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An Efficient Multicarrier Transmission over Powerline Channel for Intra-Vehicular Applications

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Abstract: Intra-Vehicular communication from various sensors to the Engine Control Unit (ECU) as well as from other mechanical devices in a vehicle are connected to the dashboard is currently in focus due to the need to support Connected Cars in a 5G scenario. Presently dedicated power lines and data lines are used making it redundant and expensive. Here we examine methods to transfer data over a power line in a typical intra vehicular scenario noting that the power and data lines are different in various aspects. Data lines are point to point links but power lines have bridge taps connected to various sensors with varying loads. Two techniques to perform an efficient communication between the sensors and the dashboard are proposed. The first way is to use the capacity afforded by Multiple Carrier Communication that readily provides substantial redundancy in terms of bandwidth, facilitating rate reapportioning to cater to varying channel impedance. However, the data rates are unsustainable when there is a sudden change in channel response for which a second method is proposed. In the second method which includes the first method also, we compensate the time varying impedance using conjugate impedance in one arm of the Wheatstone bridge. This bridge also serves the purpose of isolation between Modem and power line. The results have been provided by using 20 metres line under varying load conditions which includes open, short and various impedances which typically matches with that of a power line in an automotive scenario.

Keywords: Multi-carrier, OFDM, Intra-vehicular communication, power-line communication.

I.INTRODUCTION

The complex wiring i.e. data and power lines in an automotive is shown in Fig. 1. The traditional data lines enjoy a big advantage i.e. they have a constant impedance and it is easily matched so the data bus is always operated close to capacity. However, this becomes redundant when we already have a real-estate in terms of a power line which can do the job by managing the impedance changes to carry the data traffic because the power line frequencies and the data carrying frequencies are entirely independent/orthogonal. Therefore, it makes sense to use much of the techniques developed for DSL in a typical automotive scenario.

The use of a power line for data communication in a typical automotive scenario was initially discussed in technology for broadband communication over DC power lines is dealt in [1]. The power line in the above figure multiplexes digital information and power. Considerations of impulsive noise is dealt exclusively in [2] using various modulation schemes like BPSK, DBPSK, OOK. An effort for the In-vehicle power line communication (PLC) by decreasing weight, volume, or cost of the wiring harnesses is made in [3]. In [3], we present some works about channel measurements in an automotive. Flex ray communication which is used for PLC transceiver has been presented in [4]. This provides a solution by decreasing weight, volume and cost of the wiring harnesses. An effort to present a detailed analysis of the periodic noise on in-vehicle power lines is made in [5]. Multi-carrier contention scheme is dealt in [6] using frequency and time multiplexing. However, despite the compact size of the in-car electrical grid, high channel attenuation, low impedance access points, and high noise can limit the applicability of PLC. In [7] an effort is made to report the results of attenuation in an automotive. In paper [8] the author focused on channel characterization and modelling of PLC in a vehicle. The existing literature has a drawback as they don't consider multiple carriers i.e. to use OFDM for a time-varying channel, no rate adaptation techniques. Their study is based on a fixed impedance but not for a time varying scenario. However, the power line poses some unique challenges that are not addressed in literature i.e. use of multi-carriers efficiently by data rate reapportioning. So, to some extent the literature does the job in addressing various problems but not in a very efficient way.

