Cross-layer Wireless Sensor Network Radio Power Management

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***Abstract* - With the progression of computer networks extending boundaries and joining distant locations, wireless sensor networks (WSNs) emerge as the new frontier in developing opportunities to collect and process data from remote locations. WSNs rely on hardware simplicity to make sensor field deployments both affordable and long-lasting without maintenance support. WSN designers strive to extend network lifetimes while meeting application-specific throughput and latency requirements. Effective power management places sensor nodes into one of the available energy-saving modes based upon the sleep period duration and the current state of the radio. The newest generation of sensor platform radios with a 250 kbps data rate does not provide adequate time to completely power off the radio during overheard 128-byte constrained IEEE 802.15.4 transmissions. This paper proposes a new radio power management (RPM) algorithm which optimizes radio sleep capabilities by transitioning nodes to intermediate power level states. Additionally, the experimental work characterizes the radio power levels, state transition times, and state transition energy costs of an IEEE 802.15.4 compliant sensor platform for improved accuracy in simulating WSN energy consumption.**

I. Introduction

Integrating sensors into wireless networks offers the ability for applications to monitor and react to events, but their remoteness also introduces challenges for network control and power management. Remote sensing platforms are typically characterized by reduced processing capabilities, limited memory capacities, and fixed battery supplies. Most wireless sensor network (WSN) energy consumption operations involve sensing, computing, and communicating. Analysis conducted in [1] demonstrates that the cost of communication dominates a WSN sensor platform's power budget. Wireless local area networks (WLANs) were designed to minimize delay and maximize throughput, but they do not provide the energy efficiency demanded by WSN networks. As technology makes the hardware smaller, WSN research continues developing innovative, energy-saving techniques at all network protocol layers in order to engineer sensor platforms which can operate unattended for months or even years. The WSN networks must also be scalable to support extremely dense sensor fields. Applications for energy-efficient WSN networks include homeland defense nuclear/biological/chemical (NBC) sensing, military surveillance, and environmental sensing [2][3][4]. These applications generally work in a self-organizing, clustered environment that supports either single or collaborative applications.

The purpose of this research effort is to introduce a cross-layer WSN radio power management (RPM) algorithm operating in the medium access control (MAC) layer which sets the physical (PHY) layer radio low power modes (LPMs) based upon available sleep time. This RPM algorithm effectively regains short duration, power-saving opportunities lost with the newest generation of faster IEEE 802.15.4 wireless personal area network - low rate (WPAN-LR) -based [5] sensor platform transceivers. Short duration sleep offered by a network allocation vector (NAV) sleep mechanism provides significant energy savings [6][7][8]. NAV sleep during message overhearing is significantly reduced since the new WSN platforms require more time to recover from sleep than is available during the shorter transmission time of the largest IEEE 802.15.4-compliant packet, 128-bytes. In addition to the RPM algorithm, the simulation energy consumption model presented in this paper provides increased accuracy by incorporating the average radio energy consumption costs and transition times as the radio switches between transmit, receive, and LPM sleep levels.

II. WSN Energy Loss and MAC Protocol Design

WSN MAC protocols extend network lifetimes by reducing the activity of the highest energy-demanding component of the sensor platform – the radio. Sacrificing network throughput and latency (delay), these protocols create opportunities for radios to sleep with active duty cycles reaching as low as 2.5% under minimal traffic conditions [9]. Understanding the sources of energy loss is essential in designing any power control system. Typical sources of energy loss in WSNs include idle listening, frame collisions, protocol overhead, and message overhearing. This paper addresses WSN protocols which obtain energy efficiency by reducing idle listening and message overhearing.

A. Idle Listening

Idle listening occurs when a station, or node in the WSN, listens to an inactive medium. This idle listening mode dominates power losses in networks characterized by scarce traffic and limited sleep cycles. Once all network transmissions are complete for a particular cycle or time *frame*, the protocols allow nodes to return to sleep until the next transmission period. Table I illustrates how receiving a message consumes three to four orders of magnitude more energy than the radio power-down mode.

