Performance Improvement in Passive Backscatter Based RFID System with Low DCR Modulations

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Abstract. *This paper presents application of the low Duty Cycle Ratio (DCR) modulations: isochronous Digital Pulse Position Modulation (DPPM) and anisochronous Digital Pulse Interval Modulation (DPIM) in backscatter based passive RFID communication system. The proposed modulations are compared to commonly used Amplitude Shift Keying (ASK) modulation. Low DCR modulations are customized for data transmission through inductively coupled link between reader and the tag operating at frequency of 13.56 MHz. The RFID system is mathematically formulated and the performances of the tag are evaluated for each modulation. Observed parameters are modulation depth of backscattered signal, voltage-current characteristics of tag rectifier circuit and ripple of rectifier output voltage. The application of proposed low DCR modulation techniques improves the performance of the RFID system by up to 250%.*

Keywords

Low power electronics, performance analysis, RFID tags, wireless powering.

1. Introduction

Most of the RFID devices are designed to communicate with the reader. Depending on the usage, the RFID tag returns to the reader a serial number, telemetry information, or other data streams. Even the simplest RFID tag which causes only a voltage drop in the reader coil when found in its proximity, without any data to be transmitted, can be said that it is able to "communicate" with the reader device.

When the data is transmitted from the reader to the tag, or vice versa, the data stream must be modulated. The most common modulation technique used for various RFID systems is ASK (Amplitude Shift Keying) modulation [1]-[5]. For the passive RFID systems, where the tag has no on-board power supply, the ASK modulated signal is transmitted using backscattering [6]-[8].

In this paper we present the application of two low DCR modulation techniques, DPPM (Digital Pulse Position Modulation) and DPIM (Digital Pulse Interval Modulation) [9], in passive RFID system. The proposed modulations are compared to ASK modulation with respect to effects their usage has on the performance of the RFID tag. To evaluate the performance of the RFID tag the following parameters are observed: modulation depth of the backscattered signal, voltage-current characteristics of tag rectifier circuit and ripple of rectifier output voltage.

The conventional analysis of the passive RFID tag powering [10]-[12] is performed for non-transmitting tag. But, the passive RFID tag uses backscattering for transmission. Because of the backscatter based communication the tag coil is short-circuited, and the power transfer from the reader is interrupted. For that reason the analysis of non-transmitting tag is not valid for the time periods in which the tag is transmitting. We have done all measurements and observations for transmitting tag and the obtained results give more comprehensive insight of tag performance during data transmission from the tag to the reader. And for passive RFID tag, where the power management is one of the key problems, such approach does not neglect the modulation effects [13], [14] on power transfer which only occur during data transmission.

2. Passive Backscatter Based RFID System

2.1 Mathematical Model

The schematic of the passive RFID system with backscatter based communication is given in Fig. 1. It comprises of a reader and a tag. The reader, through which the tag is power supplied, is shown as a power supply (U_S, R_S) and a reader coil (L_1) in Fig. 1. The tag input circuit is formed by resonant circuit (L_2 and C_2) followed by rectifier (D and C_{load}) and resistive load R_{load} representing power consumption of the tag.

The power transfer from the reader to the tag is realized by inductively coupled coils L_1 and L_2 which form loosely coupled air-core transformer, whose mathematical formulation is given in (1) and (2).

$$u_1 = L_1 \frac{di_1}{dt} \pm M \frac{di_2}{dt}, \quad (1)$$

$$u_2 = L_2 \frac{di_2}{dt} \pm M \frac{di_1}{dt}. \quad (2)$$

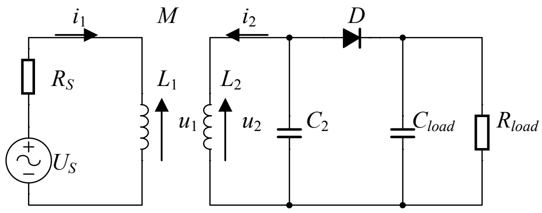

Fig. 1. Passive RFID system.

