An Energy-Efficient Body Channel Communication based on Maxwell's Equations Analysis of On-Body Transmission Mechanism

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***Abstract*—This paper presents two energy-efficient techniques to enhance the channel quality of body channel communication (BCC). From Maxwell's equations, the complete equation of electric field on the human body is obtained to develop the theoretical transmission mechanism of BCC, which consists of a combination of the quasi-static near-field coupling, and surface wave far-field propagation mechanism. Based on the channel analysis, the resonance matching (RM) and contact impedance sensing (CIS) techniques are proposed for the sake of the optimization of electric signal transmission through the human body, which leads to reduce the requirements for BCC transceiver. As a result, 1) the RM gives 4dB channel enhancement with reduced power consumption by BCC transmitter, and 2) the CIS reduces both the linearity and sensitivity requirements of the BCC receiver by 7dB with significant power saving.**

I. INTRODUCTION

Wireless Body Area Network (WBAN) is an emerging technology that can combine healthcare and consumer electronic applications around the human body. By continuously connecting and sharing the information of mobile devices around the human body, WBAN allows new convenient usages and application services. There are 3 physical layers (PHY) considered in the IEEE 802.15.6 Task Group for WBAN standardization [1]: ultra-wide band (UWB) PHY, narrow-band (NB) PHY, and body channel communication (BCC) PHY. The BCC which uses the human body as a communication channel to transmit the electric signal has advantages over UWB and NB due to the high conductivity of the human body compared to that of air. In addition, not only is most of the signal from the transmitter confined to the body area without interference from external RF devices, but also the communication frequency can be lowered without enlarging the antenna size. These reduce the power consumption of the BCC transceiver compared to the conventional RF approaches [2].

Since the introduction of the first prototype system reported by T.G. Zimmerman in 1996 [3], there have been various studies to investigate the mechanism of sending and receiving data trough human body and to model the channel for the BCC. These investigations are different from each other in terms of the operating frequency ranges and its body channel modeling approaches. Currently, two prevailing methods are used for explaining the mechanism of BCC. One is the phenomenological circuit modeling [4], and the other is the numerical electromagnetic wave modeling method [5]. From these channel characterizations, each channel model is adequately employed to implement the BCC transceiver [6]. However, previous BCC transceivers were not optimized for WBAN because the only phenomenological circuit/behavior models were used for the body-channel analysis, which means there was not a clear understanding of the on-body electric signal transmission mechanism.

In this paper, we study the theoretical transmission mechanism of BCC from the solution of Maxwell's equations. Based on that, resonance matching (RM) and contact impedance sensing (CIS) techniques are proposed to enhance the channel quality of BCC, which reduce the power consumption of the BCC transceiver. Consequently, the RM reduces the required output power of the BCC transmitter by means of 4dB channel enhancement, and the CIS mitigates both the linearity and sensitivity requirements of the BCC receiver by 7dB.

The remainder of this paper is organized as follows. Section II introduces the signal transmission mechanism of the BCC based on theoretical analysis. Then, Section III, and Section IV explains the principle of the RM and CIS technique, respectively. After that, Section V describes the energy efficient BCC transceiver design with the RM and CIS. In addition, the effectiveness is verified by measurement results. Finally, Section VI concludes the paper.

II. SIGNAL TRANSMISSION MECHANISM OF THE BCC

The concept of BCC is that the signal is applied onto the surface of the human body through signal electrode and GND electrode for sending the information, and then the potential difference, which is generated by the electric field from signal source, is sensed by electrodes contacted on the other side of

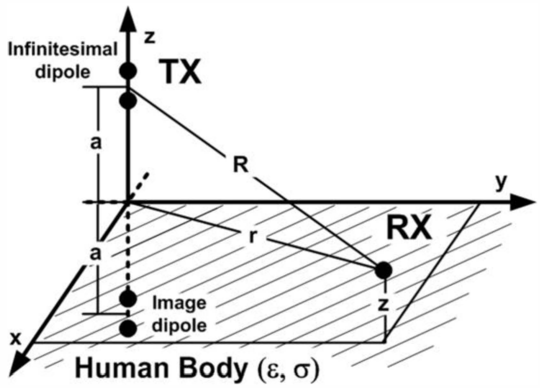


Fig. 1. Electric field from dipole and its geometry on the human body.

