Security and Privacy Vulnerabilities of In-Car Wireless Networks: A Tire Pressure Monitoring System Case Study

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Abstract

Wireless networks are being integrated into the modern automobile. The security and privacy implications of such in-car networks, however, have are not well understood as their transmissions propagate beyond the confines of a car's body. To understand the risks associated with these wireless systems, this paper presents a privacy and security evaluation of wireless Tire Pressure Monitoring Systems using both laboratory experiments with isolated tire pressure sensor modules and experiments with a complete vehicle system. We show that eavesdropping is easily possible at a distance of roughly 40m from a passing vehicle. Further, reverse-engineering of the underlying protocols revealed static 32 bit identifiers and that messages can be easily triggered remotely, which raises privacy concerns as vehicles can be tracked through these identifiers. Further, current protocols do not employ authentication and vehicle implementations do not perform basic input validation, thereby allowing for remote spoofing of sensor messages. We validated this experimentally by triggering tire pressure warning messages in a moving vehicle from a customized software radio attack platform located in a nearby vehicle. Finally, the paper concludes with a set of recommendations for improving the privacy and security of tire pressure monitoring systems and other forthcoming in-car wireless sensor networks.

1 Introduction

The quest for increased safety and efficiency of automotive transportation system is leading car makers to integrate wireless communication systems into automobiles. While vehicle-to-vehicle and vehicle-to-infrastructure systems [22] have received much attention, the first wireless network installed in every new vehicle is actually an in-vehicle sensor network: the tire pressure monitoring system (TPMS). The wide deployment of TPMSs in the United States is an outgrowth of the TREAD Act [35] resulting from the Ford-Firestone tire failure controversy [17]. Beyond preventing tire failure, alerting drivers about underinflated tires promises to increase overall road safety and fuel economy because proper tire inflation improves traction, braking distances, and tire rolling resistance. These benefits have recently led to similar legislation in the European Union [7] which mandates TPMSs on all new vehicles starting in 2012.

Tire Pressure Monitoring Systems continuously measure air pressure inside all tires of passenger cars, trucks, and multipurpose passenger vehicles, and alert drivers if any tire is significantly underinflated. While both direct and indirect measurement technologies exist, only direct measurement has the measurement sensitivity required by the TREAD Act and is thus the only one in production. A *direct measurement* system uses battery-powered pressure sensors inside each tire to measure tire pressure and can typically detect any loss greater than 1.45 psi [40]. Since a wired connection from a rotating tire to the vehicle's electronic control unit is difficult to implement, the sensor module communicates its data via a radio frequency (RF) transmitter. The receiving tire pressure control unit, in turn, analyzes the data and can send results or commands to the central car computer over the Controller-area Network (CAN) to trigger a warning message on the vehicle dashboard, for example. *Indirect measurement* systems infer pressure differences between tires from differences in the rotational speed, which can be measured using the anti-lock braking system (ABS) sensors. A lower-pressure tire has to rotate faster to travel the same distance as a higher-pressure tire. The disadvantages of this approach are that it is less accurate, requires calibration by the driver, and cannot detect the simultaneous loss of pressure from all tires (for example, due to temperature changes). While initial versions of the TREAD Act allowed indirect technology, updated rul-

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ings by the United States National Highway Transportation Safety Administration (NHTSA) have required all new cars sold or manufactured after 2008 in the United States to be equipped with direct TPMS [35] due to these disadvantages.

1.1 Security and Privacy Risks

Security and privacy aspects of vehicle-to-vehicle and vehicle-to-infrastructure communication have received significant consideration by both practitioners and researchers [3, 36]. However, the already deployed in-car sensor communication systems have received little attention, because (i) the short communication range and metal vehicle body may render eavesdropping and spoofing attacks difficult and (ii) tire pressure information appears to be relatively innocuous. While we agree that the safety-critical application scenarios for vehicle-to-vehicle communications face higher security and privacy risks, we believe that even current tire pressure measurement systems present potential for misuse.

First, wireless devices are known to present tracking risks through explicit identifiers in protocols [20] or identifiable patterns in waveforms [10]. Since automobiles have become an essential element of our social fabric — they allow us to commute to and from work; they help us take care of errands like shopping and taking our children to day care — tracking automobiles presents substantial risks to location privacy. There is significant interest in wireless tracking of cars, at least for traffic monitoring purposes. Several entities are using mobile toll tag readers [4] to monitor traffic flows. Tracking through the TPMS system, if possible, would raise greater concerns because the use of TPMS is not voluntary and they are hard to deactivate.

Second, wireless is easier to jam or spoof because no physical connection is necessary. While spoofing a low tire pressure readings does not appear to be critical at first, it will lead to a dashboard warning and will likely cause the driver to pull over and inspect the tire. This presents ample opportunities for mischief and criminal activities, if past experience is any indication. Drivers have been willing to tinker with traffic light timing to reduce their commute time [6]. It has also been reported that highway robbers make drivers pull over by puncturing the car tires [23] or by simply signaling a driver that a tire problem exists. If nothing else, repeated false alarms will undermine drivers' faith in the system and lead them to ignore subsequent TPMS-related warnings, thereby making the TMPS system ineffective.

To what extent these risks apply to TPMS and more generally to in-car sensor systems remains unknown. A key question to judge these risks is whether the range at which messages can be overheard or spoofed is large enough to make such attacks feasible from outside the vehicle. While similar range questions have recently been investigated for RFID devices [27], the radio propagation environment within an automobile is different enough to warrant study because the metal body of a car could shield RF from escaping or entering a car. It is also unclear whether the TPMS message rate is high enough to make tracking vehicles feasible. This paper aims to fill this void, and presents a security and privacy analysis of state-of-the art commercial tire pressure monitoring systems, as well as detailed measurements for the communication range for in-car sensor transmissions.

1.2 Contributions

Following our experimental analysis of two popular TPMSs used in a large fraction of vehicles in the United States, this paper presents the following contributions:

Lack of security measures. TPMS communications are based on standard modulation schemes and simple protocols. Since the protocols do not rely on cryptographic mechanisms, the communication can be reverse-engineered, as we did using GNU Radio [2] in conjunction with the Universal Software Radio Peripheral (USRP) [1], a low-cost public software radio platform. Moreover, the implementation of the in-car system appears to fully trust all received messages. We found no evidence of basic security practices, such as input validation, being followed. Therefore, spoofing attacks and battery drain attacks are made possible and can cause TPMS to malfunction.

Significant communication range. While the vehicle's metal body does shield the signal, we found a larger than expected eavesdropping range. TPMS messages can be correctly received up to 10m from the car with a cheap antenna and up to 40m with a basic low noise amplifier. This means an adversary can overhear or spoof transmissions from the roadside or possibly from a nearby vehicle, and thus the transmission powers being used are not low enough to justify the lack of other security measures.

Vehicle tracking. Each in-tire sensor module contains a 32-bit immutable identifier in every message. The length of the identifier field renders tire sensor module IDs sufficiently unique to track cars. Although tracking vehicles is possible through vision-based automatic license plate identification, or through toll tag or other wireless car components, tracking through TPMS identifiers raises new concerns, because these transmitters are difficult for drivers to deactivate as they are available in all new cars and because wireless tracking is a low-cost solution compared to employing vision technology.

Defenses. We discuss security mechanisms that are applicable to this low-power in-car sensor scenario without taking away the ease of operation when installing a new tire. The mechanisms include relatively straightforward design changes in addition to recommendations for cryptographic protocols that will significantly mitigate TMPS security risks.

