Energy Efficient Beacon Based Synchronization for Alarm Driven Wireless Sensor Networks

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***Abstract*—Many applications of wireless sensor networks require that nodes, besides monitoring a given phenomenon, must be able to detect and communicate asynchronous events (*e.g.* alarms), implying that they have to often listen to the medium in idle mode, which is inherently energy wasteful. In such a scenario time synchronization is crucial to efficiently operate in duty-cycles and minimize energy consumption. In this work we assess the impact of the trade-off between spending energy with more frequent synchronizations and in return saving it by reducing the idle listening window necessary for the desired reliability of the communication. The optimal frequency of time synchronizations is obtained analytically and corroborated by numerical results, showing that several times less overall energy may be spent with a finer synchronization when compared with maintaining the minimum clock precision required by the phenomenon being monitored, greatly extending the life-span of the network.**

***Index Terms*—Clock synchronization, energy efficiency, event detection, wireless sensor networks.**

I. Introduction

Wireless Sensor Networks (WSNs) consist of sensor nodes deployed in order to monitor phenomena of interest. One important aspect of WSN nodes is that very often they must have their clocks synchronized. This is useful not only for application specific purposes, but also for efficient channel access [1]. Many efficient synchronization protocols can be found in the literature [2]–[5], where in general the focus is on clock precision. Since the nodes are usually disposable and powered by batteries, another important goal in the design of a WSN is that it must be energy efficient [6]. With that in mind, the Guard Beacon scheme has been recently proposed in [7], focusing on optimizing the energy used on clock synchronization, as opposed to clock precision. Guard Beacon is based on using any established synchronization protocol, but reducing the idle listening window by sending synchronization beacons multiple times at optimal instants, which may result in more than 40% of savings in synchronization power consumption.

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However, a relevant scenario not considered in [7] is the possibility of the nodes detecting and communicating asynchronous events, such as alarms. In order to be able to receive alarms, the nodes must listen to the channel idly following a given pattern. Alternatively, the nodes could use a wake up radio [8], wherein a simpler energy inexpensive radio is always listening just for the alarm propagation. However, compared with usual radio modules, state of the art wake up radios have a poor sensitivity [9] resulting in short communication ranges [8], which may be insufficient for many applications.

The importance of being able to communicate alarms can be illustrated in environmental monitoring applications. The physical quantities being monitored have a slow variation most of the time [10], [11], and thus only a few spaced samples are required by the monitoring application in general. Thus, sensors can operate with a low sampling rate and a coarse time synchronization in order to save energy and storage. However, important phenomena may occur in a short time period and must be adequately monitored, being crucial to identify such events and distribute an alarm along the network in order to increase the sampling rate as to adequately acquire it.

Let us remark that idle listening is one of the major sources of energy waste in a WSN [12]. Therefore, energy efficiency can be considerably improved by strategies centered around shortening this time [6]. This goal can be achieved by making nodes communicate on a low duty-cycle [6], waking up at scheduled instants and for a predetermined amount of time, so that messages (or alarms) can be detected with a given success probability. The coarser the time synchronization, the larger must be the duration of the idle listening window to guarantee that a given message is detected, thus increasing the energy consumption. On the other hand, a finer time synchronization guarantees a shorter idle listening window, reducing the energy consumption for messages or alarm detection, but increasing the energy necessary for time synchronization.

In this paper we analyze the trade-off between the energy spent with more frequent synchronizations and the energy saved by reducing idle listening time, given that nodes must periodically listen to detect alarms. We show that by optimally reducing the idle listening window, using a finer time synchronization than the minimum demanded by the application, it is possible to reduce the overall energy consumption. The energy savings increase with the maximum synchronization interval (*i.e.* with the minimum synchronization precision required by the application), so that our contribution is more relevant for WSNs with low duty-cycles.

