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Receiver Initiated Rendezvous Schemes for Sensor Networks

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Abstract- Power efficiency is one of the most critical factors for wireless sensor networks. In this paper, we present a family of receiver-initiated pseudo-asynchronous rendezvous schemes designed specifically to reduce sensor nodes' power consumption. We analyze their performances in terms of power efficiency and latency, under different static and dynamic system parameters. In addition, we verify our analysis by extensive network simulations. Based on the results, our proposed scheme demonstrates superior performance compared to previous proposed schemes.

I. Introduction

Wireless sensor networks (WSNs) are characterized by the sensor node's limited power resources. To ensure system longevity, each node has to operate at a minimum power level while achieving acceptable performances. Another characteristic of typical WSNs is their relatively light traffic loads (0.01 to 5 packets/second) and short packets (less than 500 bits). Several researchers have demonstrated that nodes spend most of the time just monitoring the channel in anticipation of packet arrivals, which unfortunately constitutes to a great portion of the power consumption [8]. Therefore, the most straightforward way to minimize power consumption per node is to power off the nodes whenever possible. With this approach, it is necessary to arrange simultaneous on-time for nodes to communicate, a method referred to as a *rendezvous scheme.* Note that rendezvous schemes reside in the data link layer, and they regulate nodes' behavior only in the one hop neighborhood.

There are some rendezvous schemes proposed in literature so far [1]-[4]. In [1], we analyzed the pseudo-asynchronous rendezvous schemes in terms of their power efficiency, with different numbers of potential destination nodes, traffic loads and channel fading conditions. This paper focuses on one sub-category of pseudo-asynchronous schemes, namely the Receiver Initiated CyclEd Receiver (RICER) scheme [1]. Note that RICER is a novel rendezvous scheme, in that none of the receiver initiated schemes proposed in the literature [5-7] power off nodes to achieve power efficiency.

In this paper we propose and analyze several different versions of RICER. The analysis is based on our previously developed power model, along with a Gilbert-Elliot two state fading channel model [1]. In our analysis, we supply realistic data obtained from actual transceiver measurements [8] to the power model. We consider the basic characteristics of the schemes instead of treat them as detailed protocols. This helps to clearly identify the dominant design parameters and their impacts on rendezvous schemes. Therefore, our contribution also lies in the ability to identify the most suitable scheme for given scenarios. In addition, we verify our analysis by extensive network simulations.

Based on our analysis, the modified RICER is substantially superior to previously proposed schemes in most static environments [1]. We also show that in a dynamic environment with traffic load or channel fading variations, different schemes have different tradeoffs and the optimal selection depends on the characteristics of the specific WSN of interest.

Another important aspect of the analysis is our investigation in the schemes' latency, another crucial attribute in WSNs. Since system designers usually minimize power consumption subjected to some latency constraints, this work provides a guideline for such design approach.

This paper is structured as follows. In section II, we propose several different versions of RICER schemes. We analyze their power consumption and latency in section III. Then we apply real-life sensor network parameters to the analyses of the proposed schemes, and discuss their performance characteristics in section IV. In section V the analyses are verified by comparing to network simulation results, followed by conclusion and future work in section VI.

II. Communication procedure

There are two sub-categories in the realm of pseudo-asynchronous schemes, namely, the Transmitter-Initiated CyclEd Receiver (TICER), and the Receiver-Initiated CyclEd Receiver (RICER) schemes. The term *cycled receiver* refers to the periodic wake up and sleep characteristic of these schemes. Since TICER has been analyzed in [1], in this work we focus on the analysis of RICER, which includes two basic sub-classes. According to the number of required handshakes, they are named RICER3 and RICER5, respectively.

