easy to deploy on roadside lamp-posts.

II. Related Work

Any congestion detection technique for developing regions should (1) handle chaotic traffic, (2) incur low cost and (3) pose minimum hindrance to traffic while installation and maintenance. Here we review the existing techniques and see if they fulfill these conditions. These techniques can be divided into two broad categories - *(i) fixed sensor based* where the sensors, that gather various road related information, are statically placed on or by the side of the road and *(ii) probe vehicle based*, where the sensors are mobile and placed in a subset of vehicles that ply the road.

A. Fixed sensor based techniques

Dual loop detectors - Pairs of inductive loop detectors can be used to identify vehicles based on their length [4]. Identifying the same vehicle at the two detectors can give an estimate of travel time between the two detectors. Deviation from expected travel time can signal congestion.

Image sensors - These can be deployed on road side to measure congestion level by processing captured images, where slower the images change with time, higher is the level of congestion [5].

Magnetic sensors - [6] uses a single magnetic sensor to detect the ontime of vehicles passing it, calculates the length of vehicle based on the ontime assuming constant speed common to all vehicles. From a large number of samples of ontime and vehicle length, they calculate median of the two metrics and estimate median speed as $\frac{medianlength}{medianontime}$. If this median speed deviates from expected median speed, congestion is reported.

The fixed sensor based techniques can be prohibitive in terms of infrastructure and maintenance costs. As given in [16], the initial installation cost of a vehicle loop detector is approximately $26,100. With image sensors, high-resolution cameras can be quite expensive. Even if cameras are cheap, image sizes can be big, increasing data communication costs. Secondly, the inherent assumption of lane-based orderly traffic makes these techniques inapplicable for chaotic road conditions. Image processing overhead to analyze patterns in chaotic traffic can be high. Thirdly, loop and magnetic detectors need to be placed under the road. If roads need to be dug up to install and maintain the infrastructure, that will adversely affect traffic, as alternate routes are often times unavailable.

As compared to this, our technique is (1) low cost, as each installation will cost about $200 including GPRS communication to central server, (2) able to handle chaotic traffic and (3) easy to install and maintain, on roadside lamp-posts.

B. Probe vehicle based techniques

GPS based - [7] considers GPS-enabled probe-vehicles. Using GPS traces from probe-vehicles, the road network is classified into *segments* delimited by traffic signals. Thresholds of temporal and spatial speed traces within each segment are then computed to categorize traffic within the segment as congested or free-flowing. The Mobile Millennium project of UCBerkeley [8] includes a six month pilot deployment of thousands of GPS mobile phones in a number of vehicle within a focus area. From data collected using these phones, algorithms for travel time estimation, optimal sensor placement and protecting user privacy have been developed. [9] develops techniques to augment sparse GPS data with WiFi localization information and develops a new technique to map GPS traces to road segments using hidden Markov models with Viterbi matching.

Smartphone based - [12] seeks to characterize traffic and road conditions in the Indian city of Bangalore using mobile phones. Phones are localized using GSM and GPS. If sufficient braking is detected using the on-phone accelerometer and substantial honking is detected using the on-phone microphone, congestion is reported.

While probe-based techniques cost lower than the fixed sensor techniques discussed earlier, one issue is that, in India, proliferation of GPS receivers in vehicles is quite low. Only a small number of fleet companies and state transport companies have GPS units installed in their vehicles in a few metropolitan cities. Smartphone penetration in India is also quite low [17], though mobile phone penetration is extremely high. Most people have low end phones and are unable to take part in participatory sensing. Even for those who have smartphones, it is difficult to think of an incentive model to attract them to take part in GPS sensing as it involves sensing as well as communication costs.

As compared to the above, our technique uses road-side infrastructure and does not need active participation from commuters and their vehicles.

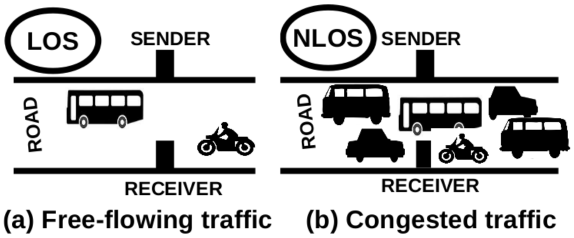
C. Acoustic sensors for chaotic roads

We proposed an acoustic sensing based congestion detection technique in [18] where we exploit the fact that chaotic traffic is noisy. Here vehicle honks recorded in roadside recorders are used to estimate vehicle speeds using differential Doppler shift. Metrics like number of vehicle honks and 70th percentile vehicle speed are used to classify traffic state into congested and free-flow using threshold based classification. About 20 hours of on-road data analysis shows the effectiveness of this technique in detecting congestion on chaotic roads. We believe that the technique proposed in this paper can complement our acoustic based technique, and can even be used on roads and in situations where honks are less.

