Performance Evaluation and Channel Modeling of IEEE 802.15.4c in Urban Scenarios

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Abstract—**The IEEE802.15.4 is a low-bit-rate wireless communicate standard that enables global inter-connectivity and inter-operability amongst Wireless Personal Area Network (WPAN) transceivers from different manufacturers. It is also considered as the PHY and MAC technology for Wireless Sensor Networks, which can be widely used for sensing, gathering and operating information in future smart cities. In Jan. 2009, the 802.15.4c amendment was approved to address the Chinese regulatory changes which have opened new bands for Wireless PAN using within China. However, the urban environments' impacts over its performance in the new band are still not clear. We demonstrate the viability of using IEEE 802.15.4c in urban scenarios by a series of real field experiments and result analysis. Results show that at 4dBm transmission power over 780MHz channel and with typical antenna setups, the effective transmission range is 200 meters in open scenario, 60 and 40 meters in light and heavy traffic scenarios respectively. We also show that the performance is not affected evidently by the mobility of transceivers up to the speed of 80 km/h. The most important performance factors are the availability of line-of-sight between sender and receiver in urban scenarios. We also use the famous Rappaport channel model for field experimental data fitting, and show that the model is valid even with moving massive reflectors. The empirical data and model fitting will benefit upper layer protocol design based on 802.15.4c in China in the future.**

Keywords- IEEE 802.15.4c, urban scenarios, channel measurement, channel modeling

I. INTRODUCTION

The IEEE 802.15.4c is a standard which specifies the Physical layer (PHY) and the Media Access Control (MAC) layer standard for low-rate wireless personal area networks (LR-WPANs) and works on 779-787 MHz bands using O-QPSK or MPSK in China. Moreover, it can also be used with 6LoWPAN [1] to build a Wireless Embedded Internet Sensor Network, which can be used to sense various physical field parameters such like urban environment and traffic information, etc. IEEE 802.15.4 based Wireless Sensor Networks (WSN) have been widely deployed for urban environment monitoring [2]. Besides traditional static sensor networks, Vehicular Sensor Network (VSN) are also used as a promising technology to improve the coverage of the sensor network with an affordable number of sensors, which take the advantages of vehicle mobility [3-6]. Plural research projects have been conducted using different WSN wireless communication technologies in urban scenarios. In [7], IEEE 802.11b has been selected as the applicable technologies for VSN because it has shown a more stable communication in preliminary tests compared to IEEE 802.11g. However, due to the high energy consumption of 802.11b equipment, it is not favorable for tiny sensors. The FleetNet [8] evaluates location-based addressing and routing schemes and found UTRA TDD to be a more appropriate radio technology for Inter-Vehicular Communications (IVCs) than IEEE 802.11b. New technologies are being standardized for IVCs such as IEEE 802.11p [9], also known as Wireless Access in Vehicular Environments (WAVE). However, WAVE standardization is still under development and there are no off-the-shelf chipsets available for mass deployment.

All the above mentioned projects faced challenges to the PHY+MAC technology arose by the complicated channel characters due to node mobility and channel fading caused by signal reflections and screening [6].

In this paper, we want to prove that IEEE 802.15.4c is also applicable to WSN in urban scenarios, although it was initially designed for low-mobility, indoor environment. Because of the complex nature of urban environments, numerical simulation can hardly reflect a real urban wireless link [10], therefore, we design field experiment to measure the link quality of IEEE 802.15.4c in different typical scenarios so as to provide helpful empirical data sets for our upper-layer protocols design in urban WSN [11]. Our test plans especially focus on the influence of obstacles in the wireless channel between sender and receiver which will lead to loss of line-of-sight as well as moving vehicle nodes' speed. To make the empirical data sets theoretically sound and thus capable for generalization, we use the Rappaport urban channel model for fitting, and find the tuned model shows satisfactory agreement with the measurement data.

This study is part of the MASON project [12], which composes of large number of mobile sensors attached to vehicles that travel in the city and provide data acquisition mechanism for green services. In the MASON system, when two sensors encounter, they exchange data over a short range wireless link, and the data eventually spread out over the entire network. When a sensor goes into the coverage of a base station, all the data it possesses will be uploaded to a server, processed and ported to Internet. In this way, the MASON provides a new method to convey delay-tolerant data traffic with very low power consumption and affordable cost. The

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experiments illustrated in this paper prove the viability of MASON using IEEE 802.15.4c as transmission technology.