B. Message Overhearing

Receiving and discarding messages intended for other nodes, or message overhearing, is tolerable in networks not constrained by energy. Receiving all messages is an efficient method to increase throughput and decrease latency, but it also causes all of the receiving nodes to expend energy. In many WSN platforms, the radio receive mode actually expends more energy than the transmission [10][11]. Message passing is an energy-efficient technique to reduce message overhearing using a four-way request to send (RTS) – clear to send (CTS) – data –acknowledgement (ACK) handshake to reserve the medium before sending data. Both the RTS and CTS messages contain a duration field which advertises to all surrounding nodes the

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TABLE I. RECEIVE AND SLEEP-MODE CURRENT CONSUMPTION

Radio	Receive mode	Power-down mode
CC2420 [12]	19.7 mA	0.1 µA
CC1000 [12]	9.6 mA	0.2 µA
RFM TR1001 [13]	3.8 mA	0.7 µA

length of the transmission exchange. Nodes set their network allocation vector (NAV) countdown timers for the duration of the exchange. Message passing provides a means for nodes to schedule a NAV sleep period after an overheard RTS-CTS handshake sequence by extracting the message duration field and scheduling a NAV table interrupt [6][7][8]. To reduce the probability of costly retransmissions and added latency, message passing also uses RTS-CTS exchanges to gain medium access and then transmits a burst of fragments of the larger message. As shown in Fig. 1, the receiver responds with an acknowledgement (ACK) message after each successful fragment transmission.

III. WSN SENSOR MAC PROTOCOL

A. Sensor MAC

Sensor MAC (SMAC) is a WSN MAC protocol which represents the baseline energy-efficient protocol designed to extend WSN network lifetime [6]. SMAC divides a time frame into listen and sleep periods. The listen period is further divided into a synchronization period and a data transfer period. The synchronization period allows nodes to periodically announce their sleep schedules to correct network time drift and synchronize their sleep times to form virtual clusters of nodes with the same active listen and sleep periods. By creating a small active duty cycle, node lifetimes can be significantly extended with bounded throughput and latency tradeoffs. Sensors that border two synchronized clusters have the option of choosing one or both sleep schedules.

The bi-directional traffic in Fig. 2 represented by arrows illustrates how creating a slotted starting time for all network traffic and concentrating the traffic into a smaller active time frame reduces idle listening, trading off latency and throughput. To minimize collisions, nodes use the IEEE 802.11 standard exponential contention backoff for all channel access attempts. Furthermore, SMAC also reduces energy consumption using the message passing techniques employed for overhearing avoidance.

B. Timeout MAC

Timeout MAC (TMAC) is a WSN MAC protocol that decreases idle listening in WSN networks by establishing a dynamic sleep cycle. TMAC nodes vary their active message exchange period depending on current traffic conditions. Unlike the SMAC static duty cycle, the TMAC dynamic duty cycle uses adaptive listening to attain significant energy savings and accommodate various network traffic loads experienced during a WSN's lifetime. TMAC nodes also form virtual clusters and automatically determine the initiation of a cluster sleep cycle based upon an adaptive timeout (TA) mechanism.

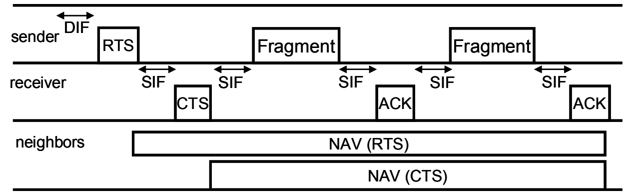

Fig. 1. Message Passing Timing and Signaling [6]

To provide for multi-hop network communication, the TA period represents the worst case delay a CTS response packet could undergo before being transmitted. Eqn. (1) highlights the parameters used to calculate the TA period:

$$TA = 1.5 * (t_{SIFS} + t_{CWmax} + t_{RTS}) \quad (1)$$

where t_{SIFS} is the duration of a short interframe spacing, t_{CWmax} is the duration of the longest contention window backoff, and t_{RTS} is the duration of a RTS packet. Simulations indicated a need to scale this TA period by 50% for effective message exchange. Fig. 2 illustrates how TMAC effectively condenses the same amount of traffic as SMAC into a smaller dynamic time window to save energy by reducing idle listening at the expense of increased message delay.

