Reducing Average Power in Wireless Sensor Networks Through Data Rate Adaptation

Steven Lanzisera Ankur M. Mehta Kristofer S. J. Pister
Department of Electrical Engineering and Computer Sciences
University of California
Berkeley, CA 94720, USA
{slanzise,mehtank,pister}@eecs.berkeley.edu

***Abstract*—Low power wireless networking standards either do not address variable rate communication or leave the selection of rate outside of the standard. The use of variable data rate can reduce network latency and average power consumption, and automatic rate selection is critical for improving scalability and minimizing network overhead. In the IEEE 802.15.4 standard the SNR can be inferred through the radio reported link quality or received signal strength, and an extension to the standard leads to highly dynamic and accurate rate selection. Using data from an experimental study of 44 IEEE 802.15.4 nodes in an industrial mesh network, SNR is extracted to show sufficient margin exists for higher data rate communication. A variable rate signaling scheme with automatic rate selection is proposed to provide links at the standard 250kb/s as well as 500kb/s, 1000kb/s and 2000kb/s with a minimum of hardware changes. Using the experimental data to generate a model of the real world system, total network energy is compared using legacy and variable rate signaling showing over 40% savings.**

***Index Terms*—Variable rate, Ad-hoc network, Wireless sensor network, IEEE 802.15.4, Energy optimization**

I. Introduction

Variable data rate communication in wireless networks is critical for optimizing throughput across channel conditions and is part of many wireless standards. In wireless networks, changing the data rate can reduce latency, congestion, and network energy consumption. Studies in ad hoc wireless sensor networks have shown that single rate communication reduces network efficiency [1], yet the most common wireless sensor network protocol, IEEE 802.15.4, provides for only a single data rate. The ultra-wideband extension IEEE 802.15.4a as well as other standards including IEEE 802.11 and Bluetooth include many data rate options but provide no mechanism for choosing the optimal rate [2], [3]. adaptation scheme is left to individual implementations, and data rate is often selected based on inferences regarding channel conditions or application requirements. Signal to noise ratio (SNR) has become a popular basis for estimating the optimal data rate, but the methods for measuring SNR are limited by the information available at the physical layer (PHY) of the radio [4], [5].

This material is based upon work supported by the National Science Foundation under Grant No. EEC-0425914.

The RF received signal strength (RSS) has been proposed as a measure of SNR, and this measure is a simple means to estimate channel capacity. It does not account for the impact of interference that effectively raises the noise floor, but it has been shown to be effective in many situations. The IEEE 802.15.4 standard uses a pseudo-orthogonal coding scheme to provide robust error correction by encoding groups of 4 bits into symbols 32 chips long [2]. As a result symbols with many chip errors are resolved correctly, and the standard provides for a link quality indicator (LQI) that is a measure of how well the received symbols match the ideal symbols. Unfortunately the LQI definition is not standardized, but a common definition provides a direct measure of SNR including the effects of interference.

In typical 802.15.4 networks most links have much more SNR than required for the base data rate. We use data collected over 26 days from a 2.4 GHz IEEE 802.15.4 compliant 44 node network in an industrial setting to show typical network conditions for RSS and LQI [6]. The channel stability over both long and short time scales is important for choosing rate because SNR at one time may not correlate with SNR at another time. The network data shows, however, that the success of a packet is a good indicator of the next packet's success even when the packets are seconds or minutes apart.

We propose Dynamic Rate Adaptation and Control for Energy Reduction (DRACER): an addition to the 802.15.4 specification adding 500kb/s, 1000kb/s and 2000kb/s data rates to the existing 250kb/s along with a media access layer (MAC) extension to select the appropriate data rate. A biorthogonal coding scheme preserves the hardware simplicity captured in the original standard while providing robust error performance. Using link level acknowledgments with the MAC extension, the data rate of the next packet is based on the SNR of the most recent packet. When a packet failure occurs, a simple backoff scheme is used to restore communication. This allows for data rate to be highly adaptable and managed on a per-link basis without the input of a centralized manager.

The total network energy consumption is extracted from a model based on the reference network data and compared to the total network energy when the variable rate scheme is applied showing significant savings in average network power. DRACER also reduces contention in the network between

competing users by minimizing the occupied channel time, and it could be used to lower latency and increase the network data capacity.

This paper continues in section II with an explanation of the DRACER protocol for variable data rates in wireless networks. Section III discusses the network experiment and the resulting data on channel conditions. A description of the implementation of the proposed protocol with an explanation of the rate selection and control mechanism is presented in Section IV. The performance of the proposed scheme is then compared to the legacy scheme in Section V.

II. Wireless Data Coding

The maximum data throughput in a wireless channel at a fixed bandwidth is a function of the SNR and the signal coding. Most paths in a typical network have SNR in excess of what is needed for reliable communication, and this excess SNR can be exploited to increase the throughput by changing to a higher rate code. In this section the IEEE 802.15.4 legacy coding scheme and a proposed variable rate scheme are introduced followed by a discussion of the performance of these methods.