This paper is structured as follows. In section II we present the setup and plans of the experiments. In section III, the measurement results are reported and analyzed. The channel model fitting and analysis are presented in section IV. Finally, the paper is concluded with future work in section V.

II. DESCRIPTION OF THE EXPERIMENTS

Fig.1 shows an IEEE802.15.4c-based communicator (referred to as "node" in the rest part of the paper) used in this study. It mainly consists of an MCU of Atmega2561, a radio transceiver of RF212 operating on 780MHz band, and an omni-directional antenna. The transmission is operated on the power level of 4dBm, and the height of both nodes' antenna is set to two meters which is the typical height of cars. The embedded operating system, Contiki [13], is ported in the MCU, with a lightweight TCP/IP and 6LoWPAN protocol stack [14].

In all the experiments, we set one node broadcasting packets continuously, and other nodes monitoring the channel to receive packets. The Packet Receive Rate (PRR) is defined as the link quality metric, which is the ratio of the number of received packets to the number of sent packets. Two typical environments are used for comparison, one is an open field near a light traffic road in Beijing, which is free of any obstacles, and the other is a road with traffic. For the latter case, tests are conducted during different time of the day for variety of traffic flow.

A. Open Scenario

The open field is a new road in the Beijing city. It is one kilometer long, and straight with multiple lanes, which is surrounded by only a few trees. This scenario is used to study the performance of the IEEE802.15.4c communicator without interferences and moving reflectors and obstacles. The impact of node's mobility is also studied in this scenario because of easiness of speed control in this scenario.

B. Urban Scenario

Figure 1. The IEEE802.15.4c-based communicator

An urban road near an industrial park and a road on campus are selected for the heavy traffic scenarios, where line-of-sight (LOS) path between the sender and the receiver is frequently blocked by moving vehicles or bicycles or pedestrians. A series of experiments are conducted to evaluate the influence of obstacles in urban environment to the link quality.

III. RESULTS AND ANALYSIS

The key variables of one-hop communication in urban scenarios during our experiments are Transmit Radius (TR) and PRR. Transmit radius in different scenarios are important because it tells us how far two nodes can establish mutual communication based on IEEE 802.15.4c. PRR provides qualitative analysis of link quality so that we can calculate the effective data throughput over time.

A. Transmit radius

To characterize the empirical link quality on this platform, we measured PRR at many different distances. Fig.2 shows the link quality in the open field experiments by the average value and the variations as a function of distance between the sender and the receiver. As expected, there is a distance, which is about 200 meters, beneath which essentially all packets enjoy good reception for the PRR is always above 80%. We call this distance the Reliable Transmit Radius. There is also a distance, which is about 350 meters, beyond which the communication can hardly be established for the PRR is less than 10%. Between these two thresholds, is the area we call the Reachable Communicate Region, in which the average link quality falls off smoothly. Similar results have also been reported in [15].

Considering the average speed of vehicles in the city is about 40 km/h, it will be about 20 seconds stable communication time. Roughly speaking, in this period, a maximum volume of 250kbps*20sec=625kByte can go through, which is acceptable for low-volume data transfer in the mobile sensor system in cities.

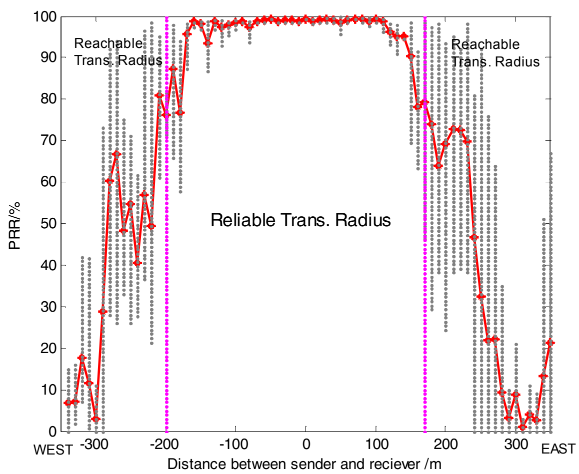

Figure 2. Transmit radius in the open scenario

In urban scenarios, vehicles move on the streets collecting information such as urban temperature, air pollution, etc. Therefore, it is important to know the performance of the IEEE 802.15.4c with the impact of moving obstacles and reflectors.

