Multi-Rate Polling: Improve the Performance of Energy Harvesting Backscatter Wireless Networks

Yu Han[1, *], Wenxian Zheng[2], Guangjun Wen[1], Chu Chu[1], Jian Su[3] and Yibo Zhang[4]

Abstract: In recent years, Researchers have proposed the concept of Energy Harvesting Backscatter Wireless Networks (EHBWN). EHBWN usually consists of one sink and several backscatter nodes. Backscatter nodes harvest energy from their environment and communicate with sink through backscattering the carrier wave transmitted by sink. Although a certain amount of access protocols for Energy Harvesting Wireless Networks have been present, they usually do not take the sink's receiver sensitivity into account, which makes those protocols unsuitable in practice. In this paper, we first give an analysis of the backscatter channel link budget and the relationship between the effective communication range and uplink data rate. After that, we point out that a single uplink data rate for all the backscatter nodes is no longer suitable due to the constraint of sink receiver sensitivity. Later we propose Multi-rate Polling which divides the network into different uplink data rata regions to make sure the correct packet reception by the sink and improve the network performance. Multi-rate Polling also introduces a parameter K, through adjusting it, we can achieve the trade-off between network throughput and fairness to meet the requirement under various scenarios. We validate Multi-rate Polling under different networks and average harvesting rates through simulation. The result shows that the proposed protocol can effectively improve the network performance and has excellent scalability, which makes it suitable for EHBWN.

Keywords: Energy harvesting, data rate, mac protocol, multi-rate, backscatter.

1 Introduction and motivation

Energy supply is one of the most critical issues of modern wireless networks [Wei, Heidemann and Estrin (2002)]. Traditional network nodes use regular batteries for power. Once the energy depleted, the node is "dead", which will reduce the system performance. To solve this problem, researchers introduced the concept of Energy Harvesting Wireless Networks (EHWN). In EHWN nodes can harvest energy from their surrounding environment and use the collected energy to power themselves [Eu, Seah and Tan (2008); Basagni, Conti, Ciordano et al. (2013)]. Nodes in EHWN do not need the battery and

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have unlimited working time in theory.

Despite the significant advances of EHWN in the last few years, there are still two drawbacks which restrict the performance of EHWN:

—Different power sources have different power densities, in some application scenarios the energy which node can harvest is very weak. For example, when using photovoltaic technology, the indoor power density is usually less than 10 μW/cm^2. The situation becomes worse when using RF energy harvesting. In Triet et al. [Triet, Mayaram and Fiez (2008)] when the distance between RF source and node is 15m, the energy harvesting power is only 5 μW.

—Most network node uses conventional power-hungry RF transceiver to communicate with sink. Commercial RF transceivers usually cost much more power than nodes can harvest. For example, the low power 2.4 GHz RF transceiver chip CC2500's power will be more than 30 mW in both receiving and transmitting.

The huge miss-match of energy harvest and cost will compel nodes to work in a very low duty-cycle, thus restrict the performance of EHWN. To solve this problem, researchers use ultralow power backscatter communication to reduce the working power of nodes. Through backscattering, nodes do not emit RF signal to transmit data. Instead, they utilize the RF carrier transmitted by sink to modulate their data and backscatter the modulated signal to sink. The receiver of backscatter nodes usually uses simple structures, and the power cost is ultralow. The transmitter of the backscatter node only needs a transistor which consumes less 1 μW power with 1Mbps data rate, which can be neglected.

Backscatter communication can effectively reduce the power of nodes. However, it brings some challenges both to sink and nodes. For nodes, because the structure of the receiver is simple, the node cannot detect other nodes' transmission. Mac protocols using CSMA strategy will not be able to use in this network; For the sink, the phase noise of the leakage from the transmit road will increase the difficulty of demodulation [Boaventura, Santos, Oliveira et al. (2016)], thus decreases the receiver sensitivity. What's worse, the backscatter communication suffers the "double-decrease" character, which means the received power of sink will be double reduced compared with the received power of nodes due to the increase of communication range. *With the improvement of nodes' receiver sensitivity, the limitation of the network communication distance has changed from nodes to sink.*