IV. RADIO POWER MANAGEMENT

The radio power management (RPM) algorithm creates graduated sleep modes for additional opportunities to transition the radio to lower power states. The Moteiv Tmote Sky [10] and Crossbow MICAz [11] WSN platform radio characterizations in this section offer experimentally-derived data to improve simulation accuracy and to optimize power-saving mode energy transitions for short duration sleep opportunities.

A. WSN Platform Energy Consumption Model

WSN network designers extend network lifetimes by minimizing frame collisions, message overhearing, and idle listening. The most significant method in extending network lifetime is to synchronize nodes so that they actively pass data and then sleep as much as possible. Fig. 3 shows that the CC2420 radio consumes up to 19.7 mA in the receive mode, but only 1 µA in power off mode. With two 3000 mAh AA batteries, the difference in lifetime of a fully active MICAz sensor mote platform (22.0 mA) and a sleeping platform (190 µA) is 5.7 days vs. 1.8 years (or battery shelf life).

Sleep transition measurements of the CC2420 radio integrated onto the MICAz platform indicate a 5.87 ms sleep and recovery transition time for the lowest LPM3 sleep mode. The average energy during the sleep transition is less than the receive mode, so time is the only transition cost. Effective power management places nodes into the various power-saving modes based upon the duration of the sleep period and can extend the lifetime of a network by two to three orders of magnitude. Previous communications platforms with effective data rates on the order of 46 kbps did not have a need for intermediate sleep levels. These low data rates provided nodes with enough time to completely power off and restart the radio

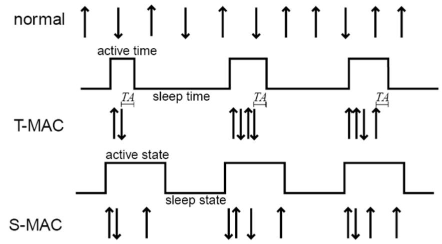

Fig. 2. SMAC static and TMAC dynamic duty cycles [6][7]

during CTS-data-ACK transmissions. The new generation of radios with 250 kbps data rates transmits the data more rapidly and does not provide the time to completely power off the radio during overheard transmissions, but the nodes may be able to transition to an intermediate power-saving mode. Analyzing the 2.4 GHz, 250 kbps Chipcon CC2420 radio reveals three distinct power-saving levels: low power mode 1 (LPM1) through low power mode 3 (LPM3). LPM1 idle mode saves energy by turning off the radio frequency synthesizer which controls channel selection and up/down RF conversion. In addition to the frequency synthesizer, LPM2 power down mode also turns off the crystal oscillator which provides the timing reference for the entire radio chip. This step saves an additional 445 µA for the platform, but suspends all digital communications on the chip. The final radio power-saving level is the LPM3 power off mode. This mode turns off the voltage regulator which powers the radio chip. An interrupt from the microcontroller is required to restart the radio from this mode. Analyzing the proposed RPM algorithm shown in Fig. 4 reveals that the LPM transition conditions require more than just the consideration of the available sleep time. Turning off the crystal oscillator in LPM2 with receive data waiting in the radio receive buffer would suspend the data transfer to the microcontroller. The radio needs the timing signal generated from the crystal oscillator circuit to clock the data onto the system bus. The receive data would be delayed in LPM2, but not lost. Unfortunately, turning of the voltage regulator in LPM3 with data in either the receive or the transmit buffer would cause the data to be lost in the volatile radio RAM memory.