The main idea of RICER is to let *destination nodes* initiate packet exchanges, as opposed to many traditional designs. In particular, when a node X periodically wakes up, after detecting the channel as free, it transmits a wakeup beacon (WB) to announce that it is awake. The WB is of a broadcast nature such that any node that is awake and within X's radio range can receive it. Neighboring nodes that receive the WB know X is ready to receive a data packet (DATA), and the nodes that have a DATA for X prepare to transmit. However, it is possible that more than one of X's neighboring nodes attempt to transmit a DATA to X, and this may lead to collision. To mitigate collisions resulting from more than one source node intending to transmit, we propose using the WB as a time synchronization reference point for all source nodes, and apply a slotted scheme after the WB is transmitted. Specifically, the slots may be used in two different ways, as described in the following:

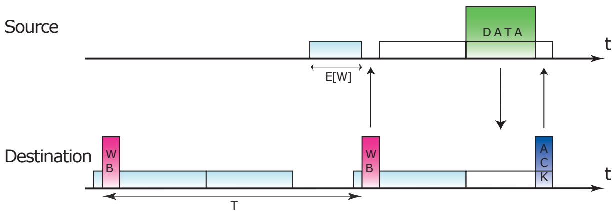

Figure 1. RICER3

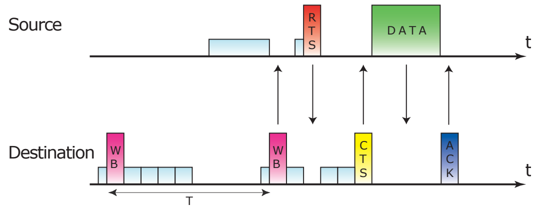

Figure 2. RICER5

RICER3

Shown in Fig 1, after node X transmits a WB to announce that it is awake, it monitors the channel for a response for N slots, each slot being able to accommodate a DATA and an acknowledgment (ACK). If there is no response, the node goes back to sleep. On the other hand, a source node with DATA to transmit stays awake and monitors the channel, awaiting a WB from the destination node. Upon reception, it randomly chooses one of the N slots to transmit its DATA. After correctly receiving the DATA, the destination node ends the session with an ACK designated to the source node. As described above, the complete handshake consists of three packets. This is the version of RICER previously proposed in [1]. Note that to prevent the WBs from repeatedly colliding due to the same wakeup period T adopted by all nodes, WBs are transmitted with a period equal to T plus a short random offset.

RICER5

Shown in Fig 2, in RICER5 each slot after the WB is shorter and only accommodates a request-to-send (RTS). Assume there are M RTS slots. When a source node receives the WB, instead of choosing from N slots to transmit DATA, it chooses from M slots to transmit its RTS and waits for a clear-to-send (CTS) at the end of the M slots. The destination node will pick one of the source nodes that transmitted an RTS to respond with a CTS. Afterwards, the nodes follow a typical CTS-DATA-ACK session. Accordingly, this is a 5-way handshake.

RICER buzz schemes

In RICER3 and RICER5, after a node transmits a WB, it monitors the channel for N DATA+ACK slots or M RTS slots. If there is no source node attempting to transmit, which occurs often in typical WSN traffic loads, the monitor power is wasted. To reduce this unnecessary overhead, we introduce a *buzz signal* scheme for both RICER3 and RICER5 as follows. When a source node receives the desired WB, before responding with a DATA or RTS, it transmits a short (few bits) buzz signal (BZ) right after the WB. The BZ indicates to the destination node that there is at least one source node attempting to start a communication session. A destination node that detects a busy channel after it transmits a WB remains monitoring the channel for N slots or M slots in RICER3 and RICER5. Otherwise, the node goes back to sleep immediately because there is no DATA to receive in this period T. Note that BZs do not have a preamble, and they may collide with one another without affecting their functionality. We refer to these RICER variants as RICER3b and RICER5b, respectively.

