Scheduled Rendezvous and RFID Wakeup in Embedded Wireless Networks

Milan Nosovic and Terence D. Todd
Department of Electrical and Computer Engineering
McMaster University
Hamilton, Ontario, CANADA

***Abstract*—*Scheduled rendezvous* is a common technique for reducing power consumption in embedded wireless networks [1] [2]. In scheduled rendezvous, nodes remain in a low power sleep mode whenever possible and periodically awaken to rendezvous with other nodes. Unfortunately, in many embedded wireless systems node power consumption may be unnecessarily dominated by this rendezvous activity [3]. In this paper we study the use of radio frequency identification (RFID) technology, as a low power wakeup mechanism for embedded radio networks. RFID radios are very low cost and can currently be operated at power consumptions of over three orders of magnitude lower than that of typical commercial radios operating in the Mbps range [4]. We first compare the regions of operation where RFID wakeup and scheduled rendezvous are preferred. A protocol is proposed which allows the basestation to block transmissions that may interfere with the wakeup process. In addition, a hybrid low power rendezvous wakeup protocol is proposed which attains very low power consumption. We find that in low utilization situations where a high level of responsiveness is needed, low power wakeup can achieve much lower levels of power consumption than scheduled rendezvous. The results also suggest that adaptive schemes are possible where the mode used is selected dynamically by the basestation.**

I. INTRODUCTION

A common technique for reducing power consumption in embedded wireless networks is to place nodes into a low power sleep mode whenever possible, and have them periodically awaken to perform communication tasks. This type of action is often referred to as a *scheduled rendezvous*. Scheduled rendezvous is a very strong power-saving technique, and has been included in past wireless protocols such as IEEE 802.11 [1] and Bluetooth [2]. Unfortunately, it is expected that many embedded nodes will operate at very low utilization, and yet applications will require high levels of responsiveness. Since the responsiveness of the system is proportional to the rendezvous rate, an embedded node's power consumption may be heavily dominated by its rendezvous activity [3].

An alternative to scheduled rendezvous is to use a low power wakeup mechanism at the embedded node [5][6]. Low power wakeup relies on the use of a low power radio circuit which can be activated by the basestation when communication with the node is desired. In this paper we study the use of radio frequency identification (RFID) technology as a low power wakeup mechanism for embedded radio. RFID has many strengths in this regard. The technology is relatively mature, and reasonable data links are possible over picocellular coverage areas. RFID radios can currently be operated at power consumptions of roughly three orders of magnitude lower than those of typical commercial radios operating in the Mbps range [4]. In addition, RFID radios are very low in cost and complexity. Radio frequency identification (RFID) is currently used in many commercial applications including smart cards, security tags and vehicle identification systems [7].

RFID systems are classified into two types. In close/remote coupled systems the reader and transponder have a maximum separation of about 1 meter. In this case the reader often provides enough power to the transponder to operate a micro-chip so that highly complex tasks may be performed [7]. Long range RFID systems however often operate with coverage areas of 10 meters or more in the 2.4 GHz - 24 GHz range. In this case battery-operated transponders are more common since regulatory constraints normally preclude passive systems. An example of a long range RFID design which permits two-way data transfer uses a modulated backscatter uplink [7] [4]. Unfortunately the achievable uplink data rates are typically on the order of a few bps, which is much too low for many potential applications.

A possible approach to wireless node power saving is to use RFID downlink signaling to awaken a high powered radio when needed [5]. We first compare the regions of operation where RFID wakeup and scheduled rendezvous are preferred. A protocol is proposed which allows the basestation to block transmissions that may interfere with the wakeup process. We also propose a hybrid low power rendezvous wakeup protocol which attains very low power consumption. We find that in low utilization situations where a high level of responsiveness is needed, low power wakeup can achieve much lower levels of power consumption than scheduled rendezvous. The results also suggest that adaptive schemes are possible where the mode used is selected dynamically by the basestation.