For the purpose of mathematical analysis the air core transformer is replaced with *T* equivalent circuit (Fig. 2). Resistors R_1 and R_2 are resistive parts of coils L_1 and L_2, respectively.

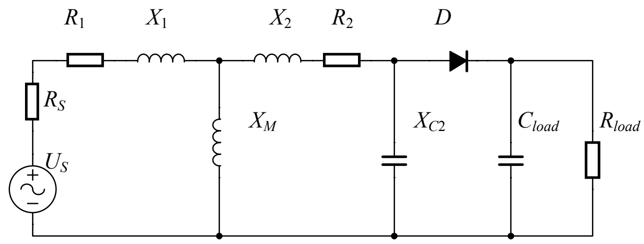

Fig. 2. RFID system with *T* equivalent circuit for air-core transformer.

The values X_1, X_2, X_M and X_{C2} in equivalent circuit are as given in (3)-(6), respectively. This corresponds to a phasor analysis. The aim is to replace the power supply of tag rectifier with Thevenin voltage and Thevenin impendance. By doing so the mathematical formulation of the tag output characteristic can be evaluated.

$$X_1 = j\omega(L_1 - M), \quad (3)$$

$$X_2 = j\omega(L_2 - M), \quad (4)$$

$$X_M = j\omega M, \quad (5)$$

$$X_{C_2} = \frac{1}{j\omega C_2}. \quad (6)$$

Equations (7) and (8) give the calculated values for Thevenin voltage U_T and impedance Z_T. Fig. 3 shows the RFID system with equivalent Thevenin power supply. For a better illustration Fig. 4 gives the graphic representation of Thevenin voltage and impedance values with respect to the mutual inductance value *M*. Both values are calculated for tag operating at its resonant frequency (9).

$$U_T = U_S \frac{M}{C_2} \cdot \frac{R_2(R_S + R_1) + \omega^2 M^2 - j\omega L_1 R_2}{\left[R_2(R_S + R_1) + \omega^2 M^2\right]^2 + (\omega L_1 R_2)^2}, \quad (7)$$

$$Z_T = \omega^2 L_2^2 \frac{\omega^2\left[L_1^2 R_2 + M^2(R_S + R_1)\right] + R_2(R_S + R_1)^2}{\left[R_2(R_S + R_1) + \omega^2 M^2\right]^2 + (\omega L_1 R_2)^2} + j\omega L_2\left[\frac{\omega^4 M^2 L_1 L_2}{\left[R_2(R_S + R_1) + \omega^2 M^2\right]^2 + (\omega L_1 R_2)^2} - 1\right], \quad (8)$$

$$\omega = \frac{1}{\sqrt{L_2 C_2}}. \quad (9)$$

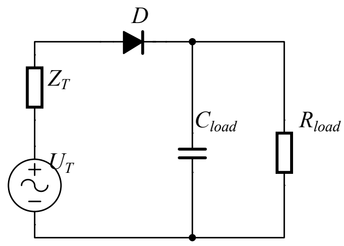

Fig. 3. RFID system with equivalent Thevenin power supply.

The mathematical model (7)-(9) and results given in Fig. 4 and Fig. 5 correspond to the laboratory model used for measurements. The value of each component matches those used in laboratory model, and are given in more detail in Section 4 - Measurement.

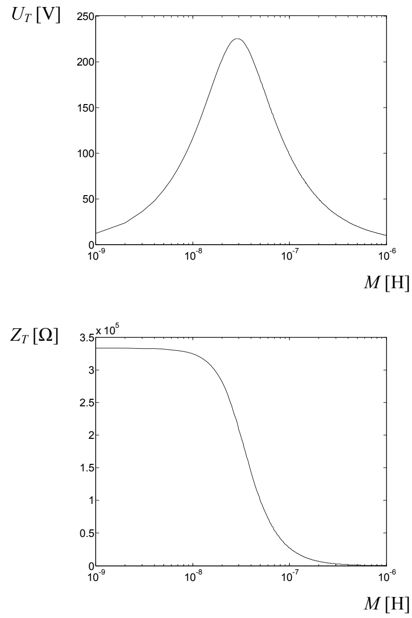

Fig. 4. Thevenin voltage and impedance for different values of mutual inductance *M*.