Consider a single-hop wireless network using backscatter communication. Sink transmits a constant RF carrier to all the nodes in the network. Because of the different distances between sink and nodes, the received backscatter signal power from different nodes will suffer a huge difference at the sink side. Due to the limitation of the sink's receiver sensitivity, different nodes should have different uplink data rates to guarantee the successful reception. However, to the best of our knowledge, most of the mac protocols designed for wireless networks ignored the physical difference between sink-node pairs and assigned a single data rate to all the network nodes [Fafoutis and Dragoni (2011); Naderi, Nintanavongsa and Chowdhury (2014); Eu, Tan and Seah (2011)], which is not suitable for EHBWN:

—If the sink assigns a high uplink data rate for all nodes, then the long-range node's data packet will not be received correctly due to the limitation of sink receiver sensitivity. Thus, the network coverage and fairness will be decreased. What's worse the fault packet may disturb the reception of packets sent from short-range nodes by collision, which reduces the network throughput.

—If the sink node assigns a low uplink data rate for all nodes, the long-range node's reply will be correctly received. However, the network will not make the full use of uplink channel capacity of short-range nodes which support a relatively high data rate. The network's ability will not be fully utilized.

There are some speed selection schemes used for Wi-Fi networks [Lacage, Manshaei and Turletti (2004); Rahul, Edalat, Katabi et al. (2009)]. However, Wi-Fi uses CSMA as their basic media access principle, which is not suitable for backscatter network. In recent years researcher proposed several schemes [Zhang, Gummeson and Ganesan (2012); Gong, Liu, Ma et al. (2016); Gong, Liu, Fan et al. (2018)] of data rate selection used for the RFID system. Unfortunately, all of them are based on the slotted aloha protocols which require nodes be awake during the whole network working time [Chen, Liu, Ma et al. (2018)], thus cannot be used in EHBWN either.

The above problem motivates us to find a solution. The contribution of this paper can be summarized as follows:

1. We give an analysis of the link budget of backscatter communication and calculate the sink receiver sensitivity under different uplink data rates. We point out the correlation between the effective communication range and uplink data rates.

2. Then we propose a media access protocol used for EHBWN named Multi-rate Polling. Multi-rate Polling divides the network working area into several regions. Nodes in different regions use different uplink data rates to upload their data so that the sink can effectively receive the packets with a low error probability.

3. A parameter K is defined. Through adjusting the parameter, the network can change the media access priority of nodes in different regions, thus to help the system make the trade-off between network throughput and fairness.

4. We make a simulation of the proposed Multi-rate Polling protocol with different network sizes and average energy harvesting rates. The result shows Multi-rate Polling can effectively improve the overall network performance and scales well.

The rest of this paper is organized as follows: In Section 2, we give an analysis of the physical constraints of the sink's receiver ability. According to the result of Section 2, we propose the Multi-rate Polling in Section 3. Section 4 shows the simulation results of the proposed protocol. Finally, in Section 5, we conclude the paper.

2 Physical constraints of sink's receiver

2.1 Backscatter link budget

In this paper, we focus on a single-hop energy harvesting wireless networks with one sink and several backscatter nodes. Sink connects with a power line, so it always has enough energy to work continuously and plays a role of data collection. Nodes harvest energy from their surrounding environment and use the collected energy to communicate with sink by backscattering the carrier wave transmitted by the sink.

Fig. 1 illustrates the basic principle of backscatter communication. Instead of transmitting RF signal actively, nodes in backscatter network use a single RF switch to alternate the antenna termination load between two values according to the data needed to send. Different termination load will have different reflection coefficients, thus modulate the data into the backscattered wave with different amplitude and phase. The sink is monostatic for its simplicity and low cost, which means it uses a single antenna for both transmitting and receiving