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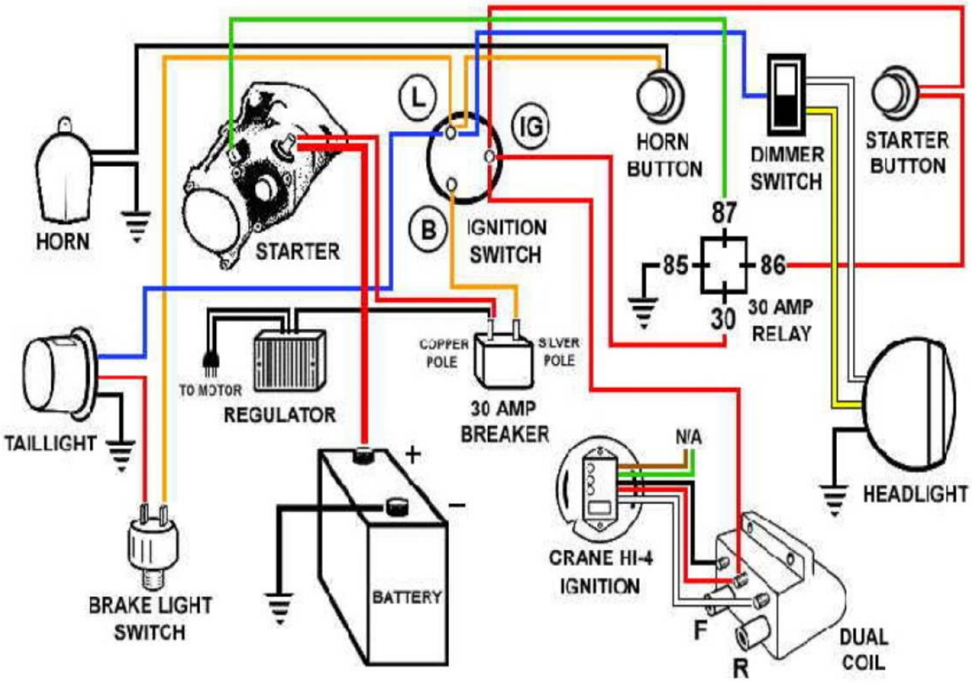

Fig. 1 Wiring inside an automotive setup

In this paper, we try to address this issue using the flexibility offered by OFDM. Fundamentally we are making use of the fact that the data rates that are required which are perhaps one portion of the spectra can be easily shifted to other portions of the spectra depending upon changes in channel impedance. This is called Rate Reapportioning i.e. rate is reapportioned to some other space. This works fine provided the impedance changes are not too much. However, when there are considerable changes in impedance this Rate Reapportion may not work. Then the severe impedance mismatches in the power line are compensated by means of a conjugate impedance provided in the Wheatstone bridge. We are a step ahead by using the Impedance compensation techniques with Wheatstone bridge.

The paper is organized as follows - In section II the channel modelling has been developed based on the transfer function (S_{21}) obtained by analysing RLCG Parameters. The channel capacities with impulse noise, employing DMT are analysed in section III, and Simulation results for different topologies are presented in section IV.

I. CHANNEL MODELLING / DESIGN OF MULTICARRIER CHANNEL

A. *Specifications for design*

As mentioned earlier we can use techniques developed for DSL in an automotive scenario. Gauges #24 and #26 are most important in DSL applications. The gauges are the indicative of the diameter of the copper wire making up the twisted pair. For DSL technologies high twisted pairs are used. These twisted pair lines are modelled using resistance, inductance, capacitance and admittance i.e. the RLCG Parameters. These RLCG parameters are with respect to 1000 feet, a common measure of distance in twisted pairs which can be converted to other scales depending on the application. The following specifications in Table 1. are considered for analytic model transmission line. These values are obtained from [9].

TABLE I PARAMETERS FOR ANALYTIC TWISTED PAIR MODEL

Parameters	**#24 Gauge**	**#26 Gauge**
R(ohms/kft)	0.15	0.195
L(mH/kft)	0.188	0.205
C(nF/kft)	15.7	15.7
G(mho/kfy)	0	0

We are considering the channel for higher bandwidth applications and at frequencies above voice band the RLCG parameters vary with frequency.

$$R = R_0 * \sqrt[2]{f} \tag{2.1.1}$$

$$L = L_0 \tag{2.1.2}$$

$$C = C_0 \tag{2.1.3}$$

$$G = 0 \tag{2.1.4}$$

Using the approximation set forth, the propagation constant of a twisted pair can be shown as

$$\gamma = \sqrt{j\omega C}\,\sqrt{R + j\omega L} = j\omega\sqrt{LC}\,\sqrt{\frac{R}{j\omega L} + 1}$$

$$\approx j\omega\,\sqrt{LC}\,\sqrt{\frac{R}{j\omega L} + 1}$$

$$= R\sqrt{\frac{C}{L}} + j\omega\,\sqrt{LC} \tag{2.1.5}$$

In term α (real part) of the propagation constant is called attenuation.

$$\alpha = R\,\sqrt{\frac{C}{L}} = \alpha_0 f^{1/2} \tag{2.1.6}$$

The final result for α from analytic approximation for RLCG parameters. α is proportional to the square root of frequency because capacitance and inductance are assumed to be constant and R is proportional to $f^{1/2}$ due to skin effect. Based on this observation the transfer function for attenuation is

$$H(f) = e^{\alpha . z} \tag{2.1.7}$$

Where z = length of the line.