II. Problem Formulation

A. Baseline Scenario

Since nodes usually use crystals to count time, which may have distinct oscillation frequencies, there is an inherent difference in clock for two nodes at a given time [13]. In a classical synchronization scenario, every T seconds (synchronization interval) node A sends a beacon to node B containing the time with respect to (w.r.t.) A's clock. Moreover, a clock instant w.r.t. node B can be related to an instant w.r.t node A using the propagation delay and the relative oscillation and offset of the clocks [13]. In order for node B to synchronize its clock with node A, it must estimate such parameters and correct its clock accordingly, which can be performed by plenty of well established methods [2]–[5]. Following [7]–considering that just after each synchronization the error between the clocks is zero–at each synchronization round the error between the two clocks can be expressed as a random variable that follows a normal distribution with zero mean and standard deviation

$$\sigma_e = \sqrt{T^2\sigma_f^2 + \sigma_\tau^2 + \sigma_\theta^2}, \tag{1}$$

where σ_f^2 is the variance of the relative clock skew, σ_τ^2 is the variance of the propagation delay and σ_θ^2 is the variance of the relative offset. Let us assume that the particular application demands certain precision among clocks, which imposes a maximum synchronization interval T_s, and therefore $T \leq T_s$. Then, to ensure a β_0 probability of listening to the synchronization beacon sent by node A, node B must wake up

$$t_a = K\sigma_e \tag{2}$$

seconds in advance–this is denoted advance time–, where $K = Q^{-1}(1-\beta_0)$ and Q^{-1} is the inverse Q-function. Node B then listens to the medium for at least a guard time $t_g = 2t_a$ before sleeping again. The duration from the moment B wakes up to the instant it catches a beacon is t_w, the average waiting time is $\bar{t}_w$. If the beacon is missed, node B doubles t_g for the next round as part of a synchronization recovery strategy [7], otherwise it calibrates its clock and resumes sleeping.

In order to minimize the overall energy spent during synchronization, the authors in [7] recently proposed sending more than a single beacon, which in turn reduces $\bar{t}_w$. Methods for determining N, the optimal number of synchronization beacons, as well as the optimal instants to send them, are presented. However, since the exact solution does not have a closed form, a tight approximation for N is presented in [7]

$$N \approx n = \sqrt{\frac{t_a P_l}{T_b P_s}}, \tag{3}$$

yielding an average waiting time of

$$\bar{t}_w \approx \frac{t_a}{n}, \tag{4}$$

where $n \in \mathbb{R} | n \geq 1$, P_l and P_s are the idle listening and transmitting powers, respectively, and T_b is the beacon duration. Moreover, in order to obtain the above results, the total power spent on synchronization

$$P_{\text{sync}} = \frac{\bar{t}_w P_l}{T} + \frac{T_b}{T}P_r + \frac{NT_b}{T}P_s, \tag{5}$$

is minimized given a probability of the node being awake to listen to at least one beacon, where P_r is the receiving power.

B. Low Duty-Cycle Alarm-Aware WSN

Let us now extend the baseline scenario to the possibility of detecting and propagating asynchronous events between each T_s, specially for relatively large T_s. In this scenario, large synchronization intervals imply a large value of t_g to guarantee β_0 probability of beacons (be them for synchronization or alarm purposes) being detected. This also increases the cost of idle listening increasing the energy consumption [12].

Considering p equally spaced idle listening windows within every T_s with the purpose of communicating alarms, our goal is to determine the optimal synchronization frequency in terms of energy efficiency. The choice of p depends on the particular application and phenomena being monitored. Note that our scenario reduces to that of [7] if $p = 0$, because the possibility of alarms propagation is not accounted for in [7]. In principle our goal can be achieved by reducing t_g through synchronizing the nodes more often ensuring a finer clock synchronization and reducing overall energy consumption. Furthermore, it is important to point out that over-synchronizing may not be efficient, since too much energy might be wasted with more frequent synchronizations[1]. Hence, based on this trade-off, the idea is to determine the optimal number of times to synchronize every T_s seconds in order to balance the energy spent idly listening (E_{idle}) and the energy spent to perform $M \in \mathbb{N}^*$ synchronizations (E_{sync}) within T_s. Thus, we minimize the total energy E by reducing t_g at the cost of increasing M, which can be formulated as

$$\min_M E = E_{\text{sync}} + E_{\text{idle}}, \tag{6}$$

where E_{sync} is composed of the energy spent receiving the beacons, the energy spent waiting for the beacons and the energy spent transmitting beacons, so that

$$E_{\text{sync}} = M\left(\bar{t}_w P_l + T_b P_r + NT_b P_s\right), \tag{7}$$

whereas

$$E_{\text{idle}} = p t_g P_l = 2pP_l K\sigma_e. \tag{8}$$

Moreover, in this novel scenario, (1) must be rewritten as

$$\sigma_e = \sqrt{\left(\frac{T_s}{M}\right)^2 \sigma_f^2 + \sigma_\tau^2 + \sigma_\theta^2}. \tag{9}$$

Note that when $M = 1$ and $T = T_s$ we have the same baseline scenario considered in [7].