II. EMBEDDED SYSTEM MODEL

In the system considered, we assume that a single basestation node with large power reserves communicates with a population of embedded nodes operating under battery power. In the applications of interest the basestation coverage area would

This work was supported by a grant from the Natural Sciences and Engineering Research Council of Canada and Communications and Information Technology Ontario (CITO). The authors may be reached at `todd@mcmaster.ca`

0-7803-7400-2/02/$17.00 © 2002 IEEE

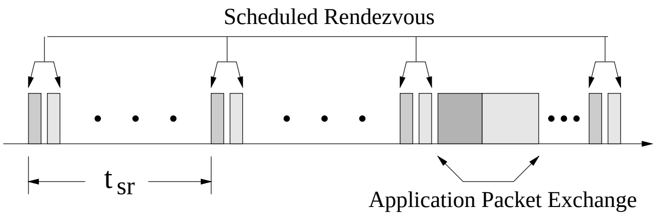

Fig. 1. Scheduled Rendezvous Example

typically have a radius of ten meters or more. There are many examples of this type of system in personal area networks and other applications [8]. As discussed in [3], many applications will require simple maximum latency based quality of service constraints. For example, when querying an embedded node for an image, an application may require a maximum response time of several seconds. This response time constraint is referred to as $\mathbf{D}_{max}$.

A. Scheduled Rendezvous (SR)

Scheduled rendezvous [3] is a standard power saving technique and has been used in many different wireless standards such as IEEE 802.11 [1] and Bluetooth [2]. A diagram showing a scheduled rendezvous example is shown in Figure 1. Under this scheme, the embedded nodes spend most of their time in a low power sleep state, in which the node's transmitter and receiver are both turned off. Periodically, every t_{SR} seconds, each node awakens and transmits a short beacon packet to the basestation. The basestation then responds to the beacon with a handshake/acknowledgement. At this time any enqueued packets at the two nodes that are destined for each other will be sent. Following the end of the rendezvous the embedded node goes back into the sleep state and schedules a new rendezvous, t_{SR} seconds from the time of last contact with the basestation. The nominal maximum time between rendezvous events is often dictated by the governing application's maximum allowable response time, $\mathbf{D}_{max}$. Thus t_{SR} is set equal to $\mathbf{D}_{max}$.

B. Addressed Low Power Wakeup (LPW)

An example of the addressed low power wakeup protocol is shown in Figure 2. Under this scheme, embedded nodes have a low power RFID radio in addition to the regular high power radio. Embedded nodes spend most of their time with the high powered radio turned off and the RFID radio in an addressable low power wakeup state referred to as the RFID state.

When data packets arrive at the basestation destined for an embedded node, the basestation first issues a high speed pre-wakeup announcement to any nodes which are awake in order to prevent them from attempting to access the channel for the duration of the upcoming wakeup. As shown in Figure 2, the basestation then goes on to issue an addressed wakeup for that node. The bit rate of the addressed wakeup is typically on the order of 1 kb/s [4]. The destination node's RFID radio recognizes the wakeup and proceeds to turn on its high power radio. All further data and acknowledgement communication between the basestation and the embedded node take place with this radio. Following the conclusion of the data transfer, the embedded node shuts off its high power radio and goes back into the RFID state.