A. IEEE 802.15.4

The legacy 802.15.4 coding scheme uses pseudo-orthogonal codes where $k = 4$ bits are encoded together into a $n = 32$ chip signal for a code rate $k/n = 1/8$. These pseudo-orthogonal codes provide good spectral characteristics and autocorrelation properties with only a small reduction in performance compared to orthogonal coding. The raw signaling is carried out using offset quadrature phase shift keying with half sine shaping (OQPSKHSS) at a rate of 2Mchip/s. The 1/8th rate coding then results in a throughput of 250kb/s. The standard specifies that the receiver sensitivity be measured at a packet error rate (PER) of 1% for packets that have a 20B PHY payload plus the 6B of PHY header for a total of 52 symbols. Because a single symbol error results in a packet error, specifying a PER requirement is equivalent to specifying a symbol error rate (SER) at fixed packet length. The required SER is given by

$$SER = 1 - (1 - PER)^{1/m} \tag{1}$$

where m is the length of the packet in symbols. The required SER is thus 1.9×10^{-4}. The maximum packet length allowed by the standard is a total of 133B. Rearranging equation 1 for PER based on this maximum packet length, the acceptable PER for maximum length packets is 5.0%.

B. Proposed Additional Coding Schemes

The proposed Dynamic Rate Adaptation and Control for Energy Reduction (DRACER) uses two additional coding modes with $k/n = \{1/4, 1/2\}$ and a raw mode without coding to add data rates of 500kb/s, 1000kb/s and 2000kb/s to 802.15.4 wireless sensor networks.

Orthogonal codes are attractive for use in the DRACER coding scheme because they require few additions to the legacy baseband detection hardware while adding new data rates. The cross correlation between two codes c_i, c_j is

$$c_i \otimes c_j = \sum_{m=0}^{n-1} c_i(m) \cdot c_j(m), \tag{2}$$

where the elements of $c_{i,j}$ are from the set {-1, 1} and n is the length of the code. It follows that the autocorrelation of a code $c_i \otimes c_i = n$. An orthogonal code set is one in which the cross correlation between any two different codes $c_i \otimes c_j = 0, i \neq j$.

There are two options for increasing code rate k/n: 1) increase the number of bits per symbol k while maintaining a symbol length of $n = 32$, or 2) keep $k = 4$ bits per signal and decrease the symbol length n. Increasing k increases the coding gain thereby improving performance, but the search space at the detector grows as 2^k, quickly making this method intractable. The second option decreases the symbol energy to improve throughput yielding somewhat lower performance, but it keeps the search space the same size as the legacy system, maintaining the low hardware complexity intended by the standard.

Biorthogonal codes are formed by taking an orthogonal code set C of k' bits per symbol and inverting all of the code values to yield a new code set $\bar{C}$. The union of C and $\bar{C}$ is a biorthogonal code set with $k = k' + 1$ bits per symbol. Two codes that are biorthogonal have a cross correlation of $-n$ from equation 2, and a single correlator is required to detect two symbols now instead of just one. Biorthogonal codes exhibit slightly better symbol error performance than orthogonal codes (due to the increased average hamming distance between codes) and require half the search space in the detector for the same value of k [7].

The legacy codes exhibit some characteristics that make the design of the physical layer simple. The codes are all DC balanced, that is the sum of each code word is 0, and no code word has more than 6 of the same value in a row. These characteristics ease baseband signal detection. The 16 code words are all related by circular shifts and bit masking operations reducing code storage space and simplifying the construction of the correlator.

The characteristics of the legacy codes can be largely maintained when using a biorthogonal code set. For the 500kb/s case, codes of length $n = 16$ are used with $k = 4$, and 8 orthogonal, DC balanced code words are selected with no more than 6 consecutive chips of the same value. The remaining 8 codes are found by flipping each chip in each code word to generate the 16 biorthogonal codes. At 1000kb/s, code words of length $n = 8$ must be used. It is not possible to find 8 DC balanced orthogonal code words, but 4 DC balanced words and 4 words with a (6,2) balance can be found. These 8 words are again inverted to generate the remaining 8 words. Any combination of these code words will not yield more than 6 chips of the same value in a row. Although the DC balance is not maintained, no long stretch of single-valued chips is possible, and the code set as a whole is balanced. Importantly, this biorthogonal coding scheme can use the same

TABLE I
DRACER CODE WORDS

Code Word	500kb/s	1000kb/s
0	0x221E	0x4E
1	0x88B4	0xD7
2	0xEE11	0x82
3	0x44BB	0x1B
4	0xD22D	0x8D
5	0x7887	0x14
6	0x1E22	0x41
7	0xB488	0xD8

limited hardware available in the legacy system with only a change of correlation coefficients. The first 8 codes for the sets for 500kb/s and 1000kb/s are shown in table I after being converted into hexadecimal, and the second 8 codes can be generated by flipping each code chip. At 2000kb/s there is no guarantee of DC balance or maximum length string of identical bits because no coding occurs at this rate.

C. Coding Scheme Performance

The performance of the chosen coding scheme can be evaluated by considering both the energy per bit to noise ratio (E_b/N_0) required for a certain error performance and the minimum SNR, the ratio of signal power P_s to noise power P_n, for a given error performance. The standard metric for performance of a coding and modulation scheme is E_b/N_0 because it shows how efficient the scheme is at sending information in a noisy environment given the bandwidth of the channel. The designer of a PHY implementation, however, is concerned with SNR as this is the quantity that defines receiver sensitivity and is easiest to consider when designing radio components. These numbers are heavily dependent not only on the coding scheme but also on the detection scheme and correlation method used. Coherent detection of OQPSKHSS at baseband is possible, but the most common scheme is to demodulate at a low intermediate frequency (IF) using a non-coherent FSK detector. A significant noise penalty exists between the ideal coherent detection and the non-coherent FSK methods, but the design simplification is usually considered to be worth the performance penalties. The receiver correlator for symbol selection used soft decisions in the experimental network, and the complexity of using soft decisions in orthogonal coding schemes is small. In our performance evaluation we assume non-coherent FSK chip detection and soft decision symbol selection because these choices are popular in 802.15.4 radios including the radios used in the experimental network [8].

