2018 IEEE 19th International Workshop on Signal Processing Advances in Wireless Communications (SPAWC)

# Adaptive Mode Switching Algorithm for Dual Mode SWIPT with Duty Cycle Operation

Jong Jin Park, Jong Ho Moon, Kang-Yoon Lee, and Dong In Kim
College of Information and Communication Engineering
Sungkyunkwan University (SKKU), Korea
Email: {pjj0805, moonjh525, klee, dongin}@skku.edu

***Abstract*—In this paper, we design a self-powering dual mode simultaneous wireless information and power transfer (SWIPT) system in which a sensor node adaptively controls single tone or multi-tone communication mode. To this end, we introduce duty cycle operation for the dual mode SWIPT with self-powering, which considers nonlinear energy harvesting (EH) model for both single tone and multi-tone waveforms. We formulate an adaptive mode switching (MS) problem which maximizes the achievable rate under the *energy causality* condition. On top of this, a novel iterative inner/outer loop algorithm is implemented to solve the adaptive MS problem. Our newly designed dual mode SWIPT can be applied to low-power Internet-of-Things (IoT) network with wireless EH capability for self-powering, thereby realizing *battery-free* IoT network. From the results presented, we provide interesting insights that can be applied to design the dual mode SWIPT system over existing SWIPT.**

***Index Terms*—Dual mode SWIPT, duty cycle operation, self-powering, adaptive mode switching, nonlinear energy harvesting.**

## I. Introduction

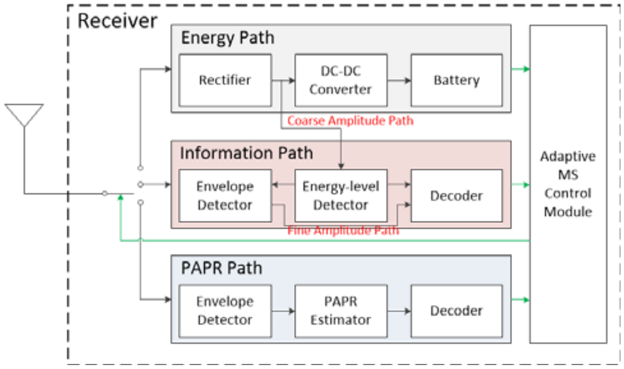
A battery lifetime of wireless devices is becoming a critical issue for perpetual operation as the massive deployment of low-power devices is foreseen for realizing Internet-of-Things (IoT) network. Low-power IoT devices shall be self-powered for energy neutral operation. Self-powered devices, charged from ambient renewable resources instead of battery replacement, can be massively deployed to self-sustain the IoT network. One of promising solutions is simultaneous wireless information and power transfer (SWIPT) [1]. SWIPT transfers both information and power in the air using a radio frequency (RF) signal. There have been many proposals for SWIPT [2] - [4] that aim at enhancing the rate-energy tradeoff through optimum receiver design for SWIPT.

Recently, it was shown that the RF-to-DC conversion efficiency in energy harvesting (EH) circuit is a function of not only the input power, but also the shape of the input signal (e.g., the number of multi-tone) due to the nonlinear rectification process [5] - [7]. In [5], it was shown that using multi-tone waveforms can boost up the efficiency of wireless power transfer (WPT) even with fixed input power. To address the nonlinear characteristics and improve accuracy, a new nonlinear EH model using Taylor series approximation for diode small signal equation was proposed in [6]. On the other hand, the nonlinear EH model based on logistic function was suggested in [7] to address diode saturation effect. In addition, to consider both the nonlinear diode characteristics at low input power (i.e., small signal model) and the saturation effect at high input power, [8] proposed the RF-to-DC power conversion efficiency (PCE) model based on smoothing spline curve fitting. But a simple modulation of single tone optimized for conventional SWIPT does not consider the efficiency of WPT, unlike those studied in [5] - [7]. To tackle this difficulty, we have proposed the peak-to-average power ratio (PAPR) based SWIPT [9] using multi-tone waveforms for energy transfer and their distinct levels of PAPR to convey information. The PAPR based SWIPT achieves higher WPT efficiency, which increases the operational range, with less energy and low complexity for information decoding (ID). But it suffers lower rate than that of the single tone SWIPT.