The influences of different traffic flow to link quality are shown in Fig.3 and Fig.4. These figures show PRR as a function of distance between sender and receiver. Fig.4 shows the results of the first experiment with a slow traffic flow between sender and receiver, which is about 11 vehicles/min/lane, and Fig.4 is the result in heavy traffic flow situation, which is about 19 vehicles/min/lane. Compared to Fig.2, the reliable transmit radius reduces by 140 meters from 200 meters to 60 meters as well as the reachable transmit radius reduces by 100 meters from 300 meters to 200 meters in the slow traffic flow situation. As the traffic grow heavier to 19 vehicles/min/lane, the LOS path becomes impossible. The link quality degrades to 40 meters for reliable transmit radius and 100 meters for reachable transmit radius. In the reachable communication region, the average of the PRR falls off smoothly, but fluctuates enormously, reflecting the fast and deep fading characters of the channel. The transmit radius in different scenarios are summarized in Table I.

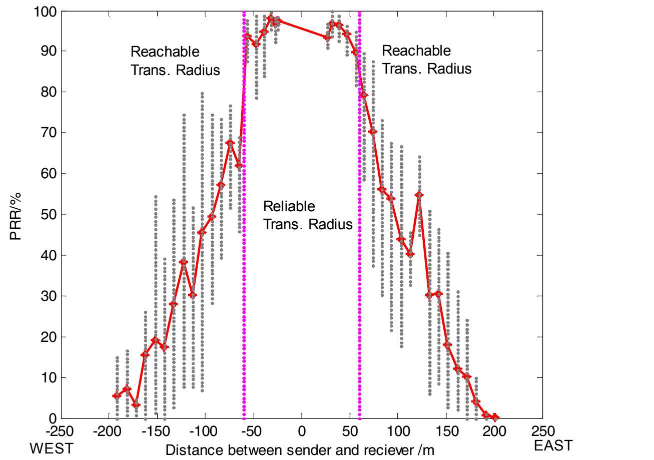

Figure 3. Influence of slow traffic flow (11 cars/min/lan) to link quality

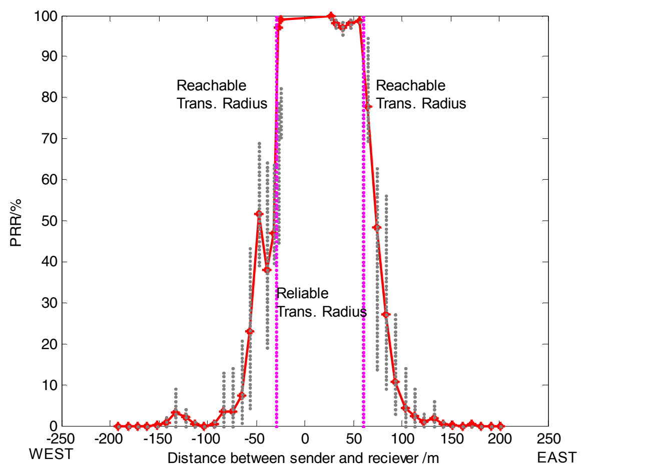

Figure 4. Influence of heavy traffic flow (19 cars/min/lane) to link quality

TABLE I. TRANSMIT RADIUS (IN METER) IN DIFFERENT SCENARIOS

Scenario	***Open Field /m***	***Urban /m (slow traffic)***	***Urban /m (heavy traffic)***
Reliable TR	200	60	40
Reachable TR	350	200	100

We learn that the absence of LOS path reduces both reliable and reachable communication radius significantly, which is an important influence and should be taken into consideration in actual use of IEEE 802.15.4c in urban scenarios.

B. Temporal Analysis of Packet Reception in the Urban Area

Obstacles such as vehicles and bicycles between the sender and the receiver would lead to link quality deterioration. We have done several experiments to find out the impact in a temporal distribution manner. During these experiments, we put the sender node on one side of road and the receiver node on the other side, and then record the packet reception when the road is empty, full of moving cars, and moving bicycles. The height of antenna is about 2 meters, and the distance between sender and receiver fixed on 150 meters.

