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# Power-Efficient Rendez-vous Schemes for Dense Wireless Sensor Networks

En-Yi A. Lin, Jan M. Rabaey
Berkeley Wireless Research Center
University of California, Berkeley, USA
enyi, jan@eecs.berkeley.edu

Adam Wolisz
Telecommunication Networks Group (TKN)
Technische Universitaet Berlin, Germany
awo@ieee.org

*Abstract*—**Two generic rendez-vous schemes— transmitter and receiver initiated, respectively— for dense wireless sensor networks are presented. Their power efficiency is analyzed and compared under fading channel conditions and for realistic physical layers. The modeling strategy as well as the obtained results are applicable to any rendez-vous scheme of the cycled-receiver nature. The paper further proposes precise guidelines and optimization strategies for synchronization in sensor networks.**

## I. Introduction

Recently, the advance in integrated circuit technology enabled the realization of wireless sensor networks (WSNs). Potential applications of WSNs are quite extensive, including smart buildings, environment monitoring, energy management, and so on. Wireless sensor nodes are characterized by their limited energy; accordingly, to ensure system longevity, each node has to operate at a minimum power level while meeting acceptable performance levels. Another typical characteristic of most sensor networks is that communication is relatively rare (0.1 to 10 packets/second) and packets are short (less than 500 bits). Several authors have argued and demonstrated that under these conditions nodes spend most of the time just monitoring the channel in expectation of a packet arrival. Unfortunately, the power consumption for channel monitoring is significant [1]. Thus the most straightforward way to minimize power consumption per node is to power off the nodes as often and as long as possible. Communication between any two nodes is, however, possible only if both of them are powered on simultaneously. Hence, a way to arrange simultaneous on-time of nodes wishing to communicate— typically called a *rendez-vous scheme*— is necessary. It should be stressed that determining which node (partner) a given node should rendez-vous with in order to forward a packet is the concern of the routing scheme. Depending on the routing policy, this might be:

i) a specific partner,

ii) a set of specific partners,

iii) a set of potential partners, from which one should be selected.

In this paper, we focus exclusively on the power consumption of various rendez-vous schemes, not on the most appropriate routing scheme.

More in particular, we will examine one type of rendez-vous scheme called the *cycled receiver*. While this synchronization strategy is not new and has been discussed by other authors, our paper brings the following unique perspectives:

- It analyzes the cycled receiver scheme *in a generic way*, and actually brings some interesting *new variants* to the table. The analysis approach used can be adapted to other protocols of the cycled receiver nature with at most slight modifications. In fact, the approach could be used to analyze virtually any rendez-vous scheme. The methodology also helps to clearly identify the dominant design parameters and their impacts. The model allows us to further explore various "what-if" scenarios in a quick and quantifiable fashion.
- It is based on a realistic model of the physical layer and the underlying hardware. The full effect of cycling transceivers is visible and realistic only if the power consumption of a node in its different states is adequately modeled. In addition, our analysis is based on real numbers obtained from actual hardware [1] rather than being based on assumptions.
- It takes into account the effect of channel fading, hence approximating the real environment the network is operating in. Fading is inevitable in wireless channels, and has a considerable impact on the power dissipation and the performance of a rendez-vous scheme, as will be shown later.

The paper is structured as following. In section II, we introduce a generic cycled receiver scheme, along with some design rules and potential variations. We then proceed to propose a 5 state MAC and physical layer model for the wireless transceiver, as well as a channel model. These models will be used to analyze and compare the power of the various cycled receiver schemes in section IV, and to derive the optimal cycling strategies as a function of traffic. Up to this point, all nodes are assumed to have no knowledge of other nodes' wakeup schedule. Doing so can lead to a more optimal performance, as is discussed in section V, where a semi-synchronous cycle receiver scheme is introduced. The purely-asynchronous scheme is then introduced and compared to the pseudo-asynchronous schemes in section VI. In section VII, we overview different ways of performing rendez-vous between two nodes, and review prior efforts in this space. The paper concludes with a summary and future perspectives.

## II. RENDEZ-VOUS SCHEMES BETWEEN SENSOR NODES

It is crucial to outline that there are multiple ways of accomplishing rendez-vous between wireless nodes. The can be grouped in three major categories:

1. **Purely synchronous**. Nodes are synchronized in time and agree on specific time slots for communication. This is hard to accomplish in a fully ad-hoc multi-hop scenario, and tends to translate into a major overhead in power consumption.
2. **Purely asynchronous.** Nodes have the capability of waking up one another on demand. While this approach has the potential to lead to the lowest power dissipation, it requires extra hardware that is typically not available on standard parts (such as a wakeup radio [2]). It also leads to some small standby power, which might become dominant for networks with very low activity levels.
3. **Pseudo-asynchronous (or cycled receiver)**. Nodes establish rendez-vous on demand, but underlying is a periodic wakeup scheme.

The *cycled receiver* scheme is a popular approach, versions of which have been proposed by a variety of authors (for instance, [4-5]). Nodes are powered on and off periodically, and a beaconing approach is used to express the desire or willingness to communicate. Obviously, the pattern of periodic on/off powering has to satisfy some performance requirements, like throughput and delay. Our primary interest in this investigation is to determine how the parameters of this pattern influence the power consumption, and to understand how a proper tradeoff between performance and power can be achieved.