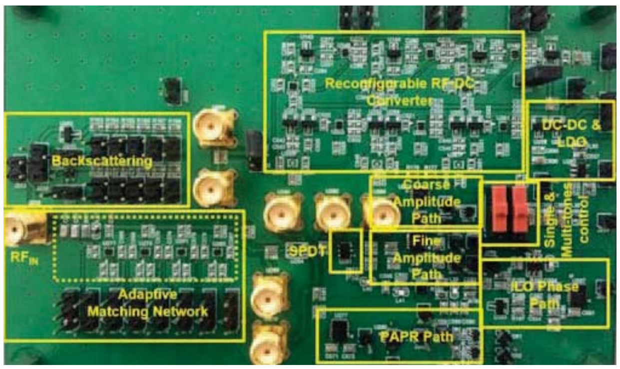
To overcome such limit in the rate-energy tradeoff of the PAPR based SWIPT and extend the operational range of the single tone SWIPT, [8] proposed the concept of dual mode SWIPT with adaptive transceiver architecture using both single tone and multi-tone waveforms. [8] first designed the adaptive power management and information decoding (PM-&-ID) module to control the communication mode according to the receive power. This is because the WPT efficiency exhibits the cross-over behavior depending on the receive power, namely the single tone SWIPT yields higher WPT efficiency at higher receive power while the multi-tone (PAPR based) SWIPT at lower receive power. Thus, the mode switching (MS) algorithm developed in [8] is crucial for the energy-constrained devices in IoT applications. In conjunction with low-power IoT applications, duty cycle operation is indispensable for realizing self-powering [10]. Considering the duty cycle operation, we will optimize the receive power threshold which largely affects the system performance, thereby optimizing the entire behavior of MS for the dual mode SWIPT with self-powering.

For this, we propose duty cycle based dual mode SWIPT for self-powered devices. First, the duty cycle operation meets the *energy causality* condition, a critical one for self-powering. Then, we propose a novel iterative inner/outer loop MS algorithm that optimizes the receive power threshold for maximizing the achievable rate, considering the nonlinear PCE model for energy neutral power management. Here, the MS threshold decides the switching boundary for dual mode operation that alternates between single tone and multi-tone. The proposed duty cycle based dual mode SWIPT will enable to self-power low-power IoT devices effectively while assuring the energy neutral operation.

978-1-5386-3512-4/18/$31.00 ©2018 IEEE




(a) Block diagram of proposed dual mode SWIPT receiver




(b) Dual mode SWIPT testbed circuit implementation

Fig. 1. A receiver architecture and circuit implementation for dual mode SWIPT.

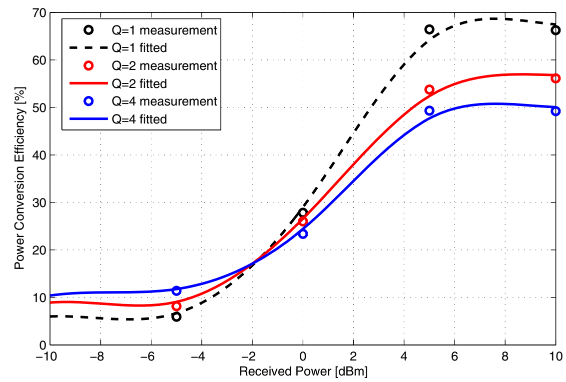



Fig. 2. Curve fitting of the nonlinear energy harvesting model. Data was obtained by testbed circuit measurement.

## II. System Model

We consider point-to-point SWIPT systems with one transmitter and one receiver, each equipped with a single antenna. The SWIPT signal is assumed to pass through frequency flat (FF) and block fading channel, where the channel gain remains constant during one single block. We also assume that the transmitter knows channel state information (i.e., CSIT), which can be obtained by sending a short pilot signal from the receiver before each frame transmission to estimate the channel gains. Let $h$ denote the complex channel gain of the fading channel over which the transmitter sends a Gaussian-distributed symbol with average power $P_T$.