For orthogonal signaling and non-coherent FSK detection, the symbol error probability as a function of SNR is given by

$$pe_s = \frac{2^k - 1}{2} \cdot \exp\left(-\sqrt{\left(n \times \frac{SNR}{2}\right)}\right). \qquad (3)$$

This equation is an upper bound for the biorthogonal coding used here for 500kb/s and 1000kb/s. The symbol error rates

TABLE II
SNR AND E_b/N_0 REQUIREMENTS

Data rate	Coding scheme	Minimum SNR required (dB)	E_b/N_0 required (dB)
250 kb/s	802.15.4	8.3	17.3
500 kb/s	Biorthogonal	10.9	16.9
1000 kb/s	Biorthogonal	13.9	16.9
2000 kb/s	Raw	22.3	22.3

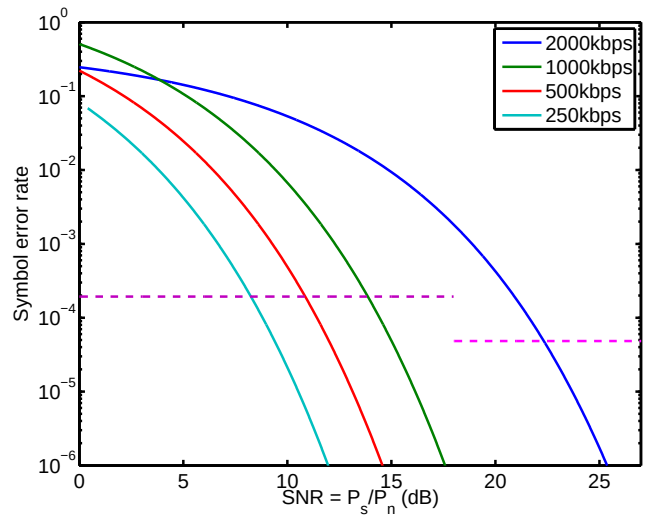

Fig. 1. A waterfall plot showing symbol error rates using legacy 250kb/s 802.15.4 coding and 500 and 1000kb/s biorthogonal coding and bit error rate of 2000kb/s raw coding across SNR. The horizontal dashed line indicates the minimum acceptable error rates to meet the 802.15.4 PER specification.

for all four rates are shown in figure 1. The permitted error rate is different between the coded rates and the raw rate because of the difference between symbol errors and bit errors. There is a 2.6dB difference in required SNR for the 500kb/s and 250kb/s cases, and (3) suggests a 3dB difference. The legacy codes are not orthogonal resulting in this 0.4dB penalty. The required SNR and E_b/N_0 for each of the four schemes is shown in table II.

III. EXPERIMENTAL WIRELESS NETWORK SETUP AND MEASUREMENTS

A. Setup

Data collected from a Dust Networks test network deployed in an industrial environment is used in this paper to analyze the performance of a typical 802.15.4 wireless network, and this network was originally reported in [6]. The nodes consisted of a microcontroller, CC2420 radio [8], and +15dBm power amplifier. The network was deployed in a three story building where each floor is 76m x 70m, and the building houses the offices and production equipment for a printing factory. A single network manager (data sink node) was placed on the 3rd floor, and the 44 nodes were connected to the manager using a time synchronized, frequency hopping, multi-hop, mesh network [9]. Each node recorded data regarding the conditions on each

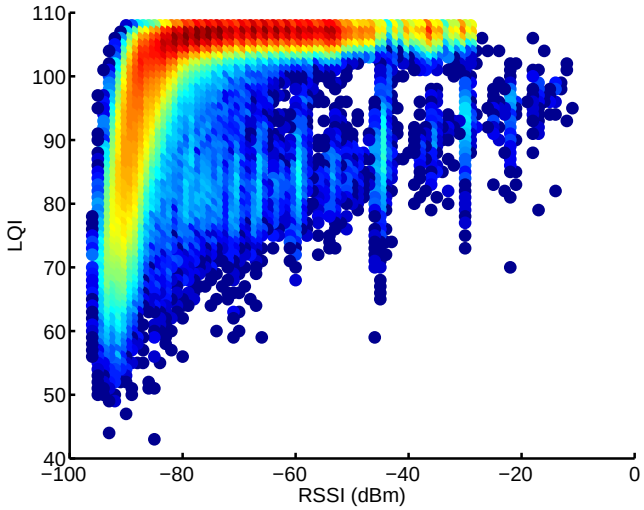

Fig. 2. The number of links at a given RSSI and LQI is shown in this density plot. Red points indicate numbers on the order of 10^4 while blue points indicate numbers on the order of 10^0.