The attenuation offered by the channel to the signal is dependent on the frequency of the signal and length of the channel. The time varying channel is analysed till frequency where this attenuation is minimum i.e. till 1.1 MHz So the S-parameters were extracted for this range.

B. *Wheatstone Bridge*

Now this power line becomes an arm of the Wheatstone bridge as shown in Fig. 1. The variable impedance in the balancing arm is used to balance the look-in impedance of the time varying power line given by

$$Zin = Z_0 * \frac{Z_L cos\beta l + j\, Z_0 sin\beta l}{Z_0 cos\beta l + j\, Z_L sin\beta l} \tag{2.2.1}$$

Where Z_0 = characteristic impedance which is normally 50 ohms.
Z_L= Load impedance
$\beta = Phase\ factor$
L = length of the power line
When power line is open $Z_L = \infty$
When power line is shorted $Z_L = 0$.

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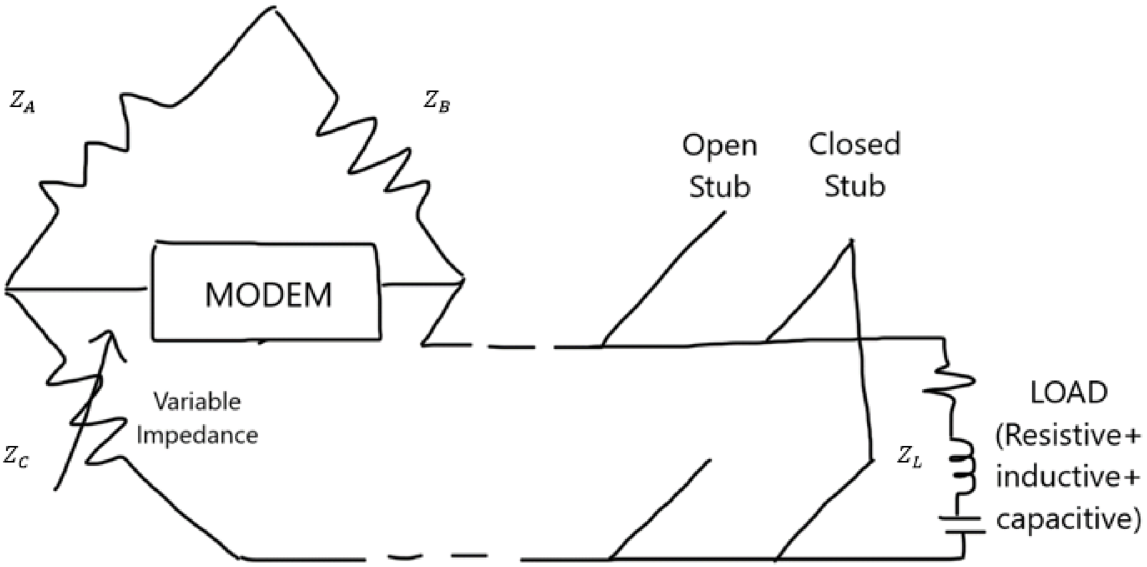

Fig. 2 Wheatstone Bridge

$$Z_A * Z_L = Z_C * Z_B$$

$$\frac{Z_A * Z_L}{Z_B} = Z_C \qquad (2.2.2)$$

The power line inside a vehicle would typically be of 24 AWG and not exceed twenty meters in length. However, the connections to various sensors and Devices would be bridged across as taps from the main line. These bridge taps would be typically no more than two meters and have a complex impedance at its ends. These complex impedances may be switched in or out depending on events scheduled. Hence, we can term the look in impedance of the power line as a time varying channel. As explained a time varying channel exhibits a varying channel transfer function in respect of data and hence would have a severe impact on the capacity for data transmission. In this algorithm a three-step strategy is proposed to manage the time varying channel and hence the capacity can be maintained constant.

1. If a change in look in impedance results in a small change in capacity them a bit swap procedure to redistribute the bits to sub channels where the SNR has improved or same is executed apart form a small power management procedure to increase or decrease power spectral density in the loaded tones of the transmission band of the modem to restore the original capacity.
2. If a change in look in impedance results in a medium change in capacity (between 20 – 40%) then a seamless rate repartitioning procedure could be executed across bunches of subchannels apart from redistribution of power spectral density over the newly selected subcarriers.
3. If the change in capacity due to change in look in impedance is greater than 40% then a conjugate load is added at the Master transmitter modem end to balance out the change in impedance that has occurred. This is followed by a seamless rate repartitioning procedure to restore the original capacity data rate. The modem DSP has to be isolated from the line through a bridge as shown in figure 3.2. The balance arm of the bridge contains suitable impedance that caters to a variety of impedances that are possible looking into transmission line. This has to be necessarily known prior fixing the conjugate balance impedance so as to render the modem look in resistive.