### *A. Nonlinear Energy Harvesting Model*

As shown in Fig. 1(a), the energy path consists of three components, such as a diode rectifier, DC-DC converter, and a battery. Because of the nonlinear rectification process (diode turn-on/breakdown voltages, diode nonlinearity, and saturation effects reported in [5]–[7]), the harvested power $P_{EH}$ cannot be modeled as conventional linear model. To address the nonlinear characteristics, [6] and [7] proposed the nonlinear models based on Taylor series approximation of diode small signal equation and logistic curve fitting for measured experiment data, respectively. However, those models may not be accurate when both saturation effect and small signal model are considered. To resolve this problem, we proposed the RF-to-DC PCE model in [8], where the PCE is defined by $P_{eff} = P_{EH}/P_R$. Here, $P_R$ is the receive power at the diode rectifier. In this model, the PCE is fitted by a smoothing spline curve fitting method which is non-parametric. Given the data set of $(x_i, y_i)$, where $y_i = \Psi_{EH}(x_i)$ for $i = 1, \ldots, k$, the cubic smoothing spline estimate $\hat{\Psi}_{EH}$ of the PCE function $P_{eff} = \Psi_{EH}(P_R)$ is defined as the minimizer of the following optimization problem:

$$\text{(P0)} : \min_{\hat{\Psi}_{EH}} \sum_{i=1}^{k} \left\{ y_i - \hat{\Psi}_{EH}(x_i) \right\}^2 + \lambda \int \hat{\Psi}''_{EH}(x)^2 \, dx$$

where $\lambda$ is a smoothing parameter obtained from the curve fitting tool. Fig. 2 shows the smoothing spline curve fitted results over the receive power using multi-tone $Q = 1, 2, 4$, where $Q$ is the number of multi-tone waveforms. The measurement data was obtained by real circuit experimentation, where the testbed implementation is depicted on Fig. 1(b) [10]. In low receive power region, the PCE is proportional to the number of multi-tone, which matches the results from the small signal model in [6]. However, single tone shows better PCE when the receive power is high due to the saturation effect. In other words, multi-tone waveforms cause large voltage swing due to large PAPR, which leads to more clipping at high power region. Following this observation, we define the MS threshold $P_{th}$ for switching the communication mode adaptively to achieve the maximum system performance.

### *B. Waveform and Receiver Design with Duty Cycle Operation*

For the dual mode SWIPT, a transmitter generates two types of single tone and multi-tone waveforms. Depending on feedback information from the receiver, a waveform is selected according to the proposed adaptive MS algorithm. The transmitter details are omitted due to space limitation.

*Single tone/M-ary ASK.* The single tone waveform is designed for supporting high data rate relative to the multi-tone one. We consider a single tone signaling of M-ary amplitude-shift keying (ASK), which is expressed as

$$s_s(t) = \text{Re}\left\{ A \exp(j2\pi f_c t + j\theta) \right\} \quad (1)$$

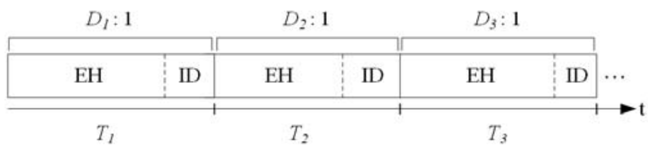



Fig. 3. Time diagram of duty cycle operation.

where $A \in \{\alpha, 2\alpha, ..., M\alpha\}$ and $\theta$ are the amplitude and reference phase of the modulated symbol, respectively, and $f_c$ is the center frequency of the signal. $M$ denotes the number of energy (amplitude) levels. The unit amplitude $\alpha$ can be evaluated from the average signal power relationship as $P_T = \frac{1}{M}\sum_{l=1}^{M}\left(l\frac{\alpha}{\sqrt{2}}\right)^2$. At the receiver, the received signal is decoded jointly using both coarse and fine amplitude paths, which are depicted in Fig. 1(a). The former maps to coarse energy levels (e.g., high/low amplitude levels), while the latter fine constellation points associated with the energy level.

*Multi-tone/PAPR modulation.* Thanks to the nonlinear rectification process, we can enhance the WPT efficiency by using multi-tone waveforms. Furthermore, the PAPR based information transmission facilitates low-power decoding via simple PAPR measurements [9]. The PAPR modulated signal, which uses a subset of $N$ tones from $Q$ available tones (i.e., $N \in \{1, ..., Q\}$), is expressed as

$$s_m(t) = \mathrm{Re}\left\{\sum_{n=1}^{N}\sqrt{\frac{2P_T}{N}}\exp(j2\pi f_n t + j\phi)\right\} \tag{2}$$

where $f_n$ is the frequency of the $n$th tone with $f_n = f_1 + (n-1)\Delta f$, $n = 1, ..., Q$ and $\phi$ is an aligned initial phase for achieving the maximum transmit PAPR. We assume that the minimum tone spacing $\Delta f$ is set to the inverse of multi-tone waveform symbol time (i.e., $\Delta f = T_m^{-1}$) to assure the orthogonality among any pair of tones.