Measuring micro-amp (µA) current consumption and micro-second (µs) state transitions for simulation modeling and the RPM algorithm required developing an instrumentation circuit to amplify the signal prior to measurement on an oscilloscope. The *Platform Current* columns in Fig. 3 show the static radio mode platform energy costs, and Table II shows the Tmote Sky and MICAz platform sleep transition times and average transition current consumption rates to enhance the simulation model accuracy. Most WSN simulations do not adequately model the sleep transition costs. The simulation models either ignore the sleep transition energy costs or charge the transition to the highest energy state [9]. The current (I) measurements in Table II indicate that the average transition cost of 3.20 mA for a MICAz receive-LPM3-receive transition is an order of magnitude larger than the average LPM3 sleep mode base current (190 µA) and an order of magnitude smaller than the receive mode current (21.97 mA). Additionally, the time required to recover from the LPM3 mode (5.87 ms) precludes many of the leading protocols from obtaining NAV

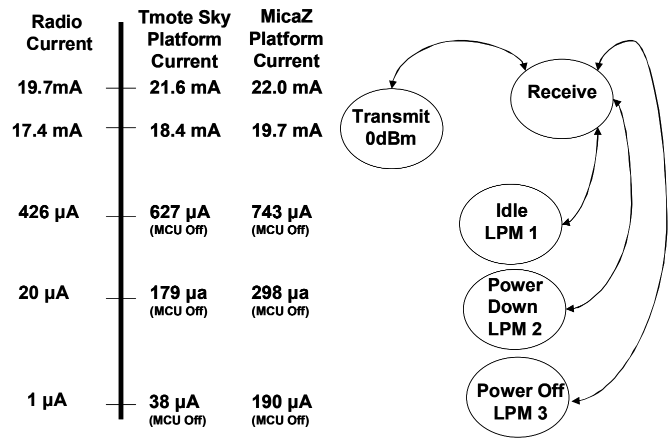

Fig. 3. CC2420 Radio Energy Modes and Platform Energy Allocations [12]

sleep opportunities. Incorporating the RPM algorithm intermediate sleep modes allows these protocols to regain some of the energy savings. These measurements establish a power consumption model that increases the accuracy of WSN protocol simulation for future research and produces transition threshold parameters for the radio power management algorithm to optimize sleep transitions.

B. Radio Power Management Algorithm

Integrating the radio power management (RPM) algorithm detailed in Fig. 4 with WSN MAC protocols allows nodes to regain some of the short duration sleep opportunities lost with the faster 250 kbps IEEE 802.15.4 data rate. Previous technologies with slower data rates permitted nodes to transition to the lowest power mode (LPM3) for all data exchanges [14]. If a node using the RPM algorithm is not the intended receiver of an RTS, the node uses the duration of the remaining CTS-data-ACK transmission sequence to optimize its power saving mode to LPM1, LPM2, or LPM3. While the experimentally obtained CC2420 radio mode transition times in Table II establish the RPM transition thresholds, Table III illustrates the potential energy savings regained using LPM1 and LPM2 for the various packet data sizes and their associated RTS durations. The WSN hardware platforms only have the capability to support 128-byte packets. Since the WSN packets require an approximate 11-byte MAC service data unit (MSDU) header, the maximum data payload size in a data message is constrained to 117 bytes. Without RPM, nodes are only able to transition to LPM3. If NAV sleep is enabled, nodes also transition to sleep for the short duration of an ongoing data transmission.

V. OPNET WSN MODEL SIMULATION

A simulation scenario was designed in OPNET™ Modeler [15] to compare the energy efficiency of the SMAC and TMAC protocols with message passing NAV sleep and the RPM algorithm. The scenario was composed of 20 WSN nodes operating with a 500 ms active/sleep frame period, and the SMAC protocol was set for a static 10% active duty cycle. The

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TABLE II. TMOTE AND MICAZ LPM TRANSITION RESPONSES

Low Power Mode	Total Transition Time (ms)		Average Transition Current (mA)		Average Base Current (mA)		System Effect
	TMote	MICAz	TMote	MICAz	TMote	MICAz	
Receive (RX)	-	-	-	-	21.56	21.97	
Transmit (TX)	-	-	-	-	18.40	19.70	
LPM1: Idle	4.56	4.38	3.72	3.04	0.627	0.743	Freq. Synthesizer Off
LPM2: Power Down	5.15	5.58	2.96	2.94	0.179	0.298	Crystal Oscillator Off Freq. Synthesizer Off
LPM3: Power Off	6.81	5.87	1.88	3.20	0.038	0.190	Voltage Regulator Off Crystal Oscillator Off Freq. Synthesizer Off

