# State Observation in Automotive Aftertreatment Systems Based on Wireless Communication Links

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***Abstract*—We propose a novel approach for a cheap and easy implementable microwave-based system for the state determination of emission control and exhaust gas aftertreatment systems in motor vehicles, trucks, combustion installations, and similar equipment. It is particularly important to monitor the state of diesel particulate filters (DPF), three-way catalytic converters (TWC), and selective catalytic reduction (SCR) catalysts. It is proposed to consider the volume inside the housing of the DPF, TWC, or SCR as a communications channel between two terminals of a wireless communications system. From the transmission channel characteristics, the properties of the catalyst, such as the catalyst state, can be estimated. Measurement results for both soot-loaded and empty DPFs are presented. The technique involves a small-size and cost-effective modular architecture and has the potential for serial application.**

***Index Terms*—Microwave, emission control, aftertreatment systems, diesel particulate filter (DPF), three-way catalyst (TWC), selective catalytic reduction (SCR).**

## I. Introduction

Modern regulations of the soot emissions and other exhaust gas components like Euro 5 and Euro 6 require new methods both for the emissions control and for the monitoring and operation of the emissions control systems in the diesel and gasoline engines. This is of a particular importance for heavy duty vehicles.

During the diesel engines operation, soot is captured in the pores of the diesel particulate filters (DPF) or selective catalytic reduction (SCR) catalysts. The ceramic filter must be periodically regenerated to avoid blocking. The knowledge about soot load of the DPF is useful for the engine control in a number of ways [1], [2]. The state of the art is, however, that the soot load cannot be measured directly, but is determined indirectly through the flow pressure (when the filter begins to clog, the pressure difference between points in the flow before and after the DPF increases). This approach requires a pressure measuring element.

For the gasoline engines, a so-called three-way catalyst (TWC) is used to keep the polluting emissions low. The TWC stores and releases oxygen depending on the operating conditions. As in the DPF case, it would be of a great advantage from the control engineering point of view to know the inner state of the catalyst and especially the oxygen loading state. However, it is the state of the art that the loading state cannot be measured directly, but is derived indirectly from the oxygen concentration in the exhaust stream before and after the catalytic converter. The oxygen-measuring elements (so-called lambda sensors) are implemented for the loading state estimation [3].

There are many more examples from the automotive and process engineering industries which corroborate the statement that the knowledge of the internal state of electrochemical systems is beneficial. This includes a variety of catalytic converter types. For the sake of brevity, the term $catalyst$ is used throughout the paper.

There are known a few approaches for the direct measurement of the desired internal parameters [4], [5]. These and similar ones also based on physical sensors can in principle deliver local information about the catalyst. However, one can learn nothing about the global state, such as the overall loading degree. Additionally, these approaches suffer from the complexities involving the mounting of the sensors in the catalyst and the communication with them.

Since the catalytic converter is typically located in a metallic housing, it and its housing together act as a filled cavity resonator. The resonances are influenced by the changes of material parameters in the catalyst so that the catalyst state can be determined from the appropriate signal characteristics of the resonances. The feasibility of this approach is well documented in the literature [6]–[9]. Typically, to observe the cavity resonances one or two simple thin probe feeds (short stubs) are connected to an automatic vector network analyzer (VNA) via coaxial lines. The changes in the resonant cavity are observed via the scattering matrix parameters $S_{ij}$ measured by the VNA in the laboratory conditions.

The described laboratory equipment cannot be used in the field, i.e., inside a vehicle or in the manufacturing plant, owing to space and cost reasons. For the practical application it should be replaced by smaller and cheaper solutions. The current contribution aims to demonstrate a possible solution to this task.

The rest of the paper is organized as follows. In Sect. II the experimental setup is described, in Sect. III we discuss the possible hardware realization of the system, and in Sect. IV we present the measurement results. The conclusions follow in Sect. V.

## II. Experimental Setup

It is proposed to consider the interior of the catalyst housing as a communications channel between two terminals of a wireless communications system (Fig. 1). The most important parameters during the data transmission are the characteristics of the communications channel. From the characteristics of the transmission channel, the properties of the catalyst such as the catalyst state can be determined. To this end, the communications channel parameters (rather than the S-parameters of a microwave two-port) have to be measured.

The system in Fig.1 consists of a conductive (usually metallic) housing of the catalyst (1) and the catalyst itself (2). Two gas-permeable conductive grids (3, 4) which limit the resonating cavity are of great advantage. These grids are effectively short-circuiting the electric field. Two thin probe feeds (short stubs 5, 6) are connecting the cavity with the system environment. The probe feeds are connected either with communication end devices (7, 8) or measurement equipment (in a more expensive and precise realization) by coaxial cables. The short stubs play the same role for the communications system as the antennas in the common message transmission and the catalyst in its housing plays the same role as the wireless transmission channel for the ordinary message transmission.