It can be seen (Fig. 3) that the capacitor C_{load} from the rectifier circuit charges through impedance Z_T when the following criterion is satisfied:

$$U_T + U_{th} > U_{Cload}, \quad (10)$$

where U_{th} is threshold voltage of diode *D*. Since power supply U_s has a sine waveform voltage, as follows:

$$U_S = \hat{U}_S \sin(\omega t + \vartheta), \quad (11)$$

Thevenin voltage U_T has also a sine waveform. With sine voltage waveform of Thevenin voltage U_T, the criteria (10) is met only for a part of a positive half period of the supply voltage, while the capacitor C_{load} discharges continuously in exponential fashion through the resistor R_{load}. Because of the sine wave charging and exponential discharging of C_{load}, no analytical solution can be derived.

Furthermore, the possible optimization of the powering circuit can only be done for a known value of Z_T. The impedance Z_T is highly dependent on the mutual inductance M, which derives from physical placement of the coupled coils L_1 and L_2. Since the distance between coupled coils and the three-axial alignment are not constant, the M and Z_T vary in a wide range of values (Fig. 4). For that reason it is not possible to optimize the load resistance R_{load}, and the capacitor C_{load} value based on the impedance Z_T. Also the value of Thevenin voltage U_T varies (7) with the change of the mutual inductance M (Fig. 4).

In order to cope with the problem of wide value changes of the power source which is supplying the tag rectifier circuit, the tag must be designed as versatile as possible. The best way to accomplish this is to minimize the power consumption. This way, the power transfer from the reader device is not optimal, but the tag gains much wider operating range. The term "wider operating range" refers to the larger span of distances and axial alignments between the tag and the reader under which the tag can operate. But with larger distances between the tag and the reader, the modulation depth of the backscattered signal lowers significantly.

2.2 Modulation Depth and Power Transfer

Modulation depth is a voltage change across the reader coil L_1 which occurs when the voltage and current conditions across tag coil L_2 are changed. From equivalent circuit for RFID system (Fig. 2) the maximal values of modulation depth are calculated. To obtain the maximal values, the rectifier circuit and resistive load R_{load} are not used in analysis. This way, there is no load current, thus, the change in tag coil current is maximal spanning from no current in open circuit to short circuit current with short-circuited tag coil L_2. The mathematical formulation for voltage across the reader coil for the unloaded tag (open-circuited) and for the short-circuited tag is given by (12) and (13), respectively.

$$U_{1_{OC}} = U_S \cdot \frac{R_1 R_2 + \omega^2 M^2 + j\omega L_1 R_2}{R_2(R_S + R_1) + \omega^2 M^2 + j\omega L_1 R_2}, \quad (12)$$

$$U_{1_{SC}} = U_S \cdot \frac{R_1 R_2 + \omega^2 (M^2 - L_1 L_2) + j\omega (L_2 R_1 + L_1 R_2)}{R_2(R_S + R_1) + \omega^2 (M^2 - L_1 L_2) + j\omega (L_2 R_1 + L_1 R_2 + L_2 R_S)} \quad (13)$$

Fig. 5 is given for the tag with no power consumption. Accordingly, the calculated modulation depth values are maximal possible. The power consumption of operating tag affects the modulation depth as given in Fig. 6.

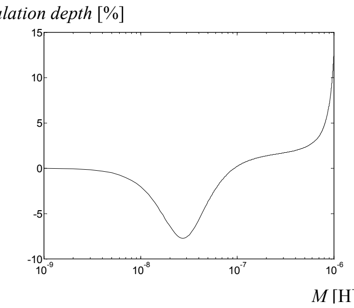

Fig. 5. Modulation depth for different M values.