The cycled receiver schemes can be classified into two groups, depending upon who (transmitter or receiver) initiates the rendez-vous. We call these schemes 'Transmitter /Receiver Initiated CyclEd Receivers', respectively, or TICER and RICER in short.

### A. *TICER (Transmitter Initiated CyclEd Receiver)*

For the sake of simplicity but without any impact on generality, we assume a single destination node in the following discussion. When a sensor node has no data packet to transmit, it wakes up to monitor the channel with a period $T$ and goes back to sleep after a wakeup duration $T_{on}$, as shown in Fig. 1. As soon as a node has a data packet to transmit —either generated from the upper layers of the protocol stack or forwarded by another node— it wakes up and monitors the channel for duration of $T_{on}$. If it does not hear any ongoing transmissions on the channel, it starts transmitting request-to-send (RTS) signals to the destination node, and monitors the channel for a time $T_l$ for responses after each RTS transmission. The destination node, upon waking up according to its regular wakeup schedule, immediately acquires and receives the RTS's, upon which it responds with a clear-to-send (CTS) signal to the source node.

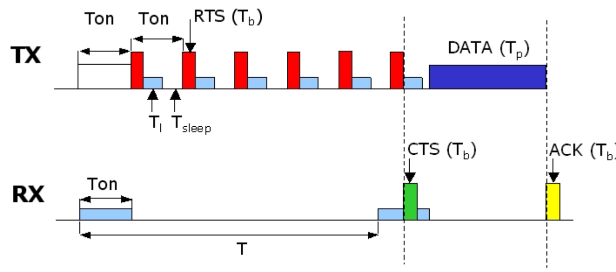



Figure 1. TICER Scheme

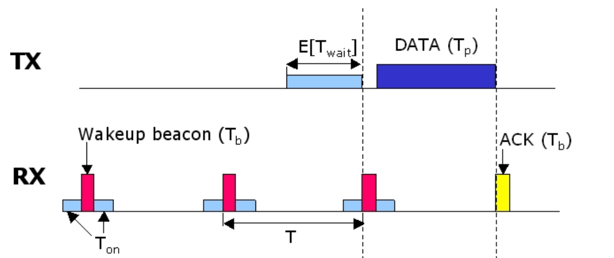



Figure 2. RICER Scheme

After reception of the CTS signal, the source node transmits the data packet. The session ends with an acknowledgement (ACK) signal transmitted from the destination node to the source node, after correctly receiving the data packet.

Some rules should be considered when designing a TICER protocol:

i. Since a longer $T_{on}$ implies more monitoring power with no enhancement in performance, $T_{on}$ should be as short as possible to save power. The lower bound is set by the shortest time needed to receive an RTS. Similarly, $T_l$ is set to a minimal time needed to receive a CTS.
ii. To minimize transmit power, the control packets RTS, CTS and ACK (with length $T_b$) are made as short as possible. They consist of the local MAC addresses of the source and destination node, and a preamble for acquisition.
iii. The frequency of transmitting RTS's should be as low as possible to save transmit power. However, the period cannot be longer than $T_{on}$, otherwise the destination node might wake up and go back to sleep in between two RTS's and miss rendez-vous. Thus, the period is set to be slightly shorter than $T_{on.}$

### B. *RICER (Receiver Initiated CyclEd Receiver)*

Similar to the TICER scheme, a sensor node with no data packet to transmit wakes up with period $T$. As illustrated in Fig. 2, it then proceeds by transmitting a short wakeup beacon with length $T_b$ to announce that it is awake, and by monitoring the channel for a response for duration of $T_l$. If there is no response, the node goes back to sleep. A source node with data to transmit stays awake and monitors the channel, awaiting a wakeup beacon from the destination. Upon reception, it starts transmitting the data packet. The session ends with an acknowledgement (ACK) signal transmitted from the destination node to the source node, after correctly receiving the data packet.

The design rules of RICER are similar to those of TICER:

i. $T_l$ is set just long enough for the destination node to recognize a data packet coming in its way.

ii. The wakeup beacon length $T_b$ is set to minimal.

*C. Multiple Potential Receivers*

The discussion so far has been focused on a single transmitter-receiver pair. If there are multiple desirable receivers (as determined by the routing protocol), even more power can be saved. More specifically, the expected number of RTS's transmitted from the source node until one of the potential receivers wakes up decreases in TICER. Similarly, the expected waiting period of the source node for one of the potential receivers to wake up in RICER is shorter. The potential savings as a result of this are analyzed in section IV.

*D. Collisions in TICER and RICER*

To avoid collisions between control packets (RTS, CTS, ACK and wakeup beacon) and data packets, it is common to adopt a multi-channel approach, with one channel for all control packets and one or more channels for data packets [2]. In the following analysis, we will assume— with no impact on generality— a single control channel and a single data channel. Having two channels does not affect power consumption, as they are never powered on simultaneously. Unfortunately, this approach does not completely eliminate the possibility of collisions in T(R)ICER. For TICER, a node X might be receiving a data packet from node Y, while one of its neighbors U starts transmitting a data packet to another node Z, because U was powered off during X's setup handshake. A data collision hence may occur, albeit with a very small probability in most WSN scenarios.