the body for receiving the information. The signal source is generalized by a vertical electrical dipole over the human body, and the detector measures the intensity of electrical signal at the remote location on the body. The BCC is based on the principle of electric field propagation from dipole source over the human body as shown in Fig. 1. The electric field intensity at the any point above the human body, which has finite conductivity (σ) and permittivity (ε) from infinitesimal dipole, is calculated for the BCC model. Since dipole source is much smaller than the wavelength of the BCC signal, infinitesimal dipole gives proper modeling for the signal source of the BCC. The *R*, *a*, *r*, *x*, *y*, *z* are adequately defined in Fig.1. The *R*, and *a* means distance between TX and RX, and human body and signal source (electrodes), respectively. For the generality and simplicity of the analysis, we assume the surface of the human body as an infinite half-plane with an imperfectly conducting property. A general solution of Maxwell's equations of the vertical component of electric field intensity from vertical dipole is given by [7]. From the solution in [7], it consists of space wave terms, surface wave terms, and near-field terms. The space wave predominates at large distances above the surface, whereas the surface wave is dominant near the surface. The distance between dipole and the human body significantly influences on the electric field intensity. Since in BCC application, we mainly consider the electric signal near the surface of the human body, we can assume *a* and *z* are close to 0, and we can obtain the electric field intensity near the human body as follows.

$$|E_{Z^v}| = 2k\left|\underbrace{(1-u^2+u^4)F\cdot\frac{e^{i(kr-wt)}}{r}}_{\text{surface wave}} + \underbrace{\frac{i}{k}\cdot\frac{e^{i(kr-wt)}}{r^2}}_{\text{reactive radiation}} - \underbrace{\frac{1}{k^2}\frac{e^{i(kr-wt)}}{r^3}}_{\text{quasi-static}}\right|$$

$$= 2\left|k(1-u^2+u^4)F\cdot\frac{1}{r} + i\cdot\frac{1}{r^2} - \frac{1}{k}\cdot\frac{1}{r^3}\right| \qquad (1)$$

$$F = 1 - u^2 e^{p_2-p_1} - u\theta e^{-p_1}\int_{\sqrt{p_2}}^{\sqrt{p_1}}\frac{e^{\omega^2}d\omega}{(\omega^2+\theta)^{1/2}} \qquad (2)$$

$$u = (\epsilon + ix)^{-1/2} \qquad (3)$$

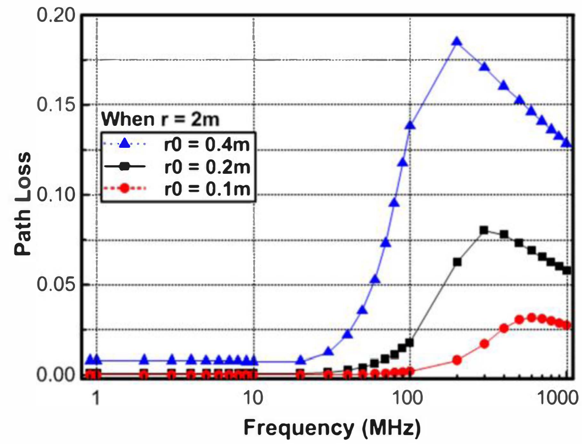


Fig. 2. Frequency response using theoretical analysis.

$$p_1 = ikr[1-(1+u^2)^{-1/2}] \qquad (4)$$

$$p_2 = ikr[u^{-1}-(1+u^2)^{-1/2}] \qquad (5)$$

$$\theta = 2ikr(1+u^2)^{-1/2} \qquad (6)$$

where, F is an attenuation function, wavenumber is k=2π/λ, relative conductivity is $x = 1.8\cdot\frac{10^{10}\sigma}{f}\ (\frac{\sigma}{\omega\epsilon_0})$, and ε is the dielectric constant of the human body referred to air as unity while σ is the conductivity of the human body, f is the operating frequency, and λ is the corresponding wavelength.