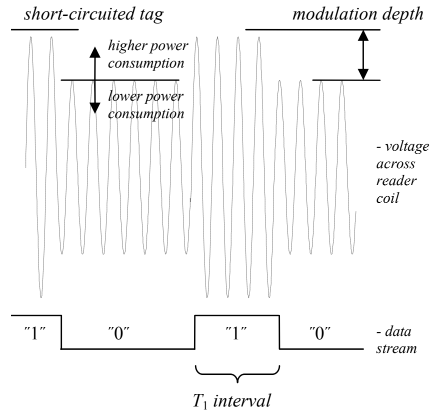

Fig. 6. Influence of power consumption on modulation depth.

With higher power consumption the modulation depth of the backscattered signal lowers. One would assume that keeping the tag consumption low solves the problem and ensures sufficient modulation depth. But, the average power consumption of the tag is tightly connected to the Duty Cycle Ratio (DCR) of the modulation used [13]. When the tag transmits data using backscattering, the power transfer from the reader is interrupted. Depending on modulation used, the tag coil is short-circuited for a certain percentage of the time (Fig. 6).

During the time interval (marked T_1 in Fig. 6.) while the logical "1" is sent (Fig. 6) the tag cannot receive power and it must rely on the energy (charge) stored in the capacitor C_{load}. With higher DCR of modulation used, the charge in the C_{load} gets more depleted. With more depleted C_{load}, the charging current after T_1 is also higher. This consequently leads to higher average power consumption and to a lower modulation depth.

As with modulation depth and average power consumption, the power transfer from the reader to the tag during data transmission depends on DCR of the modulation used. With higher DCR the average power input to the tag decreases, because the percentage of time in which the tag can receive power from the reader equals $T_{power\ input} = 1 - DCR$.

3. Modulation Type Comparison

To solve the power management problems during data transmission, two low DCR modulation techniques, DPPM and DPIM, are presented and evaluated beside the commonly used ASK modulation.

ASK is a modulation technique commonly used for RFID systems, which uses the variations in the amplitude of the carrier wave to code the digital data. Since the detection of various amplitude levels in the RFID system is not used, the ASK modulation used for RFID usually carries only one bit of information. Thus, the transmitted signal is "1" or "0". This is similar to the OOK (On-Off Keying) modulation used in optical systems.

DPPM is an isochronous orthogonal modulation technique which, keeping the amplitude constant, changes position of the pulse inside the symbol in order to encode the data to be transmitted. For a given value of N bits per symbol, DCR and length of the DPPM symbol remains constant.

DPIM is an anisochronous modulation technique where the data is coded as a number of discreet time slots between two adjacent pulses. Since the duration of the DPIM symbol is not constant, the average length of the symbol varies (Tab. 1). Advantage of the DPIM is that symbol synchronization is not needed between the tag and the reader, since every symbol begins with the rising edge of the incoming pulse and ends with the rising edge of the following symbol.

Tab. 1 gives the comparison of three presented modulations. An example of source code encoding is given for each modulation, and mathematical expressions for average symbol length L_{ave} and for the percentage of time in which the tag can receive power $T_{power\ input}$.

3-bit source code	**DPPM**	**DPIM**	**ASK**
000	10000000	10	000
001	01000000	100	001
010	00100000	1000	010
011	00010000	10000	011
100	00001000	100000	100
101	00000100	1000000	101
110	00000010	10000000	110
111	00000001	100000000	111
L_{ave} Average symbol length for N-bit source code	2^N	$\frac{1}{2}\left(2^N+3\right)$	N
$T_{power\ input}$ Power receiving ability [% of time]	$1-\frac{1}{2^N}$	$1-\frac{2}{2^N+3}$	$\frac{1}{2}$

Tab. 1. Modulation comparison.