The signal transmitted through the wireless channel inside the catalyst suffers from such effects as attenuation, fading, multipath propagation, scattering, etc. The characteristics of the received information transferred from the transmitter to the receiver depend on the propagation medium. The effect on the signal is similar to the effect of the common signal wireless propagation in space with building, trees, autos, rain, humidity and other implications on the propagation direction. The only difference in our case is the closed space propagation with soot and other chemical elements changing the medium characteristics affecting the received signal parameters.

Such quantities as the bit error rate (BER), the packet error rate (PER), the ratio of the energy per bit to the noise power spectral density $E_b/N_0$ , and the data receive rate (Rx data rate) are among the most important parameters characterizing the performance of a communications system or channel. It is proposed to determine the state of the catalyst by evaluating the BER, PER, $E_b/N_0$ levels, and the Rx data rate.

BER is the number of bit errors divided by the total number of transferred bits during a studied time interval:

$$BER = \frac{number\ of\ bit\ errors}{number\ of\ transferred\ bits} \tag{1}$$

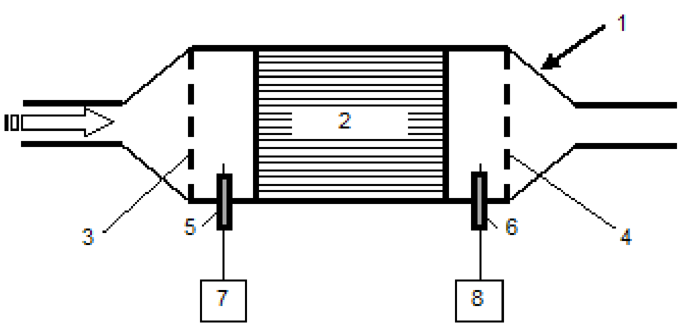


Fig. 1. Basic structure of the proposed measurement system.

PER is the number of incorrectly received data packets divided by the total number of received packets. A packet is decided incorrectly received if at least one bit in this packet is erroneous. PER can be expressed as:

$$PER = 1 - (1 - BER)^l, \tag{2}$$

where $l$ is the packet length.

## III. Hardware Realization

Based on the proposed method, the catalyst state can be estimated with commercially available and inexpensive hardware. The functional diagram of such a system is shown in Fig. 2. The pattern generator creates a defined test pattern which is later on transmitted by the transmitter to the device under test (catalyst). After the signal is received, the BER, PER, $E_b/N_0$, Rx data rate or other values are measured and the catalyst state is estimated.

In Fig. 3 a possible hardware implementation is proposed. The pattern generator and the transmitter are part of a communication module (e.g., Xilinx Spartan) and the receiver is part of a second communication module. After determining the desired communication parameters, the catalyst state can be derived.

Such devices as Altera Stratix, Xilinx Virtex, Xilinx Spartan ZigBee, Wireless HART, Nanonet, PulsON 410 and any other including (but not limited to) field-programmable gate array (FPGA) based integrated circuits and devices could be used for building an appropriate communication systems for the intended application purpose. A variety of functions for estimating the catalyst state can be provided by changing and customizing the codes in the numerical computing environments and programming languages (such as MATLAB, C, C++, Java, etc.).

## IV. Measurement Results

For test purposes, two DPFs were measured with the described system architecture (Fig. 4). One of the DPFs was soot loaded (4.6 g) and the other was empty (not used). The aim was to compare the effect of the soot load on the communication channel and, as a result, on its parameters in order to prove the validity of the, as we believe, novel approach towards the monitoring and estimation of catalyst states.

Fig. 5 shows the measured bit error rates during the communication between two commercial PulsON 410 modules, where the interior of the catalyst-loaded metal housing is used as the radio channel. The smallest and largest measured bit error rates are shown, since BER is a random variable. Then the average values were calculated and they are shown as well. It is clear that the BER depends not only on the transmission power (which is well known) but also on the condition or state of the catalyst (which has not been described before). The bit error rates for the two extreme states of the catalyst (completely empty and completely loaded) differ by up to an order of magnitude and more depending on the transmitting power.

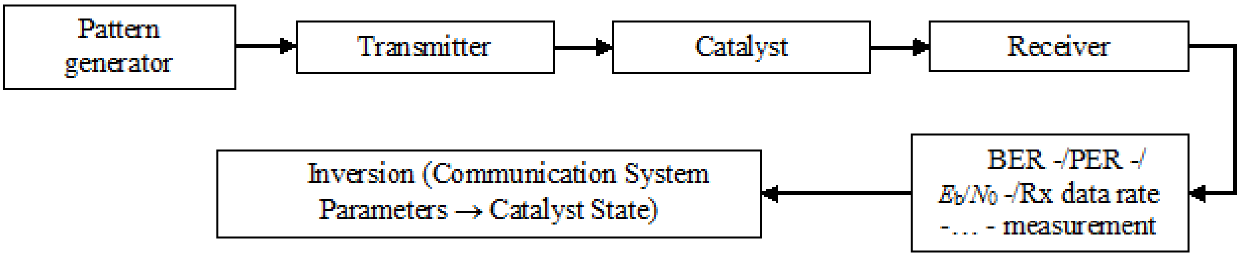


Fig. 2. Functional diagram of the proposed measurement system.