The insights obtained can benefit the design of other emerging wireless in-car sensing systems. Modern automobiles contain roughly three miles of wire [31], and this will only increase as we make our motor vehicles more intelligent through more on-board electronic components, ranging from navigation systems to entertainment systems to in-car sensors. Increasing the amount of wires directly affects car weight and wire complexity, which decreases fuel economy [13] and imposes difficulties on fault diagnosis [31]. For this reason, wireless technologies will increasingly be used in and around the car to collect control/status data of the car's electronics [16, 33]. Thus, understanding and addressing the vulnerabilities associated with internal automotive communications, and TPMS in particular, is essential to ensuring that the new wave of intelligent automotive applications will be safely deployed within our cars.

1.3 Outline

We begin in Section 2 by presenting an overview of TPMS and raising related security and privacy concerns. Although the specifics of the TPMS communication protocols are proprietary, we present our reverse-engineering effort that reveals the details of the protocols in Section 3. Then, we discuss our study on the susceptibility of TPMS to eavesdropping in Section 4 and message spoofing attacks in Section 5. After completing our security and privacy analysis, we recommend defense mechanisms to secure TPMS in Section 6. Finally, we wrap up our paper by presenting related work in Section 7 before concluding in Section 8.

2 TPMS Overview and Goals

TPMS architecture. A typical direct TPMS contains the following components: TPM sensors fitted into the back of the valve stem of each tire, a TPM electric control unit (ECU), a receiving unit (either integrated with the ECU or stand-alone), a dashboard TPM warning light, and one or four antennas connected to the receiving unit. The TPM sensors periodically broadcast the pressure and temperature measurements together with their

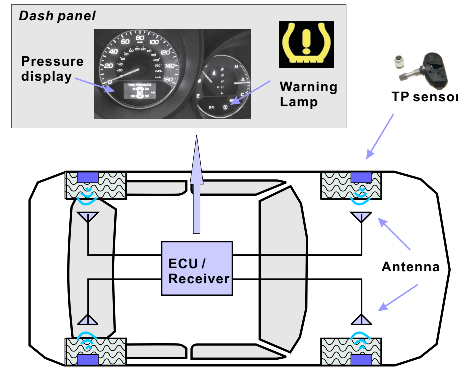


Figure 1: TPMS architecture with four antennas.

identifiers. The TPM ECU/receiver receives the packets and performs the following operations before sending messages to the TPM warning light. First, since it can receive packets from sensors belonging to neighboring cars, it filters out those packets. Second, it performs temperature compensation, where it normalizes the pressure readings and evaluates tire pressure changes. The exact design of the system differs across suppliers, particularly in terms of antenna configuration and communication protocols. A four-antenna configuration is normally used in high-end car models, whereby an antenna is mounted in each wheel housing behind the wheel arch shell and connected to a receiving unit through high frequency antenna cables, as depicted in Figure 1. The four-antenna system prolongs sensor battery life, since the antennas are mounted close to the TPM sensors which reduces the required sensor transmission power. However, to reduce automobile cost, the majority of car manufactories use one antenna, which is typically mounted on the rear window [11, 39].

Communication protocols. The communications protocols used between sensors and TPM ECUs are proprietary. From supplier websites and marketing materials, however, one learns that TPMS data transmissions commonly use the 315 MHz or 433 MHz bands (UHF) and ASK (Amplitude Shift Keying) or FSK (Frequency Shift Keying) modulation. Each tire pressure sensor carries an identifier (ID). Before the TPMS ECU can accept data reported by tire pressure sensors, IDs of the sensor and the position of the wheel that it is mounted on have to be entered to the TPMS ECU either manually in most cars or automatically in some high-end cars. This is typically done during tire installation. Afterwards, the ID of the sensor becomes the key information that assists the ECU in determining the origin of the data packet and filtering out packets transmitted by other vehicles.

To prolong battery life, tire pressure sensors are designed to sleep most of the time and wake up in two scenarios: (1) when the car starts to travel at high speeds (over 40 km/h), the sensors are required to monitor tire pressures; (2) during diagnosis and the initial sensor ID binding phases, the sensors are required to transmit their IDs or other information to facilitate the procedures. Thus, the tire pressure sensors will wake up in response to two triggering mechanisms: a speed higher than 40 km/h detected by an on-board accelerometer or an RF activation signal.

The RF activation signals operate at 125 kHz in the low frequency (LF) radio frequency band and can only wake up sensors within a short range, due to the generally poor characteristics of RF antennas at that low frequency. According to manuals from different tire sensor manufacturers, the activation signal can be either a tone or a modulated signal. In either case, the LF receiver on the tire sensor filters the incoming activation signal and wakes up the sensor only when a matching signal is recognized. Activation signals are mainly used by car dealers to install and diagnose tire sensors, and are manufacturer-specific.

2.1 Security and Privacy Analysis Goals

Our analysis will concentrate on tracking risks through eavesdropping on sensor identifiers and on message spoofing risks to insert forged data in the vehicle ECU. The presence of an identifier raises the specter of location privacy concerns. If the sensor IDs were captured at roadside tracking points and stored in databases, third parties could infer or prove that the driver has visited potentially sensitive locations such as medical clinics, political meetings, or nightclubs. A similar example is seen with electronic toll records that are captured at highway entry and exit points by private entities for traffic monitoring purposes. In some states, these records are frequently subpoenaed for civil lawsuits. If tracking through the tire pressure monitoring system were possible, this would create additional concerns, particularly because the system will soon be present in all cars and cannot easily be deactivated by a driver.

Besides these privacy risks, we will consider attacks where an adversary interferes with the normal operations of TPMS by actively injecting forged messages. For instance, an adversary could attempt to send a low pressure packet to trigger a low pressure warning. Alternatively, the adversary could cycle through a few forged low pressure packets and a few normal pressure packets, causing the low pressure warning lights to turn on and off. Such attacks, if possible, could undermine drivers' faith in the system and potentially lead them to ignore TPMS-related warnings completely. Last but not least, since the TPM sensors always respond to the corresponding activation signal, an adversary that continuously transmits activation signals can force the tire sensors to send packets constantly, greatly reducing the lifetime of TPMS.

To evaluate the privacy and security risks of such a system, we will address the issues listed below in the following sections.

Difficulty of reverse engineering. Many potential attackers are unlikely to have access to insider information and must therefore reconstruct the protocols, both to be able to extract IDs to track vehicles and to spoof messages. The level of information necessary differs among attacks; replays for example might only require knowledge of the frequency band but more sophisticated spoofing requires protocol details. For spoofing attacks we also consider whether off-the-shelf radios can generate and transmit the packets appropriately.

Identifier characteristics. Tracking requires observing identifying characteristics from a message, so that multiple messages can be linked to the same vehicle. The success of tracking is closely tied to the answers to: (1) Are the sensor IDs used temporarily or over long time intervals? (2) Does the length of the sensor ID suffice to uniquely identify a car? Since the sensor IDs are meant to primarily identify their positions in the car, they may not be globally unique and may render tracking difficult.

Transmission range and frequency. Tracking further depends on whether a road-side tracking unit will be likely to overhear a transmission from a car passing at high speed. This requires understanding the range and messaging frequency of packet transmissions. To avoid interference between cars and to prolong the battery life, the transmission powers of the sensors are deliberately chosen to be low. Is it possible to track vehicles with such low transmission power combined with low messaging frequency?

Security measures. The ease of message spoofing depends on the use of security measures in TPMSs. The key questions to make message spoofing a practical threat include: (1) Are messages authenticated? (2) Does the vehicle use consistency checks and filtering mechanisms to reject suspicious packets? (3) How long, if possible, does it take the ECU to completely recover from a spoofing attack?