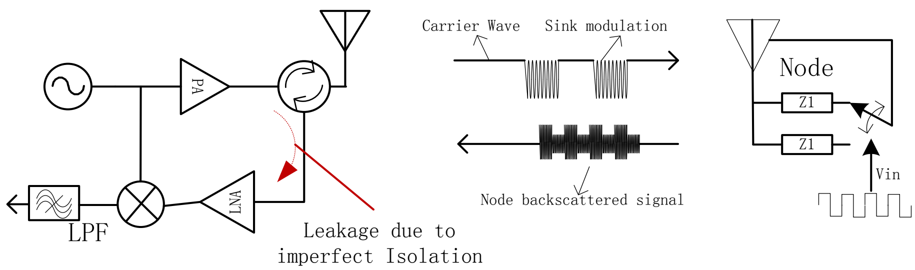


Figure 1: Backscatter communication principle

Let the power sent by sink be P_{reader} and the sink's antenna Gain be G_{reader}. Let λ be the carrier wavelength and G_{node} be the antenna Gain of nodes. Assume the transmission is in free space and the node's antenna is perfected matched. If the distance between sink and nodes is d, Define P_{node} as the power received by node. Using the Friis transmission equation, we have:

$$P_{node} = \frac{P_{reader} G_{reader} G_{node} \lambda^2}{(4\pi d)^2} \tag{1}$$

Let U be the backscatter modulation loss factor. It can be calculated using the following equation [Nikitin and Rao (2008)]:

$$U = \alpha \, |\Gamma_1 - \Gamma_2|^2 \tag{2}$$

where the α is the coefficient depends on specific modulation detailed. Assume that the data has the same probability with 0 and 1, DC block is used at the receiver baseband to remove the DC power. Then α is 0.25. Γ_1 and Γ_2 represent the reflection coefficients of the two modulation states (0 and 1). Then, the power of the modulated node signal received by the sink ($P_{reader,rx}$) can be present by:

$$P_{reader,rx} = \frac{P_{reader} G_{reader}^2 G_{tag}^2 \lambda^4 U}{(4\pi d)^4} \tag{3}$$

2.2 Sink receiver's sensitivity and effective communication range

The monostatic structure will bring the receiving road an unexpected phase noise, which will decrease the receiver sensitivity of the sink. Define $L(\Delta f)$ (dBc/Hz) as the single band phase noise, which represents the ratio between phase noise power in a 1 Hz bandwidth at the frequency offset Δf to the carrier frequency and the power of the carrier. Then the equivalent noise power density at the receiver's input introduced by the leakage be represented by:

$$P_{PN}(\Delta f)(\mathrm{dBm/Hz}) = P_{reader} - ISO + L(\Delta f) + 10\log_{10}[4\sin^2(\pi\Delta f t_d)] \tag{4}$$

where the ISO is the isolation between the transmit and receive road, $10\log_{10}[4\sin^2(\pi\Delta f t_d)]$ is the attenuation due to the range correlation effect [Jang and Yoon (2008)]. t_d means the relative delay between the local oscillator signal and the RF leakage signal, which is usually set to be 10ns in the analysis [Dobkin (2007)].

Define the thermal noise density at the receiver input as P_{TN}, when the environment temperature is 290°K, P_{tn} =-174 dBm/Hz. Let SNR_{min} be the minimum SNR needed to demodulate the signal. Then the receiver sensitivity P_{sen} can be represented by:

$$P_{sen}(\mathrm{dBm}) = 10\lg(10^{P_{TN}} + 10^{P_{PN}}) + NF_{RX} + 10\log_{10} BW_{RF} + SNR_{min} \tag{5}$$

where NF_{RX} is the noise factor in the receiver road, and BW_{RF} is the RF bandwidth of the received signal. Backscatter uplink uses FM0 or Miller-modulator subcarrier (MMS) [EPC Global (2015)] to encode their data. Define the BLF, R_b as the backscatter link frequency and uplink data rate separately. Let B_{MMS} and B_{FM0} be the baseband signal bandwidth. The modulated RF signal bandwidth can be represented by:

$$\begin{aligned} BW_{MMS} &= 2 \cdot B_{MMS} = 8 \cdot R_b = 8 \cdot BLF/M \\ BW_{FM0} &= 2 \cdot B_{FM0} = 4 \cdot R_b = 4 \cdot BLF \end{aligned} \tag{6}$$