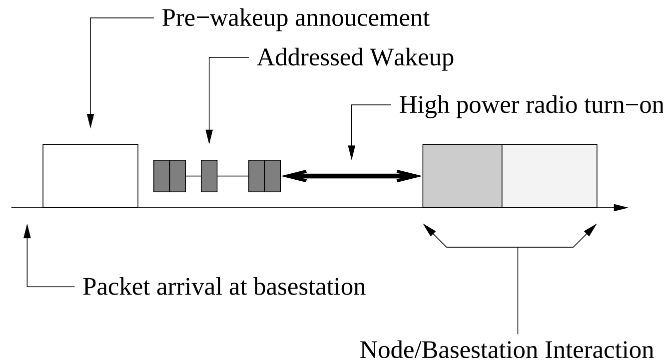

Fig. 2. Addressed Low Power Wakeup Example — Packet from Basestation

If a packet arrival occurs at the embedded node, the high power radio is powered on immediately, and the timing consists only of the high powered radio wakeup interval, followed by packet transmission. At the time that this happens, it is not aware of whether the basestation is currently transmitting a wakeup for another embedded node. It must therefore scan for a wakeup on the channel in order to avoid possible collisions. Both the high power radio and low power RFID radio must be on while scanning for a wakeup on the channel. The RFID radio alone cannot ascertain whether or not a wakeup is occurring because it is just a wideband energy detector and cannot distinguish between a wakeup and regular high speed data. If the high power radio recognizes a data packet, then the embedded station can conclude that no wakeup is occurring and can attempt to access the channel once it becomes free. If the packet is a pre-wakeup announcement it will defer in the usual manner. If the RFID radio senses energy on the channel that is not recognized as a high data rate packet, it is assumed that a wakeup is occurring and the node waits for the wakeup and the packet transfer to conclude before attempting to access the channel.

With an ASK-modulated wakeup signal [4], it is possible that the channel will be silent for several bit times because portions of the signal may involve strings of consecutive 0-bits. To prevent the embedded node from having to scan the channel for the entire length of a wakeup signal in order to determine whether or not one is being transmitted on the channel, a scheme has been employed in which a 1 bit is stuffed into every third bit position. In this way, a node will have to scan the channel for no more than three wakeup bit times before coming to a conclusion about the presence or absence of a wakeup. The fact that the high power radio must be on while the node is scanning

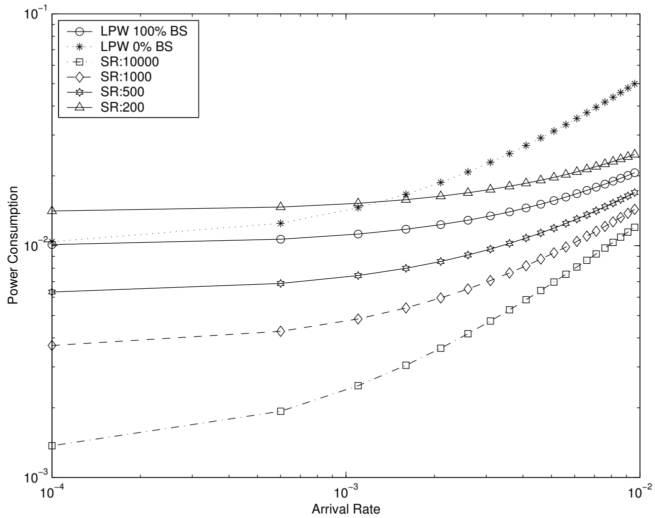

Fig. 3. Calculated SR/LPW Comparison

for a wakeup represents a significant power cost in that scanning for even a few wakeup bit-times normally takes several milliseconds.

III. Scheduled Rendezvous versus Low Power Wakeup

In our results we assume that external packet arrivals to the basestation follow a Poisson process with a mean arrival rate of of λ_B packets/ms (i.e., λ_B/N destined to each embedded node), where N is the total number of embedded nodes). Similarly, packet arrivals at the embedded nodes are also Poisson with a total mean arrival rate of λ_E packets/ms (i.e., λ_E/N arrival rate per node). The media access control (MAC) protocol used for channel access is CSMA/CA [1].

A lower bound on system power performance can be obtained by ignoring the effects of propagation delay, MAC channel contention and queueing. This bound will be very accurate in many situations due to the low duty cycle (and channel utilization) of the applications involved. Under these assumptions the energies dissipated over a large period of time, t, can be written for each of the power saving schemes. Dividing by t and taking $\lim_{t\to\infty}$ we can easily obtain the following expressions for mean power consumption. In the interests of brevity we have not included the energy expressions but have included only the final power equations. In the following expressions $\overline{P}_{TX}$, $\overline{P}_{RX}$, $\overline{P}_{RFID}$, and $\overline{P}_S$ represent the average power dissipated when in transmit mode, receive mode, RFID mode, and sleep mode, respectively. $\widehat{P}_{SR}$ and $\widehat{P}_{LPW}$ represent the average total power dissipated in the SR and LPW protocols, respectively. η_{TX}, η_{RX}, η_{RFID}, and η_S are the energies dissipated per unit time when in transmit mode, receive mode, RFID mode, and sleep mode, respectively. The equations are as follows.