To achieve the higher WPT efficiency, the pre-matched filtering is performed at the transmitter for amplitude matching and phase alignment at the receiver. Then, the transmitted signal can be expressed as

$$s(t) = \begin{cases} A\frac{h^*}{|h|}\cos(2\pi f_c t + \theta) & \text{for } s_s(t), \\ \sqrt{\frac{2P_T}{N}}\frac{h^*}{|h|}\sum_{n=1}^{N}\cos(2\pi f_n t) & \text{for } s_m(t) \end{cases} \tag{3}$$

where $h^*$ is the conjugate of complex channel gain.

*Receiver architecture.* A new receiver architecture is comprised of three (energy/information/PAPR) paths and adaptive MS control module, as shown in Fig. 1(a). For harvesting energy and decoding information from the same signal with self-powering at the receiver, the duty cycle operation is adopted (see Fig. 3). The energy path is first activated (EH block in Fig. 3) to charge the battery. When the harvested energy is sufficient for self-powering, either the information path or the PAPR path is used (ID block in Fig. 3) depending on the selected single tone/multi-tone communication mode. The received signal at the receiver can be expressed as

$$y_R(t) = hs(t) + n(t) \tag{4}$$

where $n(t)$ is the channel noise modeled as $n(t) \sim \mathcal{CN}(0, \sigma^2)$. The received signal passes through the energy path during the EH block, which can be described as $y_{EH}(t) = y_R(t)$, $t \in [0, \frac{D_v}{D_v+1}T_v]$, where $D_v$ is the duty ratio of EH to ID and $T_v$ is the frame time during one duty cycle operation at the $v$th channel block. The harvested energy $E_{EH}$ is evaluated as

$$E_{EH} = \frac{D_v}{D_v+1}T_v \times \hat{\Psi}_{EH}(P_R) \times P_R \tag{5}$$

where $P_R = \mathbf{E}[|y_{EH}(t)|^2] = |h|^2 P_T$, being used for charging the battery and decoding information at the information path as well (see Fig. 1(a)). As the signal power of the energy path is sufficient enough to ignore the noise power, the energy-level information is assumed to be reliably decoded from the coarse amplitude path in noise-free condition (i.e., high SNR).

The received signal for ID is of the form $y_{ID}(t) = y_R(t)$, $t \in [\frac{D_v}{D_v+1}T_v, T_v]$. Note that the time duration of ID block is different from that of EH block. The information path is used to decode the single tone signal with distinct energy levels. As the single tone signal is very sensitive to channel fading, we assume that channel estimation is required before decoding, which consumes more circuit power relative to that of PAPR based SWIPT. The exact energy level can be extracted by two steps: First, coarse and fine amplitudes are estimated from the energy and information paths, respectively. After that, the exact energy level is jointly decoded by exploiting both information.[1] Hence, the coarse and fine amplitude paths are combined for the proposed single tone SWIPT.

The PAPR path is used for PAPR based ID. For this, PAPR estimator simply measures the PAPR of the received signal envelope. The received PAPR in FF channel is evaluated as

$$PAPR = \frac{\max_{t\in[0,T_m]}|y_{ID}(t)|^2}{\frac{1}{T_m}\int_{T_m}|y_{ID}(t)|^2 dt} \cong 2N. \tag{6}$$

Note that the symbol time of multi-tone waveform is $T_m = T_v/(D_v+1)$. It consumes less power compared to the information path because PAPR based modulation does not require the power-hungry active devices, such as mixer and ADC, as well as channel estimation. Further, the WPT efficiency is enhanced in low power region thanks to multi-tone waveforms. Thus, the PAPR path is suitable for low circuit power consumption while increasing the operational range with lower rate.

Adaptive MS control module monitors the receive power and updates the MS threshold $P_{th}$. The communication mode is selected according to the adaptive MS algorithm which will be addressed in next section. The module also feeds back MS information to the transmitter for suitable waveform selection. For instance, when the receive power is greater than the MS threshold ($P_R \geq P_{th}$), it activates the information path for single tone mode and feeds back MS information. Otherwise, it activates the PAPR path for multi-tone mode.