The PRR declines when there are moving obstacles, although the distance between sender and receiver haven't been changed. Different traffic will lead to different degree of deterioration. We find that the PRR is always above 99% in empty road, and declines to 53% on average when there are moving vehicles on the road, and dramatically to 28% when the line-of-sight is cut off due to the increasing number of vehicles as in Fig.5. The impact of obstacles to the link quality is intermittent, when the LOS path is lost, the Packet Receive Rate decreases dramatically. Table II shows the statistics of the number of packets lost continuously. It's easy to find out that successive two or three packets loss accounts for the largest proportion, and nodes begin to suffer more successive packets loss as the traffic grows heavy. These results also indicate that moving vehicles in the channel can only bring a short-time influence to PRR, but the superposition of these little successive packets loss will lead to worse link quality.

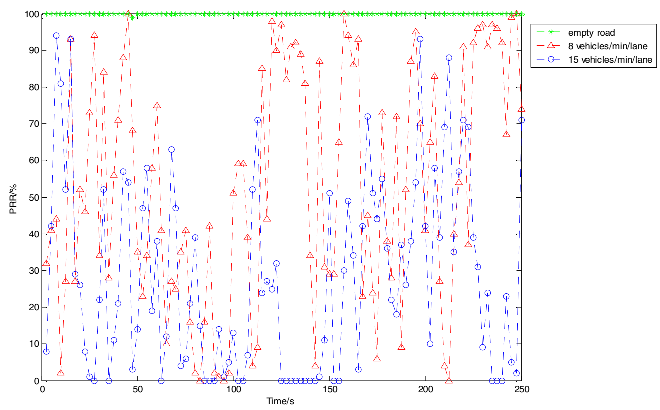

Figure 5. Temporal Analysis of PRR over fading channel in urban scenarios with the influence of moving vehicles

TABLE II. STATISTIC FOR THE NUMBER OF PACKETS LOSING CONTINUOUSLY IN TRAFFIC FLOW

Number of packets	*1 packet*	*2 packets*	*3 packets*	*4 packets*	*5 packets*	*6 packet*	*7 packets*	*8 packets*	*More than 8 packets*
Slow traffic flow	80.13%	8.44%	3.70%	1.35%	1.29%	1.13%	6.40%	5.50%	2.77%
Heavy traffic flow	63.90%	13.04%	7.06%	2.90%	2.39%	1.94%	1.37%	1.44%	6.26%

TABLE III. STATISTIC FOR THE NUMBER OF PACKETS LOSING CONTINUOUSLY INFLUENCED BY MOVING BICYCLES

Number of packets	*1 packet*	*2 packets*	*3 packets*	*4 packets*	*5 packets*	*6 packet*	*7 packets*	*8 packets*	*More than 8 packets*
A few bicycles	96.79%	2.22%	0.41%	0.13%	0.09%	0.04%	0.13%	0.04%	0.15%
Masses of bicycles	70.88%	11.03%	4.66%	3.49%	1.93%	1.27%	1.53%	0.84%	4.37%

These results and analysis are important to know for MAC layer design. To hackle this problem, people need to design a quick data link protocol for data exchange in such situations.

Fig.6 shows the influence of moving bicycles to link quality. Compared to moving vehicles, the influence of bicycles is more subtle. For example, 8 bicycles/min/lane only decreases the PRR by 5% compared to 47% caused by the same density of vehicles. Table III is the statistics for successive packet loss under the impact of bicycles. Loss of more than 3 packets are rather rare in this situation, and nodes begin to lose more packets successively with increasing number of bicycles, but the growth is slower than in the vehicle scenario.

In the urban scenario, high influence of the environment such as vehicles, bicycles, trees, buildings etc. is observed. The numerous moving vehicles or bicycles between sender and receiver produce several times of signal reflections that increase the packet error rate. This produces a dramatic decrease on the transmit radius. Moreover, obstacles in the wireless communicate channel can only bring a transitory influence to PRR, but the superposition of such periods will lead to worse link quality, and bigger obstacles will lead to more successive packets loss as well. Finally, in non-LOS urban situations, the communication could barely be maintained for data exchange.