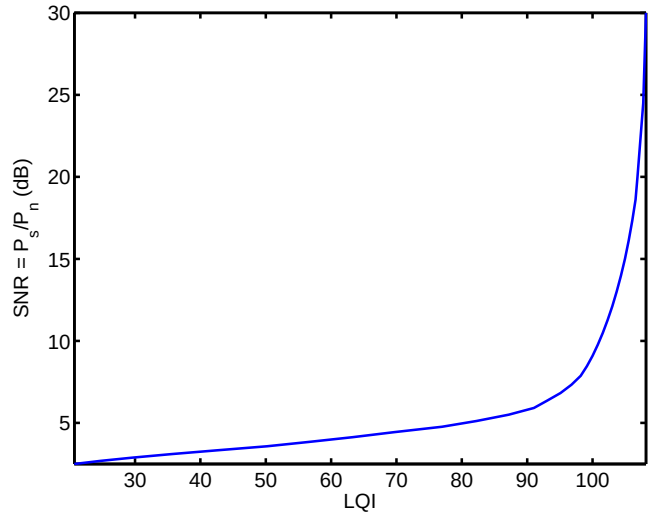

Fig. 3. Simulation results returning LQI across SNR can be inverted to predict SNR given LQI, as shown in this plot. At high SNR, the integer-level granularity of LQI results in lower SNR resolution.

link to its neighbors at the 16 carrier frequencies specified by the 802.15.4 standard. This information was collected every 15 minutes from each node and included packet error rates, received signal strength, and link quality. Each packet was 133B long including the preamble, and about 9 million successful packet transmissions and receptions occurred in the network during the 26 day study period. For this discussion a path-channel will refer to a data connection between two nodes at a particular carrier frequency, and a link represents a path-channel with conditions averaged over a particular 15 minute interval.

B. Measurements

Every successful packet received by the CC2420 returns two measures of path conditions. The received signal strength indicator (RSSI) measures the signal power P_s and is given in dBm. The link quality indicator (LQI) is a less specifically defined number, but is often thought of as a measure of chip error rate (CER). For the CC2420, which uses soft decisions, the LQI is more precisely a measure of SNR (P_s/P_n). A density plot showing the number of links returning specific RSSI and LQI values is shown in figure 2.

This plot shows that the vast majority of links lie on a single curve, monotonic in LQI with respect to RSSI. The width of this curve shows the variability in noise floor across time and channels and differing noise performance across devices. Off of this main curve, there are additional curves containing a number of links of high RSSI with notably lower LQI. These curves indicate the presence of in-band interferers artificially increasing the noise power P_n, lowering the SNR. While the signal power itself remains high, there is greater probability of error in these regions. It is useful to note though that there are far fewer links in these high-noise curves; the deployed system contained only very sporadic interference.

The 802.15.4 standard does not specify how the LQI is calculated, but the CC2420 datasheet provides information to map LQI to SNR. The datasheet specifies that soft decisions are used in the correlator, a low-IF receiver architecture is used, and that the average correlator output for 8 symbols from the preamble are averaged to calculate LQI. It is known that 3 bit quantization for soft decisions is standard design practice, and the maximum LQI output in the CC2420 case is $LQI_{max} = 8 \cdot ((2^3) - 1)/16 = 112$. This value agrees with the datasheet and experimental data. Once the method for the calculation of LQI is known, a simulation can be run using a noncoherent FSK detector and many preambles while varying SNR. The resulting data is a function that maps SNR to LQI, and inverting this function provides the desired map of LQI to SNR shown in figure 3. The mapping of LQI to SNR shows two distinct regions. When the LQI is a low value, the LQI and SNR are linearly related with a low slope. As the LQI approaches its maximum value, the received signal is very close to the ideal code. Due to dynamic range and bandwidth limits in the receiver, higher LQIs represent significantly more SNR. Due to the integer granularity on the LQI, the SNR change from one high LQI value to the next can be quite large.

An important performance metric in wireless sensor networks is packet error rate (PER). Equations 1 and 3 and figure 1 showed how SNR directly related to PER. Thus, it makes sense when considering link performance to examine the LQI as opposed to RSSI. In fact, looking at a slice across the link density plot in figure 2 at a constant RSSI, the link SNR is observed to be bimodal. Figure 4 shows the presence of a high-noise interferer resulting in low SNR despite high signal power. Estimating performance from RSSI for links in the lower hump would then result in higher than expected error rates. Again, there are considerably fewer links exhibiting this interference in the network considered here, however, other

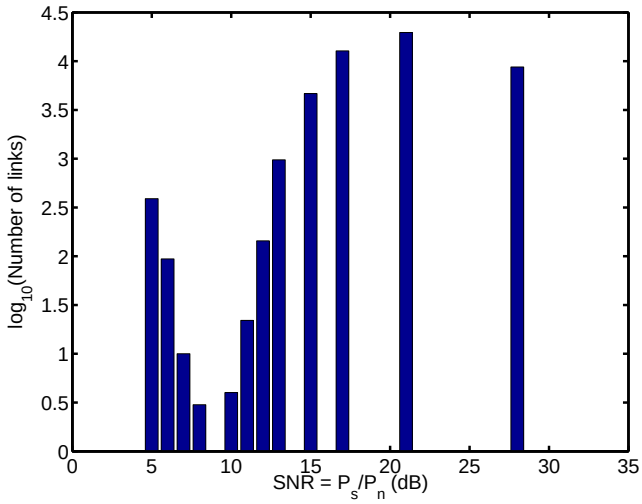

Fig. 4. A histogram of links across SNR at constant RSSI = -62 dBm shows bimodality derived from interference. The spacing towards high SNR is an artifact of the reduced resolution at high LQI.