Fig. 7 shows the average symbol length for a given modulation in relation with an N-bit source code. Since the symbol length increases much faster for DPIM and DPPM then for ASK modulation, the bit-rate of those two modulations is much lower.

With backscatter based communication, the tag coil is short-circuited for the time interval when logical "1" is sent. During that time interval the tag cannot receive power from the reader. The power receiving ability of the tag for a certain modulation is shown in Fig. 8 and it corresponds to equations given in Tab. I.

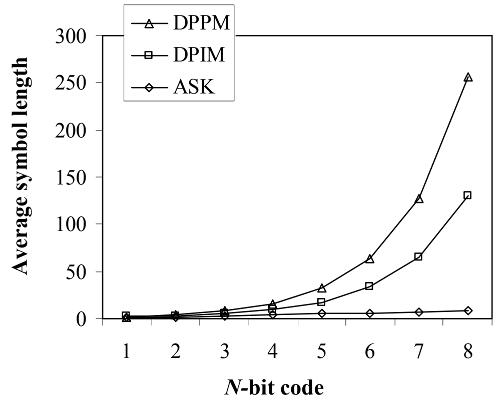

Fig. 7. Average symbol length.

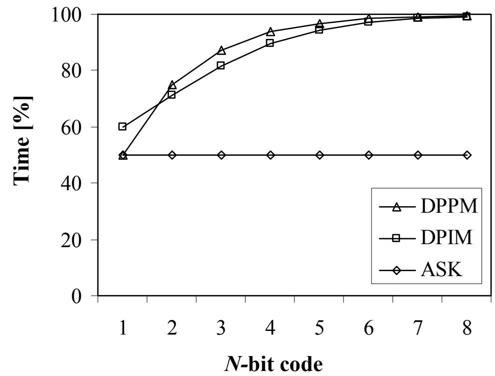

Fig. 8. Percentage of time in which the transmitting tag can receive power from the reader.

It can be seen (Fig. 8.) that low DCR modulation techniques offer a great advantage with respect to commonly used ASK. The power input from the reader device, for 4 and more bit symbols, is more than 90% of time available, allowing tag to operate with practically no drawbacks due to backscattering. The only negative effect that such modulations introduce in the performance of the tag is significantly lower bit-rate of data transmission.

4. Implementation

In order to introduce DPPM and DPIM into RFID system certain frequency requirements must be met. Possible frequencies which can be used are 125 kHz with 72 dBµA/m max, and 13.56 MHz with 60 dBµA/m max. Both frequency bands are suitable for use in bio-implantable devices.

Also, in RFID communication channel, the pulse width of the DPPM and DPIM signal must span over at least 2 periods of the carrier frequency. This is necessary due to backscatter based communication between the reader and the tag. We decided to use pulse-width that spans little over 4 periods of the carrier frequency which gives the pulse-width of 317 ns on 13.56 MHz.

The modulated data streams for all three modulations are realized using Altera Max EPM7128SLI84-10 PLD education board. Since Altera has internal clock of 25.175 MHz (39.72 ns), by dividing this frequency by 8 we have obtained the above mentioned value of 317 ns for the pulse width, which fits well in limits derived from inductive link of RFID system.

The pulse width was the same (before mentioned 317 ns) for all three modulations. This gives much lower achievable bit-rates for DPPM and DPIM. The positive side of such a limitation can be seen in the bandwidth. Since all modulations use the same pulse width, they also occupy the same spectrum bandwidth. By keeping the same bandwidth as in regular ASK, the density of the tags occupying certain area can remain the same, since the wider bandwidth would imply that the interference between tags would rise accordingly.

5. Measurement

To measure the influence of the certain modulation type on tag performance, the circuit shown in Fig. 9 is used.