Then we can get the relationship between the SNR and E_b/N_0 :

$$\begin{aligned} E_b/N_0\big|_{MMS} &= SNR \cdot B_{MMS}/R_b = 4 \cdot SNR \\ E_b/N_0\big|_{FM0} &= SNR \cdot B_{FM0}/R_b = 2 \cdot SNR \end{aligned} \tag{7}$$

Define P(e) as the error rate at the receiver's output. We can have the following equation according to Simon et al. [Simon and Divsalar (2006)]:

$$P(e) = 2Q\left(\sqrt{E_b/N_0}\right)\left[(1 - Q\left(\sqrt{E_b/N_0}\right))\right] \tag{8}$$

Let S(bytes) be the data packet size, the successful packet receiving rate P(s) is given by:

$$P(s) = (1 - P(e))^{8S} \tag{9}$$

Through Eqs. (4)-(8), we can get that the RF bandwidth will increase with the improvement of the uplink data rate. Thus, the received signal power required to meet the P(e) requirement will grow up with the growing of uplink data rate. *Therefore the receiver's sensitivity appears a negative correlation with the uplink data rate.* Equation (3) shows that the sink received power of backscatter signal will be decreased with the increase of communication range. *Due to the constraint of the receiver's sensitivity, to maintain the packet reception ratio at a right level, we have to assign different uplink data rate to different nodes in the networks according to their distances to sink.*

We fix the BLF at 640 kHz and adjust the uplink data rate R_b by using different M. Five data rates are selected: 640 kbps (M=0 FM0 coding), 320 kbps (M=2 MMS coding), 160 kbps (M=4 MMS coding), 80 kbps (M=8 MMS coding), and 40 kbps (M=16 MMS coding). To make the link timing easy to implement, we assume data packets with different rates have the same length of time. Let the size of 40 kbps data packet (S_{40}) be 16 bytes. We can get the S_{80}, S_{160}, S_{320}, and S_{640} be 32 bytes, 64 bytes, 128 bytes, and 256 bytes. We define the receiver sensitivity as the required received signal power to realize the packet reception ratio of 0.9. Then we calculate the sensitivity under different uplink data rates using the Eqs. (4)-(9). After that, we calculate the effective communication range between sink and nodes under different uplink data rates based on the Eq. (3) and the former result. We summarized the parameters used in the calculation in Tab. 1:

Table 1: Calculation parameter

Parameter	Value	Parameter	Value
P_{reader}	1 W	λ	32.8 cm (915 MHz)
α	0.25	G_{node}	3 dBi
Γ_1	0 (match)	ISO	25 dB
Γ_2	1 (open)	$L(\Delta f)$	-120 (dBc/Hz)
G_{reader}	6 dBi	t_d	10 ns
NF_{RX}	10 dB	S	16 bytes-256 bytes
Data rate	40 kbps-640 kbps	M	0,2,4,8,16
BLF	640 kHz	P(s)	0.9

For the simplicity, we assume the single band phase noise $L(\Delta f)$ and the compression of the noise density due to the range correlation effect in Eq. (3) be constant values of -120 dBc/Hz and -50 dB throughout the whole RF bandwidth. Then the equivalent phase noise power density P_{PN} is -165 dBm/Hz, which is much larger than P_{TN}. Therefore, we ignore the P_{TN} in Eq. (4). The calculation results are shown in Tab. 2