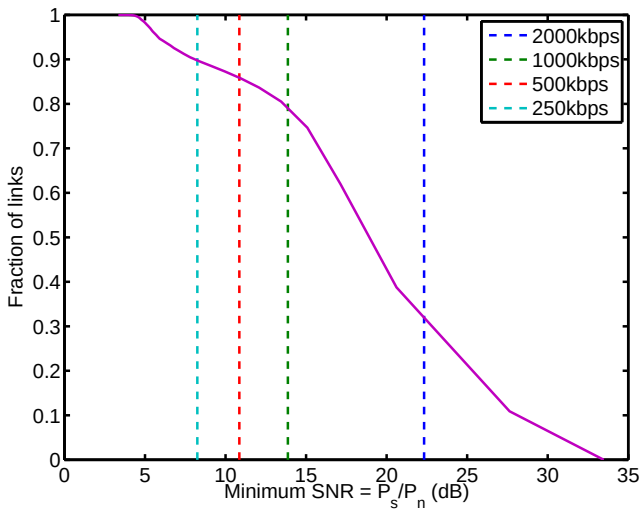

Fig. 5. The complimentary CDF shows the fraction of links in the network having SNR greater than indicated. The vertical dashed lines show the minimum SNR threshold given legacy 250kb/s 802.15.4 coding, 500 and 1000kb/s biorthogonal coding, and 2000kb/s raw schemes.

networks may be more heavily interference dominated.

C. Network Analysis

An aggregate indication of link quality in the network can be made by looking at the complimentary CDF of the SNR across all links in the network, as shown in figure 5. It is clear that most of the links contain significant excess SNR, which can be exploited to send data at higher bit rates using the DRACER protocol described above. The minimum SNR required to meet the 802.15.4 PER specification for the various data rates and the fraction of links exceeding that SNR are shown in table III.

The link quality can also be correlated across time. The packet error rate is measured for each link in the network.

TABLE III

Bit rate	Coding scheme	Minimum SNR required	Percent of links meeting SNR_{min}
250 kb/s	802.15.4	8.25	90%
500 kb/s	Biorthogonal	10.86	86%
1000 kb/s	Biorthogonal	13.87	79%
2000 kb/s	Raw	22.33	30%

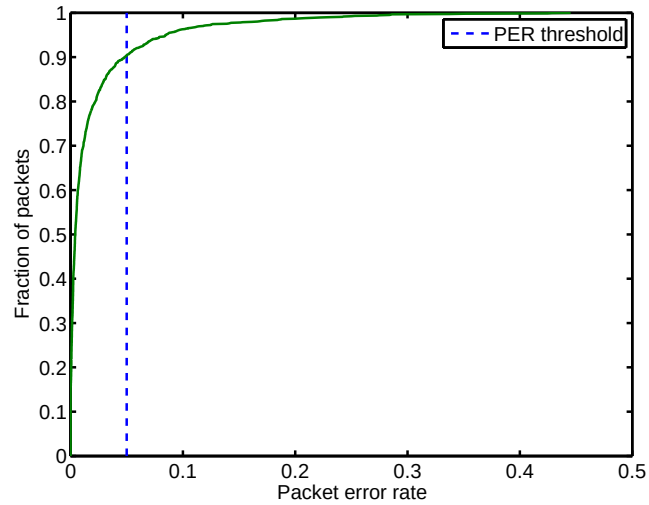

Fig. 6. The CDF of average PER across path-channels in the network following an error free time interval. The vertical dashed line indicates the minimum acceptable PER.

A CDF of the average PER in the 15 minute time interval following an error free time interval is shown in figure 6. This indicates that channels are mostly stable over time; 90% of the time, an error free interval is followed by another successful interval. The data collected in the network only resolves down to 15 minute granularity; with packets sent at faster rates, it stands to expect that a packet transmitted following a successful transmission will also be successful.

IV. Implementation of Variable Data Rate Coding

The implementation of the DRACER protocol can be accommodated in the PHY and MAC layers. The PHY changes include the inclusion of additional code sets at both the transmitter and receiver and automatic detection of the incoming data rate at the receiver. The MAC can automatically select data rate based on RSS or LQI information. Control over rate can be passed to higher levels if needed by the application, but automatic selection reduces the complexity of implementation by abstracting the communications scheme away.

The PHY must recognize the intended data rate of the incoming packet so that the appropriate detection scheme can be used. The legacy standard specifies a synchronization header to start each packet consisting of a preamble of eight 0 symbols followed by a two symbol start frame delimiter (SFD). We retain the same legacy preamble enabling the receiver to always start in legacy mode, easing the burden on initial synchronization. Four different SFDs are selected

TABLE IV
VARIABLE DATA RATE START FRAME DELIMITERS (SFDS)

Data rate	SFD byte value
250kb/s	0xE5
500kb/s	0x1A
1000kb/s	0x86
2000kb/s	0x94

from the legacy codes to denote each of the four data rates where the SFD for 250kb/s is the same as the legacy case. When the receiver detects a particular SFD, it changes the reference code set and code length used for symbol selection thereby changing the data rate. Because the signaling rate is slow compared to the speed of electronics, changing the code set between symbols is not a concern. The selected SFDs are shown in table IV. The selection of particular SFDs does not impact performance as long as they are unique for each data rate.