[1] A simple implementation for joint decoding is that the coarse amplitude path saves the information during EH block and single tone decoder reads the information during ID block.

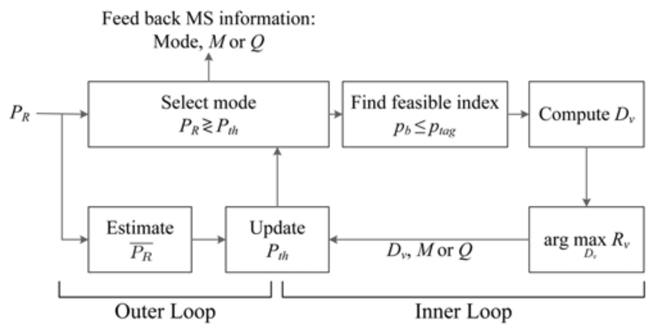



Fig. 4. Iterative inner/outer loop algorithm for adaptive mode switching.

## III. Adaptive Mode Switching Algorithm

For the proposed duty cycle based dual mode operation for SWIPT, a proper mode switching algorithm that maximizes the achievable rate should also be considered. The achievable rates of single tone/multi-tone mode are evaluated as

$$R_v = \begin{cases} \frac{1}{D_v+1}(1 - p_{out}(M)) \log_2 M & \text{for } s_s(t), \\ \frac{1}{D_v+1} \frac{1}{BT_m}(1 - p_{out}(Q)) \log_2 Q & \text{for } s_m(t) \end{cases} \tag{7}$$

for the signal bandwidth $B$. The roll-off factor of the single tone mode is set to zero for the minimum Nyquist bandwidth (i.e., symbol time $T_s = T_v/(D_v + 1) = B^{-1}$). The outage probability can be defined as $p_{out} = \Pr[p_b > p_{tag}]$, i.e., the bit-error rate (BER) given $M$ or $Q$ is higher than the target BER. Also, the duty ratio relationship for self-powering at the receiver is considered as

$$\begin{aligned} E_{EH} &\geq E_{C,i} \\ \frac{D_v}{D_v+1} T_v P_{EH} &\geq \frac{1}{D_v+1} T_v P_{C,i} \\ D_v &\geq \frac{P_{C,i}}{P_{EH}} \end{aligned} \tag{8}$$

where $i \in \{s, m\}$ and $E_{C,i}$ ($P_{C,i}$) is the circuit energy (power) consumption of single tone/multi-tone mode, respectively.

We formulate an adaptive MS optimization problem which controls the MS threshold $P_{th}$ with modulation index $M$ and multi-tone $Q$, so as to maximize the achievable rate. With the energy causality and BER constraints given above, the global optimization problem can be formulated as

$$\begin{aligned} \text{(P1)} : \max_{P_{th}} \quad & \mathbf{E}_v[R_v] \\ \text{s.t.} \quad & E_{EH} \geq E_{C,i} \\ & p_b \leq p_{tag}. \end{aligned}$$

It is difficult to solve (P1) directly because of the combinatorial problem with discrete variables such as modulation index $M$ and multi-tone $Q$. Also, the problem has the non-convex energy causality constraint due to the nonlinear energy harvesting model. To tackle these problems, we divide the global optimization problem into two inner/outer optimization problems, and the optimal solution of (P1) can be obtained by running the iterative algorithm, as illustrated in Fig. 4. In the outer loop, the algorithm solves the long-term rate maximization problem. For this, the outer loop updates the MS threshold $P_{th}$ based on the estimated average receive power $\bar{P}_R$ and the results from the inner loop. The outer-loop optimization problem can be expressed as

$$\text{(P2)} : \arg\max_{P_{th}} \quad \mathbf{E}_v[R_v^*]$$

where $R_v^*$ is the optimal achievable rate according to $D_v$, $M$ or $Q$ which are obtained from the inner loop. Then, the proper communication mode is selected based on the updated $P_{th}$ and fed back to the transmitter. With the selected mode information, the inner loop finds a feasible index set of $M$ or $Q$, and computes the duty ratio $D_v$ which maximizes the achievable rate. The inner-loop optimization problem is formulated as