The basis of the proposed optimization is illustrated in Fig. 1, where $p = 4$ idle listening windows are considered (in green). The first scenario illustrated at the top of the figure represents the baseline scenario, with $M = 1$ (in blue), $N = 4$ beacons and a guard time of $t_g = 15$ ms being necessary to ensure a β_0 target probability of a beacon being captured. At the bottom of

[1] Note that the synchronization and alarm listening windows cannot be the same as in a general scenario the node sending an alarm may not be the master node that sends the synchronization beacons, and a collision could occur.

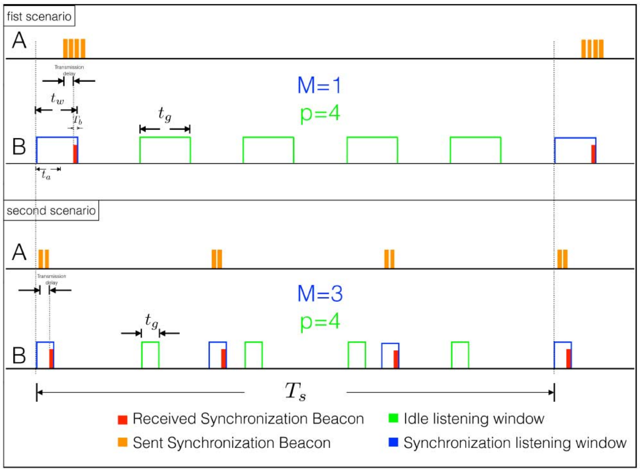

Fig. 1. Proposed scheme reducing the idle listening window (t_g) while increasing the number of synchronizations (M) within a time interval T_s.

the figure, a second scenario with $M = 3$ is shown, in which only $N = 2$ beacons and $t_g = 6$ ms are necessary. Thus, even with the cost of three times more frequent synchronizations, the total energy consumption in the second scenario may be less than in the first, as N and t_g decreased. In the next section we present closed form equations that allow the optimization of M in terms of energy.

III. Proposed Optimization

Theorem 1: The optimal amount of times $m^\star$–in terms of energy efficiency–to synchronize nodes on a WSN, wherein each node idly listens to the medium p times waiting for alarms between each maximum synchronization interval T_s, can be very well approximated by the real positive solution of

$$T_b P_r m^2 + \sqrt{T_b P_s P_l K T_s \sigma_f}\, m^{\frac{3}{2}} - 2pP_l K T_s \sigma_f = 0, \quad (10)$$

w.r.t. m, given that $8pN > m$ and where $m \in \mathbb{R}^+$.

Proof: First, given that $n \approx N$ and using (3), (4), (7) and (8) we arrive at the total consumed energy as a function of M,

$$E(M) = M\left(2\sqrt{T_b P_s P_l t_a(M)} + T_b P_r\right) + 2pP_l t_a(M). \quad (11)$$

Moreover, when $(\frac{\sigma_f T_s}{M})^2 \gg \sigma_\tau^2 + \sigma_\theta^2$, it is possible to approximate (9) well and apply it to (2), so that

$$t_a(M) \approx \frac{K T_s \sigma_f}{M}, \quad (12)$$

which is tight when the maximum synchronization interval T_s is large. Replacing M in (11) by $m \in \mathbb{R}^+$,

$$E(m) = m\left(2\sqrt{T_b P_s P_l t_a(m)} + T_b P_r\right) + 2pP_l t_a(m), \quad (13)$$

which is a function to be minimized w.r.t. m. Next, the optimum m can be found if $E(m)$ is a convex function. In this case, $\frac{\mathrm{d}^2 E(m)}{\mathrm{d}m^2} > 0$ must hold, so that

$$\frac{K T_s \sigma_f t_a(m)\left(8pP_l\sqrt{t_a(m)} - m\sqrt{P_l P_s T_b}\right)}{2\left(m\sqrt{t_a(m)}\right)^3} > 0 \quad (14)$$

is to be satisfied. Note that since m, as well as all the constants, can only assume positive values, (14) can be simplified to

$$8pN > m, \quad (15)$$

which is the condition to assure convexity. For the practical system parameters considered in this work $m^\star$ always lies within the interval in which $E(m)$ is convex. However, if for other system parameters this condition is not met, $m^\star$ can be found through other forms of optimization.

