Auxiliary-Carrier Load-Shift Keying for Reverse Data Telemetry from Biomedical Implants

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Abstract— **This paper introduces a new approach for data telemetry from biomedical implantable devices to the external world (also known as reverse data telemetry). In the proposed approach, while power (and perhaps data) is transferred to the implant using a main carrier, a second carrier is also sent to the implant through the same link. The second carrier, which is of higher frequency and smaller amplitude, is envisioned for reverse data telemetry by load-shift keying. In this work, the wireless link is realized with two resonant frequencies using closely-coupled printed spiral coils and LC matching networks. The main and auxiliary carrier frequencies are 1MHz and 10MHz with 5V and 1V peak amplitudes, respectively. While the link is capable of continuously supplying unregulated power of up to 80mW at 4V(peak) to a 100-Ω resistive load, data telemetry at a rate of 100 kbps is successfully tested in the reverse direction.**

I. Introduction

Microsystems designed to be implanted inside the body need to interface with the external world through wireless connection. In general, wireless interfacing to implantable biomedical microsystems is used for power telemetry to the implanted electronics as well as for bidirectional data exchange between the implant and the external [1].

There are two common approaches for wireless data transfer from implantable microsystems to the outside world:

- In a wide variety of microsystems, data transmission in the reverse direction (from the implant to the outside world) is realized through a wireless channel different from the one used for forward data telemetry (from an external setup to the implant). In this approach, digital data is first modulated with a wide variety of schemes such as *On-Off keying* (*OOK*) [2], *frequency-shift keying* (*FSK*) [3], and *phase-shift keying* (*PSK*) [4], and then wirelessly transmitted to the outside world over a short to moderate range.
- In some other works, reverse data can be telemetered to the external setup through the same link used for both power and forward data telemetry. This can potentially save considerable amount of power and physical dimensions by not using a separate transmitter for reverse data telemetry. The price is, however, paid by some additional circuit complexity and power consumption on the external side of the wireless link, where there is virtually no constraint on power and size. In this approach, referred to as *passive telemetry* or *load-shift keying* (*LSK*), the link is usually realized using two closely coupled coils, one on the external side and the other on the implant side [5]-[6]. Digital data is transferred in the reverse direction by heavily loading the secondary coil when a logical *1* is to be telemetered and not loading it for a logical *0* (or vice versa). The resulting loading variations on the secondary side of the link are reflected back to the primary coil, and can be large enough to be used for the detection of the reverse data. Main drawback of this method is, however, the rather large disturbance it generates on the voltage induced on the secondary side of the link. As a result, regulation of a clean and reliable supply voltage will be very difficult.

In this work, a new approach is proposed for reverse data telemetry from biomedical implant to the outside world. Although the proposed approach is conceptually based on the LSK method, it allows for the continuous transfer of power from the external world to the implantable microsystem.

II. Auxiliary-Carrier Load-Shift Keying

In the conventional LSK approach, heavily loading the secondary side of the link causes rather large disturbances in the amplitude of the voltage induced on the secondary coil, leading to significant degradation of the quality of the power retrieved on the implant side. As a solution, the *auxiliary-carrier LSK* (*AC-LSK*) scheme, illustrated in Fig. 1, is proposed in this work. In this approach, an *auxiliary carrier* (f_A) is superposed on the *main carrier* (f_M) used for power telemetry. A dual-resonance inductive link is used to transfer both of the carriers from the external setup to the implant. In such a *dual-carrier link*, the main carrier is in charge of

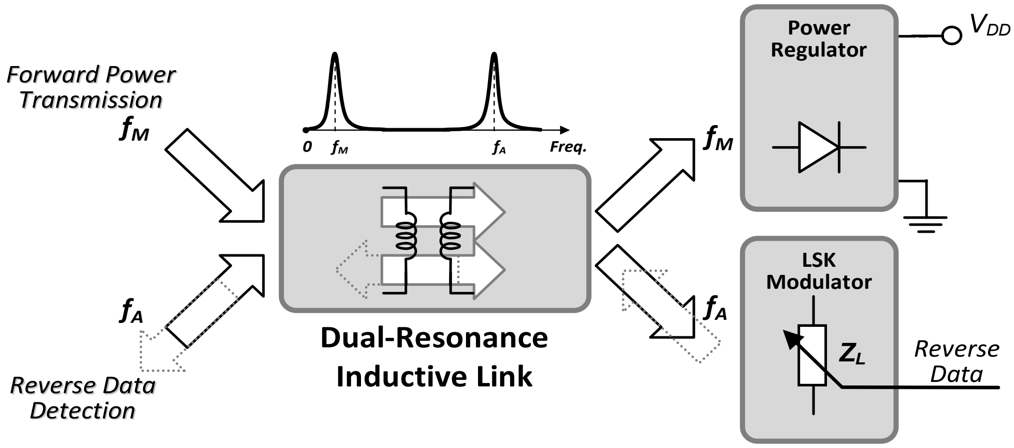

Fig.1: Basic concept of the proposed *auxiliary-carrier load-shift keying* approach for reverse data telemetry off biomedical implant s

transferring electric power to the implant, and the auxiliary carrier will be used for telemetering data in the reverse direction by load-shift keying.