TMAC adaptive timeout algorithm produced a 13.48 ms idle channel sleep interrupt. The SMAC and TMAC models only permit LPM sleep transitions when the sleep duration request contains sufficient time to recover from an available sleep level. Additionally, the OPNET models charge the nodes for the transition energy costs (Table II: transition time x average transition current x 3V battery voltage) and the appropriate LPM static base energy rate for the residual sleep duration. Although the sleep energy costs are lower than remaining in the receive mode and make any possible sleep transition an energy-saving event, these transition energy costs significantly decrease the expected network lifetime when compared to models which do not account for these transition costs. Finally, applying the 250 kbps data rate for the network represented the transmission speed of the new generation IEEE 802.15.4-compliant motes.

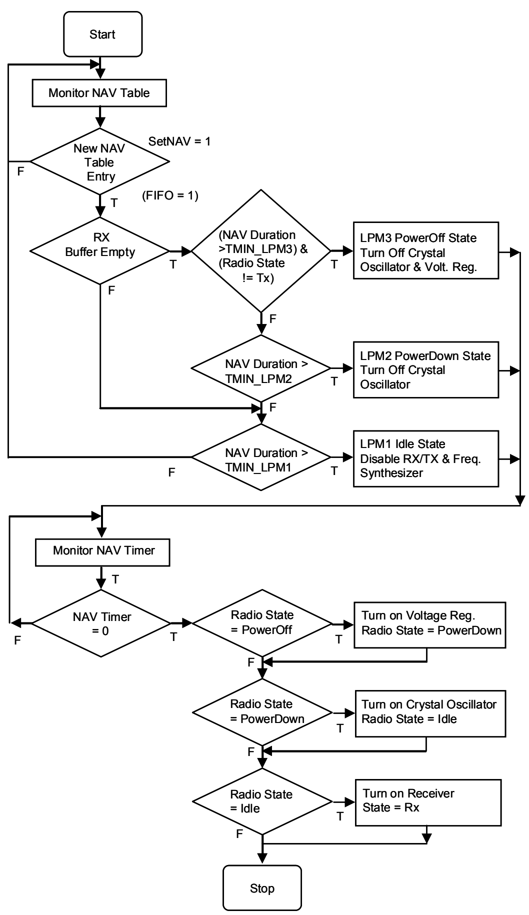

Fig. 4. Radio Power Management Algorithm (RPM)

The scenario generated a uniform packet size distribution with a minimum outcome of 32 data bytes and a maximum outcome of 117 data bytes to represent an average WSN data exchange. The efficiency of NAV sleep was evaluated by simulating the SMAC and TMAC models both with message passing enabled and disabled. Next, the efficiency of the RPM algorithm was evaluated by simulating SMAC and TMAC with the RPM algorithm integrated into NAV sleep. Each model was simulated over a range of 0 to 20 packet/s to test its energy efficiency over sparse to saturated traffic conditions. Although TMAC can extend its duty cycle to accommodate 180 data packets/s, the SMAC protocol's 10% active duty cycle limited the exponential packet generation rate to 20 data packet/s. The performance of the WSN models was then evaluated based upon network lifetime and average node sleep percentage. These performance metrics are defined as follows:

Network Lifetime is a measurement that can be categorized as either the time from network deployment to the first node failure or the time from deployment until the WSN connectivity becomes partitioned. This measurement provides a fair evaluation of how all nodes work together as a system to extend network longevity. The SMAC and TMAC performance evaluations measure the time from network deployment until the failure of the first node. Network lifetime is expressed in days, and the performance rating increases with a higher number of days.

