Feasibility of In-car Wireless Sensor Networks: A Statistical Evaluation

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Abstract—Statistical characterization of in-car wireless communication channels has recently gained significance, mainly due to the possibility of deploying a wireless sensor network in the vehicle. In this paper, we report different aspects of a statistical analysis of four representative in-car wireless channels based on the received power data collected from a BPSK transmission experiment. It is shown that the communication channel between the base station and a sensor placed under the engine compartment is the worst in terms of stability, average fade duration, and fade proportion, while the channel between the base station and a sensor placed in the trunk and the channel between the base station and a sensor placed on the hood are the best. We also show that the 4 representative in-car wireless channels can satisfy the maximum packet delay requirement of less than 500 ms and the Trunk channel and the In-the-Engine-compartment channels can satisfy the requirement of up to 98% packet reception rate. These statistical characteristics of the in-car wireless channels provide important guidelines for the designer of an in-car sensor system.

I. INTRODUCTION

The number of sensors in the car has increased significantly over the past few years, mainly due to various safety and convenience applications. Currently, the sensors and the microprocessor in a car communicate over a serial data bus and are connected with physical wires. The most significant problem of the current wired architecture is scalability \cite{1}\cite{2}, resulting in the emerging need to develop an in-car wireless sensor network to provide a flexible open architecture to incorporate hundreds of sensors which will be installed in future cars.

Detailed studies on in-car wireless channels are essential for designing the underlying communication system for an in-car wireless sensor network. Among different components of the characterizations of the wireless channel, statistical characterization is crucial. This is because of the fact that the results of statistical characterization can alleviate the most common skepticism about replacing wires with wireless technology: the misconception that wireless links may not be as reliable as wires. Specifically, in this paper we define wireless communication reliability via the following two performance
metrics: packet reception rate and maximum packet delay. When implementing the car sensor system, the designer specifies the level of reliability in terms of the aforementioned two metrics according to the sensor specifications. Statistical characterization can be used to verify that the required level of reliability in different scenarios can be satisfied, as well as to determine the amount of additional transmitting power needed. In this paper, we report the statistical characterization of 4 representative in-car wireless channels on the basis of the results of received power measurements in a BPSK transmission experiment performed at 915 MHz.

II. THEORETICAL BACKGROUND

The main problem investigated in this paper is: what is the level of reliability which can be provided by the in-car wireless channels in terms of packet reception rate and maximum packet delay? In this section, we provide the theoretical background necessary for answering this question.

The time variations of the received power are usually caused by the changes in the transmission medium or paths. These can be further categorized into large-scale fading and small-scale fading. Large-scale fading includes factors such as path losses and shadowing effects. Since the locations of the base station and the sensor nodes are fixed in an in-car wireless sensor network, large-scale fading does not contribute much to the time variations of the received power.

Small-scale fading is used to describe the rapid fluctuation of the received power over a short period of time [3]. It is caused by the interference between multiple versions of the transmitted signal which arrive at the receiver at slightly different times. Three different propagation mechanisms can happen between the antennas of the transmitter and receiver in the car [4]: i) Reflection occurs when an electromagnetic signal encounters a surface that is large relative to the wavelength of the signal. ii) Diffraction occurs at the edge of an impenetrable body that is large compared to the wavelength of the radio wave. When a radio wave encounters such an edge, waves propagate in different directions with the edge as the source. iii) Scattering occurs if the size of an obstacle is on the order of the wavelength of the signal or less, and an incoming signal is scattered into several weaker outgoing signals. Signals propagating through different paths arrive at the antenna of the receiver with different amplitude, phase, and time. These different versions of signals can interfere either constructively or destructively with each other. In an in-car wireless sensor network, both the locations of the antennas of the transmitter and the receiver are fixed. However, the locations of the obstacles, i.e., the reflectors, scatterers, etc., change with time and hence create changes of the propagating paths between the antennas of the transmitter and the receiver. These changes result in the time variations of the received power. Note that the power of diffraction and scattering signals are usually much smaller than the power of the signal propagating through line-of-sight path, and hence diffraction and scattering have minor effects when a line-of-sight signal is present.