Main advantages achieved by the proposed AC-LSK can be summarized as follows:

- Contrary to the conventional LSK method, while reverse data is transferred to the outside, power is continuously telemetered to the implant without noticeable degradation in the quality of the retrieved power.
- According to the standards available for the exposure of living tissues to radio-frequency (RF) electromagnetic fields [7], to safely transfer a certain amount of power through a given area of living tissue, restrictions apply on the carrier frequency. In the conventional LSK method, since the same carrier is used for both forward power telemetry to and reverse data transfer from the implant, data rate in the reverse direction is limited by the power carrier frequency. In the proposed scheme (i.e., the AC-LSK), the auxiliary carrier frequency can be chosen independently from the main carrier frequency. The f_A can, therefore, be chosen higher than the f_M in order to allow for reverse data telemetry with higher bit rates.
- Compared with other multi-carrier alternatives to the conventional LSK that try to separate the carriers used for forward power transfer and reverse data telemetry, the AC-LSK approach does not require additional complexity in the coils used to realize the inductive link itself. In both multi-carrier inductive links and the proposed approach, however, some added complexity in the power amplifiers, matching networks, and reverse data detection circuitry is inevitable.

III. Realization of the AC-LSK Approach

Fig. 2 shows a simplified diagram, illustrating how the proposed reverse data telemetry approach is realized in the circuit level. Each one of the two carriers, f_M and f_A, are generated by a class-E power amplifier (PA). The main carrier frequency (f_M) is set to 1MHz. This frequency is within the typical range used for power telemetry to biomedical implants, and is low enough to allow for the transfer of rather large amount of power [7]. Frequency of the auxiliary carrier (which is generated with smaller amplitude compared with the main carrier) is set to 10MHz in this work. The two carrier frequencies are chosen to be far enough from each other in order to relax the design of the band-pass filters on the implant side.

The outputs of the PAs are then superposed by using two transformers, secondary windings of which are connected in series. To realize a dual-resonance inductive link, a series LC tank (C_T, L_T) resonating at f_M and a parallel LC resonance with a resonance frequency of f_A are used. It should be added that the self-inductors (L_T, L_R) used in the two tanks are mutually coupled together with a factor of k. The dual-resonance inductive link allows for the transfer of the two carriers, f_M and f_A, from the external world to the implant. Transfer characteristics for the link, peaking at around 1MHz and 10MHz, is shown in Fig. 3. On the receiver side of the link, the main and the auxiliary carriers are separated using two band-pass filters, centered at f_M and f_A, respectively. Both of the filters are 2^{nd}-order filters, designed and implemented using passive components in the first prototype.

As shown in Fig. 2, to realize reverse data telemetry, the band-pass filter associated with the auxiliary carrier is heavily loaded on implant side when a logical 1 is to be transmitted back to the external side, and is left unloaded when the reverse data is a 0.