III. Performance Analysis

i. Performance evaluation metrics

In the following, we quantitatively evaluate the performance of RICER schemes focusing on their power efficiency and latency. Power efficiency is chosen as one of the performance metrics because it is one of the most crucial and limiting factors in wireless sensor nodes. Packet latency, on the other hand, is usually constrained according to upper layer system specifications. Note that *latency* refers to the point-to-point latency, since rendezvous schemes reside in the data link layer. In pseudo-asynchronous schemes, latency inevitably increases because destination nodes are not always awake at the instant when the source node is ready to transmit. Therefore, it is important to verify if the latency imposed by rendezvous schemes is acceptable. Since system designers usually try to minimize a protocol's power consumption subjected to given latency constraints, we investigate in the *joint performance of power consumption and latency* in this paper.

ii. Theoretical analysis

In the system of interest, assume each node has n neighbors and m potential destination nodes ($n>m$). Note that while n is determined by the network topology, m is a choice made by the routing protocol. Assume each node knows of all its neighbors. RTS, CTS, DATA, ACK, WB and BZ take T_{RTS}, T_{CTS}, T_{DATA}, T_{ACK}, T_{WB} and T_{BZ} seconds to transmit. All packets except for BZ include a preamble for bit synchronization that takes T_a seconds. All packet durations defined above depend on their packet lengths and the data rate R, and they already include T_a. The propagation delay of any packet 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 bit error rate (BER) of 10^{-4}.

Assume the traffic a node needs to transmit has a distribution with mean of λ packets per second per node, and a reasonably bounded variance. One typical traffic pattern with such characteristics is Poisson distribution. Note that this traffic load takes into account both the originating and the forwarding traffic:

λ = (generated traffic load per node)(average number of hops per route)/(number of nodes in network)

ii.1 Power consumption analysis

With the power model and channel model discussed in [1], let P_{tx}, P_{rx}, P_{aq}, P_{mn} and P_{sp} be the power consumption levels of the transceiver while transmitting, receiving, acquiring the preamble, monitoring the channel, and powered off, and let δ_{tx}, δ_{rx}, δ_{aq}, δ_{mn} and δ_{sp} be the average probability of being in the above states.

RICER3

Let λ'[I] be the scaled traffic load due to channel fading, $E[W]$[I] be the expected wait time for the source node, then the total power consumption per node P_{total} is calculated as follows:

$$\delta_{tx} = E[N_{WB}]T_{WB} + \lambda'(T_{DATA} + T_{ACK}) \quad (1)$$

$$\delta_{rx} = \lambda'(T_{WB} + T_{DATA} + T_{ACK} - 3T_a) \quad (2)$$

$$\delta_{aq} = \lambda'(3T_a) \quad (3)$$

$$\delta_{mn} = E[N_{WB}]NT_{DATA} + \lambda' E[W] \quad (4)$$

$$\delta_{sp} = 1 - \delta_{tx} - \delta_{rx} - \delta_{aq} - \delta_{mn} \quad (5)$$

$$P_{total} = \delta_{tx}P_{tx} + \delta_{rx}P_{rx} + \delta_{aq}P_{aq} + \delta_{mn}P_{mn} + \delta_{sp}P_{sp} \quad (6)$$

where $E[N_{WB}]=(1-p_{by})(1-\lambda'(E[W]+2T_{DATA}+2T_{ACK}))/T$ is the expected number of received WBs, and $p_{by}=1-(1-(E[N_{WB}]T_{WB} +\lambda'(T_{DATA}+T_{ACK})))^n$ is the channel busy rate.

RICER3b

In RICER3b, (3), (5) and (6) still applies, while (1) and (2) need to be modified by adding an additional term $\lambda' T_{BZ}$ and $E[N_{BZ}]T_{BZ}$,, respectively. Equation (4) becomes:

$$\delta_{mn} = E[N_{BZ}]NT_{DATA} + (E[N_{WB}] - E[N_{BZ}])T_{BZ} + \lambda' E[W]$$

where $E[N_{BZ}]= \lambda'$.