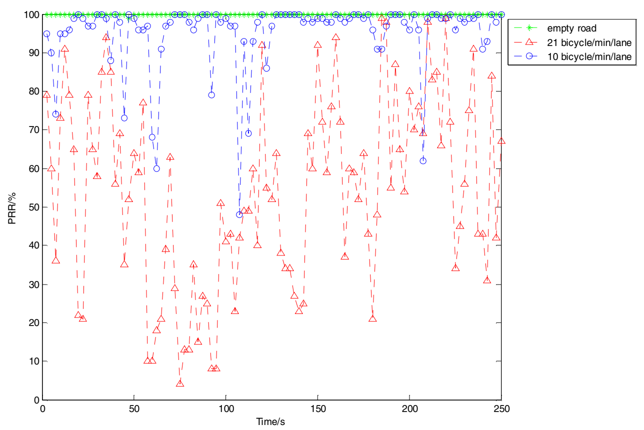

Figure 6. Temporal Analysis of PRR over fading channel in urban scenarios with the influence of moving bicycles

C. *Influence of moving nodes' velocity to Link Quality*

In order to evaluate the impact of the vehicle speed to link quality, we did a series of inter-vehicle communication experiments at the speed of 0, 40, and 60, 80 km/h in the open suburban field away from signal interferences due to the signal reflections produced by buildings, trees or other vehicles. Fig.7 shows the influence of the speed to the link quality. The five curves in different colors show PRR as function to distance with different speeds. They have the same tendency and the thresholds between reliable transmission radius and the reachable transmission range are almost the same in all speed, and they are very close to the thresholds in Fig.2. It means that the mobility is not the major impact factors of link quality. From these results, it can be concluded that the IEEE 802.15.4c with the selected hardware configuration allows the communication between vehicles travelling with relative speeds up to 80 km/h and with distances up to 300m in LOS situations.

IV. Channel Modeling

In this section, the model and simulation of wireless channels is shown. We calculate the PRR as a function of distance between sender and receiver in different environments according to channel model.

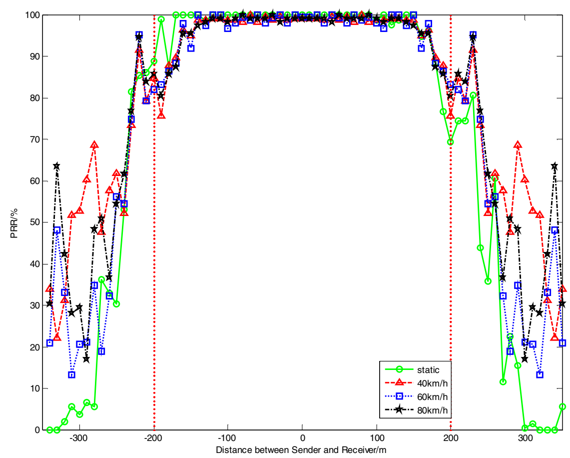

Figure 7. Influence of moving vehicle nodes' speed to link quality

Rappaport's widely acknowledged wireless channel model that has been demonstrated through measurements [16] uses the parameter n to denote the different power law relationship between distance and received power in different environments. This model is formulated as following

$$\mathrm{PL}(d) = PL(d_0) + 10n\log(d / d_0) + X_\delta \qquad \text{(a)}$$

, where PL (Path Loss) denotes the local average receiving power relative to the transmit power. The term PL (d_0) simply gives PL at a certain reference distance d_0 and X_δ stand for a zero mean Gaussian random variable that reflects the variation in average received power that naturally occurs when a PL model of this type is used. The n equals to 2 in the free space without interference, and is generally higher for practical wireless channels. The other path loss exponent measured in different environment can be found in [17]. But there are little measurements as well as analysis in urban scenarios. Combined with the real field measurement results in our environments, we want to find out the path loss exponent n in these two typical scenarios.