The electric field in (1) consists of terms of the first order in 1/r, second order in 1/r, and third order in 1/r. The first terms of (1) correlates with far-field propagation in combination with attenuation factor of the surface wave, $(1-u^2+u^4)F$, which is an inherent property of electric field at the surface of the half-plane with finite conductivity. On the other hand, the second and the third term correspond to the induction-field and electrostatic-filed of the dipole, respectively. Consequently, the mechanism of BCC can be divided into two parts: the surface wave far-field propagation of the first term, and the quasi-static near-field coupling of the second and third terms. The intensity of the electric field is a function of communication distance and wavenumber. As the wavenumber *k* or frequency *f*, and the distance *r* increase, the surface wave propagation term has significant effect on the overall electric field intensity whereas the quasi-static coupling term is negligible and vice versa.

The path loss of BCC can be expressed as the ratio of received signal to transmitted signal as follows.

$$\frac{|E_{Z^v}(r,k)|}{|E_{Z^v}(r_0,k)|} = \left|\frac{k(1-u^2+u^4)F(r,k)\cdot\frac{1}{r}+i\cdot\frac{1}{r^2}-\frac{1}{k}\frac{1}{r^3}}{k(1-u^2+u^4)F(r_0,k)\cdot\frac{1}{r_0}+i\cdot\frac{1}{r_0^{\,2}}-\frac{1}{k}\frac{1}{r_0^{\,3}}}\right| \qquad (7)$$

where, r is the communication distance, k is the wavenumber of operating frequency, and r_0 is the reference distance regarded as transmitting point which is determined by the

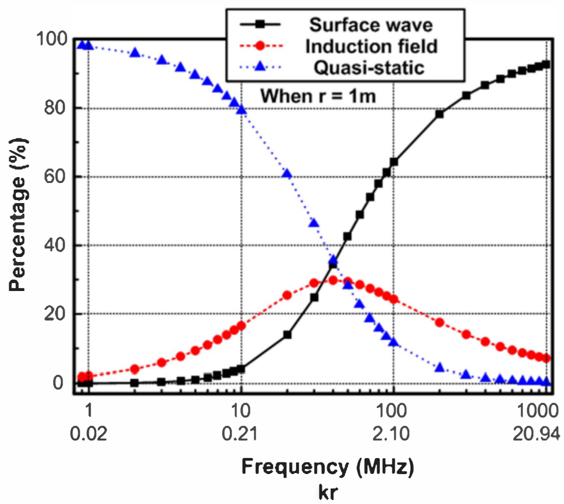


Fig. 3. Contribution ratio of each mechanism in terms of frequency.

physical size of the electrode. To represent the frequency response, Fig. 2 shows the frequency response in the frequency range from 100 kHz to 1 GHz with respect to various channel distance r and r_0 by plotting the value obtained from conductivity and dielectric properties of human body's dry skin [8]. The graph resembles band-pass filter response since the first surface term of (1) is proportional to the frequency, and the third quasi-static term of (1) is inversely proportional to the frequency. The path loss characteristics could be approximated by means of the frequency range as the following equation.

$$\frac{|E_{Z^v}(r,k)|}{|E_{Z^v}(r_0,k)|} \approx \begin{cases} \left|\frac{r_0^3}{r^3}\right|, & \text{at a low frequency} \\ \left|\frac{F(r,k)\cdot r_0}{F(r_0,k)\cdot r}\right|, & \text{at a high frequency} \end{cases} \tag{8}$$

Since r_0/r is far smaller than 1, as frequency increases, frequency response looks like high-pass filter. Meanwhile, because the attenuation factor F exponentially decreases with operating frequency [7], frequency response goes gradually downward at a high frequency. In brief, for the high frequency and low frequency, surface wave propagation and quasi-static coupling mechanism is dominant, respectively. In order to represent the amount of contribution of each term to overall term in (1) as frequency increases, the ratios of near-field part, induction-field part, and far-field part to overall response are shown in Fig. 3 with the channel distance of 1m. The far-field surface wave term becomes equal to the sum of other two terms when frequency is about 70 MHz, and corresponding value of kr is about 1.5.