RICER5

Similarly, for RICER5,

$$\delta_{tx} = E[N_{WB}]T_{WB} + \lambda'((T_{RTS} + T_{CTS})/p_{RTS} + T_{DATA} + T_{ACK}) \quad (7)$$

$$\delta_{rx} = \lambda'((T_{WB} + T_{RTS} + T_{CTS})/p_{RTS} + T_{DATA} + T_{ACK} - (3/p_{RTS} + 2)T_a) \quad (8)$$

$$\delta_{aq} = \lambda'(3/p_{RTS} + 2)T_a \quad (9)$$

$$\delta_{mn} = E[N_{WB}]MT_{RTS} + \lambda' E[W] \quad (10)$$

where δ_{sp} and P_{total} are defined as in (5) and (6), p_{RTS}[II] is the probability that an RTS is successfully responded by a CTS, and $E[N_{WB}]=(1-p_{by})(1-\lambda'(E[W]+2MT_{RTS}+2T_{CTS}+2T_{DATA}+2T_{ACK}))/T$, where $p_{by} = 1-(1-(E[N_{WB}]T_{WB} + \lambda'(T_{RTS} + T_{CTS} + T_{DATA} + T_{ACK})))^n$.

RICER5b

In RICER5b, (11) and (12) need to be modified by adding an additional term $\lambda' T_{BZ}/p_{RTS}$ and $E[N_{BZ}]T_{BZ}$, respectively. Equation (10) becomes:

$$\delta_{mn} = E[N_{BZ}]MT_{RTS} + (E[N_{WB}] - E[N_{BZ}])T_{BZ} + \lambda' E[W]$$

where $E[N_{BZ}] = \lambda'/p_{RTS} + n\lambda'(T_{CTS} + T_{BZ})/T$.

ii.2 Latency analysis

We define latency as the time elapsed from the instance when a data packet arrives at the MAC layer until when the data packet starts being transmitted. Let p_{f3} and p_{f5}[II] be the handshake failure rate due to busy channel or channel fading in RICER3 and RICER5, then:

$$L_3 = T_{WB} + NT_{DATA}/2 + E[W]/(1-p_{f3}) + p_{f3}T/(1-p_{f3}) \quad (11)$$

$$L_5 = T_{WB} + MT_{RTS} + T_{CTS} + E[W]/(1-p_{f5}) + p_{f5}T/(1-p_{f5}) \quad (12)$$

For RICER3b and RICER5b, add an additional T_{BZ} to both (11) and (12).

[I] See appendix.

[II] See appendix.

IV. Results and Observations

We choose the system parameters to resemble a realistic wireless sensor network environment. Specifically, assume the BZ, DATA and all other packets are 4, 230 and 60 bits, respectively. Consider a network of 7 nodes in range of one another. If not noted otherwise, total traffic load of λ=0.5 pkt/sec is assumed. Adopting an On-Off-Keying transceiver designed by the PicoRadio RF group in BWRC [8], the average acquire, receive and monitor power levels evaluate to $P_{aq}=P_{rx}=P_{mn}$=2.5mW. The nodes operate at a data rate of R=40 kbps, and with nodes separated by an average distance of d=10m, the required transmit power to achieve the target bit error rate is P_{tx}=4.15mW. Finally, the sleep state consumes P_{sp}=0.04mW. While we adhere to this transceiver in the following discussions, it is verified that the same conclusions can be reached if any other transceiver were adopted. The channel model parameters [1] are p_{GB}=0.05 and p_{BG}=0.95 for weak fading, and p_{GB}=0.35 and p_{BG}=0.65 strong fading. For the number of slots after WBs, let N=2 in RICER3 and M=2 in RICER5, because according to our analysis it is a reasonable and optimal choice.