Generally speaking, the fading distributions of wireless channels can be characterized into two distribution functions: Ricean and Rayleigh distributions [5]. The small-scale fading envelope distribution is Ricean when there is a dominant stationary signal component present, such as a line-of-sight propagation path. In such a situation, random multipath components arriving at different angles are superimposed on a stationary dominant signal. Due to the a large number of multipath components, central limit theorem can be applied and the sum of these random components can be approximated by the Gaussian distribution. The Ricean distribution is given by

$$p(r) = \frac{r}{\sigma^2} e^{-\frac{r^2 + A^2}{2\sigma^2}} I_0\left(\frac{Ar}{\sigma^2}\right)$$  \hspace{1cm} (1)$$

where $r$ is the received signal amplitude, $A$ is the peak amplitude of the dominant signal, and $I_0(\cdot)$ is the modified Bessel function of the first kind and zero-order. As the dominant signal becomes weaker and comparable to other random multipath components, the distribution will degenerate to a Rayleigh distribution, which is given by

$$p(r) = \frac{r}{\sigma^2} e^{-\frac{r^2}{2\sigma^2}}.$$  \hspace{1cm} (2)$$

The Ricean distribution can be described in terms of a parameter $K$ which is defined as the ratio between the deterministic signal power and the variance of the
The Rayleigh distribution can be considered as a special case of the Ricean distribution with $K = -\infty$. One would expect that the in-car wireless channels with strong line-of-sight signals (such as the channel between the base station placed in the passenger compartment and a sensor node placed on the hood or in the trunk) to follow the Ricean distributions while the others without line-of-sight signals to follow the Rayleigh distributions (such as the channel between the base station placed in the passenger compartment and a sensor node placed in the engine compartment or under the engine compartment). However, due to the complex environment created by a large number of parts inside the car, conventional wisdom may not apply. The actual distributions need to be obtained by analyzing the experimental data.

The fading distribution of the channel can be used to determine the packet reception rate. Assume that the packet size is small and the BER is uniform for the whole packet. The packet reception rate is then given by

$$P_{RR} = 1 - \int_0^\infty p(r) \cdot PER(r) dr$$

(4)

where $p(r)$ is the received power probability distribution function (PDF) and $PER(r)$ is the packet error rate function given that the received power is equal to $r$. Note that low received power results in high PER. Hence, the probability of low received power dictates the packet reception rate.

However, determining the fading distribution from the experimental data is hard because a large number of received power values is needed. Instead of the distribution, one only needs to know the probability of low received power, i.e., fade proportion, which is easier to determine with smaller sets of data. Fade proportion is defined as the proportion of time in which the received signal power is below a certain threshold. To use fade proportion to determine the packet reception rate, we need an additional assumption which states that the Forward Error Correction (FEC) code used by the sensor node can correct up to a certain percentage of errors. If the received power threshold is defined in a way such that the FEC code can correct all errors if the received power is higher than the threshold, then the fade proportion that corresponds to this threshold is exactly the packet reception rate.

For example, assume that the Forward Error Correction (FEC) code used by the sensor node can correct up to 0.1% of errors and the BPSK modulation is used. Let $P_{FEC}$ denote the received power threshold. $P_{FEC}$ can be determined by mapping a BER of $10^{-3}$ to the corresponding received power value, which is -67.665 dBm (see Figure 2). The received power value larger than the threshold is considered as reliable received power. In this case, the packet reception rate is the fade proportion corresponding to the threshold, -67.665 dBm, and is equal to 2.3% (see Figure 1). If a higher level of reliability is required or the error-correcting capability of the FEC code is weaker, then the received power threshold has to be increased.

Another important performance metric is the maximum packet delay which can be tolerated by the in-car sensor system. To quantify this metric, the time period in which the received power continuously stays below a certain threshold, i.e., fade duration, needs to be determined. With the aforementioned assumption, the packet cannot be successfully received when the received power drops below the threshold determined by the FEC code. Hence, the maximum packet delay which can be supported by the channel is the fade duration corresponding to that threshold.