Table 2: Calculation results

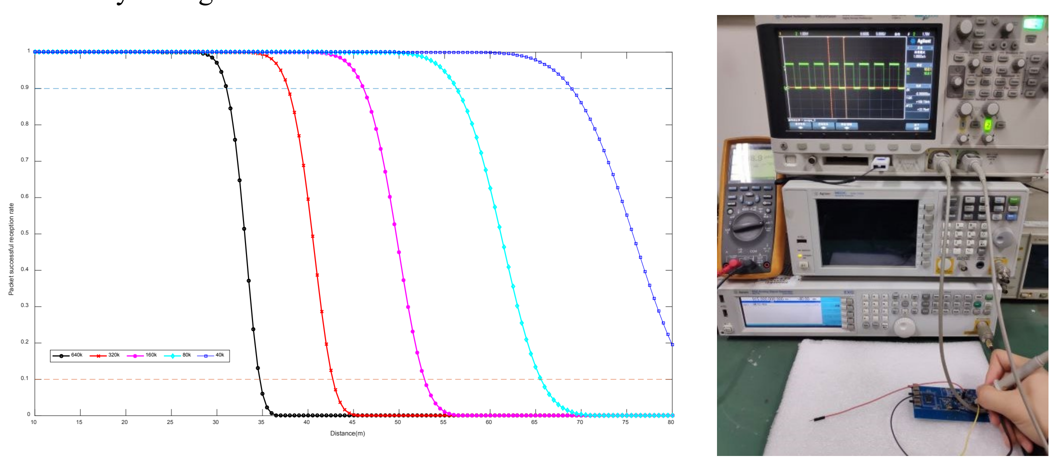
Uplink data rate (kbps)	Coding	Sensitivity (dBm)	Max Distance (P(s)=0.9)
640	M=0, FM0	-81.2	31.6 m
320	M=2, MMS	-84.6	38.3 m
160	M=4, MMS	-88	46.6 m
80	M=8, MMS	-91.5	56.8 m
40	M=16, MMS	-95	69.5 m

So far when calculating the max effective communication distances under different uplink rates, we assume that backscatter nodes can always successfully receive the packet sent from sink and the network is sink-constrained. To verify the assumption, we do an experiment, and the result is shown in Fig. 2. When the packet rate is 160 Kbps, backscatter nodes can effectively decode the signal under the received power of -40 dBm with working current of 100 μA. Using the Equation (1), we can get that the distance nodes support is more than 200 m which is far beyond the limitation of sink. What's more Fig. 2(a) shows that the packet reception ratio at sink side will suffer a sharp decrease when the distance exceeds a certain range. All the results in this Section encourage us to propose Multi-rate Polling, which will be introduced in the next section.

3 Multi-rate polling

3.1 Multi-rate polling overview

From the results of Section 2, we can get that nodes with different distances to sink will have different maximum uplink data rates to make sure the packet reception ratio at the sink side. Multi-rate Polling takes the above characteristic into account and separates the backscatter nodes into several regions due to the uplink data rates they use. Data packets with different data rates in Multi-rate Polling have the same time length so that the packet size will vary a big difference between different regions. If nodes in different regions have the same channel access priority, the network fairness will be relatively poor. To solve this problem, we introduce a parameter named K with its range changes from 0 to 1. The larger K is, the nodes in low data rates regions will have a higher priority to access the channel. Thus, the network can achieve the trade-off between Throughput and Fairness by tuning K.



(A) (B)

Figure 2: (a) The relationship between distance and successful packet reception ratio under different uplink data rates. (b) Backscatter node can effectively decode the packet under the received power of -40 dBm

Nodes employ a harvest-use energy management scheme for its simplicity and easy to implement. Backscatter nodes will turn to receive mode immediately and always have a data packet needed to upload once their energy reaches the threshold E_f. When the operation is over, backscatter nodes will return to the charging mode and waiting for their energy reaches the E_f again. The network structure and backscatter node energy model are shown in Fig. 3.