Finally, the optimum can be found by solving $\frac{\mathrm{d}E(m)}{\mathrm{d}m} = 0$, which can be written as

$$2\sqrt{T_b P_s P_l}\left(\sqrt{t_a} + \frac{m}{2\sqrt{t_a}}\frac{\mathrm{d}t_a}{\mathrm{d}m}\right) + T_b P_r + 2pP_l\frac{\mathrm{d}t_a}{\mathrm{d}m} = 0. \quad (16)$$

Using (12) in (16) and rearranging terms, we arrive at (10) concluding the proof. Moreover, note that in practice instead of $m^\star$ we use the closest integer solution, denoted by $M^\star$. ■

Theorem 2: The optimal amount of synchronization rounds within each maximum synchronization interval T_s is upper bounded by

$$m_b = \sqrt[3]{\frac{4p^2 P_l K T_s \sigma_f}{T_b P_s}} \quad (17)$$

given that $P_r \ll NP_s$ and where $m_b \in \mathbb{R}^+$.

Proof: When the total transmit power is much larger than the receive power ($P_r \ll NP_s$), (13) is very well approximated by disregarding the term that considers P_r. This assumption is based on the fact that there are off-the-shelf radios such as the LoRa modem [14] which have receive power specifications in the order of 40 mW as opposed to a transmit power of up to 400 mW. This difference is even greater when considering state of the art radio circuitry, whose receive power may be as low as 15 mW [15]. Therefore (11) can be simplified to

$$E(M) \approx M\left(2\sqrt{T_b P_s P_l t_a(M)}\right) + 2pP_l t_a(M). \quad (18)$$

The first step towards minimizing (18) is to replace the integer M with the real m. Then, we determine the convexity constraints for $E(m)$ by evaluating $\frac{\mathrm{d}^2 E(m)}{\mathrm{d}m^2} > 0$, which results in (15), and thus we are able to minimize $E(m)$ by solving

$$2\sqrt{T_b P_s P_l}\left(\sqrt{t_a} + \frac{m\frac{dt_a}{dm}}{2\sqrt{t_a}}\right) + 2pP_l\frac{dt_a}{dm} = 0. \quad (19)$$

Using (12) in (19) and rearranging the terms, we arrive at (17). Since the synchronization cost is being reduced by disregarding P_r, the tradeoff tends towards a more synchronized scenario which translates into more frequent synchronizations being optimal, making m_b an upper bound to $m^\star$. ■

The upper bound in Theorem 2 can be exploited for obtaining useful insights. Analyzing (17) we can see that the optimal number of synchronizations within T_s increases with the frequency that the node has to idly listen for alarms. Also, we note that $m^\star$ decreases with the increase of transmit power, which is intuitive to assume since each synchronization would be more expensive in terms of energy. Conversely, as P_l grows,

TABLE I
SIMULATION PARAMETERS

Beacon duration (T_b)	2 ms [7]
Estimated deviation of clock drift rate (σ_f)	50 ppm [7]
Estimated deviation of clock offset (σ_θ)	20 μ s [7]
Estimated deviation of message delivery delay (σ_τ)	11 μ s [7]
Power consumption for data transmission (P_s)	396 mW [14]
Power consumption for data receiving (P_r)	37 mW [14]
Power consumption for idle listening (P_l)	37 mW [14]
Synchronization confidence level (β_0)	99.5% [7]

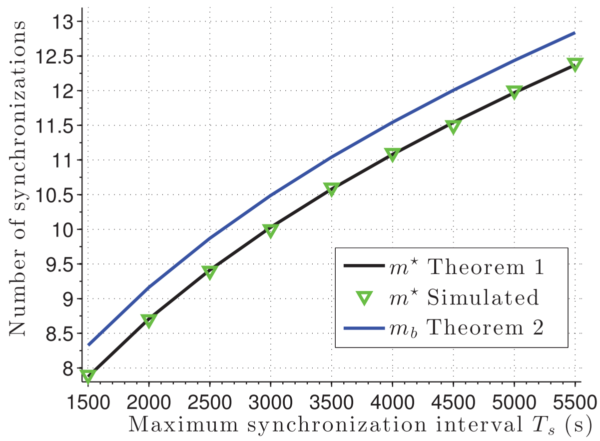

Fig. 2. Theoretical and simulated optimal number of synchronizations $m^\star$ within T_s, and the upper bound m_b.