Devices able to select the appropriate rate without higher layers in the stack being involved will reduce the network organization overhead. An unused bit in the PHY packet length field can be changed from 0 to 1 to denote a radio capable of higher rate communication. When this flag is set acknowledgments (ACKs) must be enabled either in the standard MAC or in a MAC augmentation so that both radios in a link are able to measure channel conditions for each packet sent. Initial communication occurs at the legacy rate, and either the RSS or LQI is used as an estimate of channel capacity. LQI provides better performance in the presence of interference, but the conversion from LQI to available capacity is not always known. It was shown that over time scales of minutes, the typical channel characteristics remain similar with high probability. Therefore the best predictor of the current channel is simply the conditions seen by the last packet. Regardless of current data rate, the rate for the next packet is selected based on the most recent RSS/LQI at that frequency and for that point to point link. Packets sent at different carrier frequencies or on different point to point links are not correlated and are not used as a reference for rate selection. The thresholds for selecting the appropriate data rate can be derived from the network model, as in section V-C.

Failure to receive an ACK for the packet results in its retransmission, and there are a variety of options for retransmitting a packet sent at a higher data rate. The transmitter could continue to send at the higher data rate until it is successful, with no backoff in rate (backoff scheme A in table VI below). Alternately, the transmitter could back off a little, and upon a packet failure drop down one data rate and transmit on that until receiving an ACK (backoff scheme B). The transmitter could also back off all the way, and upon a single packet failure drop to the legacy 802.15.4 coding (backoff scheme C). Finally, the transmitter could slowly back down to the 802.15.4 rate, trying once at each higher data rate (backoff scheme D). Different network conditions may require different strategies: in networks primarily dominated by multipath fading and noise, a gradual backoff will provide the best performance, while in networks primarily dominated by interference from other RF devices, maintaining higher data rates (and therefore shorter packets) can reduce the number of collisions and improve performance. In the following performance evaluation, different back off schemes are shown to provide similar performance.

TABLE V
RELEVANT COMPONENT POWERS AND TIME REQUIREMENTS AT VARIOUS BIT RATES

	Microprocessor	Radio RX	Radio TX
Power consumption	9 mW	66 mW	150 mW

	Component on time in ms			
Event	250kb/s	500kb/s	1000kb/s	2000kb/s
Packet TX	4.26	2.19	1.18	0.67
Successful Packet RX	5.26	3.19	2.18	1.67
Failed Packet RX	2.00	2.00	2.00	2.00
ACK TX	0.83	0.48	0.32	0.24
Successful ACK RX	0.96	0.61	0.45	0.37
Failed ACK RX	0.25	0.25	0.25	0.25

V. PERFORMANCE

In the network examined here, packets are generated at a low enough rate that network congestion is not an issue. As such, impacts on latency and throughput cannot be investigated. However, the overall power consumption of the network can be extracted from simulation, and will be used to demonstrate the effectiveness of the variable data rate scheme.

To calculate the network energy, some network parameters must be known and some assumptions made for simplicity and clarity. The packet transmissions are globally scheduled in the network protocol used here, and as such, the receiver will be listening every time the transmitter attempts to send a packet. If the receiver successfully receives the packet, it will respond with an ACK. The transmitter listens for an ACK after every TX attempt, and it is assumed it will hear one if it is generated. Since the packet success rate was found to be correlated over much longer time scales, it is highly unlikely that an ACK will not be heard. There are a fixed number of packets that need to be sent over each link, and each will be retransmitted until they have all gone through. Finally, the microprocessor will be running during any TX or RX, with an additional 10% overhead for required synchronization and logic. The time each component needs to be on for all network events is shown in table V, which can then be applied to derive energies.

A. Legacy performance

The data returned from the network gives us the number of TX attempts and the number of ACKs received. Using the assumptions listed above, the amount of time spent in TX and RX for each node can be calculated, and the total energy of all nodes other than the base station can be extracted. This

TABLE VI
PERCENT ENERGY SAVINGS

Backoff scheme	LQI thresholding	RSSI thresholding
A	33.8%	23.8%
B	38.7%	24.4%
C	40.1%	38.9%
D	41.0%	39.6%

value is 15.0 kJ which is an average power of 5.9mW for the entire network or 135μW per node.

B. Model setup

To evaluate the variable data rate scheme proposed, the network needs to be simulated. As mentioned above, a fixed number of packets must be sent over each link, and will be retransmitted upon failure. This number is taken as the number of successful ACKs received over each link from the network data. The total packet error rate of each link pe_{tot} is also taken from the network data. This error rate can be divided into two components, errors due to interference and errors due to insufficient SNR. That is, Pr{Packet success} = Pr{No interference} * Pr{Sufficient SNR}, or

$$1 - pe_{tot} = (1 - pe_i)(1 - pe_{SNR}). \quad (4)$$

The PER due to SNR pe_{SNR} can be calculated from equations 1 and 3 using the LQI taken from the network data, and thus the interference based PER pe_i can be inferred. This can be combined with the SNR-based PER calculated for the alternate coding schemes to yield the total PER at each of the four bit rates. This value can then be applied to packet transmission as a Bernoulli process, and the expected number of TX failures can be estimated. This model for the network using only 802.15.4 coding necessarily yields the same packet behavior as the true network.