In RICER, when a node transmits a wakeup beacon, more than one of its neighbors might respond with a data packet. The probability for this to happen is not ignorable, but can be reduced by introducing a random delay between the hearing of the wakeup beacon and the start of the transmission of the data packet at the source node. This comes at the penalty of an increase in channel monitoring time. The subsequent analysis uses an estimated value of the collision rate (see [6] for a more detailed description), and the increased traffic load due to packet retransmissions after collisions is taken into account. Prolonged monitoring time due to collision resolution is also approximated and included by minor modifications to the analysis in section IV.

## III. MODELS FOR TRANSCEIVER AND CHANNEL

*A. MAC and Physical Layer Power Model*

In order to evaluate the power consumption of TICER and RICER, a power model is built called the *MAC And Physical LAyer Power* (MAPLAP) Model for wireless sensor nodes, as shown in Fig. 3. A transceiver node is modeled as a probabilistic state machine with 5 operational states, which are the *transmit* (TX), *receive* (RX), *acquire* (AQ), *monitor* (MN)

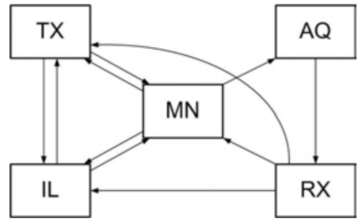


Figure 3. State Diagram of MAPLAP Model

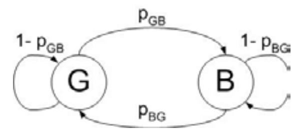


Figure 4. Gilbert-Elliot Channel Model

and *idle* (IL) state. The acquire state always precedes the receive state, and represents the compute and power intensive timing, phase and/or frequency acquisition phase (as represented by the preamble). A node carrier senses the channel in the monitor state; in the idle state, the majority of the radio is turned off and negligible power is consumed. A transceiver node is in exactly one of these states at any given time instant.

Given this model, average power consumption per node can be expressed as

$$P_{total} = \Delta_{TX} P_{TX} + \Delta_{RX} P_{RX} + \Delta_{AQ} P_{AQ} + \Delta_{MN} P_{MN} + \Delta_{IL} P_{IL} \quad (1)$$

where $\Delta_{TX}, \Delta_{RX}, \Delta_{AQ}, \Delta_{MN}, \Delta_{IL}$ are the average probability of being in each state, and $P_{TX}$, $P_{RX}$, $P_{AQ}$, $P_{MN}$ and $P_{IL}$ are the power consumption levels in each state. The $\Delta$'s are a function of the rendez-vous schemes under analysis, as well as operational network (system) parameters such as traffic loads and network density. The $P$ parameters are obtained by analysis and/or measurement of actual transceivers. The numbers used in this paper are obtained from measurements of a low-power On-Off Keying (OOK) transceiver designed by the PicoRadio RF group in BWRC [1]. Roughly speaking, $P_{TX}$ consists mainly of power consumed by the oscillator (0.5mW) and the power amplifier, which depends on data rate, distance between nodes and the targeted BER. $P_{RX}$, $P_{AQ}$ and $P_{MN}$ share a common component; that is the standby power consumed in the RF front-end circuitry once turned on (1.5mW). $P_{MN}$ further includes power dissipation of the carrier-detect circuitry (0.25mW). $P_{RX}$ and $P_{AQ}$ have a number of components that depend on the data rate. $P_{IL}$ is assumed to be negligible.

*B. Channel Model*

To account for the bursty nature of a wireless channel with fading effects, a Gilbert-Elliot channel model is used as shown in Fig. 4. This model is a two state discrete time Markov Chain, with a good state (G) and a bad state (B). The bit error rates in each state are $p_{bG}$ and $p_{bB}$; usually $p_{bG} \ll p_{bB}$. The transition probability from G to B and B to G are $p_{GB}$ and $p_{BG}$, respectively. A transition takes place every $T_{coh}$ seconds with probability $p_{coh}$, where $T_{coh}$ is the coherence time of the channel and $p_{coh}$ is the percentage of correlation. The average probability of being in G and B are $\pi_G = p_{BG}/(p_{GB}+p_{BG})$ and $\pi_B = p_{GB}/(p_{GB}+p_{BG})$. Observe that the two-channel model is a rough approximation. However, for simple narrowband radios used in WSNs, the model proves to be quite adequate as these transceivers transition very slowly between good and bad states.