III. RF-based Road Congestion Detection

The basis of our proposed road congestion detection technique is the differential behaviour of RF wireless links in LOS (line-of-sight) vs NLOS (non-LOS) conditions. In the field of wireless networks, there have been several studies [13], [14], [15], to characterize wireless link behavior in different environments. [13] has done a series of controlled experiments using seven 802.11 a/b/g nodes in an indoor office environment. Experiments have been conducted for nodes in clear line of sight (LOS) with each other and also in partial or no line of sight (NLOS). [14] has done similar experiments in three environments - road with foliage, corridor and lab. They have used 802.15.4 compliant Moteiv Tmote Sky motes. Two key results, reported in both these papers are (1) mean Received Signal Strength Indicator (RSSI) in NLOS conditions is much lower than the mean RSSI in LOS. (2) Variance of NLOS RSSI is much higher than variance of LOS RSSI. The signal strength at a wireless receiver degrades due to multipath fading, scattering and reflection. If obstacles hinder LOS between the sender and the receiver, these propagation effects can become more acute. Low value and high variability of RSSI cause related link characteristics like link quality indicator (LQI) and packet reception to suffer too. In conventional wireless and sensor networks, this is considered as a negative phenomenon. Node placement with LOS is preferred to prevent this, and in unavoidable situations of NLOS, protocols try to adapt link parameters to improve network performance.

In this paper, we seek to positively exploit this difference in link behaviour between LOS and NLOS conditions. As shown in Fig. 1, we place a wireless sender receiver pair across a road. Fig. 1(a) shows free-flowing traffic. In this condition, sender and receiver are mostly in LOS, other than when few vehicles pass between them at relatively high speed. Fig. 1(b) shows congested traffic. In this condition, sender and receiver are mostly in NLOS, other than when movement of some vehicles create short-lived LOS. In our method, we propose that the sender continuously send packets to the receiver and the receiver log the link metrics like RSSI, LQI and packet reception. Based on the results in [13], [14], we expect these metrics to show marked difference in values between free-flowing (mostly LOS) and congested (mostly NLOS) conditions, which can be used to develop a technique for congestion detection.



(a) Free-flowing traffic (b) Congested traffic

Fig. 1. Wireless Communication Across Road

Which wireless technology to use is an important design question. Ideally, we want (1) the technology to show marked difference in link characteristics under LOS and NLOS conditions, (2) power consumption to be low, as sensors might need to run on batteries if grid power is unavailable in road deployments, (3) hardware to be inexpensive, (4) minimum 20 m range to be usable across roads and (5) off-the-shelf hardware to be available for the initial proof-of-concept. We initially tried using *Bluetooth* dongles; these links show good difference in link characteristics between LOS and NLOS indoor, but fail to establish link even in LOS on actual roads wider than 10 m. *802.11 Wi-Fi* has high power requirements for both radio and computation platform [19] and hence seems less suitable for this application.

Active *Infrared* (IR), can be used to send condensed beam across road. There is, in fact, a commercial system [20], that counts vehicles based on beam-cutting by vehicle wheels. But this system has been tested only in very sparse lane-based traffic. On roads, which are wide as well as busy, even free-flowing traffic can cause continuous beam-cutting, giving false indication of congestion. Thus RF with its spread propagation model, instead of light with sight propagation, seems more practical to use for this application.

In this paper, we have used IEEE 802.15.4 (Zigbee) compliant CROSSBOW Telosb motes with CC2420 radios. These motes consume 35 mW of active power and have a unit price of $80. The outdoor range with integrated antenna is 75-100m [21], which is much more than the width of most Indian roads. Choice of this technology thus satisfies the desired conditions (2), (3), (4) and (5) listed earlier.

To check (1), i.e. performance difference between LOS and NLOS, we performed some preliminary experiments. Using two motes, one as sender and one as receiver, we do similar experiments, as in [14], inside our five floor CSE department building. The sender and the receiver are placed sometimes in LOS and at other times in NLOS and RSSI, LQI and packet reception metrics are measured at the receiver. The key observations from these experiments are that (1) RSSI and LQI variations are very high in NLOS compared to LOS (2) Absolute value of RSSI and LQI is low in NLOS compared to LOS. (3) Packet loss is much higher in NLOS than in LOS. These results match the results in prior work, giving us confidence to use the motes in our proposed road congestion detection technique.