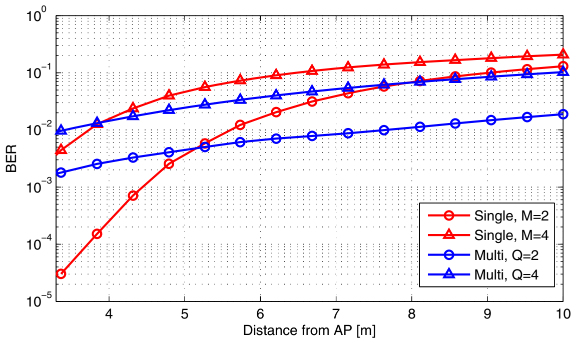
$$\begin{aligned} \text{(P3)} : \arg\max_{D_v} \quad & R_v \\ \text{s.t.} \quad & D_v \geq \frac{P_{C,i}}{P_{EH}} \\ & p_b \leq p_{tag}, \end{aligned}$$

which is the short-term rate maximization for the $v$th channel block with a given communication mode. The results of the inner loop (i.e., $D_v$, $M$ or $Q$ in Fig. 4) are fed back to the outer loop for next iterative step. Note that an optimal duty ratio is one-to-one mapped to the number of multi-tone $Q$ with given $P_R$ because the harvested power $P_{EH}$ is only affected by $Q$ when $P_R$ is fixed, as shown in Fig. 2.

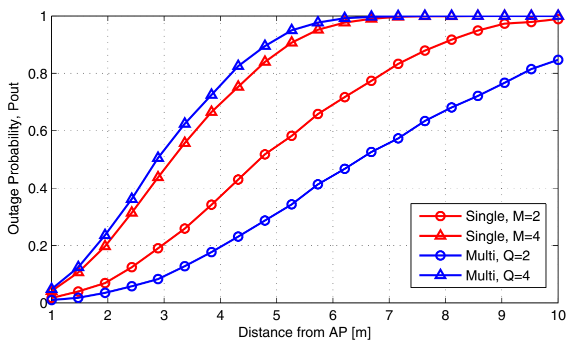
## IV. Results

The performance of the proposed dual mode SWIPT and existing SWIPT systems is compared. We assume the bandwidth $B$ = 1MHz where the center frequency $f_c$ is 900MHz. We consider Rayleigh FF channel with path-loss exponent set to 2.5. Also, the noise power spectral density is assumed to be -130dBm/Hz. For the smoothing spline curve fitting of the PCE nonlinear EH model, we set $\lambda = 0.3472$. Figs. 5(a) and (b) show the BER and outage probability performance of the proposed single tone/multi-tone SWIPT system when $M = 2, 4$ and $Q = 2, 4$, respectively. They were evaluated through simulations based on the Monte Carlo method. In Fig. 5(a), we see that the BER performance of PAPR modulation is degraded gradually compared to that of M-ary ASK as the distance is increased. This is because PAPR modulation is less sensitive to channel fading than M-ary ASK. Based on the BER results of the single tone/multi-tone SWIPT system, Fig. 5(b) shows the outage probability when the target BER is set to $p_{tag} = 0.01$.

Fig. 6 shows the achievable rate versus receive power, subject to the BER and energy causality constraints. The achievable rate here is maximized by setting an optimal MS threshold, and the circuit power consumption for decoding single tone/multi-tone signals is set to be $P_{C,s} = 0.2$mW and $P_{C,m} = 0.12$mW. Compared to the existing SWIPT system, the proposed dual mode SWIPT system achieves higher rate thanks to the adaptive MS operation. This is because the




(a) Bit-error rate (BER)




(b) Outage probability $p_{out}$

Fig. 5. Bit-error rate (BER) and outage probability versus distance from AP when $P_T = 40$dBm.

adaptive MS algorithm iteratively updates $P_{th}$ and switches the communication mode with optimum $D_v$, $M$ or $Q$ according to the receive power for maximizing the achievable rate. In Fig. 6, we further observe how the performance depends on $P_{ch,est}$. Here, $P_{ch,est}$ is the power consumption for channel estimation when the single tone mode is used and $\beta$ is the ratio of consumption power for channel estimation to that for decoding information (i.e., $\beta = P_{ch,est}/P_{C,s}$). As $\beta$ increases, the achievable rate gets worse since more power is required for channel estimation. This implies that the large $\beta$ forces the adaptive MS threshold $P_{th}$ to be increased. In other words, multi-tone mode selection is more likely as the large $\beta$ causes the self-powering less feasible with the single tone mode.