II. DMT AND CHANNEL CAPACITY

A. *Discrete Multi-Tone Modulation*

In Fig. 3 a conceptual view of a specific Multicarrier modulation DMT is shown. The subcarriers are independent and carry part of user data only. [9].

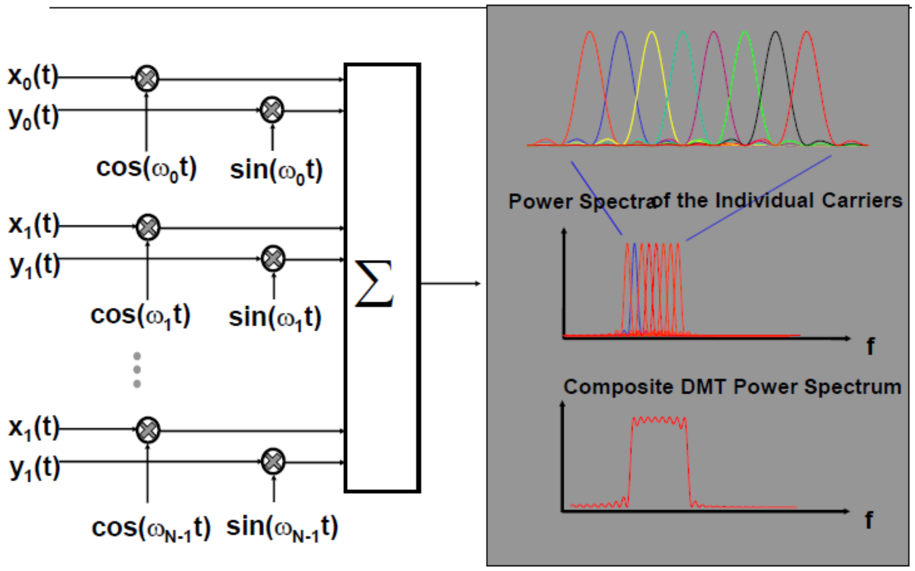

Fig. 3 Conceptual view of DMT

Discrete multitone (DMT) is used like in a Digital Subscriber Line (DSL) with 256 sub-carriers spaced at 4.3125 KHz each as shown in Fig. 4. The capacity available far exceeds the requirement of intra vehicular data rates. Hence only a portion of the subcarriers are typically proposed to be used based on the SNR monitored continuously. When the impedance changes over the power line the SNR profile over the subcarriers also changes. In this case a set of subcarriers can be chosen to transfer the data. This is called rate reapportioning and is easily provided into modem 's finite state machine.

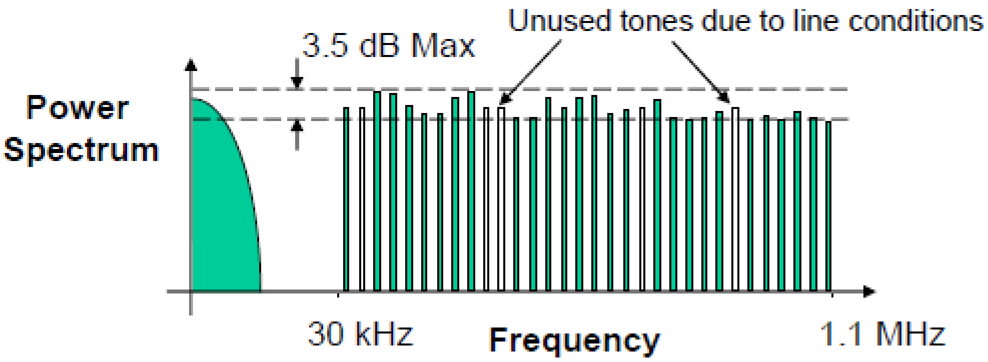

Fig. 4 Power Spectrum v/s Frequency plot

B. *Channel Capacity*

The process begins with modelling the test channel as an open, shorted and transmission line with load. Load comes when any motor is attached or any sensor becomes active. The channel is analogous to a two-port network as shown in Fig. 5.