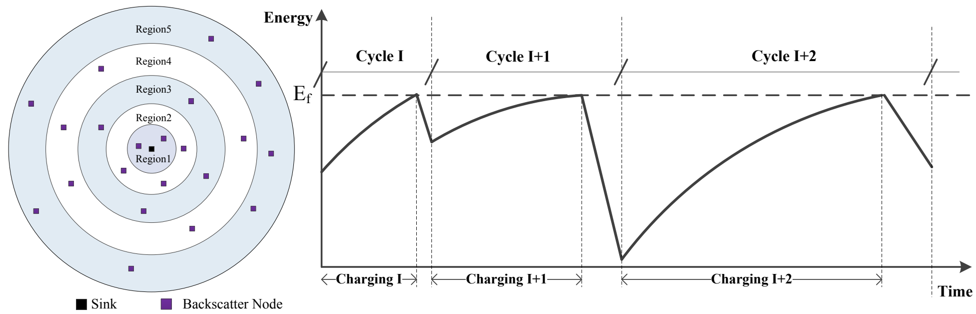


Figure 3: Network structure and backscatter node energy model

3.2 Multi-rate polling detailed

3.2.1 Setup phase

In the setup phase, the sink has to divide the network backscatter nodes into different regions and sets their uplink data rates. We assume that sink knows all the backscatter node's ID information. Then at the beginning of the network, Sink sends a polling packet which contains an ID of a backscatter node and will repeat the packet until the node reply the polling packet with a short probe packet. The probe packet employs the lowest data rate and is used for the sink to calculate the received power. Sink then feedback the data rate allotted for the node by an ack packet. The sink repeats the above operation with another ID and will finish the Setup Phase until all the backscatter nodes have been allotted an uplink data rate.

The node in Setup Phase will listen to the channel and receive the polling packet once their energy reaches the E_f. If the ID contained in Polling Packet does not match, the node will ignore the Polling packet; If the ID contained in Polling packet matches, the node will reply a probe packet with the lowest data rate and will set their uplink data rate according to the ack packet received.

3.2.2 Working phase

After the Setup Phase, all the nodes in the network have their uplink data rate. Let assume all the transmissions are in free space. Then the backscatter nodes will be divided into five different regions due to their distances to sink. Nodes in the same region will have the same uplink data rate.

Multi-rate Polling is inspired by PP-MAC [Eu, Tan and Seah (2011)] which has been proved to have a better performance than other protocols in the single-hop energy harvesting wireless network scenario. Experiments in Eu et al. [Eu, Tan and Seah (2011)] have shown that the energy harvesting process of nodes is random. Sink in EHBWN is hard to have information about the status of backscatter nodes at the beginning of every polling cycle. Thus, in Multi-rate Polling's working phase sink broadcasts a polling command contains with two basic parameters: region index N and the associated contention probability P_N instead of a node ID which is used in traditional polling schemes. We also introduce the trade-off parameter K which is used to achieve the trade-off between network throughput and fairness. The K can change from 0-1. With the improvement of K, Multi-rate Polling will increase the channel access priority of low data rate regions, thus improve the network fairness at the cost of decreasing the network throughput.

At the beginning of every polling cycle, the sink will randomly choose a region to poll. Define $P_{regionN}$ as the probability of the region N to be chosen. Then we have:

$$P\_cal\_N = \left(\frac{numberN}{S_N}\right)^K, P_{regionN} = \frac{P\_cal\_N}{\sum_N^{1-5} P\_cal\_N} \tag{10}$$

where *numberN* is the number of backscatter nodes in region N, and S_N is the uplink data rate of region N. The associated contention probability P_N in the polling command is derived from the vector of P=[P_1, P_2, P_3, P_4, P_5], which is maintained by sink and represent the contention probability of different regions. Sink will adjust the parameter P_N after every polling cycle based on the transmission condition. Specifically, the sink will increase P_N if there is no node transmit data packet during the last cycle. On the other hand, sink will decrease P_N if a collision happens. If sink receives a data packet successfully, it will keep P_N unchanged. More specifically, we use AIMD (additive-increase with multiplicative-decrease) scheme to adjust P_N with the linear factor P_{lin} as 0.01 and the multiplicative-decrease factor P_{md} as 0.5. Then we have:

$$P_N = \begin{cases} \max(P_N + 0.01, 1) & \text{if no reply} \\ P_N & \text{if success} \\ \min(P_N - P_N \times 0.5, 0) & \text{if collision} \end{cases} \tag{11}$$

Backscatter nodes which energy reach the threshold will turn to receive state. Upon receiving a Polling command, the node will first check the Region index N in the command and will generate a random number P_{node} between 0 and 1 only of the index N matches the node's region. Otherwise, it will ignore the command. The node will compare the P_{node} with P_N and will transmit a data packet to sink if the P_{node} is smaller than P_N. After actions, nodes will turn to charging state waiting for their energy reaches E_f again. We give an example of the Multi-rate Polling in Fig. 4