IV. Experimental Evaluation

In this section, we describe the various on-road experiments, that we performed to design and evaluate our proposed technique.

A. Setup

We create the experimental setup shown in Fig. 1 on Adi Shankaracharya Marg, a road in Mumbai, 25m wide in each direction. This road has all varieties of vehicles – trucks, buses, cars, autos, bikes and remains heavily congested from approximately 6:45 pm - 8:45 pm on most weekdays. The congestion is because of slow lane merging with another road ahead. We keep the sender and receiver across the road on a line perpendicular to the length of the road, i.e. at a distance of about 25m. The height of the motes from the ground is about 2 feet. The sender sends 25 packets per second of 100 bytes each at -25dBm transmit power. The receiver logs the RSSI and LQI values for each received packet. One person stands on the roadside footpath holding the receiver. The other stands across the road, on the road divider, with the sender. These two persons also observe the road to note the ground truth of the traffic situation. We collect 14 logs of 5 minutes each from about 5:30 pm to 7 pm. The ground truth observed is, initially traffic is free-flowing, it becomes slow at around 6:20 pm and then heavy congestion sets in within a short time and remains so until the end of the experiment. The left side of Fig 2 illustrates the free-flowing traffic while the right side shows congestion on this particular road. Videos of the traffic during the experiment can be found at [22].

Fig. 2. Free-flowing to congested traffic

B. Method of analysis

An insight that we got from our indoor experiments is that, there is some inherent variability in the wireless link characteristics. This is also reported in prior studies [14]. RSSI can occasionally be good in NLOS and bad in LOS. So instead of isolated values, we think the distribution of link metrics, over some time interval T, will smoothen out such fluctuations and show the average behavior more clearly. A second advantage of using distribution is as follows. Sometimes NLOS is created in free-flowing traffic if a particular vehicle or pedestrian comes and stops in front of either mote. Similarly LOS can be created in congested traffic through gaps between standing vehicles. Such transient fluctuations in the metric values can be smoothened using a distribution. Thus in our road experiments, we plot the CDF of the metrics RSSI, LQI and packet reception rate over a duration of T = 5 minutes. As seen from our results, this handles fluctuations well. We compare the CDF of the metrics between free-flowing and congested traffic to see if they are different.

C. Results

Figures 3, 4 and 5 show the CDF of RSSI, LQI and packet reception rate respectively. Each graph shows 14 plots: each a CDF calculated over 5 minutes. RSSI and LQI are obtained for only the successfully received packets.

As seen from the figures, the curves in each graph can be classified into three distinct groups – *Group1* between 5:37-6:21pm, *Group2* between 6:22-6:27pm and *Group3* between 6:30-7:05pm. The ground truth of traffic state noted was free-flowing till 6:20pm, slow for a short time and then heavily congested till the end of the experiment. Thus *Group1* corresponds to free-flowing traffic, *Group2* to slow traffic, intermediate between free-flowing and congested and *Group3* to congested traffic. The high correlation of the CDFs with traffic state is apparent visually. For e.g., (a) the 50^{th} and 70^{th} percentiles of RSSI are around -93dBm in congestion and -78dBm in free-flow (b) the 20^{th} and 40^{th} percentiles of LQI are around 85 in congestion and 105 in free-flow (c) the 60^{th} and 80^{th} percentiles of reception rate are around 0 packets/sec in congestion and 24 packets/sec in free-flow. Thus the trend of CDFs corresponding to different traffic states differ widely. This shows that this technique has great promise in traffic state classification.

D. Choice of experimentation parameters

Transmit power - CC2420 has 8 discrete power levels . The difference between CDF of metric values with LOS and with NLOS remains similar for the different power levels. Hence choice of transmit power does not seem to be critical. We use the lowest power of -25 dBm in our experiments.

Height from the ground - The body of most vehicles, other than buses and trucks, rises to about 3 feet from the ground. Keeping the sender and receiver pair too high will therefore defeat the purpose of creating NLOS under congestion. Keeping them too low will cause multipath reflection with the road, causing instability in link characteristics. Our initial experimental results remain similar for 1.5 feet and 2 feet from the ground. We use a height of 2 feet from the ground in most experiments.

Distance between sender and receiver - The same experiment, as described in Section IV-A, is also conducted on a narrow road, approximately 8 m wide. Here link characteristics show no difference between LOS and NLOS. This is because, at such small distance, RSSI is so high that NLOS doesn't have much effect even at the lowest transmit power.

To be able to use our technique on narrow roads, we thus decide to put the sender in Position 2 instead of Position 1, as shown in Fig. 6. Thus though d is small, d' will be large, giving good difference in link characteristics between congested and free-flowing states.