To find S_{21} i.e., the gain of the topology.

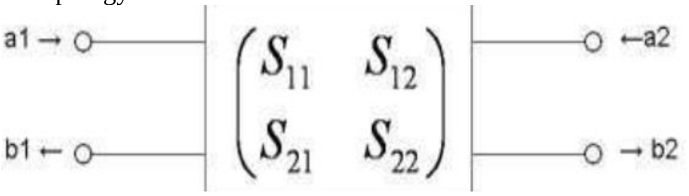

Fig. 5 Two-port network with S-Parameters

$$S_{11} = \frac{b1}{a1} \tag{3.2.1}$$

$$S_{12} = \frac{b1}{a2} \tag{3.2.2}$$

$$S_{21} = \frac{b2}{a1} \tag{3.2.3}$$

$$S_{22} = \frac{b2}{a2} \tag{3.2.4}$$

As we have 256 frequency points, we have a 256-point vector. Converting it into Frequency domain by applying 256-point FFT to obtain the transfer function H(f). Find the absolute value of each complex number in H(f) and convert them into db.
We generate the pseudo random binary sequence of 512 bits with total power of 1W. From these 512 bits, we map 2 bits to one complex number obtaining 256 symbols. This is called Constellation Mapping. Constellation mapping (CM) is used to increase the spectral efficiency and to further approach the Shannon limit. The spectral efficiency determines the modulation scheme and we prefer to use 4 QAM/QPSK. So, the entire set of 512 bits is mapped to 256 complex numbers using QPSK scheme. Encoding is done prior to CM. As the total power is 1W, the power on each symbol is 3.9 mW. This sequence is transmitted and the transmission energy is constant on each tone i.e. 3.9mW. Convert them dbm. The transfer function (db) and the transmitter sequence (dbm) are added. The received power in dbm is converted back into milliwatts. This received power is divided with noise power in the channel in order to calculate the SNR. These SNR values are converted to db and a margin of 15.8 db is given. Now these SNR values are converted back to normal scale and the number of bits on each tone is found out by using the Shannon's Formula.

$$\mathrm{b_i} = \log_2\left(1 + \frac{\mathrm{E}}{\mathrm{N}}\right) \tag{3.2.5}$$

By using the above formula, we get the bit allocation on each tone. But these have some fractional parts. In order to convert them to integers and adjust the fine gains we use the rounding operation
Ex: Sub channel-i can support 1.6 bits -> rounds to 2 bits.
Ex: Sub channel-j can support 2.4 bits -> rounds to 2 bits.

C. *Reason for the margin*

The channel capacity provided by Shannon's theorem however has three assumptions that are
a. Source Pdf is Gaussian
b. Channel is an ideal channel with constant gain and linear phase
c. Noise PSD in the channel is constant

The BER obtained on every subchannel assumes a uniform discrete Pdf for the source. Thus, the SNR measured cannot be employed as the same value in the Shannon's capacity theorem. To cater to the difference in SNR due to source pdf not being Gaussian in Shannon's theorem a degradation factor called 'gap' is appended to SNR measured when used in the capacity equation. Thus, the modified Shannon's theorem that is employed in realizable situations now reads as

$$\text{Capacity C} = (1/2)\log_2\left(1 + \left(\frac{SNR}{\gamma}\right)\right) \tag{3.3.1}$$

Where the gap factor □□= 9.8 + margin – coding gain. Typically, margin is taken to be 6 db.

D. *Fine Gain Adjustments*

An increase/decrease of 3 dB in SNR corresponds to an increase/decrease of 1 bit per sub-symbol i.e. doubling of power. So, we need to adjust the Fine Gains in the window of -2.5db to +2.5db.

$$\text{Capacity} = \sum_{i=1}^{256} bits\ on\ ith\ channel * 4000. \tag{3.4.1}$$

The *channel capacity, C,* is defined to be the maximum rate at which information can be transmitted through a channel. The modified version of Shannon's theorem has been applied to discrete channel partitioning which uses DMT or OFDM. OFDM is a very suitable scheme based on the partitioning the channel and modulating with individual sub-carriers. It is based on partitioning the data rate before modulating digitally with several carriers in narrow sub-bands and then they are summed to create an OFDM symbol. Due to the connection and disconnection of the electrical devices mainly on the power line the impedance is going to change considerably. This time temporal event is going to change the capacity. The desired capacity is 2 Mbps. But in some cases, it might be a lot more, so to get it down to the desired value an algorithm is used.