## IV. PERFORMANCE ANALYSIS OF TICER & RICER

### A. *TICER/RICER Power Consumption Models*

Using the models presented above, we can analyze the power dissipation of the proposed rendez-vous schemes. First, we have to define the operational system and network parameters. We assume the traffic to be Poisson distributed with $\lambda$ packets generated per second per node. Each node has $n$ neighbors and $k$ potential receivers ($n \geq k$). RTS, CTS and ACK all take $T_b$ second to transmit, while data packets take $T_p$ second. $T_b$ and $T_p$ depend on the message lengths and the data rate $R$. The propagation delay of any message is assumed to be negligible compared to the transmission time. Transmission power, data rate and distance between nodes are selected jointly to achieve an average BER of $10^{-4}$. Under these conditions, we can compute the power consumption of TICER as follows: [7]

$$\Delta_{TX} = \lambda\{(E[N_b]+2)T_b + T_p\} \quad (2)$$

$$\Delta_{RX} = \lambda\{3T_b + T_p\} \quad (3)$$

$$\Delta_{MN} = \lambda\{(\frac{1}{\lambda} - 2T_p - (E[N_b]+2)T_{on})\frac{T_{on}}{T} + (E[N_b]+1)T_l\} \quad (4)$$

$$P_{total} = \Delta_{TX}P_{TX} + \Delta_{RX}P_{RX} + \Delta_{MN}P_{MN} \quad (5)$$

where $E[N_b]$ is the expected number of RTS's. Similarly, for RICER,

$$\Delta_{TX} = \lambda\{(\frac{1}{\lambda} - 2T_p - 2T_b - E[T_{wait}])\frac{T_b}{T} + T_b + T_p\} \quad (6)$$

$$\Delta_{RX} = \lambda\{2T_b + T_p\} \quad (7)$$

$$\Delta_{MN} = P_{mn}\lambda\{(\frac{1}{\lambda} - 2T_p - 2T_b - E[T_{wait}])\frac{T_{on}}{T} + E[T_{wait}]\} \quad (8)$$

where $E[T_{wait}]$ is the expected wait time for the source node. With $p_{TICER}$ and $p_{RICER}$ being the probabilities of RTS/CTS exchange failure due to fading, $q_{TICER}$ and $q_{RICER}$ the probabilities of data packet or ACK failure given RTS/CTS exchange success, $p_{coh}$ the probability that the channel remains within the coherence time, and $p_{c,TICER}$ and $p_{c,RICER}$ the collision rates for TICER and RICER respectively, we find:

$$E[N_b] = \frac{p_{TICER}}{1-p_{TICER}}\left\lceil\frac{E[W]}{T_{on}}\right\rceil + \left\lceil\frac{E[W_1]}{T_{on}}\right\rceil + 1 \quad (9)$$

$$E[T_{wait}] = \frac{p_{RICER}}{1-p_{RICER}}\frac{T}{k} + E[W_1] \quad (10)$$

where

$$E[W_1] = \frac{k}{T^k}(T-T_{on})^{k+1}(\frac{1}{k} - \frac{1}{k+1}),\ E[W] = T/k \quad (11,12)$$

Also,

$$1 - p_{TICER} = [1p_{coh} + (1-p_{GB})(1-p_{coh})]\pi_G \quad (13)$$

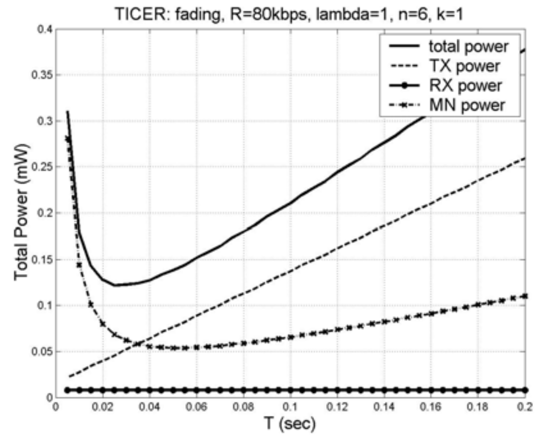



Figure 5a. TICER: Power Breakdown

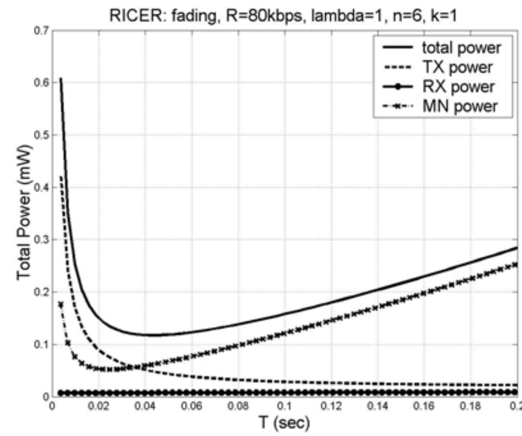



Figure 5b. RICER: Power Breakdown

$$1 - q_{TICER} = (1-p_{TICER})[p_{coh} + (1-p_{GB})(1-p_{coh})] \quad (14)$$

$$1 - p_{RICER} = \pi_G \quad (15)$$

$$1 - q_{RICER} = (1-p_{RICER})[p_{coh} + (1-p_{GB})(1-p_{coh})] \quad (16)$$

The modified traffic load due to fading and collision is:

$$\lambda/[(1-q_{TICER})(1-p_{c,TICER})],\ \lambda/[(1-q_{RICER})(1-p_{c,RICER})] \quad (17,18)$$

### B. *Results and Observations*

In the subsequent analysis, we assume control and data packets to be 30 bits and 200 bits, respectively (these numbers are quite typical for the radios and applications under consideration). For the OOK radio discussed in III.A operated at a data rate $R$ of 80 kbps and transceiver nodes separated by an average distance $d$=10m, transmit power of $P_{TX}$=4.15mW is needed to achieve a BER of $10^{-4}$; average receive and monitor power levels evaluate to $P_{RX}$=2.1mW and $P_{MN}$=1.75mW, respectively.