Scheduled Rendezvous (SR):

$$\begin{aligned}
\overline{P}_{TX} &= \eta_{TX}\left(\lambda_B\overline{T^B_{EB}} + \lambda_E\overline{T^E_{EB}} + N\frac{T_{BEACON}}{t_{SR}}\right),\\
\overline{P}_{RX} &= \eta_{RX}\left(\lambda_B\overline{T^B_{BE}} + \lambda_E\overline{T^E_{BE}} + N\frac{T_{BEACONACK}}{t_{SR}}\right),\\
\overline{P}_{S} &= \eta_{S}\left(N\left(1 - \frac{T_{BEACON}+T_{BEACONACK}}{t_{SR}}\right)\right.\\
&\quad \left. -\lambda_B\left(\overline{T^B_{BE}}+\overline{T^B_{EB}}\right) - \lambda_E\left(\overline{T^E_{EB}}+\overline{T^E_{BE}}\right)\right).
\end{aligned}$$

$$\begin{aligned}
\widehat{P}_{SR} &= \lambda_B\left(\overline{T^B_{BE}}(\eta_{RX}-\eta_S) + \overline{T^B_{EB}}(\eta_{TX}-\eta_S)\right)\\
&+ \lambda_E\left(\overline{T^E_{EB}}(\eta_{TX}-\eta_S) + \overline{T^E_{BE}}(\eta_{RX}-\eta_S)\right)\\
&+ N\left(\eta_S + T_{BEACON}/t_{SR}(\eta_{TX}-\eta_S)\right.\\
&+ \left. T_{BEACONACK}/t_{SR}(\eta_{RX}-\eta_S)\right)
\end{aligned} \quad (1)$$

Here, $\overline{T^B_{BE}}$ is the mean packet transmission time for basestation originated packets, $\overline{T^B_{EB}}$ is the mean embedded node ACK transmission time, $\overline{T^E_{EB}}$ is the mean embedded node packet transmission time, and $\overline{T^E_{BE}}$ is the corresponding ACK transmission time. T_{BEACON} is the embedded node beacon transmission time and $T_{BEACONACK}$ is the corresponding ACK. t_{SR} is the length of time between rendezvous events.

Low Power Wakeup (LPW):

$$\begin{aligned}
\overline{P}_{TX} &= \eta_{TX}\left(\lambda_B\overline{T^B_{EB}} + \lambda_E\overline{T^E_{EB}}\right),\\
\overline{P}_{RX} &= \eta_{RX}\left(\lambda_B\overline{T^B_{BE}} + \lambda_E\overline{T^E_{BE}} + \lambda_E\overline{T_{SCAN}}\right),\\
\overline{P}_{RFID} &= \eta_{RFID}\left(N - \lambda_B\left(\overline{T^B_{BE}}+\overline{T^B_{EB}}\right)\right.\\
&- \left.\lambda_E\left(\overline{T^E_{EB}}+\overline{T^E_{BE}}\right)\right).
\end{aligned}$$

$$\begin{aligned}
\widehat{P}_{LPW} &= \lambda_B\left(\overline{T^B_{BE}}(\eta_{RX}-\eta_{RFID})\overline{T^B_{EB}}(\eta_{TX}-\eta_{RFID})\right)\\
&+ \lambda_E\left(\overline{T^E_{EB}}(\eta_{TX}-\eta_{RFID}) + \overline{T^E_{BE}}(\eta_{RX}-\eta_{RFID})\right.\\
&+ \left.\overline{T_{SCAN}}\eta_{RX}\right) + N\eta_{RFID}
\end{aligned} \quad (2)$$

$\overline{T_{SCAN}}$ is the average time required for an embedded node to scan the channel for an in-progress wakeup.