3 Reverse Engineering TPMS Communication Protocols

Analyzing security and privacy risks begins with obtaining a thorough comprehension of the protocols for *specific* sensor systems. To elaborate, one needs to know the modulation schemes, encoding schemes, and message formats, in addition to the activation and reporting

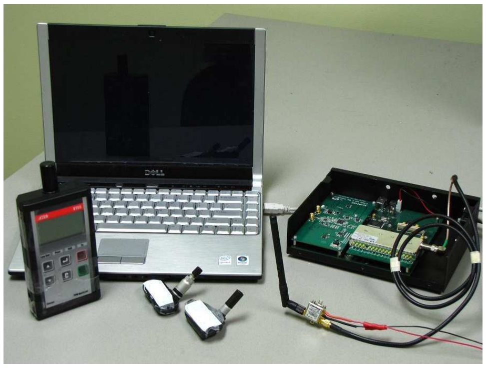


Figure 2: Equipment used for packet sniffing. At the bottom, from left to right are the ATEQ VT55 TPMS trigger tool, two tire pressure sensors (TPS-A and TPS-B), and a low noise amplifier (LNA). At the top is one laptop connected with a USRP with a TVRX daughterboard attached.

methodologies to properly decode or spoof sensor messages. Apart from access to an insider or the actual specifications, this information requires reverse-engineering by an adversary. To convey the level of difficulty of this process for in-car sensor protocols, we provide a brief walk-through of our approach below, where we begin by presenting relevant hardware.

Tire pressure sensor equipment. We selected two representative tire pressure sensors that employ different modulation schemes. Both sensors are used in automobiles with high market shares in the US. To prevent misuse of the information here, we refer to these sensors simply as *tire pressure sensor A (TPS-A)* and *tire pressure sensor B (TPS-B)*. To help our process, we also acquired a *TPMS trigger tool*, which is available for a few hundred dollars. Such tools are handheld devices that can activate and decode information from a variety of tire sensor implementations. These tools are commonly used by car technicians and mechanics for troubleshooting. For our experiments, we used a TPMS trigger tool from ATEQ [8] (ATEQ VT55).

Raw signal sniffer. Reverse engineering the TPMS protocols requires the capture and analysis of raw signal data. For this, we used GNU Radio [2] in conjunction with the Universal Software Radio Peripheral (USRP) [1]. GNU Radio is an open source, free software toolkit that provides a library of signal processing blocks that run on a host processing platform. Algorithms implemented using GNU Radio can receive data directly from the USRP, which is the hardware that provides RF access via an assortment of daughterboards. They include the TVRX daughterboard capable of receiving RF in the range of 50 Mhz to 870 MHz and the LFRX daughterboard able to receive from DC to 30 MHz. For convenience, we initially used an Agilent 89600 Vector Signal Analyzer (VSA) for data capture (but such equipment is not necessary). The pressure sensor modules, trigger tool, and software radio platform are shown in Figure 2.

3.1 Reverse Engineering Walk Through

While our public domain search resulted in only high-level knowledge about the TPM communication protocol specifics, anticipating sensor activity in the 315/433 MHz bands did provide us with a starting point for our reverse engineering analysis.

We began by collecting a few transmissions from each of the TPM sensors. The VSA was used to narrow down the spectral bandwidth necessary for fully capturing the transmissions. The sensors were placed close to the VSA receiving antenna while we used the ATEQ VT55 to trigger the sensors. Although initial data collections were obtained using the VSA, the research team switched to using the USRP to illustrate that our findings (and subsequently our attacks) can be achieved with low-cost hardware. An added benefit of using the USRP for the data collections is that it is capable of providing synchronized collects for the LF and HF frequency bands — thus allowing us to extract important timing information between the activation signals and the sensor responses. To perform these collects, the TVRX and LFRX daughterboards were used to provide access to the proper radio frequencies. Once the sensor bursts were collected, we began our signal analysis in MATLAB to understand the modulation and encoding schemes. The final step was to map out the message format.

Determine coarse physical layer characteristics. The first phase of characterizing the sensors involved measuring burst widths, bandwidth, and other physical layer properties. We observed that burst widths were on the order of 15 ms. During this initial analysis, we noted that each sensor transmitted multiple bursts in response to their respective activation signals. TPS-A used 4 bursts, while TPS-B responded with 5 bursts. Individual bursts in the series were determined to be exact copies of each other, thus each burst encapsulates a complete sensor report.

Identify the modulation scheme. Analysis of the baseband waveforms revealed two distinct modulation schemes. TPS-A employed amplitude shift keying (ASK), while TPS-B employed a hybrid modulation scheme — simultaneous usage of ASK and frequency shift keying (FSK). We speculate that the hybrid scheme is used for two reasons: (1) to maximize operability with TPM readers and (2) to mitigate the effects of an adverse channel during normal operation. Figure 3 illustrates the differences between the sensors' transmission in both the time and frequency domains. The modulation schemes are also observable in these plots.

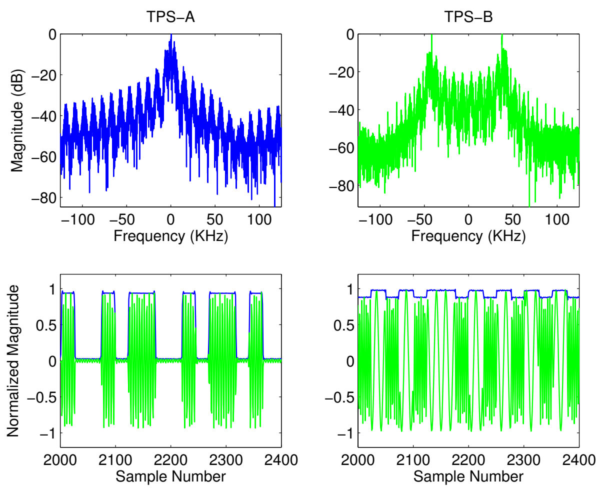


Figure 3: A comparison of FFT and signal strength time series between TSP-A and TSP-B sensors.

Resolve the encoding scheme. Despite the different modulation schemes, it was immediately apparent that both sensors were utilizing Manchester encoding (after distinct preamble sequences). The baud rate is directly observable under Manchester encoding and was on the order of 5 kBd. The next step was to determine the bit mappings from the Manchester encoded signal. In order to accomplish this goal, we leveraged knowledge of a known bit sequence in each message. We knew the sensor ID because it was printed on each sensor and assumed that this bit sequence must be contained in the message. We found that applying differential Manchester decoding generated a bit sequence containing the sensor ID.

Reconstructing the message format. While both sensors used differential Manchester encoding, their packet formats differed significantly. Thus, our next step was to determine the message mappings for the rest of the bits for each sensor. To understand the size and meaning of each bitfield, we manipulated sensor transmissions by varying a single parameter and observed which bits changed in the message. For instance, we adjusted the temperature using hot guns and refrigerators, or adjusted the pressure. By simultaneously using the ATEQ VT55, we were also able to observe the actual transmitted values and correlate them with our decoded bits. Using this approach, we managed to determine the majority of message fields and their meanings for both TPS-A and TPS-B. These included temperature, pressure, and sensor ID, as illustrated in Figure 4. We also identified the use of a CRC checksum and determined the CRC polynomials through a brute force search.

At this point, we did not yet understand the meaning of a few bits in the message. We were later able to reconstruct these by generating messages with our software radio, changing these bits, and observing the output of the

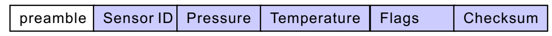


Figure 4: An illustration of a packet format. Note the size is not proportional to real packet fields.

TPMS tool or a real car. It turned out that these were parameters like battery status, over which we had no direct control by purely manipulating the sensor module. More details on message spoofing are presented in Section 5.

3.2 Lessons Learned

The aforementioned reverse-engineering can be accomplished with a reasonable background in communications and computer engineering. It took a few days for a PhD-level engineer experienced with reverse engineering to build an *initial* system. It took several weeks for an MS-level student with no prior experience in reverse engineering and GNU Radio programming to understand and reproduce the attack. The equipment used (the VTEQ VT55 and USRP attached with TVRX) is openly available and costs $1500 at current market prices.