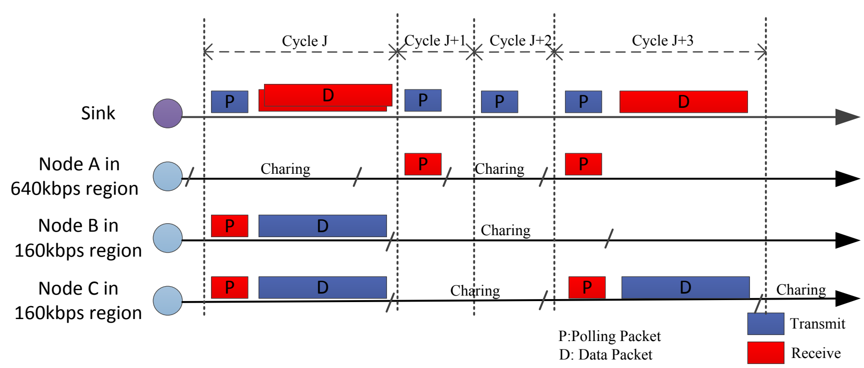


Figure 4: Four polling cycles are displayed. In cycle J, node B and node C transmitted a data packet to sink thus caused a collision. In cycle J+1, only node A received the polling

packet. However, the random number generated by node A was bigger than the contention probability P_N. Therefore node A ignored the poll. In Cycle J+2，there was no node in receiving state. In Cycle J+3, node A and node C received the poll packet. The region index N contained in the polling packet did not match the region where node A belonged. Only node C transmitted a data packet to sink. Thus, the data packet was successfully uploaded

4 Performance evaluation

4.1 Parameter description

The network is deployed in a circular region with the radius to be 70m. Sink locates the center of the circle, and backscatter nodes are randomly spread. Based on the experiment results from Eu et al. [Eu, Tan and Seah (2011)], we assume that the energy harvesting rate of the node in every second is a continuous variable with an expectation λ and independent from each other. Assume that the backscatter node has a solar panel with a size of 3×3 cm^2, and the energy density node can get is 10 $\mu W/cm^2$, then the average harvest rate λ is 90 μW. We set the backscatter node's receive circuit power be 250 μW (main consumed by OPA), and ignore the node's transmit circuit power(less than 1μW). We choose the MSP430 series MCU as the node's microcontroller. The operating frequency is set to be 16 MHz, and the operating voltage is set to be 2.5 V, then the working power of the MCU is 4 mW. Thus the node's transmitting, receiving and turnaround power are 4.25 mW, 4 mW, and 4 mW separately. We set the forward link data rate to be 160 kbps. Both the polling, ack and probe packet size are 15 bytes. Nodes with different uplink data rates will have different data packet sizes in order to keep the same transmit time of data packets. The turnaround and CCA time is the same with Eu et al. [Eu, Tan and Seah (2011)]. We summarize the parameters in the following table:

Table 3: Parameters used in simulation

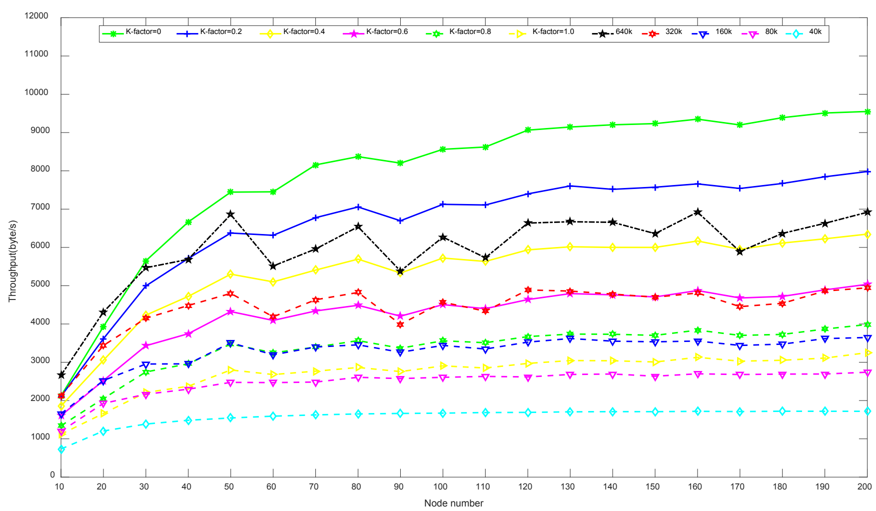
Parameter	Value
node number(n)	10-200
energy harvesting rate(λ)	30 μW-600 μW
node transmit power (P_{tx})	4 mW
node turnaround power (P_{ta})	4 mW
node receive power (P_{rx})	4.25 mW
Date packet size(S)	16-256 bytes
Polling packet time (T_{poll})	0.75 ms
Date packet time (T_{data})	3.2 ms
Turnaround time (T_{ta})	192 μs
CCA time (T_{cca})	128 μs