III. Enhancing Quasi-Static Coupling

Based on the analysis of on-body transmission mechanism, channel enhancement method can be obtained. As shown in Fig. 2, at a low frequency, the frequency response looks like high-pass filter, which means the signal propagation is mainly determined by the capacitive impedance. The reason is as follows. At a frequency less than tens of megahertz whose wave length is much larger than the size of the human body, the electric field around the human body is almost constant with time, which means that its phase is nearly uniform everywhere on the body. In this condition, the time-varying electric field around the human body can be regarded as quasi-static field. The quasi-static assumption simplifies the analysis by ignoring reactive contributions and only considering the resistance on the human body. The human body can be approximated as an almost conducting wire in this frequency range, and a complete closed loop should be formed for the signal transmission. Therefore, the return signal is transferred onto the human body through capacitive near-filed coupling mechanism. Since the closed-loop signal path of the electric field is provided by electrostatic coupling between GND electrodes of transmitter and receiver, the body channel has been modeled with the capacitor circuits, as shown in Fig. 4. The signal path loss is mainly determined by the capacitive impedance because the small capacitance of C_R has the highest impedance value compared with the impedance value from the human body.

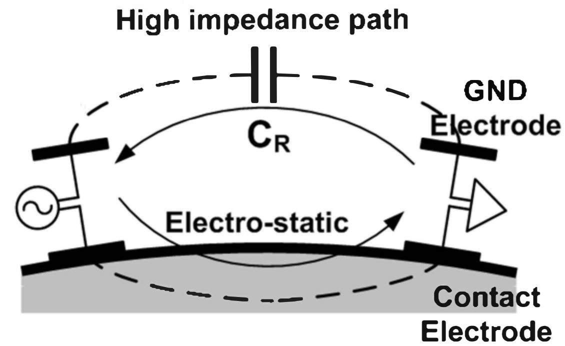


Fig. 4. Quasi-static coupling mechanism.

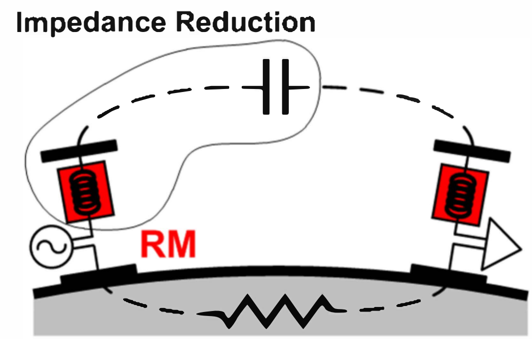


Fig. 5. RM technique.

In order to enhance the quasi-static coupling mechanism, RM, inserting a resonating series inductance between GND electrodes of transmitter and receiver, is proposed as represented in Fig. 5. Around the resonance frequency formed by RM network and C_R, the impedance between transmitter and receiver can be significantly reduced. Therefore, a high signal-to-noise ratio (SNR) can be achieved in RX with the same transmitter's power consumption, which reduces power consumption of the transmitter for the same SNR at the receiver input.

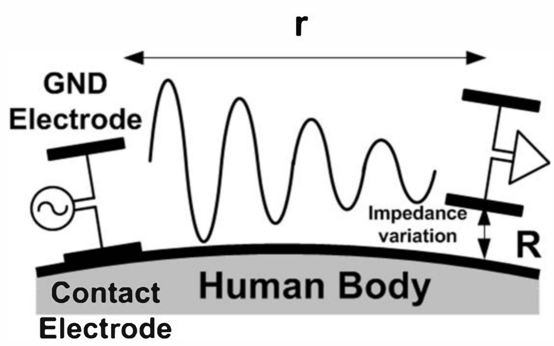


Fig. 6. Surface wave propagation mechanism.

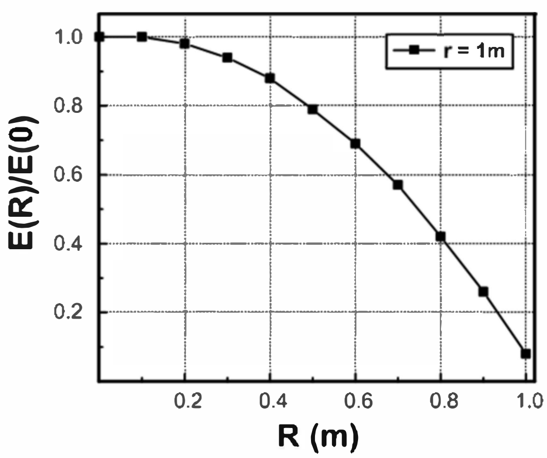


Fig. 7. Effect of the distance between body and contact electrode.