In Table I the default values of the parameters are given. The values used for η_{RX}, η_{TX} and η_S were taken from recent implementations of low power radio and RFID systems [4][7].

In Figure 3 a comparison of the scheduled rendezvous and low power wakeup is given. The graph shows mean power consumption versus packet arrival rate for very low values of loading, using Equations 1 and 2. Simulation results show that for this arrival rate range, the computed bounds are extremely accurate. In the graph there are four different SR curves with inter-beacon intervals, t_{SR}, ranging from 200 ms to 10 seconds.

N	10
η_{RX}, η_{TX}	1
η_{RFID}	10^{-3}
η_S	10^{-4}
T_{BE}^B, T_{EB}^E	$1ms$
T_{EB}^B, T_{BE}^E	$0.1ms$
$T_{BEACON}, T_{BEACONACK}$	$0.1ms$
$T_{RESYNCH}, T_{WAKEUP}$	$15ms$
$DIFS$	$50\mu s$
$SIFS$	$10\mu s$
slot time	$20\mu s$

TABLE I
DEFAULT PARAMETER VALUES

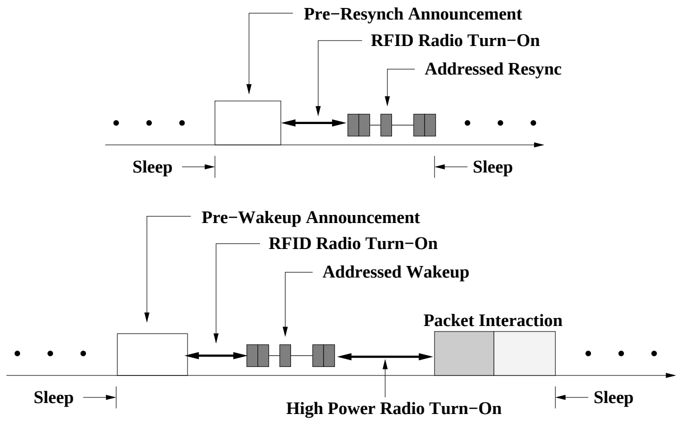

Fig. 5. Hybrid Low Power Rendezvous Wakeup Example

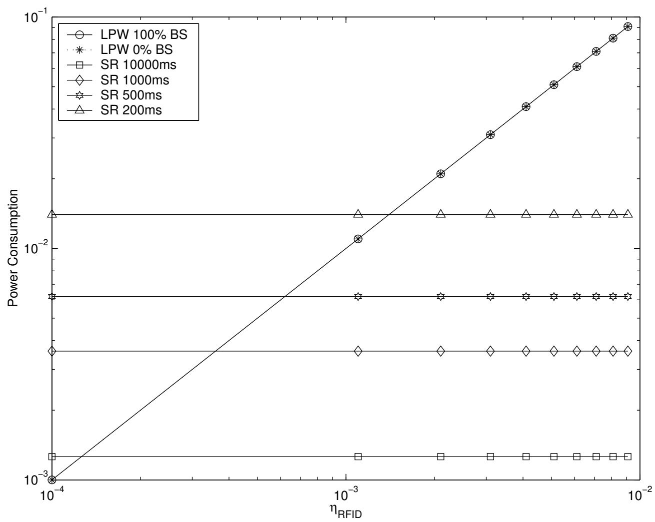

Fig. 4. SR/LPW Power Consumption

There are two LPW curves, one corresponding to 100% of the packet arrival rate coming from the basestation side (i.e., 100% BS) and 100% of the traffic coming from the embedded node side (i.e., 0% BS). Note that the power consumption for SR is independent of this mixture. It can be seen that under higher values of arrival rate, when traffic is originating at the embedded nodes there is an increase in power consumption due to the scanning procedure discussed in Section II-B.