$m^\star$ becomes larger, since the node draws more energy for idly listen to the medium and thus a smaller t_g is desirable, which in turn means that synchronizing more often would be less energy consuming. In addition, as shown in (12), the listening window $t_g = 2t_a$ depends directly on $KT_s\sigma_f$, and thus an increase in the value of any of the factors also increases $m^\star$.

Finally, let us recall that we relaxed the optimization solution in order to consider that $\{m^\star, m_b\} \in \mathbb{R}^+$. In practice we assume the closest integer solution of $m^\star$, denoted by $M^\star$.

IV. NUMERICAL RESULTS

In order to investigate the correctness and the impact of the proposed optimization, this section presents some numerical examples using the parameters in Table I, which are obtained from [7] and [14]. First, Fig. 2. plots $m^\star$ and m_b, as well as computer simulations, as a function of T_s for the case of $p = 4$. It is clear that $m^\star$ grows with T_s, as predicted in Section III. In addition, note that Theorem 1 and the computer simulations agree very well, while the upper bound is just a bit pessimistic.

Next, we compute the ratio $\eta = \frac{E(M^\star)}{E(1)}$, between the energy spent when using $M = M^\star$ and $M = 1$, in order to show the potential energy savings. Note that, from now on, we only plot the closest integer solution of $m^\star$, denoted by $M^\star$. Using N, in order to evaluate performance in a real scenario, Fig. 3. plots η for different values of T_s and p, from which we can observe relevant energy savings. For instance, for $p = 6$ and $T_s = 1$ hour the energy consumption is around five times smaller when $M^\star$ is employed, while the savings increase with both p and T_s. Moreover, Fig. 4. shows the overall energy consumption as a function of M. Note that, as expected, there is an optimal $M^\star$ for each set of parameters, while the potential energy savings can be quite large. In addition, Figs. 3. and 4 also reveal that the proposed optimization leads to higher energy savings when either p or T_s increase, *i.e.*, applications with severe alarm timing restrictions or low duty-cycles, respectively.

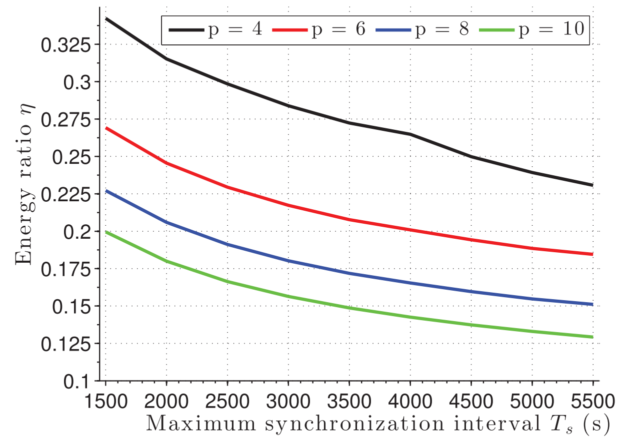

Fig. 3. Ratio $\eta = \frac{E(M^\star)}{E(1)}$ for different values of p and T_s.

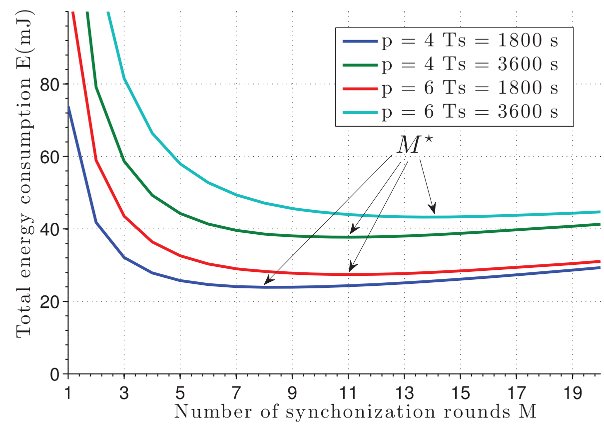

Fig. 4. Overall energy consumption as a function of M, for different values of p and T_s.