E. *Algorithm*

In order to obtain a capacity of 2 Mbps, the sum of the bits on tones should be 500.
1. Check the sum of bits.
2. If sum > 500 cut down one bit per tone in each iteration using a for loop until the sum is equal to 500.
3. If sum < 500 increase one bit per tone in each iteration using a for loop until the sum is equal to 500.
4. The incrementing/decrementing operation is done using a reference array which shows the maximum bits on each tone.

III.RESULTS AND DISCUSSIONS

We have exercised our analysis using DMT for the particular channel described in Section 3. In order to obtain the graphs, we simulated the whole condition stated in Section I using DMT which is mentioned in 3.1. A comprehensive analysis of the results obtained is explained in this section. We obtained the transfer function in order to find out the capacity and input impedance of the topology in order to implement the Wheatstone bridge stated in 2.2. The following parameters were used to plot the SNR profile and bit loading of the 256 tones.

- 256, 4 KHz sub channels are divided with equal spacing of 4.3125 KHz between sub channels. Hence, the frequency is scaled from 0 to 1.1 MHz
- Bit loading is done based on SNR of the channel i.e., up to 15 bits per subchannel.
- The symbol rate is 4 K baud.
- American Wire Gauge (AWG) of Analytic Model is #24.
- Noise power in the channel= -140dbm/Hz.
- The position of the stub i.e. open, closed and load is 10 metres from the modem. (Generator in microwaves scenario).
- The length of the stub is 10 metres.
- Load used is 1KΩ resistor, 1H inductance and 470 pF capacitor in series.

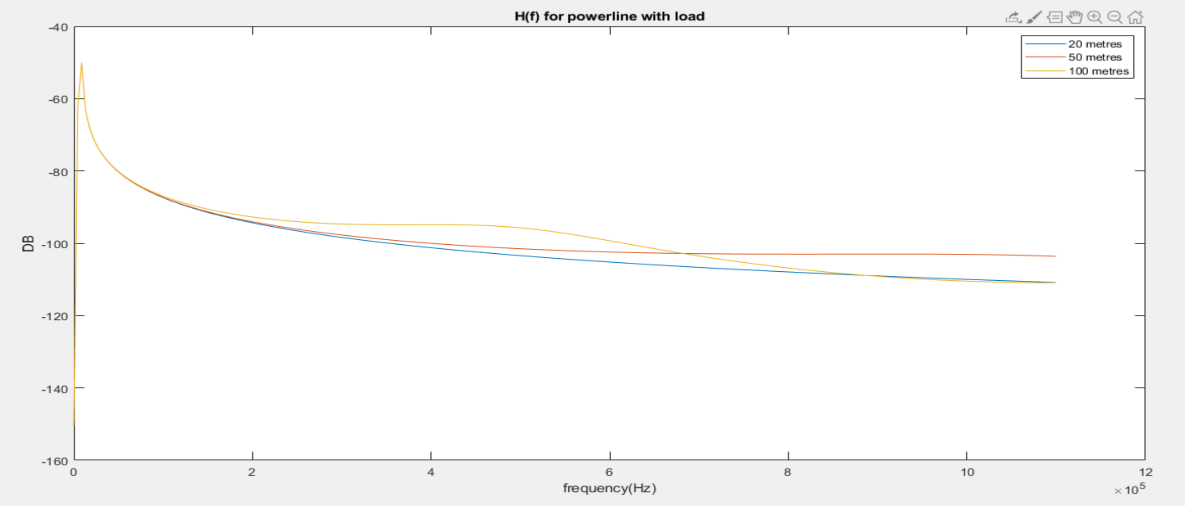

Fig. 6 Obtained graph for transfer function for a transmission line with load

The Fig. 6 shows the graph obtained from the mathematical model designed in MATLAB by considering the parameters for the #24 AWG transmission line. This shows the transfer function V/S frequency of a transmission line with resistive, inductive and capacitive load with lengths 20 metres, 50 metres and 100 metres.