If the probability distribution of received power when using a lower transmitting power setting is known, what can we say about the probability distribution or statistical characteristics when using a higher transmitting power setting? The average received power is primarily determined by the line-of-sight signal or the reflected signals, which are proportional to the transmitting power, and hence the K value is higher when the transmitting power is higher. The probability of low received power is lower when having a higher K value. Hence, one can conclude that, in terms of statistical characteristics the channel is worse when using lower transmitting power. The statistical characteristics of the channel when using lower transmitting power can serve as a lower bound of the statistical characteristics of the channel when using
TABLE I
THE SPECIFICATIONS OF THE Omni-DIRECTIONAL ANTENNA

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value/Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>824-960 MHz</td>
</tr>
<tr>
<td>Gain</td>
<td>5 dBi</td>
</tr>
<tr>
<td>VSWR</td>
<td>2.0</td>
</tr>
<tr>
<td>Polarization</td>
<td>Vertical</td>
</tr>
</tbody>
</table>

TABLE II
THE SETTINGS OF THE SIGNAL GENERATOR

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value/Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulation</td>
<td>BPSK</td>
</tr>
<tr>
<td>Symbol Rate</td>
<td>300 KHz</td>
</tr>
<tr>
<td>Center Frequency</td>
<td>915 MHz</td>
</tr>
<tr>
<td>Filter</td>
<td>Square-root Raised Cosine ($\alpha = 0.1$)</td>
</tr>
<tr>
<td>Bit Sequency</td>
<td>Pseudo Random Bit Sequency (15 bits)</td>
</tr>
<tr>
<td>Power Level</td>
<td>0, -10, -20, -30, -40 dBm</td>
</tr>
</tbody>
</table>

higher transmitting power.

III. EXPERIMENTAL SETUP

In this paper, we assume that a master-slave type of in-car sensor network, i.e. a star topology, is used. In this scenario, all sensor nodes directly transmit the packets to the base station. One omni-directional antenna (see Table I for specifications of the antenna), representing the antenna of the base station, is placed on the ceiling of the passenger compartment and is right above the driver’s head. The other omni-directional antenna is placed in different locations in the car to represent the communication channels in the following cases: (i) channel to/from a sensor node on the hood (two locations, H1 and H2); (ii) channel to/from a sensor node in the trunk (TR); (iii) channel to/from a sensor node inside the engine compartment (two locations, IE1 and IE2); and (iv) channel to/from a sensor node under the engine compartment (UE).

The experiment was performed in a ’96 General Motors Buick LaSabre car parked in a parking lot at Carnegie Mellon University in Pittsburgh, Pennsylvania. The car was turned off and kept static throughout the whole measurement period. Cars and people were sometimes passing by when we were performing the measurements.

Figure 4 shows the block diagram representing the experimental setup. The signal generator was configured to transmit a BPSK signal (see Table II for the settings of the signal generator) centered at 915 MHz. The signal in turn propagates through the connecting cable, the transmitting antenna, the wireless channel, the receiving antenna, the connecting cable, and is finally received by the real-time spectrum analyzer.

The reason for using a BPSK signal in the experiment is that it is more realistic compared to an impulse signal, i.e., it occupies and utilizes a certain amount of bandwidth. On the other hand, the traditional frequency sweep channel sounding method requires a certain amount of time to sweep through the measuring frequency band and relies on the unverified assumption that the channel coherence time is larger than the time to complete the sweep. Moreover, a BPSK signal is representative in the sense that it is the simplest modulation format and might be suitable for an in-car sensor network with low power consumption requirement. Since most of the sensors have data rates up to a few hundred kilo bits per second, we choose a reasonable value, 500 KHz\(^1\), as the symbol rate of the BPSK signals in the experiment.