Sleep Percentage is a measurement of the amount of time nodes spend in any sleep state. Sleep percentage is calculated as the average time nodes spend in the LPM3, LPM2, or LPM1 sleep mode divided by the network lifetime. The performance rating increases with a higher sleep percentage.

A uniform packet traffic distribution scenario from 32 to 117 data byte packets provides insight into the effectiveness of message passing and the RPM algorithm. As shown in Table III, the non-RPM assisted NAV sleep models lose efficiency when the raw data size becomes smaller than 115 bytes for the MICAz because NAV sleep is limited to LPM3 mode. Likewise, the Tmote Sky is not able to transition to LPM3 sleep for the duration of a CTS-data-ACK exchange for any of the 117 data byte limited transmissions. In order for regular NAV

TABLE III. RPM TRANSITIONS BASED UPON PACKET DATA SIZES

Radio Low Power Saving Mode	IEEE 802.15.4 Data Packet Size (bytes) MICAz	Tmote Sky
LPM 1	81 to 105 data bytes	76 to 93 data bytes
LPM 2	106 to 114 data bytes	94 to 117 data bytes
LPM 3	115 to 117 bytes	None
Note: Packets limited to 117 bytes due to 11-byte MSDU Header		

sleep to be effective, data packet durations must be sufficiently long for nodes to enter the most energy-efficient LPM3 sleep level. Without sufficient time to transition to sleep, nodes remain awake in the receive mode for most packet exchanges. As illustrated in Figs. 5 through 8, NAV sleep loses efficiency for both SMAC and TMAC in this simulation set due to the majority of the transmitted packets falling in the LPM2 and LPM1 sleep range. The RPM SMAC and RPM TMAC models outperformed the other non-RPM models by regaining the sleep lost by the faster IEEE 802.15.4 data rates and the slower recovery times.

The SMAC model simulations in Figs. 5 and 6 show that the message passing NAV sleep method was unable to save any appreciable energy over the No-NAV sleep model. The No-NAV sleep model was only able to sleep during the 90% inactive sleep cycle at an LPM3 level, and the NAV Sleep model was only able to sleep for the 90% static sleep cycle and the CTS-data-ACK duration for three packets sizes out of the range of 86 data packet sizes. By permitting the motes to sleep for the 90% static sleep cycle and the duration of the 37 LPM1, LPM2, and LPM3 packet sizes in the range 32 to 117 data bytes shown in Table III, the MICAz RPM model was able to extend the network lifetime from 56.4 days to 78.4 days (32% increase). The Tmote Sky platform using the SMAC RPM algorithm extended the network lifetime from 56.4 days to 88.0 days (56% increase).

Unless the network saturates, every frame cycle each TMAC node consumes a fixed 13.48 ms TA adaptive timeout listening cost in the receive mode. With no network traffic, TMAC networks are able to sleep 97.3% of the time and live 153.7 days with the MICAz. With the Tmote Sky, TMAC networks operate for 194.3 days under empty traffic conditions. Unlike the SMAC models, the NAV and RPM sleep during transmissions do not increase lifetime, these mechanisms only slow down the rate of network energy consumption. Fig. 7 illustrates that the slope of the TMAC network lifetime vs. network packet interarrival time decreases with the RPM algorithm, extending the lifetime from 37.6 days to 51.7 days (37% increase) for the MICAz and 40 days to 56 days (40% increase) for the Tmote Sky. Compared with SMAC, TMAC had a lower network lifetime while operating at the SMAC saturation point because TMAC must remain in the receive mode for an additional 13.48 ms TA time beyond the SMAC 10% duty cycle.