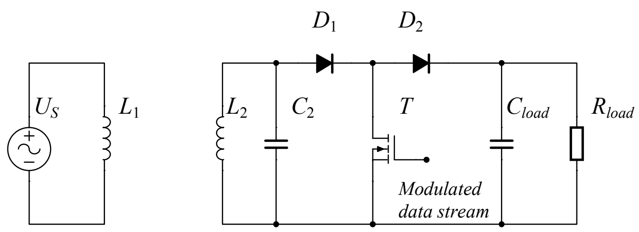

Fig. 9. Circuit used for measurement.

For the power supply labeled U_S, the Agilent signal generator 33250A is used, with frequency set to 13.56 MHz and sine voltage amplitude of 10 V. Internal resistance (R_S from Fig. 1 and Fig. 2) of power supply is 50 Ω. Coil L_1 is circular coil with 10 turns and 10 mm in diameter with approximate value of the inductance equal to 2 μH. Coil L_2 is also a circular coil with 20 turns and 5 mm in diameter with approximate value of the inductance equal to 1 μH. Capacitor C_2 is a ceramic 35 pF capacitor. Both diodes, D_1 and D_2, are silicon fast switching diodes 1N4148. The differences between circuits given by Fig. 1 and Fig. 9 are one additional diode (D_1) and switch (MOSFET *T*). Diode D_1 must be added because of the substrate diode in MOSFET *T*. Without diode D_1 the resonant circuit would be short-circuited for each negative half-period of the supply signal. MOSFET *T* used for data stream modulation is *N*-channel enhancement mode field effect transistor BS170. For capacitor C_{load}, a ceramic 1 nF capacitor is used. Resistors R_{load} value is varied from 10 kΩ to 1 MΩ in order to measure the tag performance under various load currents. For the data stream generation, Altera Max EPM7128SLI84-10 PLD education board was used. The transmitted data is 4-bit data stream which consists of 16 symbols.

Two sets of measurements are done for each parameter (modulation depth, tag rectifier output characteristics and rectifier voltage ripple) while the tag is transmitting. The first set for fixed reader-tag distance (5 mm) with different modulations, and the second set of measurements for the same modulation (DPIM) with different reader-tag distances. As a reference for each measurement except modulation depth measurement, the characteristic of non-transmitting tag is also given.

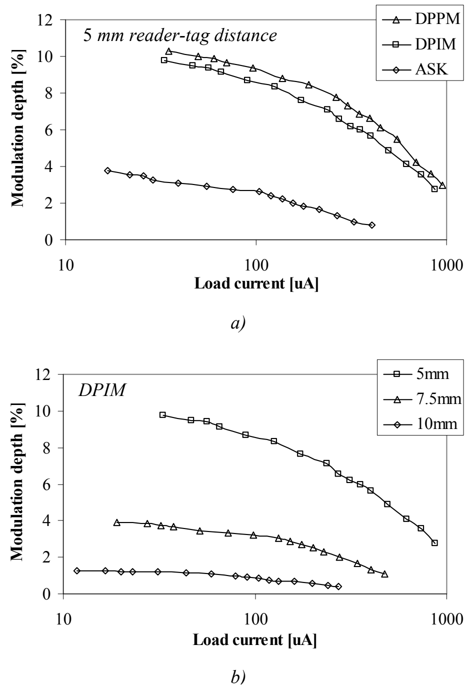

Fig. 10. Modulation depth of the backscattered signal for a) different modulations used and b) different reader-tag distances.

Fig. 10 shows the results of modulation depth measurement where the benefits of using low DCR modulations can be seen. Modulation depth of the backscattered signal is 2.5 times higher (approx. 10% as opposed to 4%) for DPPM and DPIM than for ASK modulation. With DPIM the modulation depth is lower than with DPPM, what corresponds to higher DCR of DPIM. Also, is can be seen that DPIM modulation achieves the same modulation depth as ASK for 150% higher distance between the reader and the tag.