The total average power consumption as well as a breakdown of the power over the different states are plotted against length of the wakeup period $T$ in Fig. 5a and 5b (for TICER and RICER, respectively). $T_{on}$ and $T_l$ are fixed and set to 30/$R$. It can be observed for both schemes that the choice of $T$ has a substantial impact on the power dissipation, and, in addition, that there exists **an optimal wakeup period *T***. For

TICER, this can be understood as follows: an increase in $T$ leads to a reduced duty cycle $T_{on}/T$, equivalent to a reduction in the periodic monitoring power in the MN state; on the other hand, for longer $T$, a source node has to wait longer until the destination node wakes up, and the expected number of RTS's transmitted increases. The reasoning for RICER is quite similar. It can also be seen that power consumed in the MN state is at least as significant as the transmit power at the optimal $T$. It can even be several times higher than the power in the TX state, if the optimal $T$ is not adopted. This contradicts the general belief that transmit power is the most dominant factor in WSN nodes, and as such, fine-tuning of radiated power does not save much power. This also justifies the design of putting nodes to sleep periodically, so as to save MN power as much as possible.

Next, the effect of the *traffic load* is evaluated. With the wakeup period $T$ set to the optimal value for each case, it is seen in Fig. 6 that at lower traffic loads RICER and TICER are quite comparable, while TICER performs better at higher loads. Also notice the effect of fading. Since RICER has a three way handshake as opposed to the four way handshake in TICER, RICER has a lower chance of having an unsuccessful exchange of data because of channel fading than TICER does. Therefore, as fading becomes more profound, RICER suffers less than TICER, as evident from Fig. 6.

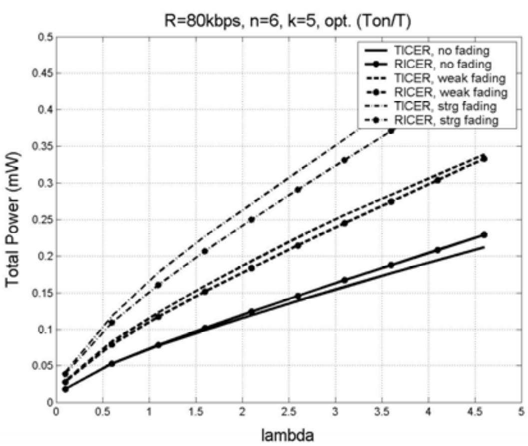



Figure 6. Impact of Traffic Load

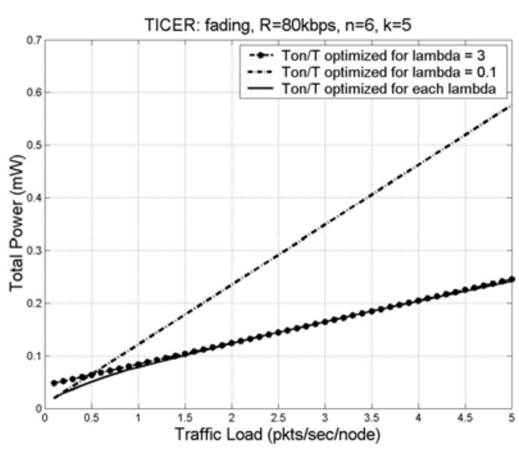



Figure 7. Impact of Non-Optimal Duty Cycle

The disadvantage of RICER having a three way handshake, i.e., more collisions, has a minor effect on the total power consumption as compared to fading effects. Overall, it can be observed that fading effects have a major impact on the power consumption, especially under heavy traffic loads. This demonstrates that fading cannot be ignored in the analysis of WSNs protocols.

From the above, we can conclude that the most power savings can be obtained by adjusting the wakeup period $T$ adaptively to the traffic load. However, predicting the traffic load in WSNs is non-trivial. Suppose now that $T$ is optimized and fixed for a given traffic load. The penalty of not adjusting $T$ under varying traffic conditions adaptively (with respect to the optimal case) is shown in Fig. 7 for TICER. If $T$ is optimized for a lighter load, the penalty of waking up not often enough leads to serious penalty in power; on the other hand, if $T$ is optimized for a heavier load, the penalty at lighter loads is marginal. Hence, if an adaptive scheme is not feasible, it is advisable to keep $T$ smaller than larger, so the source node will not send RTS's endlessly. Similar effects are observed for RICER.