Perhaps one of the most difficult issues involved baud rate estimation. Since Manchester encoding is used, our initial baud rate estimates involved averaging the gaps between the transition edges of the signal. However, the jitter (most likely associated with the local oscillators of the sensors) makes it almost impossible to estimate a baud rate accurate enough for a simple software-based decoder to work correctly. To address this problem, we modified our decoders to be self-adjustable to compensate for the estimation errors throughout the burst.

The reverse engineering revealed the following observations. First, it is evident that encryption has not been used—which makes the system vulnerable to various attacks. Second, each message contains a 28-bit or 32-bit sensor ID depending on the type of sensor. Regardless of the sensor type, the IDs do not change during the sensors' lifetimes.

Given that there are 254.4 million registered passenger vehicles in United States [34], one 28-bit Sensor ID is enough to track each registered car. Even in the future when the number of cars may exceed 256 million, we can still identify a car using a collection of tire IDs — a 4-tuple of tire IDs. Assuming a uniform distribution across the 28-bit ID space, the probability of an exact match of two cars' IDs is $4!/2^{112}$ without considering the ordering. To determine how many cars R can be on the road in the US with a guarantee that there is a less than P chance of any two or more cars having the same ID-set, is a classical birthday problem calculation:

$$R = \sqrt{\frac{2^{113}}{4!} ln(\frac{1}{1-P})}$$

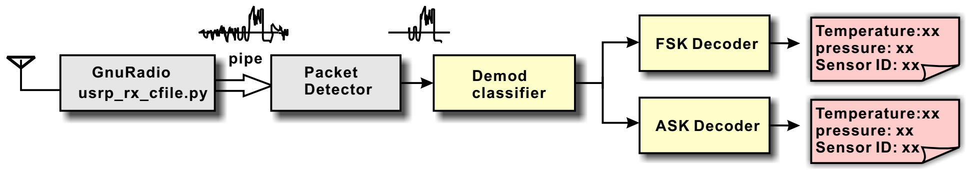


Figure 5: Block chart of the live decoder/eavesdropper.

To achieve a match rate of larger than $P = 1\%$, more than 10^{15} cars need to be on the road, which is significantly more than 1 billion cars. This calculation, of course, is predicated on the assumption of a uniform allocation across the 28-bit ID space. Even if we relax this assumption and assume 20 bits of entropy in a single 28-bit ID space, we would still need roughly 38 billion cars in the US to get a match rate of more than $P = 1\%$.

We note that this calculation is based on the unrealistic assumption that all 38 billion cars are co-located, and are using the same modulation and coding schemes. Ultimately, it is very unlikely to have two cars that would be falsely mistaken for each other.

4 Feasibility of Eavesdropping

A critical question for evaluating privacy implications of in-car wireless networks is whether the transmissions can be easily overheard from outside the vehicle body. While tire pressure data does not require strong confidentiality, the TPMS protocols contain identifiers that can be used to track the locations of a device. In practice, the probability that a transmission can be observed by a stationary receiver depends not only on the communication range but also on the messaging frequency and speed of the vehicle under observation, because these factors affect whether a transmission occurs in communication range.

The transmission power of pressure sensors is relatively small to prolong sensor battery lifetime and reduce cross-interference. Additionally, the NHTSA requires tire pressure sensors to transmit data only once every 60 seconds to 90 seconds. The low transmission power, low data report rate, and high travel speeds of automobiles raise questions about the feasibility of eavesdropping.

In this section, we experimentally evaluate the range of TPMS communications and further evaluate the feasibility of tracking. This range study will use TPS-A sensors, since their TPMS uses a four-antenna structure and operates at a lower transmission power. It should therefore be more difficult to overhear.

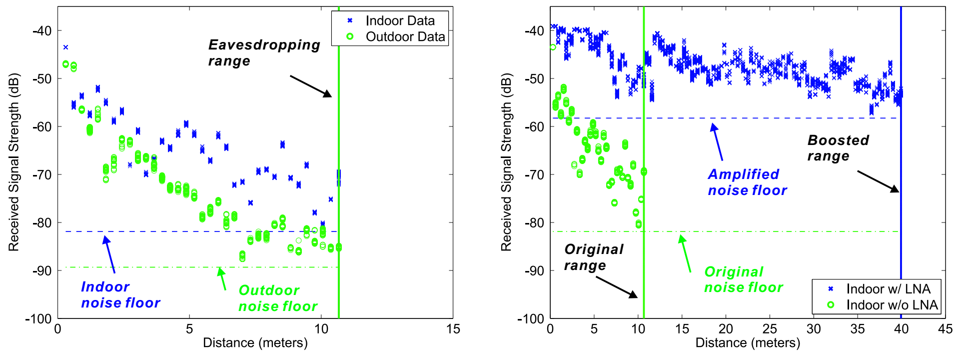
4.1 Eavesdropping System

During the reverse engineering steps, we developed two Matlab decoders: one for decoding ASK modulated TPS-A and the other for decoding the FSK modulated TPS-B. In order to reuse our decoders yet be able to constantly monitor the channel and only record useful data using GNU radio together with the USRP, we created a live decoder/eavesdropper leveraging pipes. We used the GNU Radio standard Python script `usrp_rx_cfile.py` to sample channels at a rate of 250 kHz, where the recorded data was then piped to a packet detector. Once the packet detector identifies high energy in the channel, it extracts the complete packet and passes the corresponding data to the decoder to extract the pressure, temperature, and the sensor ID. If decoding is successful, the sensor ID will be output to the screen and the raw packet signal along with the time stamp will be stored for later analysis. To be able to capture data from multiple different TPMS systems, the eavesdropping system would also need a modulation classifier to recognizes the modulation scheme and choose the corresponding decoder. For example, Liedtke's [29] algorithm could be used to differentiate ASK2 and FSK2. Such an eavesdropping system is depicted in Fig. 5.

In early experiments, we observed that the decoding script generates much erratic data from interference and artifacts of the dynamic channel environment. To address this problem, we made the script more robust and added a filter to discard erroneous data. This filter drops all signals that do not match TPS-A or TPS-B. We have tested our live decoder on the interstate highway I-26 (Columbia, South Carolina) with two cars running in parallel at speeds exceeding 110 km/h.

4.2 Eavesdropping Range

We measured the eavesdropping range in both indoor and outdoor scenarios by having the ATEQ VT55 trigger the sensors. In both scenarios, we fixed the location of the USRP at the origin $(0, 0)$ in Figure 7 and moved the sensor along the y-axis. In the indoor environment, we studied the reception range of stand-alone sensors in a hallway. In the outdoor environment, we drove one of the authors' cars around to measure the reception range of the sensors mounted in its front left wheel while the car's body was parallel to the x-axis, as shown in Figure 7. In our experiment, we noticed that we were able to decode the packets when the received signal strength is larger than the ambient noise floor. The resulting signal strength over the area where packets could be decoded



(a) indoor vs. outdoor (w/o LNA)

(b) with LNA vs. without LNA (indoor)

Figure 6: Comparison of eavesdropping range of TPS-A.

successfully and the ambient noise floors are depicted in Figure 6 (a). The results show that both the outdoor and indoor eavesdropping ranges are roughly 10.7 m, the vehicle body appears only to have a minor attenuation effect with regard to a receiver positioned broadside.

We next performed the same set of range experiments while installing a low noise amplifier (LNA) between the antenna and the USRP radio front end, as shown in Figure 2. As indicated in Figure 6, the signal strength of the sensor transmissions still decreased with distance and the noise floor was raised because of the LNA, but the LNA amplified the received signal strength and improved the decoding range from 10.7 meters to 40 meters. This shows that with some inexpensive hardware a significant eavesdropping range can be achieved, a range that allows signals to be easily observed from the roadside.