C. Performance of proposed scheme

We can now use this model to evaluate the schemes described in section IV. The intended data rate for each link is computed from either the LQI or RSSI in the previous link, thresholded to predefined limits for each of 250, 500, 1000, and 2000 kb/s. Considering the packet success behavior as a Bernoulli trial with success probability calculated from the LQI and interference based packet success rate of the current link, the number of packet success and failures at each of the data rates can be computed for the different back off schemes. The thresholds were set to the minimum energy configuration in each case. The overall network energy savings of the data rate schemes with various thresholding and backoff options are presented in table VI.

In particular, one scheme was able to achieve 41% energy savings against the legacy system:

- If the previous time period's LQI was 99 or less, only attempt to send packets at the legacy 802.15.4 rate.
- If the previous time period's LQI was between 100 and 103, attempt to send one packet at 500kb/s. If it fails, send the remaining packets at the legacy 802.15.4 rate.
- If the previous time period's LQI was 104 or above, attempt to send one packet at 1000kb/s. If it fails, try once more at 500kb/s. If both fail, then send the remaining packets at the legacy 802.15.4 rate.

TABLE VII
ENERGY SAVINGS COMPARISON BETWEEN PA SCALING AND VARIABLE DATA RATE

Data Rate	Additional SNR Required	PA Scaling Savings	Variable Rate Savings
250kb/s	0 dB	0%	0%
500kb/s	2.6 dB	16%	48%
1000kb/s	5.6 dB	31%	72%
2000kb/s	14.1 dB	55%	84%

The 2000 kb/s raw rate was never used in this simulation due to its high SNR requirement. Though there are links with an LQI of 108, sufficiently ample for raw data transmission, the decision is based on the previous time interval, and links with an LQI of 108 rarely stayed as such during the following time interval. It is probable that with a finer time resolution, packets transmitted at 2000 kb/s would be more successful for additional savings.

A histogram of the energy savings per node using LQI thresholding with backoff scheme D is shown in figure 7, and is plotted against that node's usage in figure 8. It is clear to see that in general, the more used nodes save more energy and therefore contribute greater savings to the overall network. Thus, we would expect that as a wireless network scaled up in size and data traffic, the proposed variable data rate scheme would contribute greater energy savings, allowing for networks robust to continued growth.

An alternate way of exploiting the excess SNR to reduce power consumption could be to lower the output power of the power amplifier (PA) of the radio transmitter. However, the efficiency of a PA decreases quickly with decreasing output power; for example, an 8x reduction in transmitted power results only in a 40% savings in consumed power. A look at table VII indicates that when power savings for a single packet are calculated based on PA efficiencies, varying the data rate has much greater energy saving potential.

VI. RELATED WORK

The prior work in rate adaptation is helpful in understanding the problems faced by variable rate systems, choosing a coding scheme, and in optimizing network performance. The selection of data rate in IEEE 802.11, Bluetooth and other networks has seen a significant amount of attention, and the focus has been on reduced latency or increased throughput [4], [10]–[12]. Reducing the network energy consumption is the most important metric for wireless sensor networks even though latency and throughput can be important in some cases [13]. Many of the studies that do exist are not based on measured data, and those that are use sets that are much smaller than considered here. Energy has been considered in point to point links, but data from physical networks is not considered and

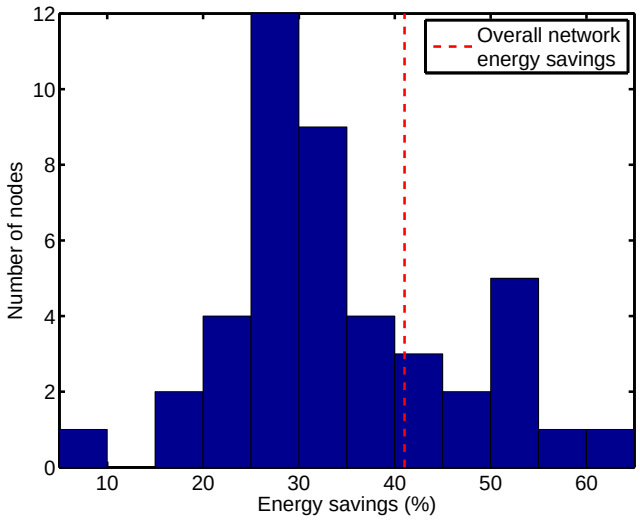

Fig. 7. A histogram of energy savings per node shows a median far below the overall network energy savings, indicating that the nodes saving the most energy contribute more to the overall network savings.

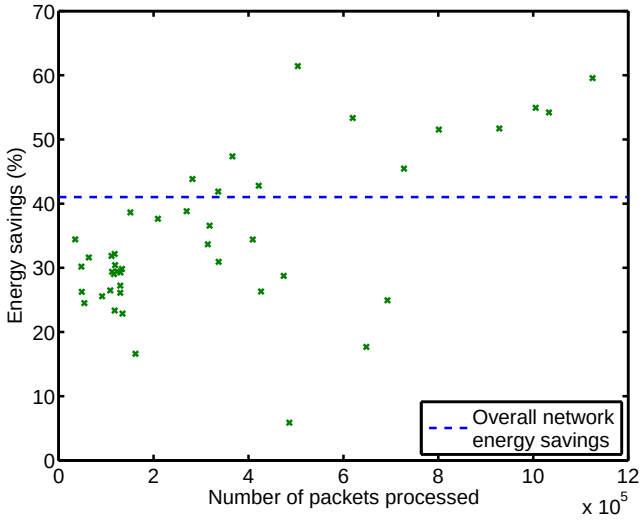

Fig. 8. A plot of each node's usage versus its energy savings show that in general, the more a node is used, the greater potential energy it can save from variable bit rate.

energy is not the dominant metric [14], [15]. Variable rate wireless sensor networks have been considered for improving routing algorithms with throughput and congestion as the motivation [1], [16].