For each transmitting power setting/wireless channel pair, the BPSK signal was transmitted for 5 minutes. The real-time spectrum analyzer recorded the waveform in time domain and arranged it in frames. Blackman window function \([7]\) was applied to each frame and an FFT was performed to convert the data into frequency domain. Then received power was calculated by summing the power values over the 500 KHz bandwidth centered at 915 MHz. The final data we got is a vector of received power values representing the received power values over this 5-minute period.

IV. RESULTS AND DISCUSSION

A. General Observation

Figure 3 shows the received power waveforms with different transmitting power settings when the antenna of the receiver was placed in the trunk (the TR channel). The received power are normalized, shown with respect to mean value (in dB), and plotted using the same y-axis scale.

Inspection of the plots in Figure 3 reveals that the variations caused by random multipath components are relatively larger (in dB) when the total received power is smaller (which implies that the dominant stationary signal is smaller). The same conclusion also applies to the other channels and is in agreement with what we expected. For instance, consider a channel which has a variation with average power equal to -80 dBm and the total received power is -50 or -70 dBm. In the case with higher total received power, the effect of the variation is

\(^1\)The data rate for an individual sensor in current cars ranges from 1 Kbit/s to 100 Kbit/s. Since the bandwidth is shared by all sensors in the car, 500 Kbit/s seems to be a reasonable data rate for an in-car wireless sensor node. Hence, the symbol rate of the BPSK signal should be $500\, \text{Kbps} / 1\, \text{symbol} = 500\, \text{Kbps}\, \text{symbol}$. UHF Passive RFID technology, which is one of the options for in-car wireless sensor network, also uses 500 KHz of bandwidth [6].
only $-50 - 10 \times \log_{10}(10^{-5} - 10^{-8}) = 0.0043$ dB. On the other hand, the effect of the variation is much larger in the case of lower total received power; $-70 - 10 \times \log_{10}(10^{-7} - 10^{-8}) = 0.4576$ dB.

Since the same level of variation creates different level of effects for different received power levels, it is necessary to choose and compare sets of data with close average received power when performing analysis. The data sets we chose to compare is summarized in table III. Among all data sets with different transmitting power settings, these are the data sets with the lowest average received power above -80 dBm, which is a typical receive sensitivity threshold for the radio receiver of a wireless sensor node.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Transmitting power</th>
<th>Averaged received power</th>
</tr>
</thead>
<tbody>
<tr>
<td>H2</td>
<td>-30 dBm</td>
<td>-71.40 dBm</td>
</tr>
<tr>
<td>TR</td>
<td>-20 dBm</td>
<td>-72.80 dBm</td>
</tr>
<tr>
<td>IE1</td>
<td>-10 dBm</td>
<td>-74.11 dBm</td>
</tr>
<tr>
<td>UE</td>
<td>0 dBm</td>
<td>-67.31 dBm</td>
</tr>
</tbody>
</table>

B. Temporal Correlation

Temporal correlation is a method to measure the degree to which the data, separated by some amount of time, are linearly related. Here we assume that the stochastic process representing the received power is wide-sense stationary. The correlation of amplitude fading between data points separated by $\Delta t$ can be numerically calculated by the correlation coefficient function, $\rho(\Delta t)$, which is given by

$$\rho(\Delta t) = \frac{E\{[a(t + \Delta t) - E[a(t + \Delta t)][a(t) - E[a(t)]]\}}{\sqrt{Var[a(t + \Delta t)]Var[a(t)]}}$$

(5)

where $a(t)$ is amplitude at time $t$ and $E[\cdot]$ and $Var[\cdot]$ denote the expected value and the variance of $\cdot$, re-
Fig. 7. Average fade duration of each channel. Only the thresholds below 0 dB are shown. The curves of TR and H2 stop between -1 and -0.5 dB because the received power values of these two channels never drop below these thresholds.