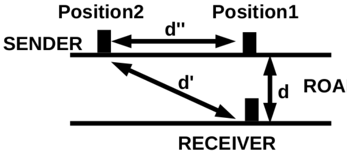


Fig. 6. Distance between sender and receiver

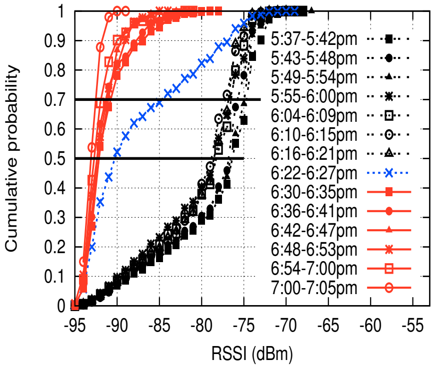


Fig. 3. CDF of RSSI (dBm)

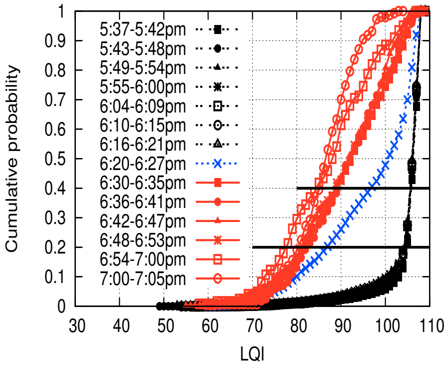


Fig. 4. CDF of LQI

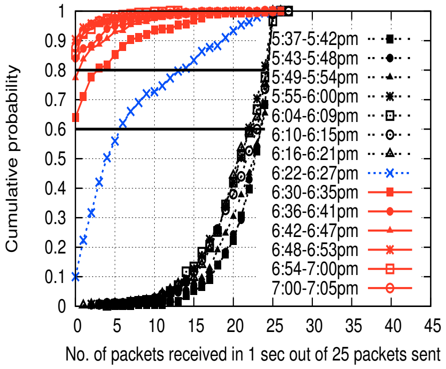


Fig. 5. CDF of Reception Rate

As directly measuring d' is difficult on a busy road with vehicles passing by, we measure d'', as shown in Fig. 6. Keeping the receiver fixed, we moved the sender from d''=5m to d''=40m in steps of 5m and let the receiver log for 5 mins at each sender position. We did this both in free-flowing and congested conditions. The CDF of reception and RSSI, for both traffic states, are shown in Fig. 7 and 8 respectively. We show the plots only for 15m, 20m, 25m and 30m to prevent the figures from getting cluttered.

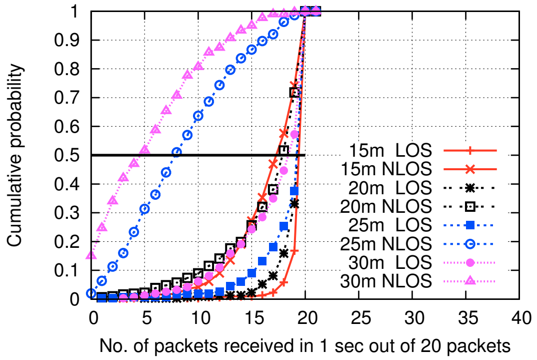


Fig. 7. CDF of Reception Rate

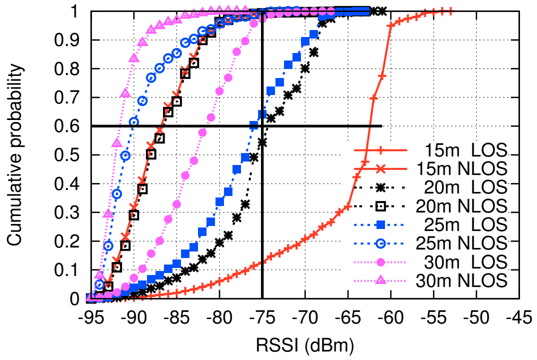


Fig. 8. CDF of RSSI

In Fig. 7, the CDFs in LOS and NLOS are very close for $d'' <= 20m$ and easily distinguishable for $d'' >= 25m$. For eg., 50^{th} percentile reception rate is 8 packets/sec in NLOS and 20 packets/sec in LOS for $d'' = 25m$., while it is about 18 packets/sec in both NLOS and LOS for $d'' = 20m$. Similar results are obtained for CDFs of LQI. Thus any $d'' >= 25m$ seems to be a good choice. When a new unit is placed on an unknown road, the rule of thumb can be to place the sender and receiver in such a way that the 60^{th} percentile RSSI in LOS $<=$ -75dBm. This is marked with black lines in Fig. 8. If this condition holds, then all the three link metrics are expected to degrade under NLOS. We make the rule of thumb in terms of RSSI, instead of distance, because RSSI and other link characteristics are a function of not only distance, but environment too.