Consider now the case where the number of potential receivers is larger than one. From Fig. 8a and 8b, which plot the total power dissipation of TICER and RICER as a function of $T$, it becomes clear that increasing the number of potential receivers $k$ substantially lowers the power consumption. For example, increasing $k$ from 1 to 5 in TICER lowers power dissipation by more than 30%, as the expected wait until a potential receiver wakes up is reduced. Another important advantage of increasing $k$ is that penalty for not adopting the optimal $T$ is reduced. Therefore, if adaptively choosing $T$ is infeasible, having a larger $k$ is a way of compensation. Again, these observations apply to both TICER and RICER.

The benefit of having more potential receivers is further demonstrated by Fig. 9. Here the lower bound is set for no fading and a perfect knowledge of receivers' wakeup schedule. According to this figure, a good choice of $k$ lies in the plateau area of the curves, as selecting more potential receivers does not save much more. Notice again that RICER is more robust in the presence of fading, and different degrees of fading lead to substantially differences in power consumption.

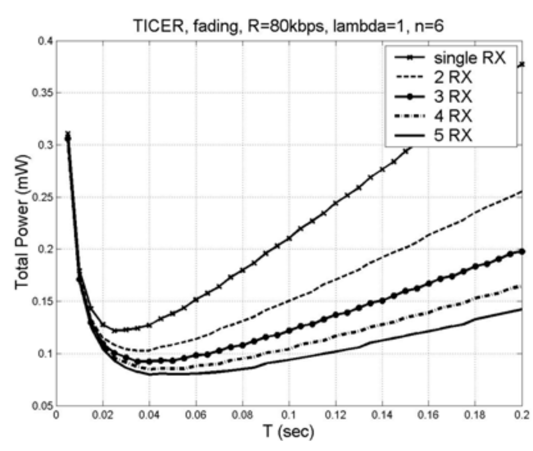



Figure 8a. Impact of Multiple Receivers in TICER

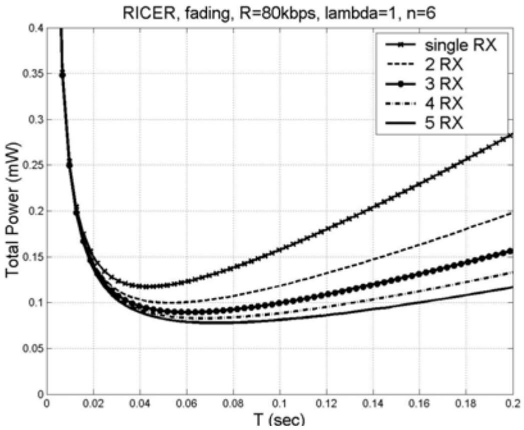



Figure 8b. Impact of Multiple Receivers in RICER

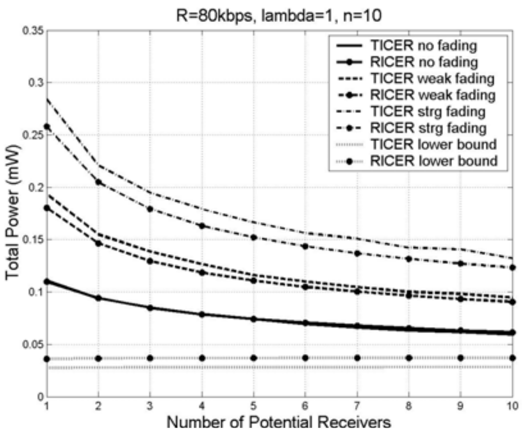



Figure 9. Impact of Multiple Potential Receivers

The important lesson from these different studies is that **network protocols that enable routing through multiple paths and use multiple potential receivers are very desirable** and can lead to substantial power reductions. The presented results can help as a guideline in the design of these protocols.

## V. SEMI-SYNCHRONOUS TICER & RICER

In the previous case studies, it is assumed that nodes have no information of their neighbors' wakeup schedule. Suppose now each node, after having transmitted packets to all its neighbors, keeps a record of each neighbors' last wakeup times. Then due to the periodicity of wakeups, each node can roughly predict its destination node's next wakeup time. The source node can then delay its own wakeup till slightly before its destination node wakes up. In this way, the expected number of RTS's sent (that is, $E[N_b]$) will decrease in TICER, and both TX and MN power are saved. Similarly, in RICER, the expected wait $E[T_{wait}]$ of the source node decreases and MN power is saved. Notice that due to discrepancy between the actual and predicted wakeup times, which comes from imprecision of clocks in each node, the source node should not wake up too close to the predicted wakeup time. Otherwise, if the prediction is wrong and the source node misses the destination, it will have to wait for much longer.

Assume the source node can estimate the wakeup time to an accuracy of $T_{sync}$ seconds with probability $p_s$. With this modification, only $E[N_b]$ and $E[T_{wait}]$ are affected:

$$E[N_b] = (1-p_{TICER})(1-p_s)(N_{bc}+1) + [1-(1-p_{TICER})(1-p_s)][N_{bc}+1+\left\lceil \frac{E[W]}{T_{on}} \right\rceil (1-p_{TICER})] \quad (19)$$

$$E[T_{wait}] = (1-p_{RICER})(1-p_s)T_{sync} + [1-(1-p_{RICER})(1-p_s)][T_{sync} + \frac{T/k}{1-p_{RICER}}] \quad (20)$$

where $N_{bc} = \lfloor T_{sync}/T_{on} \rfloor$.