In each of the subsequent figures, we vary the wakeup period T from 0.04 to 0.3 seconds and calculate the corresponding values of power consumption and latency for each value of T. Then we combine each pair of power consumption and latency resulting from the same T into one point, and plot the collection of points into a curve. The closer the curve is to the x- and y-axis, the lower the power consumption and latency, and the better the performance. Define the *region of interest* as the area where power consumption decreases with increasing latency and vice versa, because this is where a tradeoff between power and latency is available. As T exceeds a certain threshold, we may reach a region in which power consumption and latency *both* increases with increasing T, and apparently it does not make sense to select such a region. As a rule of thumb, the region of interest is confined on each curve by the leftmost point to the minimum power consumption point. After this point, power starts increasing with latency.

Buzz or not?

We first compare the performance of RICER with and without the buzz signal. The advantage of the buzz schemes is to reduce the unnecessary monitor time when there is no source nodes attempting to transmit. On the other hand, adopting the buzz signal may marginally increase power and latency. Buzz schemes may also be more sensitive to channel fading, which can cancel out the BZ completely. Fig 3 shows that for RICER3 as well as RICER5, the power efficiency and latency performance with the buzz scheme is substantially better than that without the buzz scheme. Note that this comparison is done under strong fading, which is against the benefit of the buzz schemes. Since this observation holds true for all WSN settings in our analysis, we conclude that it is always desirable to incorporate the buzz signals in RICER schemes, or in other words, RICER3b and RICER5b are always more desirable than RICER3 and RICER5.

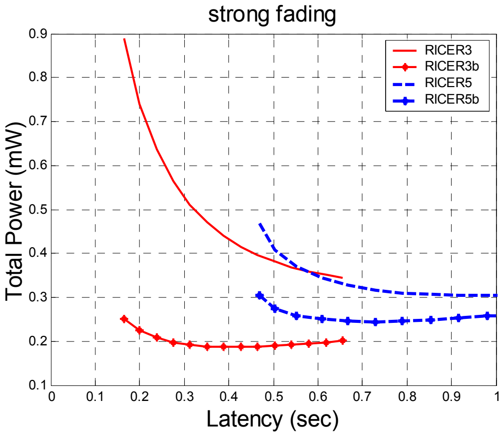

Figure 3. RICER with and without buzz, under strong fading

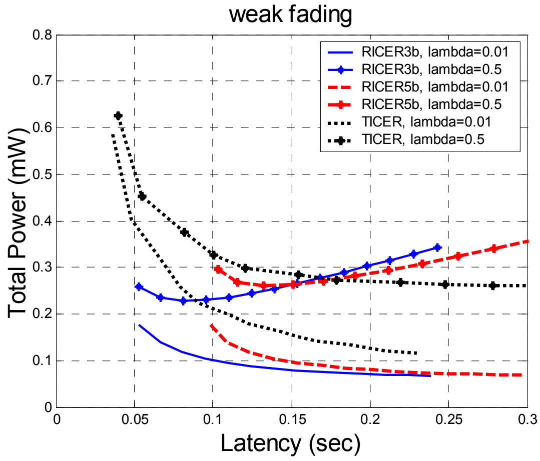

Figure 4. Two different traffic loads, under weak fading

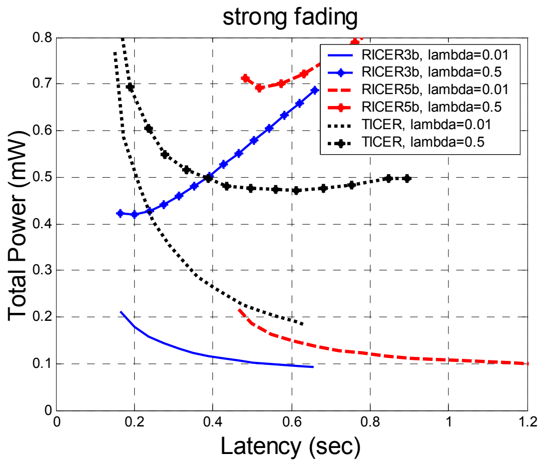

Figure 5. Two different traffic loads, under strong fading

RICER3b or RICER5b?