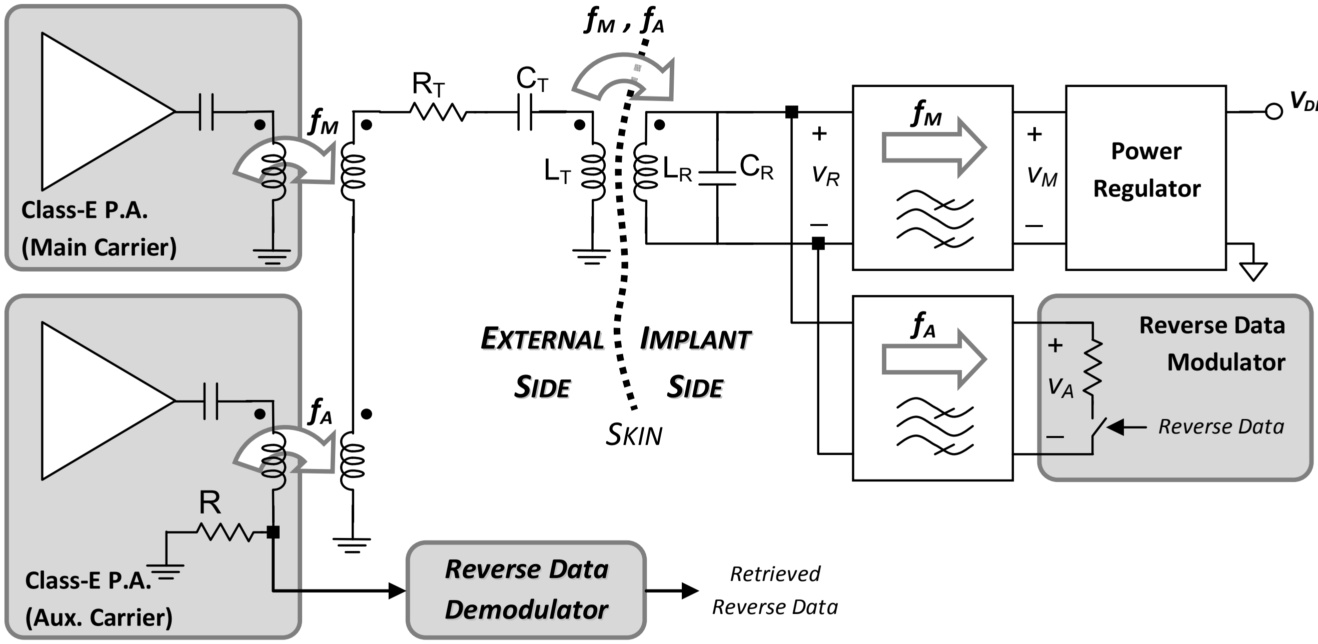

Fig. 2: Block representation for the proposed auxiliary-carrier LSK approach for reverse data telemetry

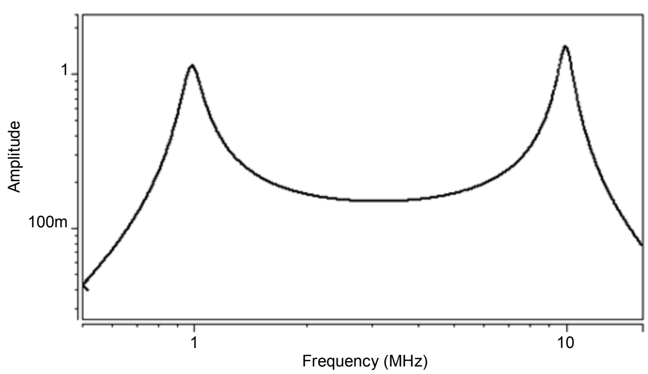

Fig. 3: Frequency characteristics of the dual-resonance inductive link

To detect the reverse data on the external side, as shown in Fig. 4, the current passing through the series LC tank of the class-E amplifier associated with the auxiliary carrier is sensed. Variations in this current, conveying the data telemetered through the link in the reverse direction, are first converted into voltage. This voltage is indeed in the form of a sinusoidal carrier with the frequency of f_A, on which the reverse data is amplitude modulated (AM). As one of the simplest implementations for AM demodulators, an envelope detector comprising a diode-connected MOS transistor followed by a parallel passive RC is used. The detected data is then amplified and low-pass filtered using a 1st-order op-amp-based active RC filter. A Schmitt trigger block is finally used in order to return clean logic levels for the detected reverse data.

IV. Experimental Results

A prototype realizing the AC-LSK method proposed in this work was developed and used to carry out experimental results. This prototype comprised all the circuit blocks on both sides of the link: two class-E power amplifiers, the transformers used to superpose the main and the auxiliary carriers, and the matching networks on the primary side, the inductive link itself, and two band-pass filters and a reverse data modulator on the secondary side. The prototype also included the reverse data demodulator of Fig. 4. To realize the