Output characteristics (Fig. 11) are measured by changing resistive load R_{load} connected to the output capacitor C_{load}. Here it can also be seen that by using low DCR modulations, more power is transferred to the tag, resulting in significantly higher rectifier output voltage and load current. In addition, the tag can operate with a very little drawback due to the backscattering since the voltage-current characteristics of non-transmitting tag is very close to the characteristics of transmitting tag which uses low DCR modulation techniques.

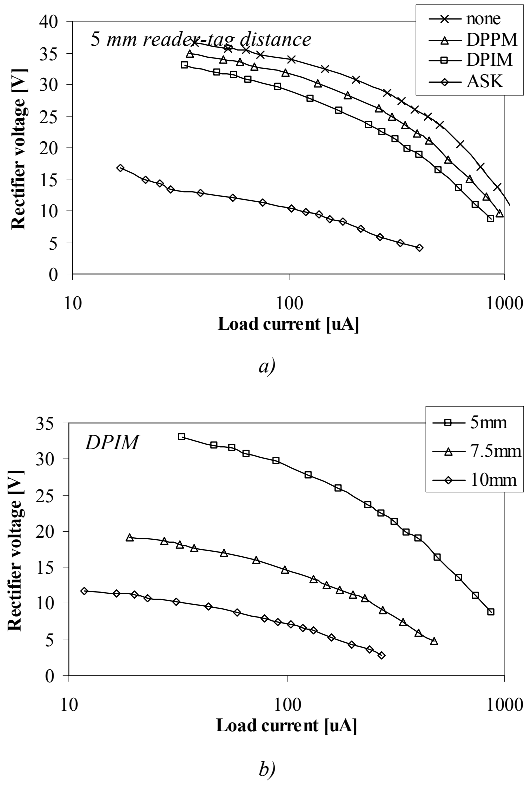

Fig. 11. Tag rectifier output characteristics for a) different modulations used and b) different reader-tag distances.

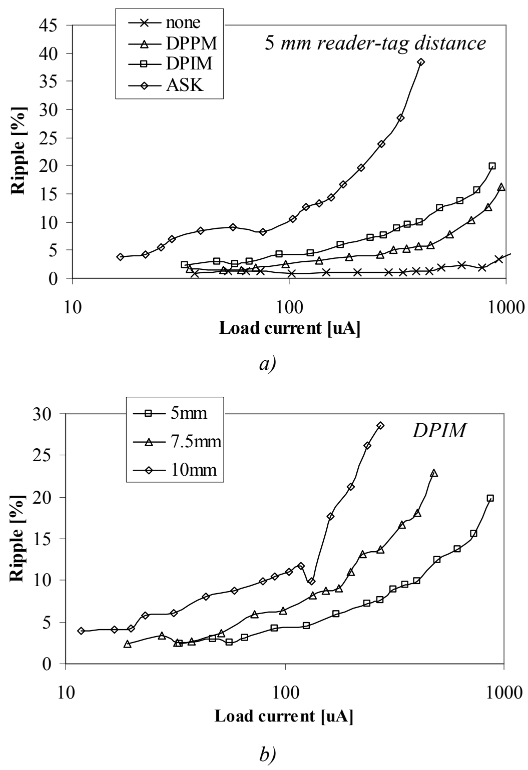

Fig. 12. Tag rectifier output voltage ripple for a) different modulations used and b) different reader-tag distances.

With lower values of R_{load}, and higher current demand, the output voltage ripple has increased. Fig. 12 shows how the ripple increases with load current increase for different modulations and reader-tag distances. For a lower current region the tag with low DCR modulations has just slightly increased rectifier voltage ripple. The voltage ripple for the tag which uses ASK modulation is significantly higher for the whole span of measured values. And this difference in voltage ripple values further increases with increase of the rectifier current.