A comparison of RICER3b and RICER5b under different channel fading conditions and traffic loads is shown in Fig 4 and 5. For completeness, the performance of TICER is also included.

Focusing on RICER3b and RICER5b, RICER5b is more advantageous in that it consumes less idle monitor power when RICER3b and 5b uses the same number of slots $N=M$, because RTS slots are shorter than DATA slots. In addition, its RTS and CTS may protect DATA packets more against collisions, and thus save retransmission power. On the other hand, RICER3b is more advantageous in that it has fewer handshakes, such that it not only consumes less power in transmitting and receiving control packets, but also has a better chance of surviving channel fading. Comparing Fig 4 and 5, RICER5b's performance degrades more under stronger channel fading conditions as expected. In other words, RICER5b is more sensitive to channel fading. Note that even under weak channel fading in Fig 5, which is in favor of RICER5b, RICER5b performs worse than RICER3b under both traffic loads 0.01 and 0.5 pkt/sec. This is because, first, with the buzz scheme, the wasted idle monitor power is minimal for both RICER3 and RICER5, and using shorter RTS slots in RICER5b do not save much more from using DATA slots in RICER3b. Secondly, introducing RTS and CTS into the handshake increases the probability of handshake failure in case the RTS or CTS is lost in collision or channel fading. While the loss of RTS or CTS affects the power consumption only marginally, latency increases significantly. Therefore, we conclude that it is redundant to use RTS and CTS to protect a DATA in typical WSNs, and RICER3b is the most favorable scheme for WSNs in the RICER family.

Note that although some of the power versus latency curves in Fig 4 and 5 cross one another, they cross outside RICER3b's region of interest. RICER3b's region of interest is always the optimal among all, under each traffic load and channel fading conditions.

RICER3b versus TICER

As shown in Fig 4 and 5, RICER3b's region of interest always has lower power consumption and latency than TICER. However, the degradation of RICER3b's performance as traffic load increases is more severe than TICER. In addition, as traffic load increases, RICER3b's region of interest becomes very narrow, while that of TICER is still wide. Therefore, we investigate in both schemes' sensitivity to traffic load. In Fig 6 and 7, the horizontal curves are the power versus latency curves for traffic loads 0.1, 0.4, 0.7, 1 and 1.3 pkt/sec, while the vertical curves, each with a different bullet, connect the points derived from the same T. Observe that if TICER uses a fixed T and traffic load starts to increase, both power consumption and latency increases. On the other hand, in RICER3b as traffic load increases, latency remains quite stable while power consumption increases much faster than in TICER. In other words, in a WSN that is prone to traffic load variations, if the network's latency constraint is tight, it is safer to adopt RICER3b so latency does not vary much as traffic load changes. But this is at the cost of higher power. Otherwise, if latency constraints are relaxed, adopting TICER usually leads to lower power consumption as traffic load increases.

Finally, note in Fig 6 and 7 that while it is desirable to use a long T at low traffic loads in TICER and RICER3b, the