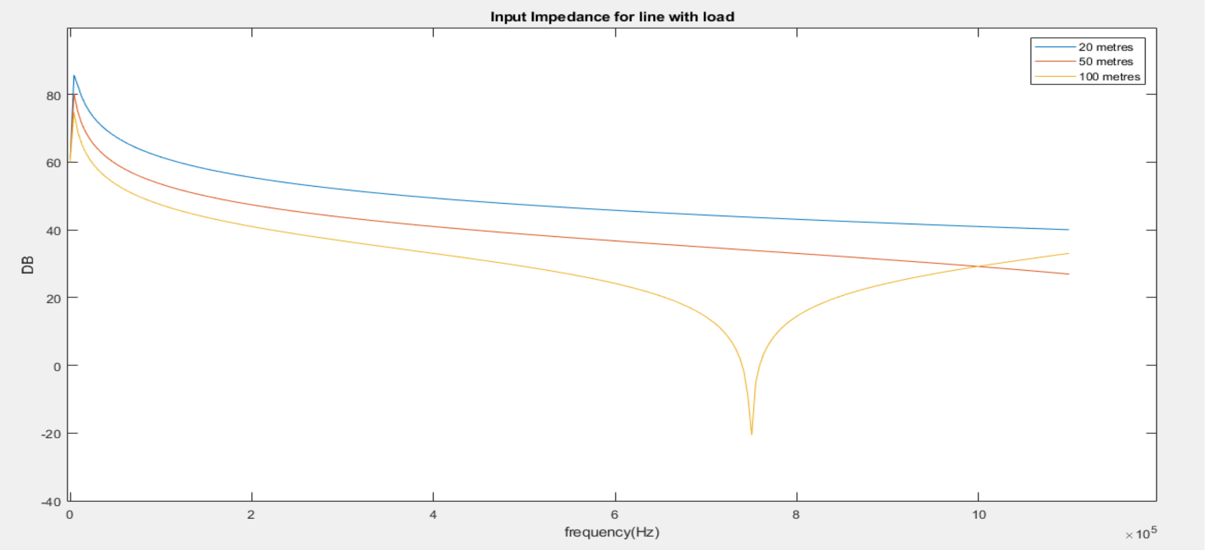

Fig. 7 Obtained graph for input impedance for a transmission line with load

The Fig. 7 shows the graph obtained from the mathematical model designed in MATLAB by considering the parameters for the #24 AWG transmission line. This shows the input impedance of a transmission line with load V/S frequency with lengths 20 metres, 50 metres and 100 metres.