Additionally, to evaluate the impact of diode (D_1 and D_2) type on tag performance the rectifier output voltage is measured for two diode types: silicon fast switching diodes 1N4148 and planar Schottky barrier diodes BAT85. Diode capacitance has a slight impact on the resonant frequency of the tag. Fig. 13 shows the frequency response of rectifier output voltage for both diode types. Measurement is carried out with 1 MΩ resistor R_{load}, DPIM and 5 mm reader-tag distance. Usage of silicon diodes results with resonant frequency of 13.55 MHz, while the Schottky diodes give resonant frequency of 13.35 MHz. This is in concordance with datasheet values where maximal diode capacitance for silicon (1N4148) and Schottky (BAT85) diode are 4 pF and 10 pF, respectively.

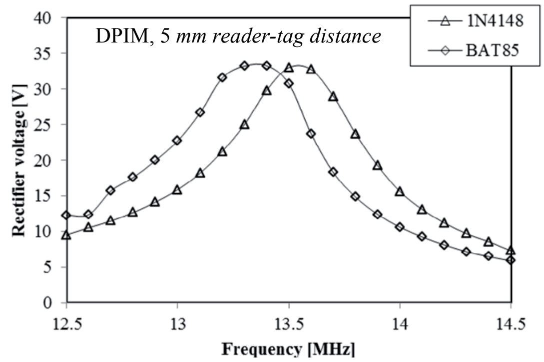

Fig. 13. Frequency response of rectifier output voltage for silicon (1N4148) and Schottky (BAT85) diodes (D_1 and D_2).

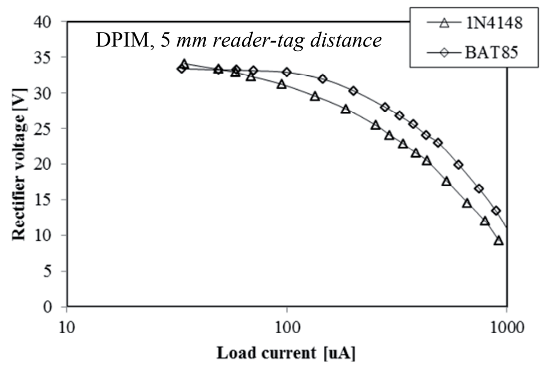

Fig. 14. Frequency response of rectifier output voltage for silicon (1N4148) and Schottky (BAT85) diodes (D_1 and D_2).

Full span of rectifier output characteristic is also evaluated with respect to diode type and the results are given in Fig. 14. Measurement is carried out for DPIM with 5 mm reader-tag distance. Frequency at which the rectifier reaches maximal output voltage differs for a diode type used (Fig. 13). Therefore, rectifier output characteristics are measured at 13.55 MHz and 13.35 MHz for silicon and Schottky diode, respectively. Results show that the rectifier which uses Schottky diodes has up to 10% higher output voltage for a given load current and can deliver up to 20% more power for a given load resistor R_{load}.

6. Conclusion

The usage of two low DCR modulation techniques in backscatter based RFID communication system is presented. Both modulations, DPPM and DPIM, are compared to ASK modulation. For passive RFID tag, the modulation depth and the power input from the reader device are the most important parameters to work with. It is shown that the usage of low DCR modulation techniques provides the number of advantages with respect to the ASK modulation. By using low DCR modulations, the RFID tag has significantly improved output characteristics with up to 250% higher output voltage and current. The ripple of the tag rectifier voltage is reduced by 60% compared to the ripple present when ASK modulation is used. The performance of the tag is evaluated during data transfer and results close to the performance of non-transmitting tag are obtained for low DCR modulation techniques. This way the power management of the passive RFID tag can be simplified and the size of the capacitor for charge storage during transmission can be decreased. From two presented modulations, DPPM has slightly better performance due to a lower DCR. Drawback of the DPPM is that it requires more complex circuitry, because it needs both chip and symbol synchronization. On the other hand, DPIM requires only chip synchronization because the beginning of the chip is also beginning of the symbol. For that reason, DPIM is more appropriate for passive RFID systems where simpler circuitry and smaller silicon area are preferred.

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