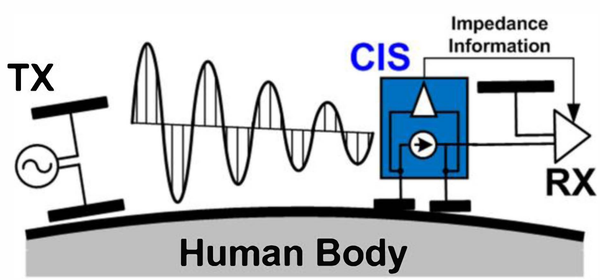


Fig. 8. CIS technique.

IV. ENHANCING SURFACE WAVE PROPAGATION

The surface wave propagation mechanism starts to predominate over quasi-static mechanism in frequencies higher than tens of megahertz. In this frequency range, the electric signal attenuates as the signal propagates through the surface of the human body as shown in Fig. 6. There are lots of factors that can affect the channel response between the transmitter and receiver. Among them, one of the most influential factor is the distance between contact electrode and the human body (R), which is even more influential than the distance between the transmitter and receiver. Since most of the surface wave signal is confined to the surface of the body, we should consider the distance or impedance between the contact electrode and the human body as shown in Fig. 7,

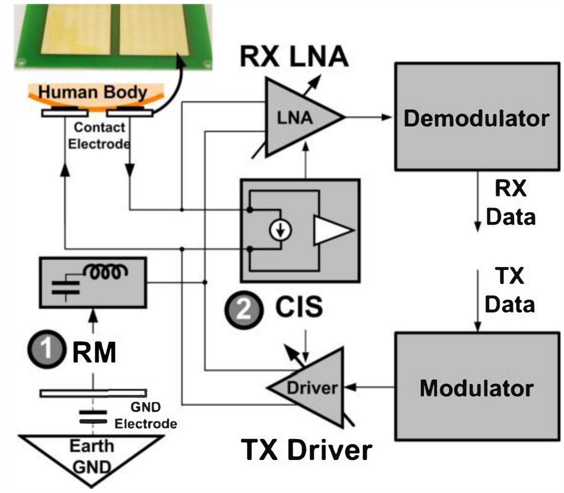


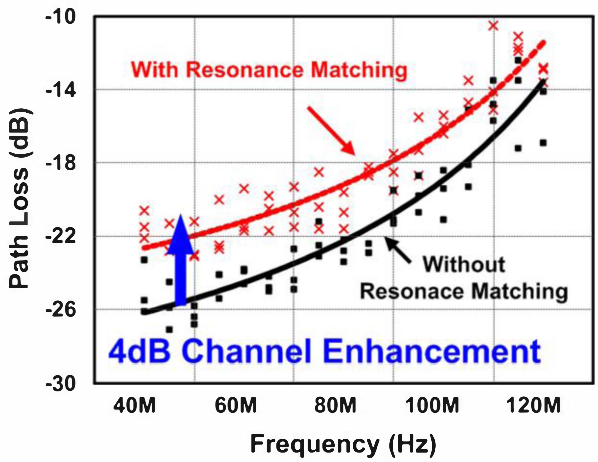
Fig. 9. Energy-efficient transceiver architecture.

obtained by the complete expression for the electric field on the human body in [7] when r is 1m and f is 80MHz. Fig. 7 plots a ratio of the electric field strength at the distance R above the surface to the electric field strength near the surface of the body. In real situation, the contact impedance or distance between the electrode and the human body varies its value dynamically, and even 20 dB overall signal path loss variation can be observed when the electrode is in contact with or apart from the body as shown in Fig. 7. Such a dynamic variation makes the receiver consume significant power because the receiver should additionally satisfy not only the high-linearity requirement at the surface of the human body but also the high-sensitivity requirement above the surface of the human body, at once.