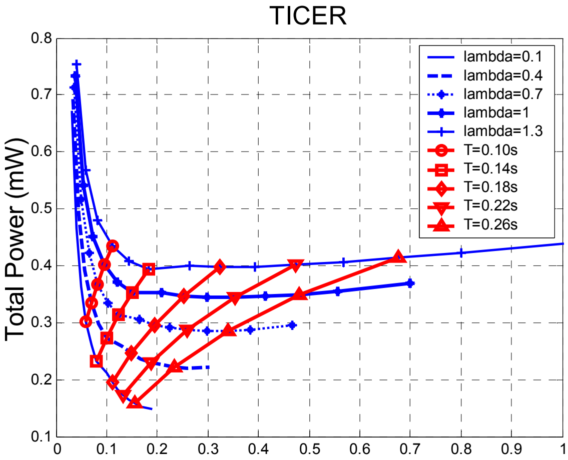

Figure 6. TICER: traffic load variation

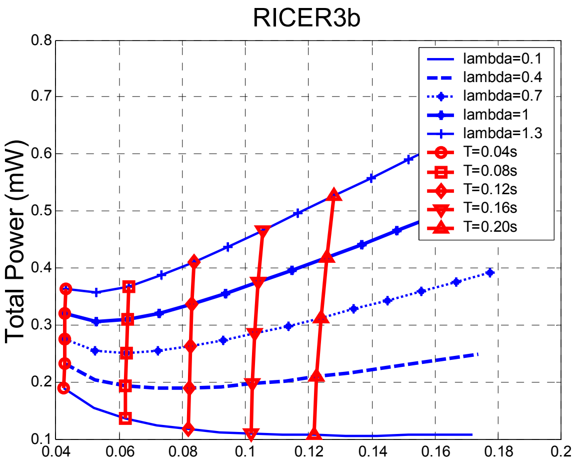

Figure 7. RICER3b: traffic load variation

longer the T, the more degradation when traffic load increases. Therefore, if traffic load variation is likely to occur in a given WSN, it is favorable to use a shorter T to gain robustness for both TICER and RICER3b.

We conduct the same analysis with channel fading variations instead of traffic load variations. The response of TICER and RICER3b' power consumption and latency to channel fading are similar to each other, and thus not shown.

V. Simulation Verification

To verify the accuracy of our analysis, we conduct network simulations for RICER3b, RICER5b and TICER. The simulation study utilizes a discrete event simulator OMNeT++ [9] enhanced by the TKN Mobility Framework [10]. Using the entire set of parameters specified in section IV, a comparison between the analytical and simulation results are shown in Fig 8. Due to space limitation, only results of the desirable schemes TICER and RICER3b with traffic load λ=0.5pkt/sec and no fading are shown. Observe that the simulation results are within 0.5%-10% to those of the theoretical analysis, as

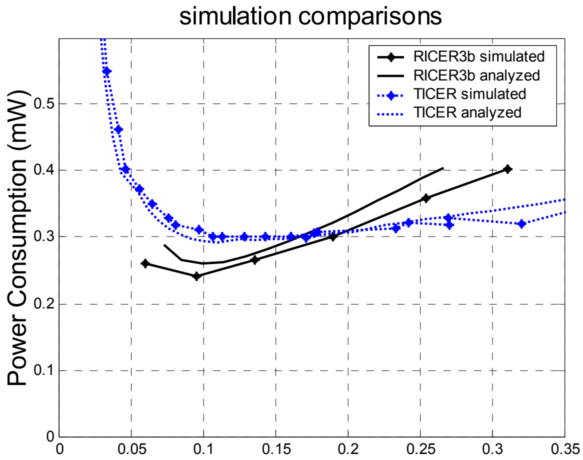

Figure 8. Comparison of analytical and simulation results

long as the traffic load is well supported by the wakeup rate. In order words, when $n\lambda<1/T$. The matching results thus validate the theoretical analysis presented in this paper.

Note that details of the simulation framework, design issues, and rendezvous scheme behavior in large networks obtained by the simulation are beyond the scope of this paper, and will be fully discussed in our future work.

VI. Conclusion and Future Work

In this research, we use power consumption and latency as the evaluation metrics to compare different versions of receiver initiated pseudo-asynchronous rendezvous schemes (RICER). Overall, RICER3b has the best performance among all RICER schemes, under all traffic load and channel fading conditions presented. RICER3b also outperforms TICER in terms of its power and latency tradeoff in most static conditions. On the other hand, with traffic variations we showed that TICER is more robust in terms of power while RICER3b is more robust in terms of latency. Therefore, a proper choice of rendezvous schemes depends on characteristics of the specific WSN of interest. The presented methodology demonstrates its capability of incorporating system parameters as well as physical layer specifications to generate a guideline for choosing the most appropriate rendezvous scheme.