![Graph showing average fade duration](image)

**TABLE IV**

<table>
<thead>
<tr>
<th>Channel</th>
<th>Upper Bound of Coherence Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>25 s</td>
</tr>
<tr>
<td>TR</td>
<td>5 s</td>
</tr>
<tr>
<td>IE</td>
<td>12 s</td>
</tr>
<tr>
<td>UE</td>
<td>25 s</td>
</tr>
</tbody>
</table>

channel crosses a given value in the positive direction. Figure 6 shows the average LCR calculated with the thresholds ranging from -3 dB to 3 dB (on a scale with respect to mean). The LCR curve for the UE channel is more scattered compared to the other channels while the TR channel has the most concentrated LCR curve. This means that the received power of the TR channel has less fluctuations than other channels.

Figure 7 shows the average fade duration (AFD) calculated for each data record and different threshold levels. The AFD corresponds to the average of time duration in which received power continuously stays below a threshold, which can be interpreted as the time that the sensor node stays in continuous outage. It was shown that the performance of indoor communication systems is sensitive not only to LCR values but also to AFD level [8] which might also be true in the case of in-car wireless communications.

It is essential to know both the LCR and AFD of the channels when designing an in-car sensor system. High LCR value when the difference between the mean and the threshold is large implies that the channel is highly unstable and the channel condition changes in a relatively short amount of time. For instance, from the LCR curves in Figure 6 one can observe that the UE channel is the most unstable channel and it would be harder for the communication system to quickly adapt to the channel conditions. On the other hand, AFD quantifies the period of time in which the sensor packets cannot be delivered to the microprocessor in the car, i.e., the maximum delay of the sensor packet. One can observe that the UE channel has the worst performance in terms of AFD, which implies the longest delay for the sensor packet.

**D. Fade Proportion Statistics**

Fade proportion measures the proportion of time in which received power is below a certain threshold. As discussed in previous subsection, the data points in the data set are not entirely independent. It is necessary to extract and consider only the data points that are independent. Hence, in each data set, the data points that are separated by the corresponding upper bound of coherence time in Table IV are selected and fade proportion is then computed. In addition, the confidence interval is calculated for each threshold level/data set. The 95% confidence interval for a proportion, p, is given by \((p - 1.96 \times \sqrt{\frac{p(1-p)}{n}}, p + 1.96 \times \sqrt{\frac{p(1-p)}{n}})\), where p is proportion of time in which received power is below the threshold, and n is total number of the samples [9]. Figure 8 shows fade proportion and its confidence interval calculated with the thresholds ranging from -3 dB to 3 dB.

**C. Level Crossing Rates and Average Fade Duration**

Level crossing rate (LCR) is defined as the number of times per unit duration in which the envelope of a fading event crosses a given value. In this context, it is used to determine the proportion of time in which received power crosses a threshold, which can be interpreted as the time that the sensor node stays in continuous outage. It was shown that the performance of indoor communication systems is sensitive not only to LCR values but also to AFD level [8] which might also be true in the case of in-car wireless communications.

Traditionally, coherence time is defined as the time over which the time correlation function is above 0.5 [3]. Here we use a more conservative value.
Inspection of Figure 8 reveals that the UE channel has the most scattered plot among all the channels, and hence is the most hostile channel. H and TR have concentrated plots, representing good channels, and the received power rarely falls below -0.5 dB with respect to mean. Note that due to the large coherence time value and hence the low number of “independent samples” of the UE channel, the confidence interval on Figure 8(d) is larger than the ones in other plots. This implies that we need to perform more measurements for the UE channel to obtain a fade proportion curve with smaller confidence interval to better quantify the fade proportion.

E. Fading Distribution

Empirical cumulative distribution functions (CDF) for each transmitting power/channel pair were obtained and tested against five theoretical fading distributions, i.e., Rayleigh, Lognormal, Nakagami, Rice, and Weibull [8] distributions.