## V. Conclusion

In this paper, we have proposed a new duty cycle based dual mode SWIPT receiver architecture with adaptive MS operation. We also implemented a new concept of adaptive MS algorithm which is comprised of the combined inner loop and outer loop. The smoothing spline curve fitting nonlinear PCE model was considered to optimize the MS threshold. To validate the system performance improvement, we have evaluated the average achievable rate subject to the energy causality constraint for self-powering. The proposed SWIPT system has enabled the self-powering to assure the energy neutral operation via the duty cycle based dual mode operation.

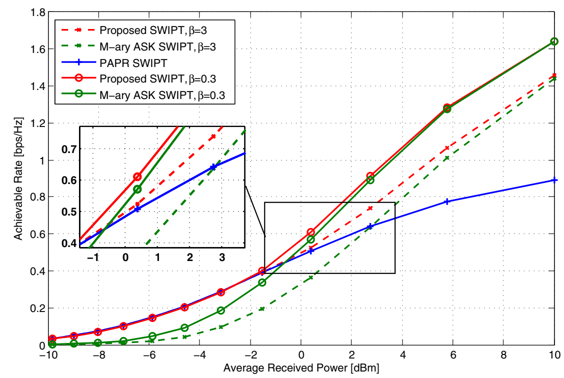



Fig. 6. Achievable rate versus average received power subject to the BER and self-powering constraints.

This will likely lead to sustaining battery-free IoT network for self-powered devices.

Future study will analyze the theoretical optimization of the proposed SWIPT system with adaptive MS operation under various network and channel conditions. We will then implement the duty cycle based dual mode SWIPT receiver prototype in IC and perform experiments for validation.

## Acknowledgment

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. 2014R1A5A1011478).

## References

[1] X. Zhou, R. Zhang, and C. K. Ho, "Wireless information and power transfer: Architecture design and rate-energy tradeoff," *IEEE Trans. Commun.*, vol. 61, pp. 4754-4767, Nov. 2013.

[2] X. Lu, P. Wang, D. Niyato, D. I. Kim, and Z. Han, "Wireless networks with RF energy harvesting: A contemporary survey," *IEEE Commun. Surveys & Tutorials*, vol. 17, no. 2, pp. 757-789, Second Quarter 2015.

[3] X. Lu, P. Wang, D. Niyato, D. I. Kim, and Z. Han, "Wireless charging technologies: Fundamentals, standards, and network applications," *IEEE Commun. Surveys & Tutorials*, vol. 18, no. 2, pp. 1413-1452, Second Quarter 2016.

[4] Y. Zeng, B. Clerckx, and R. Zhang, "Communications and signals design for wireless power transmission," *IEEE Trans. Commun.*, vol. 65, pp. 2264-2290, May 2017.

[5] A. Boaventura, D. Belo, R. Fernandes, A. Collado, A. Georgiadis, and N. B. Carvalho, "Boosting the efficiency: Unconventional waveform design for efficient wireless power transfer," *IEEE Microw. Mag.*, vol. 16, no. 3, pp. 87-96, Apr. 2015.

[6] B. Clerckx, and E. Bayguzina, "Waveform design for wireless power transfer," *IEEE Trans. Signal Process.*, vol. 64, no. 23, pp. 6313-6328, Dec. 2016.

[7] E. Boshkovska, D. W. K. Ng, N. Zlatanov, and R. Schober, "Practical non-linear energy harvesting model and resource allocation for SWIPT systems," *IEEE Commun. Letters*, vol. 19, pp. 2082-2085, Dec. 2015.

[8] J. J. Park, J. H. Moon, K. Y. Lee, and D. I. Kim, "Dual mode SWIPT: Waveform design and transceiver architecture with adaptive mode switching policy," *Proc. IEEE VTC 2018 Spring*, Porto, Portugal, Jun. 2018.

[9] D. I. Kim, J. H. Moon, and J. J. Park, "New SWIPT using PAPR: How it works," *IEEE Wireless Commun. Letters*, vol. 5, no. 6, pp. 672-675, Dec. 2016.

[10] D. I. Kim, "A unified design of wireless information and power transmission (WIPT)," (keynote) *IEEE GLOBECOM 2017 Workshop on Wireless Energy Harvesting Commun. Networks*, Singapore, Dec. 2017.