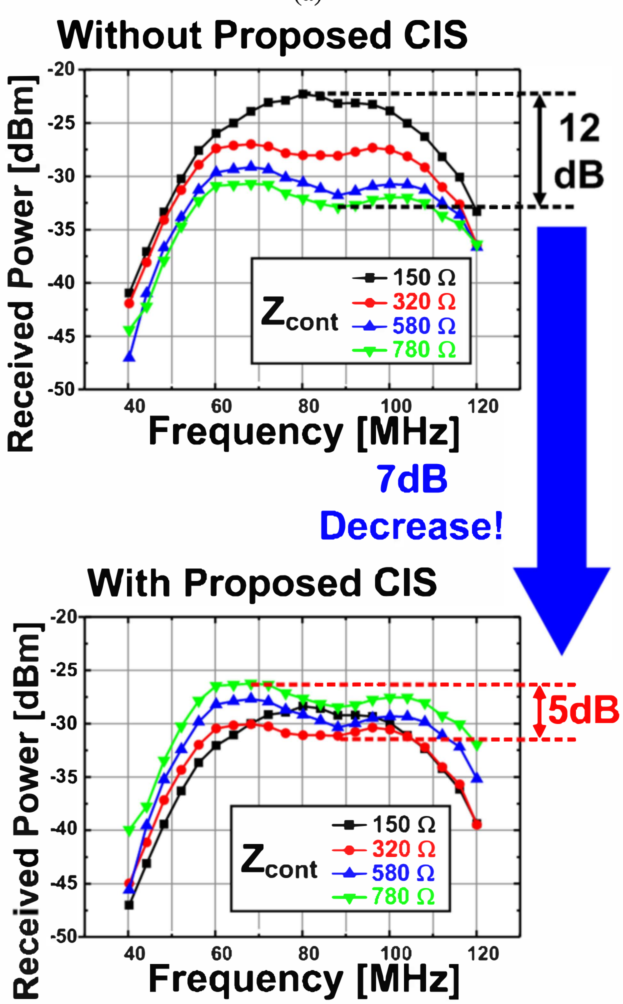
To compensate for channel quality degradation, and to mitigate the additional linearity and sensitivity requirement caused by the contact impedance variation, we employ the CIS technique as shown in Fig. 8. By means of detecting the impedance variation between the electrode and the human body, CIS automatically determines the operation mode of the receiver for better power efficiency. As a result, the receiver does not have to satisfy the high-linearity and high-noise performances simultaneously, which significantly reduces the power dissipated by the receiver.

V. ENERGY-EFFICIENT BCC TRANSCEIVER DESIGN

Fig. 9 shows the energy-efficient architecture of the BCC transceiver. The BCC uses a 40-120 MHz frequency band for the data transmission [2] while the CIS utilizes a chopper-stabilized ac current-injection source of 1.25 MHz to monitor the differential contact impedance between the contact electrode and the human body [9]. The RM is connected with a GND electrode. On the transmitter side, the TX data is modulated by the modulator that drives the electrodes by the TX driver. On the receiver side, from the receiver front-end which amplifies the received signal from the electrodes, the demodulator converts the modulated signal into the RX data. For the power-efficient front-end interface with receiver LNA and transmitter driver, 1) the RM technique reduces the capacitive impedance between GND electrodes of TX and RX,



(a)



(b)

Fig. 10. Measurement results. (a) with RM technique. (b) with CIS technique.

and 2) the CIS technique reduces the contact impedance variation between the contact electrode and the human body. From the impedance information from CIS, the low-power reconfigurable differential LNA and driver enable transceiver to operate in the better power efficiency.

To verify the effect of the proposed techniques, the measurement results of the body channel characteristics are shown in Fig. 10. Fig. 10(a) depicts the measured frequency response by shorting the contact electrodes between the transmitter and receiver with and without the RM technique. With the help of the RM, 4 dB channel enhancement can be achieved with the power reduction of driver by 66% [2]. Fig. 10(b) plots the measurement results of channel variation in terms of the contact impedance variation using a circular electrode with 1.5 cm diameter. From the contact impedance of 150 Ω to that of 780 Ω, more than 12 dB variation is observed without CIS technique. The proposed CIS, combined with the reconfigurable output driver, provides 7dB relaxation of the linearity and sensitivity requirements to the receiver front-end as shown in Fig. 10(b). Thanks to CIS, the power consumption of receiver front-end can be reduced from 2 to 0.6mW with 70% saving [2].

VI. Conclusion

Techniques to enhance the quality of the body channel are proposed for the design of the energy-efficient BCC transceiver, which is one of the most promising candidates to WBAN applications. Based on the thorough investigation of the signal propagation of the BCC, RM and CIS technique strengthens the quasi-static coupling and the surface wave propagation mechanism, respectively. As a result, 1) the RM gives 4dB channel enhancement with 66% power reduction in TX driver, and 2) the CIS reduces both the linearity and sensitivity requirements of the RX front-end by 7dB with 70% power saving.

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