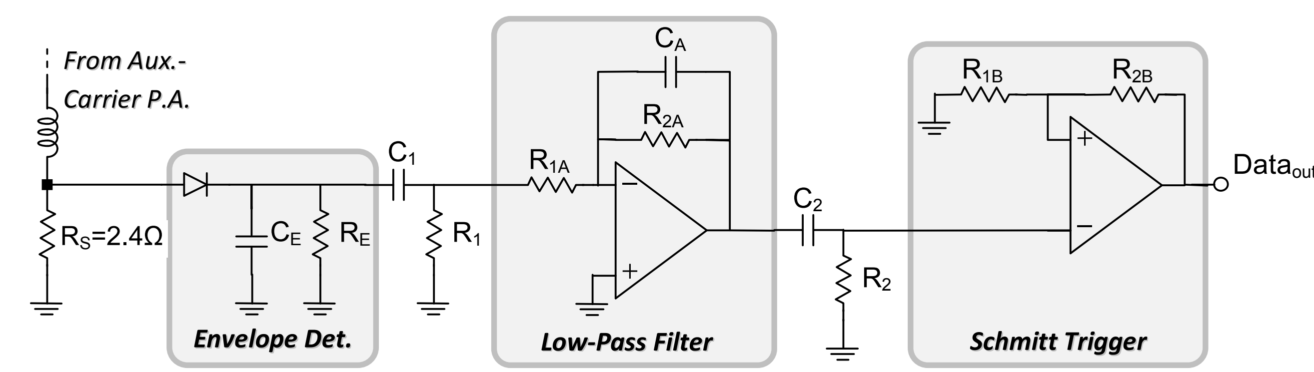

Fig. 4: Circuit schematic of the reverse data demodulator

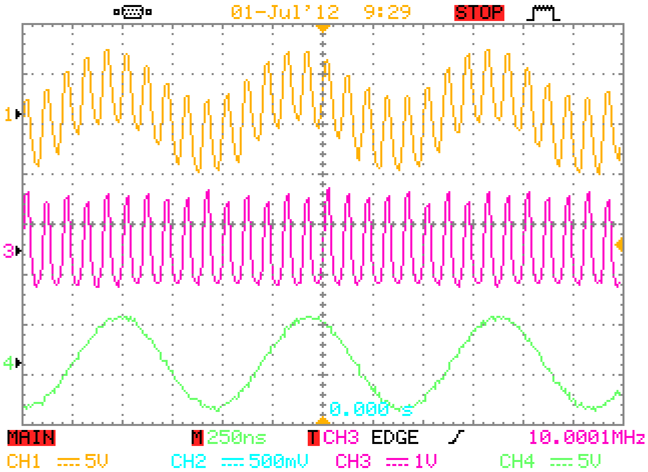

Fig. 5: (top) voltage induced on the secondary side of the link (V_R)
(middle) 10-MHz aux. carrier at the output of the associated filter (V_A)
(bottom) 1-MHz main carrier at the output of the associated filter (V_M)

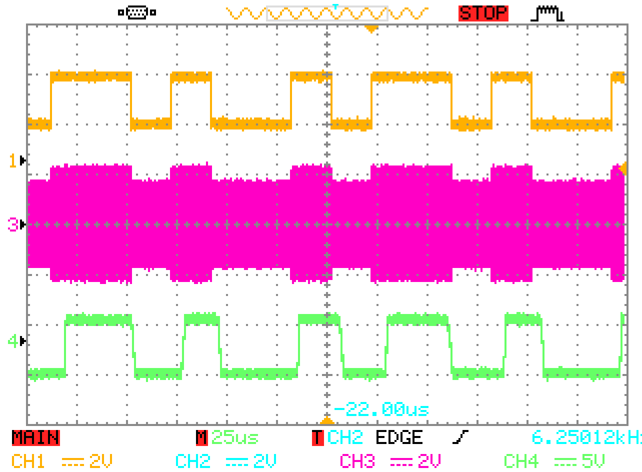

Fig. 6: (top) reverse data stream to be AC-LSK modulated
(middle) the aux. carrier modulated on the implant side
(bottom) reverse data retrieved on the external side

TABLE I. SPECIFICATIONS OF THE INDUCTIVE LINK

Parameter	*Value(transmitter/reciever)*
PSC track diameter (mm)	0.5 / 0.5
Number of turns on the PSC	15 / 8
Coils relative distance (mm)	1
Coupling coefficient(k)	0.48
L_1 / L_2(µH)	8.15 / 1.37@1MHz
L_1 / L_2(µH)	9.2/1.38@10MHz
Q_{L1}	9.5@1MHz, 27.2@10MHz
Q_{L2}	4.26@1MHz, 20.4@10MHz
Self-resonance frequency for L_1	26.8MHz
Self-resonance frequency for L_2	71.2MHz
Power transfer to the implant side	Vp=4V, 80mW@ R_L=100Ω
Reverse telemetry data rate	100kbps
Main carrier frequency	1MHz
Auxiliary carrier frequency	10MHz

inductive link, two closely-coupled printed spiral coils (PSCs) were used. Detailed specifications of the link are given in Table I. Oscilloscope screen shots exhibiting operation of the prototype realizing the proposed method are shown in Figures 5 and 6. Fig. 5 shows the voltage induced on the secondary side of the link as well as the main and auxiliary frequency components at the outputs of the band-pass filters. These voltages are designated as V_R, V_M, and V_A in Fig. 2, respectively. Fig. 6 shows the reverse data on the secondary side of the link, the auxiliary carrier modulated with the reverse data, and the associated data stream successfully retrieved on the primary side.

V. CONCLUSION

A new approach for reverse data telemetry from implantable microsystems to the outside world was proposed. In the conventional LSK method, the same carrier used for forward power telemetry is loaded according to the value of the reverse data bits. This is while in the proposed approach, named AC-LSK, a second carrier is used for reverse data telemetry. Main advantage of this approach is in the fact that the main carrier conveying electric energy to the implant is not subject to large disturbances (associated with reverse data) anymore. As a result, contrary to the conventional LSK approach, while reverse data is telemetered whenever needed, power telemetry is continuously ongoing. The price being paid for this advantage is, however, more careful design of the link and an additional power amplifier on the external side of the link.

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