Note that other ways to boost receiving range exist. Examples include the use of directional antennas or more sensitive omnidirectional antennas. We refer readers to the antenna studies in [9, 15, 42] for further information.

4.3 Eavesdropping Angle Study

We now investigate whether the car body has a larger attenuation effect if the receiver is located at different angular positions. We also study whether one USRP is enough to sniff packets from all four tire sensors.

The effect of car body. In our first set of experiments, we studied the effect of the car's metallic body on signal attenuation to determine the number of required USRPs. We placed the USRP antenna at the origin of the coordinate, as shown in Figure 7, and position the car at several points on the line of $y = 0.5$ with its body parallel to the x-axis. Eavesdropping at these points revealed that it is very hard to receive packets from four tires simultaneously. A set of received signal strength (RSS) measurements when the front left wheel was located at $(0, 0.5)$ meters are summarized in Table 1. Results show that the USRP can receive packets transmitted by the front left, front right and rear left sensors, but not from the rear right sensor due to the signal degradation caused by the car's metallic body. Thus, to assure receiving packets from all four sensors, at least two observation spots may be required, with each located on either side of the car. For instance, two USRPs can be placed at different spots, or two antennas connected to the same USRP can be meters apart.

The eavesdropping angle at various distances. We studied the range associated with one USRP receiving packets transmitted by the front left wheel. Again, we placed the USRP antenna at the origin and recorded packets when the car moved along trajectories parallel to the x-axis, as shown in Figure 7. These trajectories were 1.5 meters apart. Along each trajectory, we recorded RSS at the locations from where the USRP could decode packets. The colored region in Figure 11, therefore, denotes the eavesdropping range, and the contours illustrate the RSS distribution of the received packets.

From Figure 11, we observe that the maximum horizontal eavesdropping range, r_{max}, changes as a function of the distance between the trajectory and the USRP antenna, d. Additionally, the eavesdropping ranges on both sides of the USRP antenna are asymmetric due to the car's metallic body. Without the reflection and impediment of the car body, the USRP is able to receive the packets at further distances when the car is approaching rather than leaving. The numerical results of r_{max}, φ_1, the maximum eavesdropping angle when the car is approaching the USRP, and φ_2, the maximum angle when the car is leaving the USRP, are listed in Figure 8. Since

Location	RSS (dB)	Location	RSS (dB)
Front left	-41.8	Rear left	-55.0
Front right	-54.4	Rear right	N/A

Table 1: RSS when USPR is located 0.5 meters away from the front left wheel.

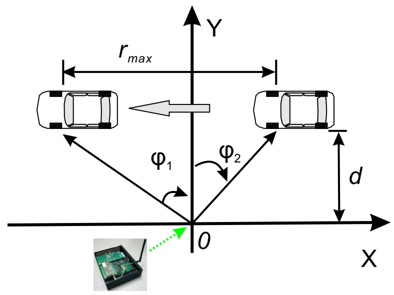


Figure 7: The experiment setup for the range study.

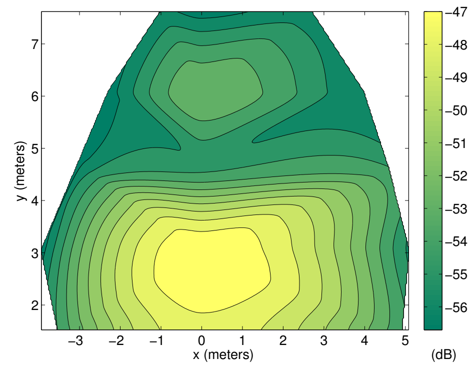


Figure 11: Study the angle of eavesdropping with LNA.

the widest range of 9.1 meters at the parallel trajectory was 3 meters away from the x-axis, an USRP should be placed 2.5 meters away from the lane marks to maximize the chance of packet reception, assuming cars travel 0.5 meter away from lane marks.

Messaging rate. According to NHTSA regulations, TPMS sensors transmit pressure information every 60 to 90 seconds. Our measurements confirmed that both TPS-A and TPS-B sensors transmit one packet every 60 seconds or so. Interestingly, contrary to documentation (where sensors should report data periodically after a speed higher than 40 km/h), both sensors periodically transmit packet even when cars are stationary. Furthermore, TPS-B transmits periodic packets even when the car is not running.

4.4 Lessons Learned: Feasibility of Tracking Automobiles

The surprising range of 40m makes it possible to capture a packet and its identifiers from the roadside, if the car is stationary (e.g., a traffic light or a parking lot). Given that a TPMS sensor only send one message per minute, tracking becomes difficult at higher speeds. Consider, for example, a passive tracking system deployed along the roadside at highway entry and exit ramps, which seeks to extract the unique sensor ID for each car and link entry and exit locations as well as subsequent trips. To ensure capturing at least one packet, a row of sniffers would be required to cover the stretch of road that takes a car 60 seconds to travel. The number of required sniffers, $n_{passive} = ceil(v * T/r_{max})$, where v is the speed of the vehicle, T is the message report period, and r_{max} is the detection range of the sniffer. Using the sniffing system described in previous sections where $r_{max} = 9.1$ m, 110 sniffers are required to guarantee capturing one packet transmitted by a car traveling at 60 km/h. Deploying such a tracking system appears cost-prohibitive.

It is possible to track with fewer sniffers, however, by leveraging the activation signal. The tracking station can send the 125kHz activation signal to trigger a transmission by the sensor. To achieve this, the triggers and sniffers should be deployed in a way such that they meet the following requirements regardless of the cars' travel speeds: (1) the transmission range of the trigger should be large enough so that the passing car is able to receive the complete activation signal; (2) the sniffer should be placed at a distance from the activation sender so that the car is in the sniffers' eavesdropping range when it starts to transmit; and (3) the car should stay within the eavesdropping range before it finishes the transmission.

To determine the configuration of the sniffers and the triggers, we conducted an epitomical study using a USRP with two daughterboards attached, one recording at 125 kHz and the other recording at 315 MHz. Our results are depicted in Figure 9 and show that the activation signal of TPS-B lasts approximately 359 ms. The sensors start to transmit 530 ms after the beginning of the activation signal, and the data takes 15 ms to transmit. This means, that to trigger a car traveling at 60 km/h, the trigger should have a transmission range of at least 6 meters. Since a sniffer can eavesdrop up to 9.1 meters, it suffices to place the sniffer right next to the trigger. Additional sniffers could be placed down the road to capture packets of cars traveling at higher speeds.

To determine the feasibility of this approach, we have conducted a roadside experiment using the ATEQ VT55 which has a transmission range of 0.5 meters. We were able to activate and extract the ID of a targeted TPMS sensor moving at the speed of 35 km/h using one sniffer. We note that ATEQ VT55 was deliberately designed with short transmission range to avoid activating multiple cars in the dealership. With a different radio frontend, such as using a matching antenna for 125 kHz, one can increase the transmission range of the trigger easily and enable capturing packets from cars at higher speeds.

Comparison between tracking via TPMS and Automatic Number Plate Reading. Automatic Number Plate Reading (ANPR) technologies have been proposed to track automobiles and leverage License Plate Capture Cameras (LPCC) to recognize license plate numbers. Due to the difference between underlying technolo-

d (m)	φ_1 (°)	φ_2(°)	r_{max} (m)
1.5	72.8	66.8	8.5
3.0	59.1	52.4	9.1
4.5	45.3	31.8	7.5
6.0	33.1	20.7	6.3
7.5	19.6	7.7	3.8

Figure 8: The eavesdropping angles and ranges when the car is traveling at various trajectories.