With the knowledge of transmit power and the pass loss, we can derive the received signal strength at each spot of the measured channel with the formula $P_r = P_t - PL$. From our measurements and other research results, we assume the environment noise in urban areas is 80dBm. So the Signal to Noise Ratio can be calculated as $SNR = P_r - P_n$. Since the nodes in our experiments use the spread-spectrum technology according to IEEE 802.15.4c, we also have to take the spread-spectrum gain into account. Through the model-based calculation, the Bit Error Rate (BER), Ps, is calculated by considering the channel as in Rician Fading. And, the PRR, Ps, can be derived using the formula $P_s = (1 - P_b)^l$, where l is the length of the packet, meaning one bit of error will destroy the packet, which is true for IEEE 802.15.4c because the absence of channel coding.

In Fig.8, the black curve is the theoretical result when n = 4, and it agrees perfectly with the red curve, the real field test results in the open environment. Reflections from the surface of the road as well as trees produce reflections that may interfere constructively or destructively at receiver.

Moving vehicles between sender and receiver will cut off the LOS path, diffraction occurs even though the radio path is obstructed accompany with none line-of-sight. This phenomenon is also called "shadowing", because the diffracted field can reach a receiver even when it is shadowed by an obstruction.[16] In order to model this type of influence caused by shadowing, we choose the heavy traffic flow, where about 19 vehicles/min/lane is presented. Fig.9 is the simulation results, with n = 4.8, in which the theoretical results agrees with the empirical data satisfactorily.

Although in open suburban environment, influence due to reflections produced by the surface of the road and other things will make path loss exponent n increase to 4. Heavy traffic with massive vehicles leads to a steep decrease of the signal strength and the path loss exponent is around 5 in our model fitting.

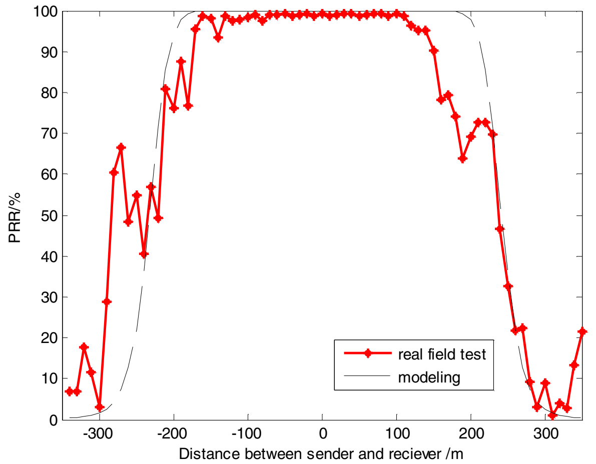

Figure 8. Simulation results for open suburban scenario

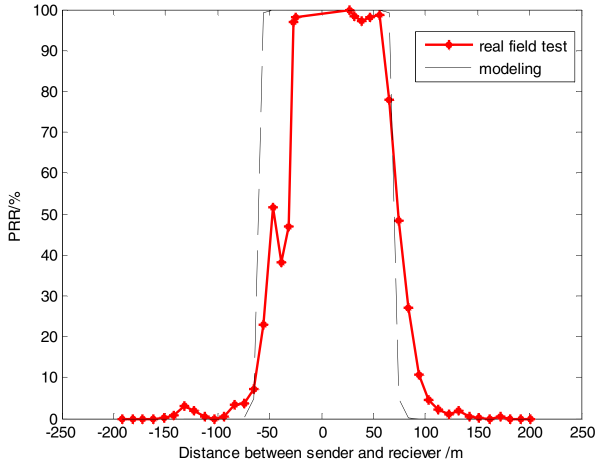

Figure 9. Simulation results for urban scenario

V. CONCLUSIONS AND FUTURE WORK

In this paper, we present results of comprehensive measurements to evaluate the performance of the IEEE 802.15.4c in urban scenarios. Although IEEE802.15.4c was designed for low-mobility, low power consumption and indoor scenarios, we demonstrate that it is possible to use it in the high-mobility, outdoor urban scenarios. We show that the velocity up to 80km/h has negligible impacts on performance. And the most important performance factor is the availability of line-of-sight between sender and receiver which is frequently blocked by moving vehicles or bicycles or pedestrians in urban scenarios. The loss of line-of-sight may lead to intermittent communication cut-off and reduce both reliable and reachable transmit radius, which is an important influence and should be taken into consideration in practice usage of the IEEE 802.15.4c. This paper will hopefully serve as guidelines for implementation of the IEEE 802.15.4c in urban WSNs and develop realistic channel models for urban scenarios.

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