VII. Conclusions

Wireless sensor network physical layers should use variable rate signaling that adapts to the environment or significant power is wasted transmitting and receiving packets. In this paper we propose using variable rate signaling in wireless sensor networks as a way to reduce the average network power consumption, and we further propose the DRACER protocol to provide 3 additional rates to the existing 802.15.4 coding scheme. This protocol provides for 250kb/s, 500kb/s, 1000kb/s and 2000kb/s data with automatic rate selection based on the observed performance of the previous packet. Through a measurement based study of a 44 node network, we show an estimated 40% average power savings using our variable rate system, and we show that savings are best when the LQI, a measure of SNR, is used to determine data rate. This work focuses on reducing the average network power through the use of an adaptive rate coding scheme for 802.15.4, but the reduced channel occupancy also reduces congestion in the shared spectrum improving performance for other users.

VIII. Acknowledgments

The authors would like to thank Lance Doherty and Dust Networks for the use of their network data.

References

[1] M. Dohler, T. Watteyne, F. Valois, and J. Lu, "Kumars, zipfs and other laws: How to structure a large-scale wireless network?" *Annals of Telecommunications*, 2008.

[2] "IEEE std 802.15.4-2006: Wireless medium access control (MAC) and physical layer (PHY) specifications for low-rate wireless personal area networks (WPANs)," http://ieeexplore.ieee.org/servlet/opac?punumber=11161.

[3] "Specification of the bluetooth system: wireless connections made easy," http://www.bluetooth.com/NR/rdonlyres/F8E8276A-3898-4EC6-B7DA-E5535258B056/6545/Core_V21__EDR.zip.

[4] J. Zhang, K. Tan, J. Zhao, H. Wu, and Y. Zhang, "A practical SNR-guided rate adaptation," in *INFOCOM 2008. The 27th Conference on Computer Communications. IEEE*, Apr. 2008, pp. 2083–2091.

[5] L.-J. Chen, R. Kapoor, M. Y. Sanadidi, and M. Gerla, "Enhancing bluetooth TCP throughput via link layer packet adaptation," in *Communications, 2004 IEEE International Conference on*, vol. 7, Jun. 20–24, 2004, pp. 4012–4016.

[6] L. Doherty, W. Lindsay, and J. Simon, "Channel-specific wireless sensor network path data," in *Computer Communications and Networks, 2007. ICCCN 2007. Proceedings of 16th International Conference on*, Aug. 2007, pp. 89–94.

[7] J. Proakis, *Digital Communication*, 3rd ed. McGraw Hill, 2001.

[8] "CC2420 2.4 GHz IEEE 802.15.4 / ZigBee-Ready RF tranceiver," http://focus.ti.com/lit/ds/symlink/cc2420.pdf.

[9] "Technical overview of time synchronized mesh protocol (TSMP)," http://www.dustnetworks.com/docs/TSMP_Whitepaper.pdf.

[10] L.-J. Chen, R. Kapoor, M. Y. Sanadidi, and M. Gerla, "Enhancing bluetooth TCP throughput via link layer packet adaptation," in *Communications, 2004 IEEE International Conference on*, vol. 7, Jun. 2004, pp. 4012–4016.

[11] B. S. Kim, Y. Fang, and T. F. Wong, "Rate-adaptive MAC protocol in high-rate personal area networks," in *Wireless Communications and Networking Conference, 2004. WCNC. 2004 IEEE*, vol. 3, Mar. 2004, pp. 1394–1399.

[12] S. H. Y. Wong, H. Yang, S. Lu, and V. Bharghavan, "Robust rate adaptation for 802.11 wireless networks," in *MobiCom '06: Proceedings of the 12th annual international conference on Mobile computing and networking*. New York, NY, USA: ACM, 2006, pp. 146–157.

[13] A. El Fawal, J. Y. Le Boudec, R. Merz, B. Radunovic, J. Widmer, and G. M. Maggio, "Trade-off analysis of PHY-aware MAC in low-rate low-power UWB networks," *IEEE Communications Magazine*, vol. 43, no. 12, pp. 147–155, Dec. 2005.

[14] C. E. Luna, Y. Eisenberg, R. Berry, T. N. Pappas, and A. K. Katsaggelos, "Joint source coding and data rate adaptation for energy efficient wireless video streaming," *IEEE Journal on Selected Areas in Communications*, vol. 21, no. 10, pp. 1710–1720, Dec. 2003.

[15] L. Alonso and R. Agusti, "Automatic rate adaptation and energy-saving mechanisms based on cross-layer information for packet-switched data networks," *IEEE Communications Magazine*, vol. 42, no. 3, Mar. 2004.

[16] Y. T. Hou, Y. Shi, J. H. Reed, and K. Sohraby, "Flow routing for variable bit rate source nodes in energy-constrained wireless sensor networks," in *Communications, 2005. ICC 2005. 2005 IEEE International Conference on*, vol. 5, May 2005, pp. 3057–3062.