The maximum likelihood test (ML) is used to obtain the best fit parameters for each distribution. Then, Mean Square Error (MSE) metric is used to measure the distance between the empirical distribution and the estimated theoretical distribution. The estimated distribution that is closest to the empirical distribution, i.e., has the smallest MSE, provides the best fit for the data. The best-fitted distributions are shown in Table V and plotted in Figure 9. Ricean and Nakagami distributions seem to be the best fit for all channels except the UE channel, for
which the best fit is the Weibull distribution. Another metric of interest is the K-factor value [10]. As expected, higher average received power provides a larger K-factor value, as shown in Table VI. In addition, the corresponding K-factors of the chosen data sets are highlighted in Table VI. The results show that the TR channel has the highest K-factor while the UE channel has the lowest. This supports the results in the previous subsections, which state that the TR channel is the most stable channel and has the smallest fluctuations while the UE channel is the most unstable one and has the largest fluctuations.

V. FEASIBILITY EVALUATION

In this section, we evaluate the feasibility of implementing an in-car wireless sensor network from a statistical point of view. To be more specific, we investigate whether the requirements of packet reception rate and maximum packet delay, which are determined by the specifications of the sensors, can be fulfilled by the statistical characteristics of the in-car wireless channels.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Assumed Value</th>
<th>Typical Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Required Pkt Reception Rate</td>
<td>98%</td>
<td>Not Available</td>
</tr>
<tr>
<td>Required Maximum Delay</td>
<td>500 ms</td>
<td>0.016 - 1000 ms</td>
</tr>
<tr>
<td>Packet Size</td>
<td>125 Bytes</td>
<td>1 - 125 Bytes</td>
</tr>
<tr>
<td>FEC Correcting capability</td>
<td>0.1%</td>
<td>Not Available</td>
</tr>
<tr>
<td>Noise Power</td>
<td>-75 dBm</td>
<td>Not Available</td>
</tr>
</tbody>
</table>
A. Packet Reception Rate

One can utilize the results of fade proportion shown in subsection IV-D to obtain an upper bound on the transmitting power which satisfies the packet reception rate requirement. For example, for the IE channel one can conclude that the probability that the received power is less than 1.5 dB below the average received power is less than 2%. Hence, to achieve 98% packet reception rate, the average received power has to be at least \( P_{FEC} + 1.5 = -67.665 + 1.5 = -66.165 \text{ dBm} \) so that more than 98% of the time the received power is larger than \( P_{FEC} \). The pathloss of the IE channel is given by \( PL = P_{RX} - P_{TX} = -74.11 - (-10) = 64.11 \text{ dB} \). The transmitting power can then be determined by \( P_{TX} = P_{RX} - PL = -69.165 - (-64.11) = -2.055 \text{ dBm} \). Inspection of Figure 10 reveals that there is sufficient evidence in our analysis to show that the in-car wireless channels can support 86%, 98%, 99%, and 90% of packet reception rate for the H, the TR, the IE, and the UE channels, respectively, with less than 2 dB of additional transmitting power. This shows that the TR and the IE channels are good enough to support most of the in-car sensor applications while more experimental data is needed for the H and the UE channels to have a smaller confidence interval and obtain a bound of higher packet reception rate.

In [11], we have proposed the use of passive RFID technology for in-car wireless sensor systems. A passive RFID tag has a requirement of having the received power higher than the “chip sensitivity” threshold, which is the minimum received RF power required to turn on the chip inside the passive RFID tag. Chip sensitivity is primarily determined by RF front end architecture and fabrication process [12][13]. The typical value of the chip sensitivity of UHF passive RFID tags is -15 to -25 dBm [14], which is much higher than \( P_{FEC} \), determined by the FEC code error-correcting capability. Hence, the chip sensitivity dominates \( P_{FEC} \) and should be used to obtain an upper bound on the optimum transmitting power with the same method described previously. Note that the obtained bound will be loose and too pessimistic. The reason is that the required average received power is much higher than the average received power of our selected data set, which is used for the fade proportion analysis. When transmitting power is higher, the fade proportion plot is more concentrated (see section II) and represent a better channel condition. The optimum transmitting power is lower in this case. To obtain a tighter bound, additional experimental data measured with higher transmitting power will be needed.

The method to obtain an upper bound on the optimum transmitting power which can satisfy the requirements of the in-car sensors is also shown. Table VII lists typical values of the specifications of in-car sensors, as well as the assumed values which are used in the following discussions.