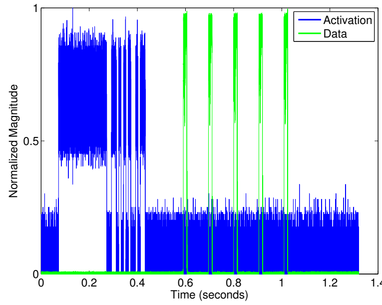


Figure 9: Time series of activation and data signals.

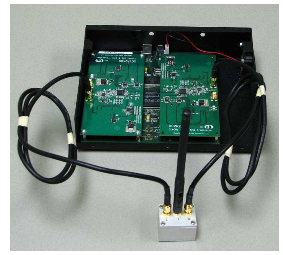


Figure 10: Frequency mixer and USRP with two daughterboards are used to transmit data packets at 315/433 MHz.

gies, TPMS and ANPR systems exhibit different characteristics. First, ANPR allows for more direct linkage to individuals through law enforcement databases. ANPR requires, however, line of sight (LOS) and its accuracy can be affected by weather conditions (e.g. light or humidity) or the dirt on the plate. In an ideal condition with excellent modern systems, the read rate for license plates is approximately 90% [25]. A good quality ANPR camera can recognize number plates at 10 meters [5]. On the contrary, the ability to eavesdrop on the RF transmission of TPMS packets does not depend on illumination or LOS. The probability of identifying the sensor ID is around 99% when the eavesdropper is placed 2.5 meters away from the lane marks. Second, the LOS requirement forces the ANPR to be installed in visible locations. Thus, a motivated driver can take alternative routes or remove/cover the license plates to avoid being detected. In comparison, the use of TPMS is harder to circumvent, and the ability to eavesdrop without LOS could lead to more pervasive automobile tracking. Although swapping or hiding license plates requires less technical sophistication, it also imposes much higher legal risks than deactivating TPMS units.

5 Feasibility of Packet Spoofing

Being able to eavesdrop on TPMS communication from a distance allows us to further explore the feasibility of inserting forged data into safety-critical in-vehicle systems. Such a threat presents potentially even greater risks than the tracking risks discussed so far. While the TPMS is not yet a highly safety-critical system, we experimented with spoofing attacks to understand: (1) whether the receiver sensitivity of an in-car radio is high enough to allow spoofing from outside the vehicle or a neighboring vehicle, and (2) security mechanisms and practices in such systems. In particular, we were curious whether the system uses authentication, input validation, or filtering mechanisms to reject suspicious packets.

The packet spoofing system. Our live eavesdropper can detect TPMS transmission and decode both ASK modulated TPS-A messages and FSK modulated TPS-B messages in real time. Our packet spoofing system is built on top of our live eavesdropper, as shown in Figure 12. The Packet Generator takes two sets of parameters —*sensor type* and *sensor ID* from the eavesdropper; *temperature*, *pressure*, and *status flags* from users—and generates a properly formulated message. It then modulates the message at baseband (using ASK or FSK) while inserting the proper preamble. Finally, the rogue sensor packets are upconverted and transmitted (either continuously or just once) at the desired frequency (315/433 MHz) using a customized GNU radio python script. We note that once the sensor ID and sensor type are captured we can create and repeatedly transmit the forged message at a pre-defined period.

At the time of our experimentation, there were no USRP daughterboards available that were capable of transmitting at 315/433 MHz. So, we used a frequency mixing approach where we leveraged two XCVR2450 daughterboards and a frequency mixer (mini-circuits ZLW11H) as depicted in Fig.10. By transmitting a tone out of one XCVR2450 into the LO port of the mixer, we were able to mix down the spoofed packet from the other XCVR2450 to the appropriate frequency. For 315 MHz, we used a tone at 5.0 GHz and the spoofed packet at 5.315 GHz.[1]

To validate our system, we decoded spoofed packets with the TPMS trigger tool. Figure 13 shows a screen snapshot of the ATEQ VT55 after receiving a spoofed packet with a sensor ID of “DEADBEEF” and a tire pressure of 0 PSI. This testing also allowed us to understand the meaning of remaining status flags in the protocol.

5.1 Exploring Vehicle Security

We next used this setup to send various forged packets to a car using TPS-A sensors (belonging to one of the

[1] For 433 MHz, the spoofed packet was transmitted at 5.433 GHz. We have also successfully conducted the experiment using two RFX-1800 daughterboards, whose operational frequencies are from 1.5 GHz to 2.1 GHz.

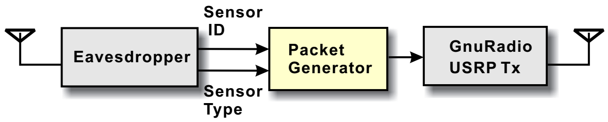


Figure 12: Block chart of the packet spoofing system.

authors) at a rate of 40 packets per second. We made the following observations.

No authentication. The vehicle ECU ignores packets with a sensor ID that does not match one of the known IDs of its tires, but appears to accept all other packets. For example, we transmitted forged packets with the ID of the left front tire and a pressure of 0 PSI and found 0 PSI immediately reflected on the dashboard tire pressure display. By transmitting messages with the alert bit set we were able to immediately illuminate the *low-pressure warning light*[2], and with about 2 seconds delay the *vehicle's general-information warning light*, as shown in Figure 14.

No input validation and weak filtering. We forged packets at a rate of 40 packets per second. Neither this increased rate, nor the occasional different reports by the real tire pressure sensor seemed to raise any suspicion in the ECU or any alert that something was wrong. The dashboard simply displayed the spoofed tire pressure. We next transmitted two packets with very different pressure values alternately at a rate of 40 packets per second. The dashboard display appeared to randomly alternate between these values. Similarly, when alternating between packets with and without the alert flag, we observed the warning lights switched on and off at non-deterministic time intervals. Occasionally, the display seemed to freeze on one value. These observations suggest that TPMS ECU employs trivial filtering mechanisms which can be easily confused by spoofed packets.

Interestingly, the illumination of the low-pressure warning light depends only on the alert bit—the light turns on even if the rest of the message reports a normal tire pressure of 32 PSI! This further illustrates that the ECU does not appear to use any input validation.

Large range of attacks. We first investigated the effectiveness of packet spoofing when vehicles are stationary. We measured the attack range when the packet spoofing system was angled towards the head of the car, and we observed a packet spoofing range of 38 meters. For the purpose of proving the concept, we only used low-cost antennas and radio devices in our experiments. We believe that the range of packet spoofing can be greatly expanded by applying amplifiers, high-gain antennas, or antenna arrays.

[2]To discover this bit we had to deflate one tire and observe the tire pressure sensors response. Simply setting a low pressure bit or reporting low pressure values did not trigger any alert in the vehicle.

Feasibility of Inter-Vehicle Spoofing. We deployed the attacks against willing participants on highway I-26 to determine if they are viable at high speeds. Two cars owned by the authors were involved in the experiment. The victim car had TPS-A sensors installed and the attacker's car was equipped with our packet spoofing system. Throughout our experiment, we transmitted alert packets using the front-left-tire ID of the target car, while the victim car was traveling to the right of the attacker's car. We observed that the attacker was able to trigger both the low-pressure warning light and the car's central-warning light on the victim's car when traveling at 55 km/h and 110 km/h, respectively. Additionally, the low-pressure-warning light illuminated immediately after the attacker entered the packet spoofing range.