V. CONCLUSION

In this work we presented a strategy to determine the most energy efficient synchronization frequency in a WSN, while assuming that the wireless nodes must have to idly listen to the medium several times within a maximum synchronization interval as specified by the particular application. This particular scenario can be found for instance in practical environmental monitoring systems. Moreover, with the proposed optimization we are able to considerably decrease the overall energy consumption required to maintain adequate synchronization. For instance, savings as large as five times were achieved in the numerical results. In addition, we presented an analytical derivation of the optimal number of synchronizations within a cycle as well as an upper bound that allowed us to obtain important insights on the behavior of the proposed optimization for different system parameters.

REFERENCES

[1] Q. Li and D. Rus, "Global clock synchronization in sensor networks," *IEEE Trans. Comput.*, vol. 55, no. 2, pp. 214–226, 2006.

[2] M. Maróti, B. Kusy, G. Simon, and Á. Lédeczi, "The flooding time synchronization protocol," *2nd Int. Conf. Embedded Netw. Sensor Syst.*, pp. 39–49, 2004.

[3] J. Elson, L. Girod, and D. Estrin, "Fine-grained network time synchronization using reference broadcasts," *ACM SIGOPS Operating Systems Review*, vol. 36, pp. 147–163, 2002.

[4] M. L. Sichitiu and C. Veerarittiphan, "Simple, accurate time synchronization for wireless sensor networks," *IEEE Wireless Commun. Netw. (WCNC)*, vol. 2, pp. 1266–1273, 2003.

[5] J. Van Greunen and J. Rabaey, "Lightweight time synchronization for sensor networks," *2nd ACM Int. Conf Wireless Sensor Netw. App.*, pp. 11–19, 2003.

[6] G. Anastasi, M. Conti, M. Di Francesco, and A. Passarella, "Energy conservation in wireless sensor networks: A survey," *Ad hoc networks*, vol. 7, no. 3, pp. 537–568, 2009.

[7] Y. Chen, F. Qin, and W. Yi, "Guard Beacon: An energy-efficient beacon strategy for time synchronization in wireless sensor networks," *IEEE Commun. Lett.*, vol. 18, no. 6, pp. 987–990, 2014.

[8] I. Demirkol, C. Ersoy, and E. Onur, "Wake-up receivers for wireless sensor networks: Benefits and challenges," *IEEE Wireless Commun.*, vol. 16, no. 4, pp. 88–96, 2009.

[9] D. De Donno, L. Catarinucci, and L. Tarricone, "Ultralong-range rfid-based wake-up radios for wireless sensor networks," *IEEE Sensors Journal*, vol. 14, no. 11, pp. 4016–4017, 2014.

[10] H. B. Pionke, W. J. Gburek, and A. N. Sharpley, "Critical source area controls on water quality in an agricultural watershed located in the chesapeake basin," *Ecological Eng.*, vol. 14, no. 4, pp. 325–335, 2000.

[11] X. Zhao, X. Wang, W. Yu, and X. Zhou, "An efficient broadcast authentication protocol in wireless sensor networks," *Chinese J. Electronics*, vol. 18, no. 2, pp. 368–372, 2009.

[12] W. Ye, F. Silva, and J. Heidemann, "Ultra-low duty cycle MAC with scheduled channel polling," *4th Int. Conf. Embedded Netw. Sensor Syst.*, pp. 321–334, 2006.

[13] Y.-C. Wu, Q. Chaudhari, and E. Serpedin, "Clock synchronization of wireless sensor networks," *IEEE Signal Process. Mag.*, vol. 28, no. 1, pp. 124–138, 2011.

[14] Semtech, *SX1272/73 - 860 MHz to 1020 MHz Low Power Long Range Transceiver*, vol. 3, 2015.

[15] L. Zhang, *et al.*, "A reconfigurable sliding-IF transceiver for 400 MHz/2.4 GHz IEEE 802.15. 6/ZigBee WBAN hubs with only 21% tuning range VCO," *IEEE J. Solid-State*, vol. 48, no. 11, pp. 2705–2716, 2013.