Here in Fig. 10abcd, the x and y-axis represents the probability of missing the destination node's wakeup, and the time difference between the actual and estimated wakeup time in seconds. The lower plane represents the ideal case with no fading and assuming that the source node wakes up just in time to catch the destination node. It is seen that if a node can estimate its neighbors' wakeup time to high accuracy with high probability, substantial power savings of up to 50% can be achieved with respect to the case without any estimation, represented by the upper plane in the figures. However, as fading becomes more severe, the benefits of the semi-synchronous approach become less significant and ultimately negligible. This is because under severe fading, the probability of missing the first destination node is high, thus estimating its wakeup time most likely will not have any effect. It is also shown that as the number of potential receivers $k$ increases from 1 to 5, the power saving remains larger for longer (for increasing $p_s$). This is because with larger $k$, if the first potential receiver is missed, the expected wait for the second or subsequent potential receiver to wake up is shorter. Similar results apply to RICER. Analysis shows that RICER benefits slightly more than TICER from this approach; also, RICER is again less sensitive to fading effects. (Due to limited space, figures of semi-synchronous RICER are not shown here.)

## VI. PURELY ASYNCHRONOUS SCHEME

As suggested in section II, TICER and RICER presented so far are pseudo-asynchronous rendez-vous schemes. With a

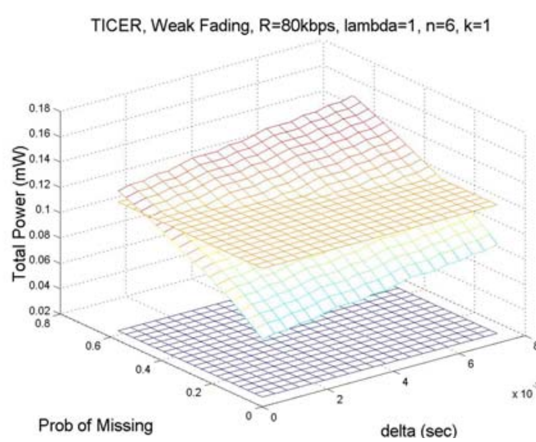
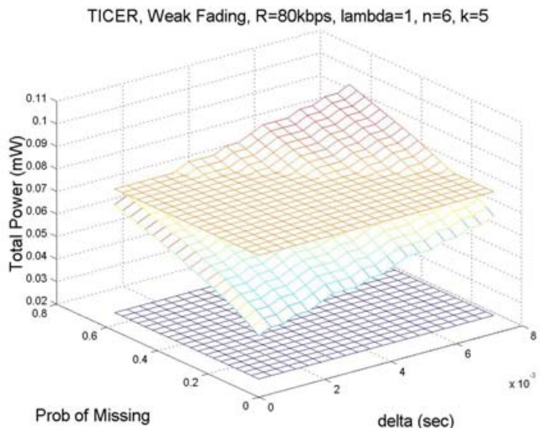
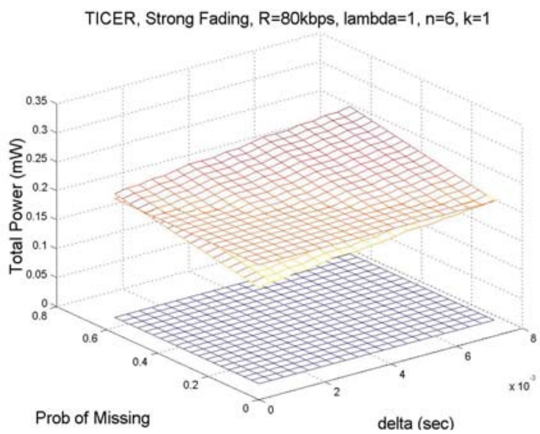