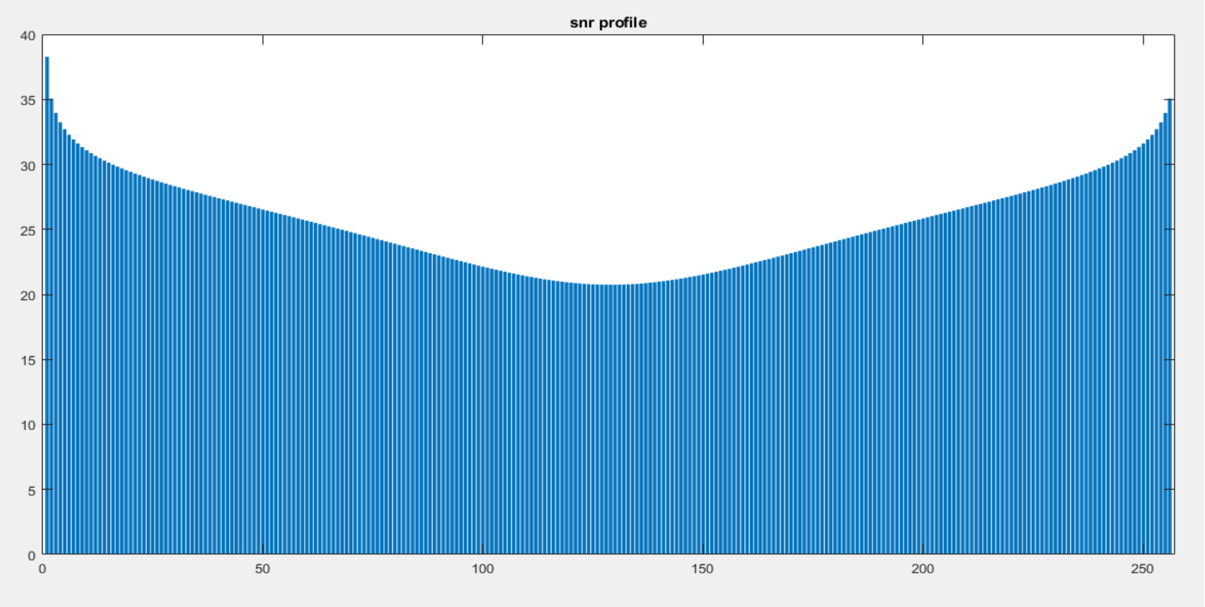

Fig. 8 Obtained graph for SNR profile of a transmission line with load

The Fig. 8 shows the graph obtained from the mathematical model designed in MATLAB by considering the parameters for the #24 AWG transmission line. This shows the SNR profile of a transmission line with load of length 20 metres.

The Fig. 9 shows the graph obtained from the mathematical model designed in MATLAB by considering the parameters for the #24 AWG transmission line. This shows the bit loading of a transmission line with load of length 20 metres.

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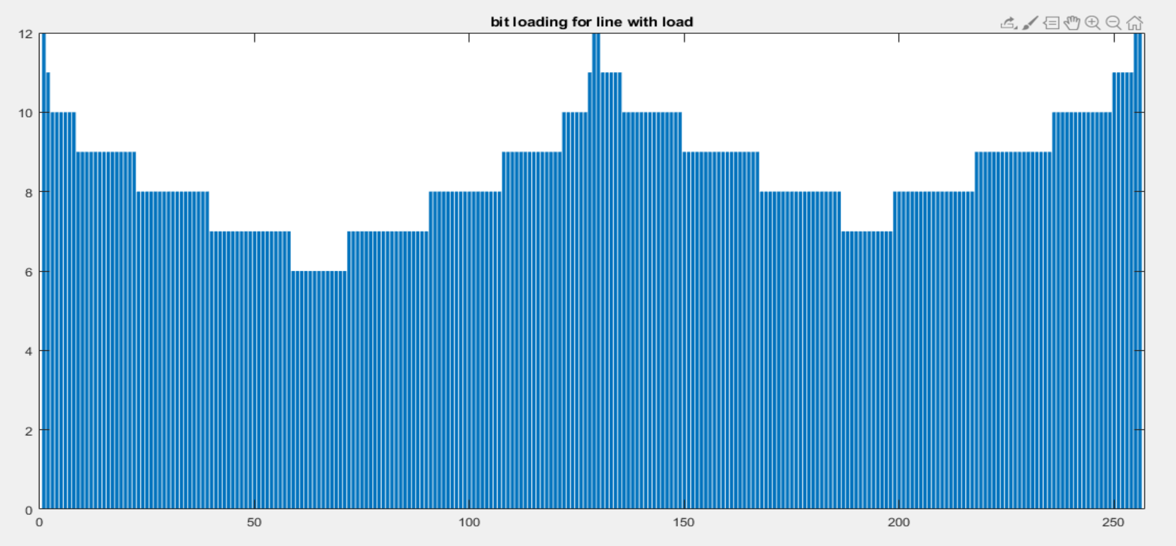

Fig. 9 Obtained graph for SNR profile of a transmission line with load

TABLE III FINE GAIN AND CHANNEL CAPACITY

Margin(dB)	Capacity(bps)	Fine Gain(dB)
15.8	8688000	0.964724167942266
9.8	10720000	3.407299792378820
3.8	12760000	3.387927285880384

The Table 2. shows the Capacity and Fine gains obtained by varying the margin for transmission line with load.

IV. CONCLUSION

A transformation is occurring for electric power lines, as the broadband services need to be carried over power lines itself with metering and control. But power lines present a difficult challenge, because reliable high-speed communication is sought over a medium designed for electrical energy delivery rather than for data transmission. Optimization of a transmission scheme can only be done after an accurate channel model is obtained. There is no universally recognized power line channel model available. But the work done in this paper marks the beginning of power line channel model addressing all the factors which make it suitable for intra vehicular communications. A cascade of bridge taps which are open and short ended are part of the line, each one described by S-Parameters. The maximum channel capacity that can be supported for specific conditions depends on SNR, which in turn depends on the line topology, load connected to the bridge taps and the impulse noise. The SNR is obtained by considering the transmit signal PSD. Apart from maximum channel capacity that can be supported for specific SNR conditions, it is preferred to fix the rate and ensure that the rate is met in the line. Impedance compensation techniques with Wheatstone bridge is developed for fixed bit rate tone loading.

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