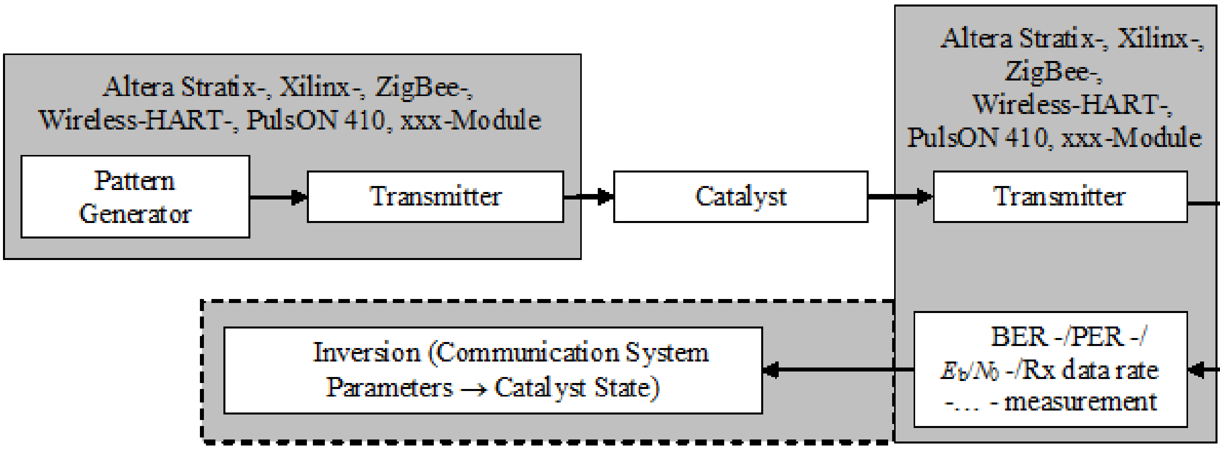


Fig. 3. Possible hardware implementation of the measurement system.

Fig. 4. Catalysts under test – empty (left) and soot loaded (right). The catalysts are the same as those described in [10].

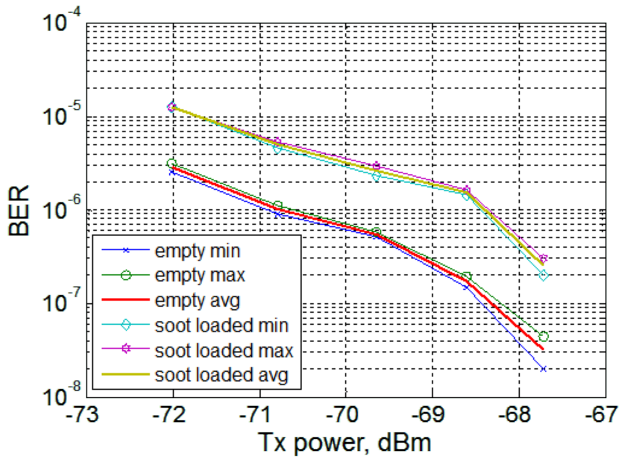


Fig. 5. Bit error rate during one of the experiments with two DPFs.

In practical applications, one could process the catalyst state determination as shown in Fig. 6. The transmitter radiated a signal with a constant power (in the example with -70 dBm).

From the bit error rate registered by the receiver, one can infer the channel attenuation and thus the oxygen storage level of a TWC, the soot loading level of a DPF, etc.

In a similar manner, one can derive the catalyst state by any other communication channel parameter. In Fig. 7, the PER measurement of the two catalysts under test is shown. It is clearly seen that the difference between the PER measurements for the soot loaded and empty catalysts, at a transmit power of -70 dBm, even exceeds an order of magnitude. In this case, the PER of the transmission channel with empty catalyst and with soot-loaded catalyst is 4.85 % and 51.9 %, respectively.

In Fig. 8, the $E_b/N_0$ at different transmit powers is shown for both tested catalysts. One can see that, to guarantee the same $E_b/N_0$ value for two channel realizations, the transmit power should be around 1 dB higher in the soot-loaded catalyst case.

Receive data rate measurement results are shown in Fig. 9. The data rate is affected by the channel quality, possible implications in the propagation medium, and the communication parameters. For some values of the transmit power (e.g., for -71 dBm) the difference of the receive data rate is more than 60 kbps for both catalysts in the implemented system.