We repeat the experiment described in Section IV-A, on the narrow road, with $d'' = 25m$ for 3 days, collecting about 3 hours log everyday. The CDFs obtained are similar to Fig. 3, 4 and 5 and match with manually observed ground truth. We have thus successfully tested our technique on two kinds of real roads: wide as well as narrow.

V. Binary Classification of Traffic States

In this section, we explore how to design a traffic classifier based on our experimental data. The classifier will take as input a 5 minute log from the wireless receiver on the road. It will output a classification of the corresponding 5 mins as having congested or free-flowing traffic. We do not use a third state of slow traffic, intermediate in between the congested and free-flowing states, as that state rarely occured during our experiments and we have very little data corresponding to it. We use decision tree classifier from WEKA, a widely used open source package for machine learning tools [23], as decision trees are known to perform well on datasets with small number of features.

For the narrow road, we have 9 hours 20 mins of data labeled with manually observed ground truth. This gives us 112 logs of 5 minutes each, 66 of which are labeled as congested and 46 as free-flowing. From each log, we compute 3 CDFs of RSSI, LQI and packet reception rate and from each CDF, we compute the 20^{th}, 30^{th}, ..., 90^{th} percentiles. Thus each 5 minute log gives 3 CDFs, each of which gives 8 percentile values, giving 24 values in all. We create a data set for the 112 logs, with the aforementioned 24 values as features and a class label of 1 for congested and 0 for free-flowing traffic, based on ground truth. On

# of *train_test* cases	Decision tree model	Average accuracy (s.d)	# of false positives	# of false negatives
34	lqi_20^{th}percentile <= 94 : 1	97.64%(4.96)	7	1
8	rssi_20^{th}percentile <= -91dBm : 1	90%(0)	0	8
3	rssi_30^{th}percentile <= -89dBm : 1	90%(0)	3	0
3	lqi_20^{th}percentile <= 93 : 1	90%(0)	0	3
2	rssi_40^{th}percentile<= -87dBm : 1	90%(0)	2	0

TABLE I. Decision tree based classification results

this dataset, we repeat the following *train_test* procedure 50 times — (1) randomly order the instances in the dataset, (2) train a decision tree model using 102 instances from the beginning of the dataset as training set, (3) test the decision tree model using remaining 10 instances as test set. The resulting decision tree model (condition : class), with average accuracy in classifying test data and number of false classifications are given in Table I. We define false positive as predicting an instance to be congested (class 1) while it is actually free-flowing (class 0) and false negative as the converse of this.

As seen from the table, out of the 50 *train_test* cases, the same decision tree model of (lqi_20^{th}percentile <= 94 : 1) is built 34 times. This model has 97.64% classification accuracy with only 8 false classifications. In the remaining 16 *train_test* cases, few other models are built, that have lower accuracy than the first model. Thus a simple threshold based classifier based on the rule (lqi_20^{th}percentile <= 94 : 1) will probably give good classification results for traffic states on this road. But we should validate this in future on a much larger dataset. We get similar classification results for another 5 hours of data collected on the wide road, which we do not detail here due to space constraints.

VI. Conclusions and Future Work

In this paper, we show how a simple technique using off-the-shelf hardware can effectively address the complex problem of traffic congestion detection on chaotic roads. The knowledge that wireless links behave badly in absence of LOS already exists. But here we apply that knowledge in a novel way and devise an effective and inexpensive sensing technique. We do 15 hours of on-road experiments, on two different roads in Mumbai, to show the efficacy of the technique in differentiating free-flowing traffic state from congested. The sensing technique is good enough for decision tree of depth only 1 to give above 97% classification accuracy.

Reducing the traffic state classification decision time from 5 minutes is necessary to support real time applications like traffic light time setting. Wi-Fi access points are not common on roads of developing countries. Even in Wi-Fi prevalent areas, our system operating in 2.4 GHz range, has low probability of causing interference, as data volumes are very low. Experimental quantification of the impact of interference would be interesting and prove useful in the solution design. Further, to prevent interference and test sensitivity of link to traffic conditions, we plan to test our technique using sub GHz radios as well. Once we decide on which technology works best, we aim to build customized hardware, that can automate sensing and sending data from road. Overall the technique is simple and effective, and shows enough promise to be studied further.

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