An interesting result seen in Figure 3 is that depending upon the value of t_{SR}, SR power consumption may be higher or lower than that for LPW. In the figure the curves for $t_{SR} > 200ms$ all lie below the LPW curves. However it can be seen that for $t_{SR} \leq 200ms$, LPW is the preferred scheme from a power consumption viewpoint. The SR/LPW crossover point occurs at interesting practical values for t_{SR}, since for the parameters we have used this happens at somewhere between 200 ms and 500 ms. It is likely that there will be future applications which require $\mathbf{D}_{max}$ to be on either side of this crossover point. This suggests that designs which include RFID wakeup may well be deployed in situations where power consumption can be improved by sometimes switching off the RFID wakeup and going to SR mode. There are also embedded node applications where the value of t_{SR} may be changed with time, e.g., lower response times may be tolerated at different times of the day. These types of environments suggest that SR/LPW adaptive schemes may be the best. An example of this would be a scheme where SR is used at night when people are not present, and LPW is in force during the daytime.

The crossover region discussed above is clearly a strong function of η_{RFID}. In Figure 4 we show a plot of SR and LPW power consumption versus η_{RFID} using Equations 1 and 2, again under very low loading conditions. We can see that if the value of η_{RFID} were smaller by an order of magnitude then this would strongly prefer LPW over SR for typical human latency values. On the other hand if η_{RFID} increases by an order of magnitude, SR would clearly be preferred over this range of values.

A. Hybrid Low Power Rendezvous Wakeup (LPR)

The third scheme considered in this paper is a hybrid of scheduled rendezvous and addressed low power wakeup which we refer to as Hybrid Low Power Rendezvous Wakeup (LPR). An example of the LPR protocol is shown in Figure 5. In this scheme the embedded nodes are normally in the sleep state, and periodically turn on their low power RFID radios every t_{LPR} seconds. As with the regular addressed low power wakeup scheme, the basestation sends out a pre-wakeup announcement to any nodes that are awake in order to protect the RFID signal. If the basestation has no data packets to transmit to the embedded node, then the node simply uses the information provided by the RFID signal to resynchronize its clock with that of the basestation to correct for any drift that may have occurred. An example of this is shown in the upper time-line of Figure 5. In such a case, the RFID signal is referred to as a resync. In the event that the basestation does have packets for the embedded

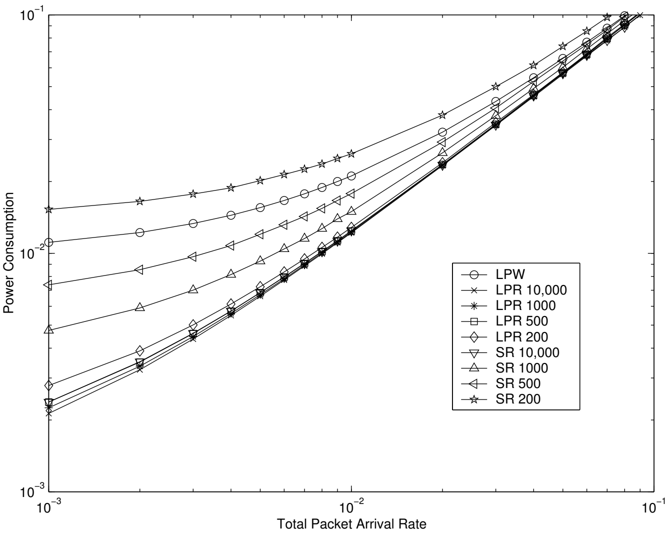

Fig. 6. LPR Comparison

node at the time of the rendezvous, the data packets will follow the wakeup. This case is shown in the lower time-line of Figure 5. If it is the case that the embedded node has packets for the basestation at the time of the rendezvous, then it will turn on its high power radio and begin transmission following the reception of the wakeup signal. After the end of the data transfer, the embedded node goes back into the sleep state. Another rendezvous occurs at t_{LPR} seconds from the time of the last rendezvous.