We are currently conducting a comprehensive comparison of all categories of rendezvous schemes, in addition to the pseudo-asynchronous category presented in this paper and [1]. Preliminary results show that different categories of schemes thrive in different network scenarios, and our methodology again can be used to facilitate the decision process in choosing the design parameters as well as the most appropriate rendezvous scheme.

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APPENDIX

<u>Expected wait time:</u> $E[W]$

Let all parameters be defined as in section III, and let p_{WB} be the probability that a WB fails to be received at its regular wakeup time. This happens if either the destination node finds the channel to be busy and backoff, or if the WB is lost in channel fading. Therefore p_{WB}=1-(1-p_{by})(1-α), where α is a channel fading probability derived below. With such, the expected wait until a node receives a WB successfully is:

$$E[W] = \frac{m}{T^k}(T - T_{WB})^{k+1}\left(\frac{1}{m} - \frac{1}{m+1}\right) + \frac{p_{WB}}{1 - p_{WB}}T$$

<u>Channel fading probabilities</u>

Adopting the channel model and its parameters described in [1], the channel fading probabilities for the WB, and for the DATA or ACK in RICER3 are:

$1 - \alpha_3 = \pi_G$

$1 - \beta_3 = (1\ p_{coh} + (1 - p_{GB})(1 - p_{coh}))^2 \pi_G$

Similarly, the channel fading probabilities for the WB or buzz, and the DATA or ACK in RICER3b are:

$1 - \alpha_{3b} = (1\ p_{coh} + (1 - p_{GB})(1 - p_{coh}))\pi_G$

$1 - \beta_{3b} = (1\ p_{coh} + (1 - p_{GB})(1 - p_{coh}))^3 \pi_G$

In the same way, the channel fading probabilities for the WB, RTS or CTS, and the DATA or ACK in RICER5 are:

$1 - \alpha_5 = (1\ p_{coh} + (1 - p_{GB})(1 - p_{coh}))^2 \pi_G$

$1 - \beta_5 = (1\ p_{coh} + (1 - p_{GB})(1 - p_{coh}))^4 \pi_G$

Finally, the channel fading probabilities for the WB, BZ, RTS or CTS, and the DATA or ACK in RICER5 are:

$1 - \alpha_{5b} = (1\ p_{coh} + (1 - p_{GB})(1 - p_{coh}))^3 \pi_G$

$1 - \beta_{5b} = (1\ p_{coh} + (1 - p_{GB})(1 - p_{coh}))^5 \pi_G$

<u>Scaled traffic load:</u> λ'

With channel fading, when DATA or ACK fails, retransmission for the entire session is required. The scaled traffic load is $\lambda' = \lambda / (1 - \beta)$ for all schemes.

<u>RTS success rate:</u> p_{RTS}

An RTS may not successfully be responded by a CTS due to various reasons. First, the source node may find the channel to be busy and thus backoff with probability p_{by}. Secondly, the RTS of interest may collide with RTSs from other nodes, or not be chosen by the destination node with probability p_1. Thirdly, the expected CTS may collide with a WB with probability p_2. Finally, the RTS or CTS may fail due to channel fading with probability (1-π_G). Combining all the cases, the RTS success rate is:

p_{RTS}=(1-p_{by}) (1-p_1) (1-p_2) π_G

where

$$p_1 \cong e^{-\lambda T} + \lambda T e^{-\lambda T}\frac{M-1}{M}\frac{1}{2} + \frac{(\lambda T)^2}{2}e^{-\lambda T}\left(\frac{(M-1)(M-2)}{M^2}\frac{1}{3} + \frac{(M-1)}{M^2}\right)$$

and $p_2 = 1 - (1 - \lambda T_{WB})^n$

<u>Handshake failure rate:</u> p_{f3} and p_{f5}

$p_{f3} = (1 - p_{by})(1 - \beta_3)$

$p_{f5} = (1 - p_{by})(1 - \beta_5)$

where p_{by} is defined in section III.