VI. FUTURE WORK AND CONCLUSION

This research makes two significant contributions to the state-of-the-art wireless sensor networks. First, the

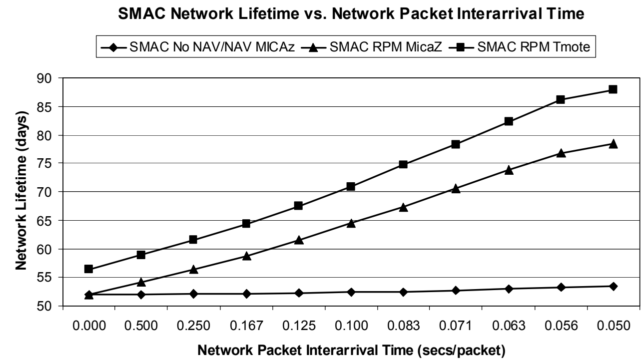

Fig. 5. SMAC WSN Traffic Network Lifetime Performance

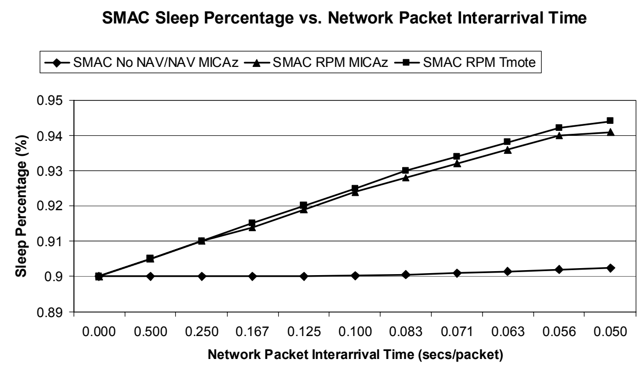

Fig. 6. SMAC WSN Average Sleep Percentage

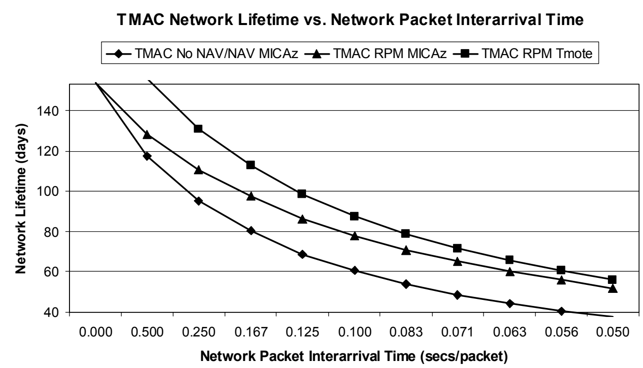

Fig. 7. TMAC WSN Traffic Network Lifetime Performance

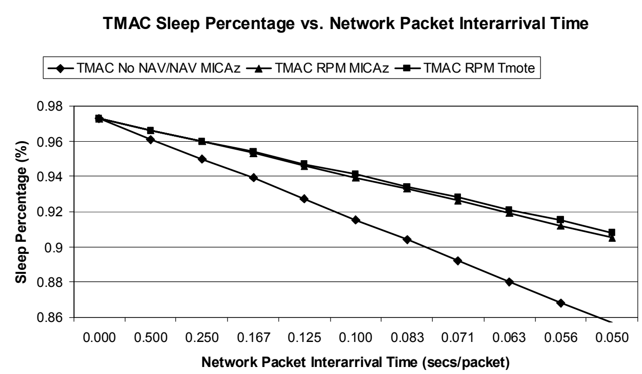

Fig. 8. TMAC WSN Average Sleep Percentage

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experimental measurements characterize the sleep mode transitions for the newest generation of WSN mote devices. These measurements provide an accurate energy simulation model for future research and establish sleep transition thresholds for the proposed RPM algorithm. The second contribution is the introduction of the wireless sensor network radio power management (RPM) algorithm designed to exploit additional power-saving opportunities required for the newest generation of faster sensor platform transceivers. The RPM algorithm optimizes sleep transition decisions based upon the power and response characteristics of the sensor platform's transceiver. Implementing the RPM algorithm into a WSN MAC protocol demonstrated the ability to attain a 56% increase in the SMAC network lifetime utilizing the current technology's realistic data patterns, and a 40% increase in the TMAC lifetime. The IEEE 802.15.4 WSN platform characterizations and the RPM algorithm provide the tools for researchers to continue their progress with the next generation of wireless sensor network platforms.

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