As in SR, the length of the period between resyncs or wakeups, t_{LPR}, is dictated by the application's responsiveness requirement, $\mathbf{D}_{max}$. However, when setting this value care must be also be taken to allow for adequate compensation of any clock drift. An embedded node must ensure that its low power RFID radio is already activated when a scheduled resync/wakeup reception reaches it. In order to do this, the node must schedule the activation of the RFID radio for a guard time of `maxdrift` seconds prior to the rendezvous time, where `maxdrift` is equal to the maximum possible clock skew between the node and the basestation since their time of last contact. The higher the time period between scheduled resyncs/wakeups for a given node, the higher the potential drift between the embedded (RFID) clock and the basestation clock, and the larger the value that `maxdrift` must assume.

Figure 6 provides a comparison of the three schemes using simulation results. In this figure the normalized mean power dissipation has been plotted as a function of total packet arrival rate. We have plotted four curves each for LPR and SR corresponding to different values of $\mathbf{D}_{max}$. From the figure it can be seen that LPR gives a lower power consumption over all values of t_{LPR} than does LPW. However, the lower power consumption enjoyed by LPR over LPW does not come without a price in terms of mean delay. Using the same parameters as in Figure 6, the mean delay experienced by LPR and SR is roughly the same for the same value of $\mathbf{D}_{max}$. It is also obvious that LPW operates with a much lower mean delay than any of the other schemes since no rendezvous function is used. For this reason we can view the process of going from LPW to LPR is a way of trading off delay for improved power consumption.

Although LPR exhibits better performance than SR, it is not always a feasible protocol to use because of scalability/channel utilization issues. This is due to the use of the individual node resync, as described above. One way of increasing the scalability in this case is to use multicast transmission so that multiple nodes can be contacted simultaneously [6].

IV. Conclusions

In this paper we have studied the use of radio frequency identification (RFID) technology as a low power wakeup mechanism for embedded radio networks. We first defined a basic protocol for low power RFID wakeup, and compared its power dissipation performance with that of conventional scheduled rendezvous. It was shown that under typical conditions the crossover region which prefers scheduled rendezvous occurs at values of system responsiveness in the hundreds of milliseconds range. In low utilization situations where a high level of responsiveness is needed, low power wakeup can achieve much lower levels of power consumption than scheduled rendezvous. The results also suggest that more complex schemes are possible where the mode used is selected dynamically by the basestation. A hybrid low power rendezvous wakeup protocol was also proposed which attains very low power consumption by combining the two techniques. The hybrid protocol always has a lower power than the other two for a given latency requirement as long as the channel capacity is not exceeded.

V. Acknowledgment

The authors would like to thank Jim Evans at WINLAB for discussions and input to this paper.

References

[1] IEEE Standards Department. *"IEEE Draft Standard - Wireless LAN"*. IEEE Press, 1996.

[2] J. Haartsen. The Bluetooth Radio System. *IEEE Personal Communications*, 7(1), February 2000.

[3] T. Todd, F. Bennett, and A. Jones. Low power rendezvous in embedded wireless networks. In *First IEEE Annual Workshop on Mobile Ad Hoc Networking and Computing (MobiHOC'2000), Boston, MA.*, August 2000.

[4] J.G. Evans, R.A. Shober, S. A. Wilkus, and G.A. Wright. "A Low-Cost Radio for an Electronic Price Label System". *Bell Labs Technical Journal*, Autumn 1996.

[5] M. Nosovic and T. D. Todd. "Low Power Rendezvous and RFID Wakeup for Embedded Wireless Networks". In *15th Annual IEEE Computer Communications Workshop (CCW 2000), Captiva Island, FL*, October 15-18 2000.

[6] C. F. Chiasserini and R. R. Rao. "Combining Paging with Dynamic Power Management". In *IEEE Infocom 2001 Anchorage, Alaska*, April 22-26 2001.

[7] K. Finkenzeller. *RFID Handbook*. John Wiley and Sons Ltd., 1999.

[8] F. Bennett, D. Clarke, J. B. Evans, A. Hopper, A. Jones, and D. Leask. Piconet: Embedded Mobile Networking. *IEEE Personal Communications*, 4(5):8–15, October 1997.