5.2 Exploring the Logic of ECU Filtering

Forging a TPMS packet and transmitting it at a high rate of 40 packets per second was useful to validate packet spoofing attacks and to gauge the spoofing range. Beyond this, though, it was unclear whether there were further vulnerabilities in the ECU logic. To characterize the logic of the ECU filtering mechanisms, we designed a variety of spoofing attacks. The key questions to be answered include: (1) what is the minimum requirement to trigger the TPMS warning light once, (2) what is the minimum requirement to keep the TPMS warning light on for an extended amount of time, and (3) can we permanently illuminate any warning light even after stopping the spoofing attack?

So far, we have observed two levels of warning lights: TPMS Low-Pressure Warning light (TPMS-LPW) and the vehicle's general-information warning light illustrating 'Check Tire Pressure'. In this section, we explored the logic of filtering strategies related to the TPMS-LPW light in detail. The logic controlling the vehicle's general-information warning light can be explored in a similar manner.

5.2.1 Triggering the TPMS-LPW Light

To understand the minimum requirement of triggering the TPMS-LPW light, we started with transmitting one spoofed packet with the rear-left-tire ID and eavesdropping the entire transmission. We observed that (1) one spoofed packet was not sufficient to trigger the TPMS-LPW light; and (2) as a response to this packet, the TPMS ECU immediately sent two activation signals through the antenna mounted close to the rear left tire, causing the rear left sensor to transmit eight packets. Hence, although a single spoofed packet does not cause the ECU to display any warning, it does open a vulnerability to battery drain attacks.

Figure 13: The TPMS trigger tool displays the spoofed packet with the sensor ID "DEADBEEF". We crossed out the brand of TP sensors to avoid legal issues.

(a) (b)

Figure 14: Dash panel snapshots: (a) the tire pressure of left front tire displayed as 0 PSI and the low tire pressure warning light was illuminated immediately after sending spoofed alert packets with 0 PSI; (b) the car computer turned on the general warning light around 2 seconds after keeping sending spoofed packets.

Next, we gradually increased the number of spoofed packets, and we found that transmitting four spoofed packets in one second suffices to illuminate the TPMS-LPW light. Additionally, we found that those four spoofed packets have to be at least 225 ms apart, otherwise multiple spoofed packets will be counted as one. When the interval between two consecutive spoofed packets is larger than 4 seconds or so, the TPMS-LPW no longer illuminates. This indicates that TPMS adopts two detection windows with sizes of 240 ms (a packet lasts for 15 ms) and 4 seconds. A 240-ms window is considered positive for low tire pressure if at least one low-pressure packet has been received in that window regardless of the presence of numerous normal packets. Four 240-ms windows need to be positive to illuminate the TPMS-LPW light. However, the counter for positive 240-ms windows will be reset if no low-pressure packet is received within a 4-s window.

Although the TPMS ECU does use a counting threshold and window-based detection strategies, they are designed to cope with occasionally corrupted packets in a benign situation and are unable to deal with malicious spoofing. Surprisingly, although the TPMS ECU does receive eight normal packets transmitted by sensors as a response to its queries, it still concludes the low-tire-pressure status based on one forged packet, ignoring the majority of normal packets!

5.2.2 Repeatedly Triggering the TPMS-LPW Light

The TPMS-LPW light turns off a few seconds if only four forged packets are received. To understand how to sustain the warning light, we repeatedly transmitted spoofed packets and increased the spoofing period gradually. The TPMS-LPW light remained illuminated when we transmitted the low-pressure packet at a rate higher than one packet per 240 ms, e.g., one packet per detection window. Spoofing at a rate between one packet per 240 ms to 4 seconds caused the TPMS-LPW light to toggle between on and off. However, spoofing at a rate slower than 4 seconds could not activate the TPMS-LPW light, which confirmed our prior experiment results. Figure 15 depicts the measured TPMS-LPW light on-durations and off-durations when the spoofing periods increased from 44 ms to 4 seconds.

As we increased the spoofing period, the TPMS-LPW light remained on for about 6 seconds on average, but the TPMS-LPW light stayed off for an incrementing amount of time which was proportional to the spoofing period. Therefore, it is very likely that the TPMS-ECU adopts a timer to control the minimum on-duration and the off-duration of TPMS-LPW light can be modeled as $t_{off} = 3.5x + 4$, where x is the spoofing period. The off-duration includes the amount of time to observe four low-pressure forged messages plus the minimum waiting duration for the TPMS-ECU to remain off, e.g., 4 seconds. In fact, this confirms our observation that there is a waiting period of approximately 4 seconds before the TPMS warning light was first illuminated.

5.2.3 Beyond Triggering the TPMS-LPW Light

Our previous spoofing attacks demonstrated that we can produce false TPMS-LPW warnings. In fact, transmitting forged packets at a rate higher than one packet per second also triggered the vehicle's general-information warning light illustrating 'Check Tire Pressure'. Depending on the spoofing period, the gap between the illumination of the TPMS-LPW light and the vehicle's general-information warning light varied between a few seconds to 130 seconds — and the TPMS-LPW light remained illuminated afterwards.

Throughout our experiments, we typically exposed the car to spoofed packets for a duration of several minutes at a time. While the TPMS-LPW light usually disappeared about 6 seconds after stopping spoofed message transmissions, we were once unable to reset the light even by turning off and restarting the ignition. It did, however, reset after about 10 minutes of driving.

To our surprise, at the end of only two days of sporadic experiments involving triggering the TPMS warning on and off, we managed to crash the TPMS ECU and

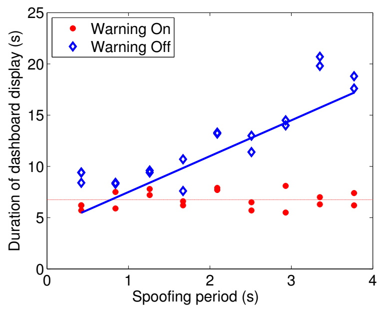


Figure 15: TPMS low-pressure warning light on and off duration vs. spoofing periods.

completely disabled the service. The vehicle's general-information warning light illustrating 'Check TPMS System' was activated and no tire pressure information was displayed on the dashboard, as shown in Figure 16. We attempted to reset the system by sending good packets, restarting the car, driving on the highway for hours, and unplugging the car battery. None of these endeavors were successful. Eventually, a visit to a dealership recovered the system at the cost of replacing the TPMS ECU. This incident suggests that it may be feasible to crash the entire TPMS and the degree of such an attack can be so severe that the owner has no option but to seek the services of a dealership. We note that one can easily explore the logic of a vehicle's general-information warning light using similar methods for TPMS-LPW light. We did not pursue further analysis due to the prohibitive cost of repairing the TPMS ECU.

5.3 Lessons Learned

The successful implementation of a series of spoofing attacks revealed that the ECU relies on sensor IDs to filter packets, and the implemented filter mechanisms are not effective in rejecting packets with conflicting information or abnormal packets transmitted at extremely high rates. In fact, the current filer mechanisms introduce security risks. For instance, the TPMS ECU will trigger the sensors to transmit several packets after receiving one spoofed message. Those packets, however, are not leveraged to detect conflicts and instead can be exploited to launch battery drain attacks. In summary, the absence of authentication mechanisms and weak filter mechanisms open many loopholes for adversaries to explore for more 'creative' attacks. Furthermore, despite the unavailability of a radio frontend that can transmit at 315/433 MHz, we managed to launch the spoofing attack using a frequency mixer. This result is both encouraging and alarming since it shows that an adversary can spoof packets even without easy access to transceivers that operate at the target frequency band.

(a) (b)

Figure 16: Dash panel snapshots indicating the TPMS system error (this error cannot be reset without the help of a dealership): (a) the vehicle's general-information warning light; (b) tire pressure readings are no longer displayed as a result of system function errors.

6 Protecting TPMS Systems from Attacks

There are several steps that can improve the TPMS dependability and security. Some of the problems arise from poor system design, while other issues are tied to the lack of cryptographic mechanisms.