According to the conclusions in section II, the statistical properties are worse when the transmitting power is lower. Hence, we will be able use previous analysis results to obtain an upper bound on the optimum transmitting power when the transmitting power is higher than the setting of the selected data sets (shown in Table III).

Theoretical BPSK BER curve\(^3\) is shown in Figure 2. The black line in the figure shows the threshold (\(P_{FEC}\)) of the received power which results in \(\text{BER}=10^{-3}\). In this analysis, we assume that the Forward Error Correction (FEC) code used by the sensor node can correct up to 0.1% of errors, and hence any received power value larger than \(P_{FEC}\) is sufficient. With our assumptions, \(P_{FEC} = -67.665 \text{ dBm}\).

To calculate the appropriate transmitting power when average received power is given, the pathloss of the channel is needed. The Pathloss (in dB), \(PL\), is given by \(PL = P_{RX} - P_{TX}\), where \(P_{RX}\) is the average received power and \(P_{TX}\) is the transmitting power.

\(^3\)The noise is assumed to be AWGN.
B. Maximum Packet Delay

Maximum packet delay is determined by the specifications of the in-car sensors. It is defined as the maximum packet delay that the in-car microprocessor can tolerate for particular sensor. Instead of average fade duration results shown in subsection IV-C, we establish 95% and 99% confidence intervals with the assumption that each fade duration value is independent of others. The upper bounds of the confidence intervals for each channel are shown in Figure 10.

Here we use the UE channel as an example to illustrate the method to obtain the upper bound of the optimum transmitting power. Figure 10(d) shows that the received power can stay lower than 1.5 dB below the average received power for up to 500 ms. The average received power needs to be at least 1.5 dB higher than $P_{FEC}$ so that the maximum packet delay, i.e., the time that the received power continuously stays below $P_{FEC}$, can be smaller than the maximum packet delay requirement, 500 ms. The average received power is given by $P_{RX} = P_{FEC} + 1.5 = -67.665 + 1.5 = -66.165$ dBm. The pathloss of the UE channel is given by $PL = P_{RX} - P_{TX} = -67.31 - 0 = -67.31$ dB. Finally, the transmitting power can be determined by $P_{TX} = P_{RX} + PL = -66.165 - (-67.31) = 1.145$ dBm.

In Figure 10, the smallest threshold value corresponds to the smallest fade duration value, which is also the smallest maximum packet delay value that can be satisfied by each channel. Hence, one can conclude that there is sufficient evidence to show that the H, the TR, the IE, and the UE channels can support maximum packet delay of 130, 170, 310, and 360 ms, respectively. To summarize, the maximum packet delay requirements of most in-car sensors can be satisfied at the expense of a small amount of additional transmitting power.

VI. Conclusion

In this paper, we have performed a statistical analysis based on the data measured for received power with 4 representative in-car wireless channels collected from a BPSK transmission experiment. Among all the channels, UE is the most unstable channel, and has the largest average fade duration and largest probability of low received power. TR and H channels are the best channels in terms of the same metrics. We have also shown that the Weibull distribution provides a reasonable fit to the empirical distribution of the UE channel while Ricean distribution provides a good fit to the empirical distributions of all other channels. The feasibility study conducted shows that the TR and the IE channels can support at least 98% packet reception rate of the sensors while all the 4 in-car wireless channels considered can support the required maximum packet delay of less than 500 ms. The statistical results obtained in this study have important implications in terms of the feasibility of a wireless sensor network in cars: depending on the level of reliability targeted for different applications, they show which sensors can be accessed wirelessly and for which sensors this might be more troublesome. This points to a possible hybrid in-car sensor network where some sensors are accessed wirelessly while others are accessed via wires. An alternative direction is the use of stronger FEC and/or transmit power and/or automatic repeat request (ARQ) techniques for an all-wireless in-car sensor network. Further research is needed to quantify the tradeoffs involved in the latter direction.

REFERENCES