Figure 10a. TICER, Semi-Sync, Weak Fading, $k$=1



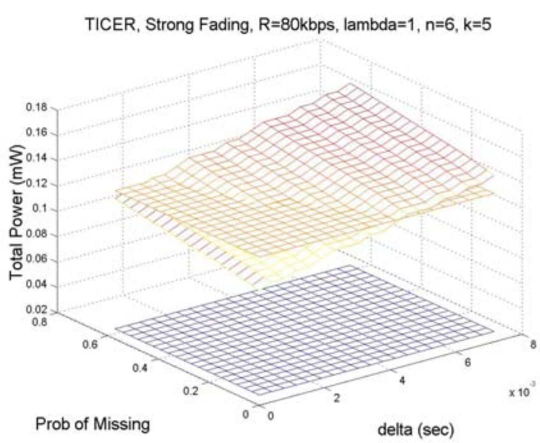




Figure 10d. TICER, Semi-Sync, Strong Fading, $k$=5

purely asynchronous scheme, a node does not wake up periodically as opposed to T(R)ICER; instead, a second radio— the wakeup radio— is introduced, which always operates with a low standby power. When a source node has a data packet to transmit, its main radio will simply transmit a wakeup signal as a RTS to wake up the destination node's wakeup radio; subsequently, the wakeup radio will wake up the main radio at the destination node, which will follow the standard CTS-data-ACK handshake. In this way, a great amount of monitor power is saved. However, extra power consumption has to be taken into account, including: (i) the constant standby power, (ii) transmission power of the wakeup signal (which is possibly higher than that for the RTS of the pseudo-asynchronous scheme to ensure adequate wake-up), and (iii) power dissipated in nodes that are erroneously waken by wakeup signals intended for other nodes. Fig. 11, obtained using a slightly modified version of our modeling tool, plots the maximum value of the continuous standby power (in mW) that the wakeup radio is allowed to consume if the purely asynchronous scheme is to outperform the pseudo-asynchronous schemes (TICER, in this case) as a function of the energy (in mJ) of the wakeup signal. The analysis assumes 6 neighbors and a traffic load of 1pkt/sec. It can be observed that the asynchronous approach becomes attractive only if a wakeup radio can be realized with standby power dissipation levels smaller than 50 uW (which is definitely feasible). Analysis of this type hence serves as a guideline for hardware design.

## VII. PUTTING THE PAPER IN PERSPECTIVE

As observed earlier, various rendez-vous schemes for wireless networks have been proposed in the literature before. However, only a few schemes propose to have the receiver as the initiator [9-11]. Moreover, none of these are designed for WSNs and low power, as they leave the nodes continuously powered on. In this, RICER is an original contribution. Although receiver initiated rendez-vous schemes have not gained much attention in the past, we found that they are quite attractive if parameterized appropriately.

In all other published rendez-vous approaches in the WSN domain, the transmitter initiates the communication session [3-5]. However, they differ from TICER in various ways. In PAMAS [3] nodes are only powered off during activity in their neighborhood rather than on a cyclic basis, so given typical WSNs traffic loads, nodes would be powered off less often than TICER. SMAC [4], being designed especially for WSNs, assumes synchronous periodic wakeups of the whole neighborhood. This calls for time synchronization between nodes, causing additional overhead.

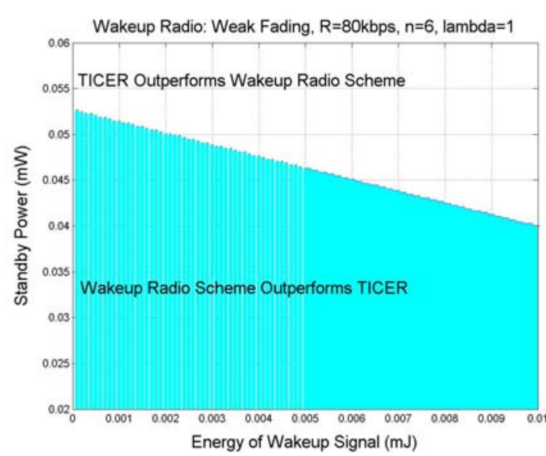



Figure 11. Wakeup Radio, Weak Fading

STEM [5] presents a scheme that is quite similar to TICER. Reference [8] introduces a further improvement to [5], in the sense that it combines the scheme with geographic routing. The actual destination node is determined after the source node transmits the data packet. There is, however, an essential difference in the goal and scope of our analysis as compared to [5] and [8], which represents complete integrated protocols. TICER, on the other hand, represents a generic scheme that can be applied and/or combined with a variety of protocols. More importantly, this paper proposes a generic qualitative approach to compare and evaluate various rendez-vous schemes using realistic models for both the wireless transceivers and the channels.

It should be noted that this paper is– up to our best knowledge– the first contribution addressing explicitly the influence of channel fading on the performance of rendez-vous schemes. This approach has allowed us to derive a number of important and influential design directives, which help to guide further research in both wireless transceivers as well as routing protocols.

## VIII. Conclusions and Further Research

A generic approach to the analysis and optimization of power efficiency in pseudo-asynchronous rendez-vous schemes for WSNs is given. We have suggested and investigated two generic variants: TICER and RICER, and presented their analysis in the presence of fading. The most interesting results are briefly summarized as follows:

- Substantial power is saved if the wakeup period $T$ is set to its optimal point; without the ability to adaptively adjust $T$, it is better to assume a heavy traffic load.

- The benefit of having multiple potential receivers is notable; guaranteeing the presence of sufficient but not too many potential receivers is the task of the routing and topology management modules.

- Semi-synchronous communication yields substantial power savings under weak fading conditions.

- TICER and RICER have comparable performance. RICER performs better than TICER under strong fading conditions.

- In general we have been able to demonstrate that the effect of fading on the performance of rendez-vous schemes is major, thus it should be considered when choosing the most appropriate scheme and parameters.

The analysis presented here is of approximate nature, containing a few simplifications. Simulation is being conducted to verify the accuracy and to take into account more details, for example, different fading and collision scenarios. It remains an open question if synchronization of a whole group of nodes would pay out in the case of multiple potential receivers. Finally, combination of RICER with proper routing and topology management approaches is under investigation.

## Acknowledgment

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