6.1 Reliable Software Design

The first recommendation that we make is that software running on TPMS should follow basic reliable software design practices. In particular, we have observed that it was possible to convince the TPMS control unit to display readings that were clearly impossible. For example, the TPMS packet format includes a field for tire pressure as well as a separate field for warning flags related to tire pressure. Unfortunately, the relationship between these fields were not checked by the TPMS ECU when processing communications from the sensors. As noted earlier, we were able to send a packet containing a legitimate tire pressure value while also containing a low tire pressure warning flag. The result was that the driver's display indicated that the tire had low pressure even though its pressure was normal. A straight forward fix for this problem (and other similar problems) would be to update the software on the TPMS control unit to perform consistency checks between the values in the data fields and the warning flags. Similarly, when launching message spoofing attacks, although the control unit does query sensors to confirm the low pressure, it neglects the legitimate packet responses completely. The control unit could have employed some detection mechanism to, at least, raise an alarm when detecting frequent conflicting information, or have enforced some majority logic operations to filter out suspicious transmissions.

6.2 Improving Data Packet Format

One fundamental reason that eavesdropping and spoofing attacks are feasible in TPMS systems is that packets are transmitted in plaintext. To prevent these attacks, a first line of defense is to encrypt TPM packets[3]. The basic packet format in a TPMS system included a sensor ID field, fields for temperature and tire pressure, fields for various warning flags, and a checksum. Unfortunately, the current packet format used is ill-suited for proper encryption, since naively encrypting the current packet format would still support dictionary-based cryptanalysis as well as replay attacks against the system. For this reason, we recommend that an additional sequence number field be added to the packet to ensure freshness of a packet. Further, requiring that the sequence number field be incremented during each transmission would ensure that subsequent encrypted packets from the same source become indistinguishable, thereby making eavesdropping and cryptanalysis significantly harder. We also recommend that an additional cryptographic checksum (e.g. a message authentication code) be placed prior to the CRC checksum to prevent message forgery.

Such a change in the payload would require that TPMS sensors have a small amount memory in order to store cryptographic keys, as well as the ability to perform encryption. An obvious concern is the selection of cryptographic algorithms that are sufficiently light-weight to be implemented on the simple processor within a TPMS sensor, yet also resistant to cryptanalysis. A secondary concern is the installation of cryptographic keys. We envision that the sensors within a tire would be have keys pre-installed, and that the corresponding keys could be entered into the ECU at the factory, dealership, or a certified garage. Although it is unlikely that encryption and authentication keys would need to be changed, it would be a simple matter to piggy-back a rekeying command on the 125kHz activation signal in a manner that only certified entities could update keys.

6.3 Preventing Spoofed Activation

The spoofing of an activation signal forces sensors to emit packets and facilitates tracking and battery drain attacks. Although activation signals are very simple, they can convey a minimal amount of bits. Thus, using a long packet format with encryption and authentication is unsuitable, and instead we suggest that the few bits they can convey be used as a sequencing field, where the sequencing follows a one-way function chain in a manner analogous to one-time signatures. Thus, the ECU would be responsible for maintaining the one-way function chain, and the TPMS sensor would simply *hash* the observed sequence number and compare with the previous sequence number. This would provide a simple means of filtering out false activation signals. We note that other legitimate sources of activation signals are specialized entities, such as dealers and garages, and such entities could access an ECU to acquire the position within the hash chain in order to reset their activation units appropriately to allow them to send valid activation signals.

[3] We note that encrypting the entire message (or at least all fields that are not constant across different cars) is essential as otherwise the ability to read these fields would support a privacy breach.

7 Related Work

Wireless devices have become an inseparable part of our social fabric. As such, much effort has been dedicated to analyze the their privacy and security issues. Devices being studied include RFID systems [27, 30, 41], mass-market UbiComp devices [38], household robots [14], and implantable medical devices [21]. Although our work falls in the same category and complements those works, TPMS in automobiles exhibits distinctive features with regard to the radio propagation environment (strong reflection within and off metal car bodies), ease of access by adversaries (cars are left unattended in public), span of usage, a tight linkage to the owners, etc. All these characteristics have motivated this in-depth study on the security and privacy of TPMS.

One related area of research is location privacy in wireless networks, which has attracted much attention since wireless devices are known to present tracking risks through explicit identifiers in protocols or identifiable patterns in waveforms. In the area of WLAN, Brik *et al.* have shown the possibility to identify users by monitoring radiometric signatures [10]. Gruteser *et al.* [19] demonstrated that one can identify a user's location through link- and application-layer information. A common countermeasure against breaching location privacy is to frequently dispose user identity. For instance, Jiang *et al.* [24] proposed a pseudonym scheme where users change MAC addresses each session. Similarly, Greenstein *et al.* [18] have suggested an identifier-free mechanism to protect user identities, whereby users can change addresses for each packet.

In cellular systems, Lee *et al.* have shown that the location information of roaming users can be released to third parties [28], and proposed using the temporary mobile subscriber identifier to cope with the location privacy concern. IPv6 also has privacy concerns caused by the fixed portion of the address [32], and thus the use of periodically varying pseudo-random addresses has been recommended. The use of pseudonyms is not sufficient to prevent automobile tracking since the sensors report tire pressure and temperature readings, which can be used to build a signature of the car. Furthermore, pseudonyms cannot defend against packet spoofing attacks such as we have examined in this paper.

Security and privacy in wireless sensor networks have been studied extensively. Perrig *et al.* [37] have proposed a suite of security protocols to provide data confidentiality and authentication for resource-constrained sensors. Random key predistribution schemes [12] have been proposed to establish pairwise keys between sensors on demand. Those key management schemes cannot work well with TPMS, since sensor networks are concerned with establishing keys among a large number of sensors while the TPMS focuses on establishing keys between four sensors and the ECU only.

Lastly, we note related work on the security of a car's computer system [26]. Their work involved analyzing the computer security within a car by directly mounting a malicious component into a car's internal network via the On Broad Diagnostics (OBD) port (typically under the dash board), and differs from our work in that we were able to remotely affect an automobile's security at distances of 40 meters without entering the car at all.

8 Concluding Remarks

Tire Pressure Monitoring Systems (TPMS) are the first in-car wireless network to be integrated into all new cars in the US and will soon be deployed in the EU. This paper has evaluated the privacy and security implications of TPMS by experimentally evaluating two representative tire pressure monitoring systems. Our study revealed several security and privacy concerns. First, we reverse engineered the protocols using the GNU Radio in conjunction with the Universal Software Radio Peripheral (USRP) and found that: (i) the TPMS does not employ any cryptographic mechanisms and (ii) transmits a fixed sensor ID in each packet, which raises the possibility of tracking vehicles through these identifiers. Sensor transmissions can be triggered from roadside stations through an activation signal. We further found that neither the heavy shielding from the metallic car body nor the low-power transmission has reduced the range of eavesdropping sufficiently to reduce eavesdropping concerns. In fact, TPMS packets can be intercepted up to 40 meters from a passing car using the GNU Radio platform with a low-cost, low-noise amplifier. We note that the eavesdropping range could be further increased with directional antennas, for example.

We also found out that current implementations do not appear to follow basic security practices. Messages are not authenticated and the vehicle ECU also does not appear to use input validation. We were able to inject spoofed messages and illuminate the low tire pressure warning lights on a car traveling at highway speeds from another nearby car, and managed to disable the TPMS ECU by leveraging packet spoofing to repeatedly turn on and off warning lights.

Finally, we have recommended security mechanisms that can alleviate the security and privacy concerns presented without unduly complicating the installation of new tires. The recommendations include standard reliable software design practices and basic cryptographic recommendations. We believe that our analysis and recommendations on TPMS can provide guidance towards designing more secure in-car wireless networks.

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