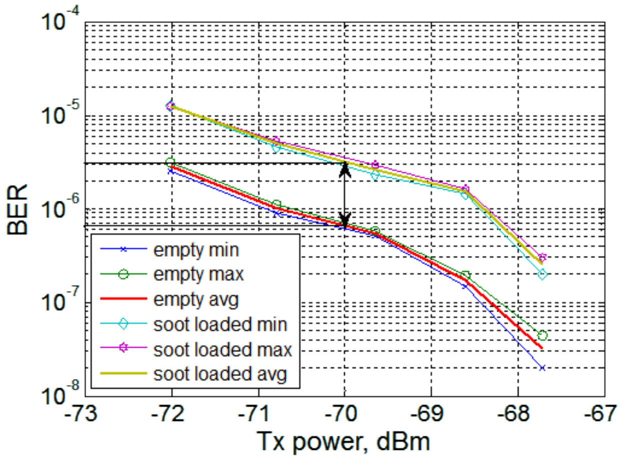


Fig. 6. Possible evaluation method for plots from Fig. 5.

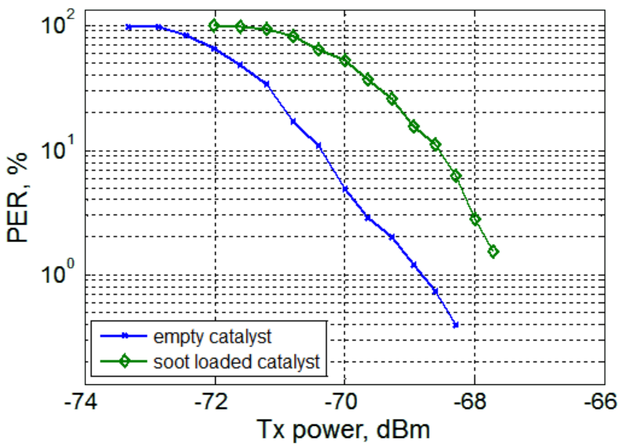


Fig. 7. Packet error rate measurement for both DPFs.

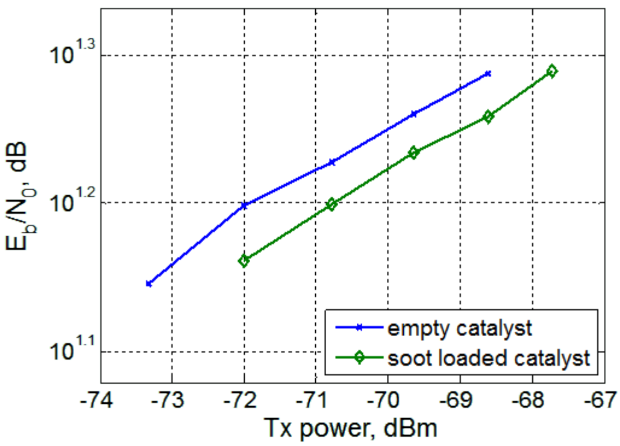


Fig. 8. $E_b/N_0$ vs. Tx power measurement result for two DPFs.

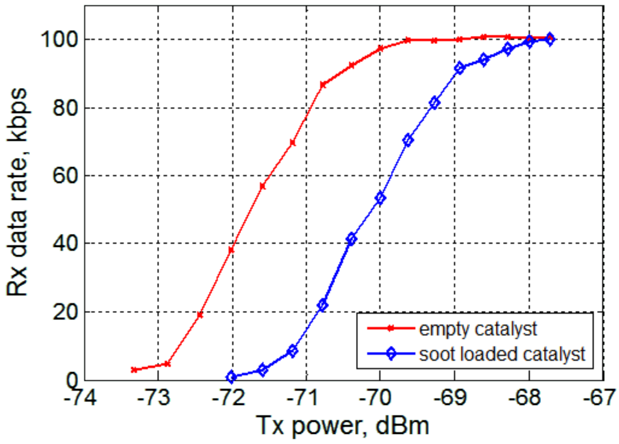


Fig. 9. Receive data rate vs. transmit power for both DPFs.

## V. Conclusions

In this work, we describe a novel approach towards the monitoring of exhaust gas aftertreatment systems, such as DPFs, SCRs, and TWCs. We propose to consider the interior of the catalyst metal housing as a communication channel with respective parameters. The effect of the catalyst state on such communication parameters as BER, PER, $E_b/N_0$ levels and the Rx data rate is demonstrated by way of an example. In some cases the difference in the measurements between the soot loaded and empty catalysts differs by more than one order of magnitude. Taking into account a broad availability of the communication systems, their scalability, size, modular architecture, and cost, the proposed approach offers considerable potential in terms of practical realization.

## VI. Acknowledgment

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