We check Multi-rate Polling's performance under different network sizes and energy harvesting rates and make a comparison with PP-MAC (using a single uplink data rate).

Every simulation runs 100 seconds (without the setup phase time), and each plotted point in the following graphs of results are the average over ten simulation runs.

4.2 Simulation results

We first fix the energy harvesting rate at 2 mW and vary the number of backscatter nodes from 10 to 200 to check the network performance under different network densities. Then we let the node number to be 100 and vary the energy harvesting rate from 30 μW to 600 μW to test the network performance under different energy harvesting conditions. For each simulation scenarios, two deployment strategies of backscatter nodes are used with one putting all the nodes randomly into the whole network area and another putting the fixed number of nodes into different regions according to the ratio of different regions' area.



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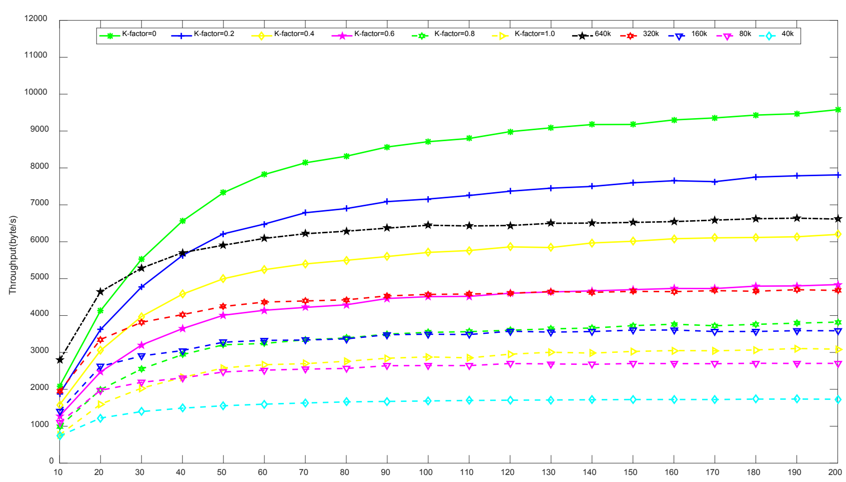

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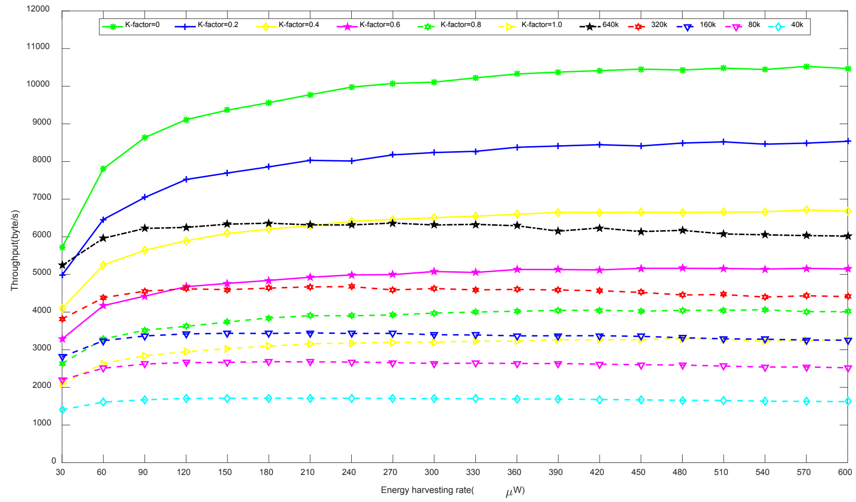

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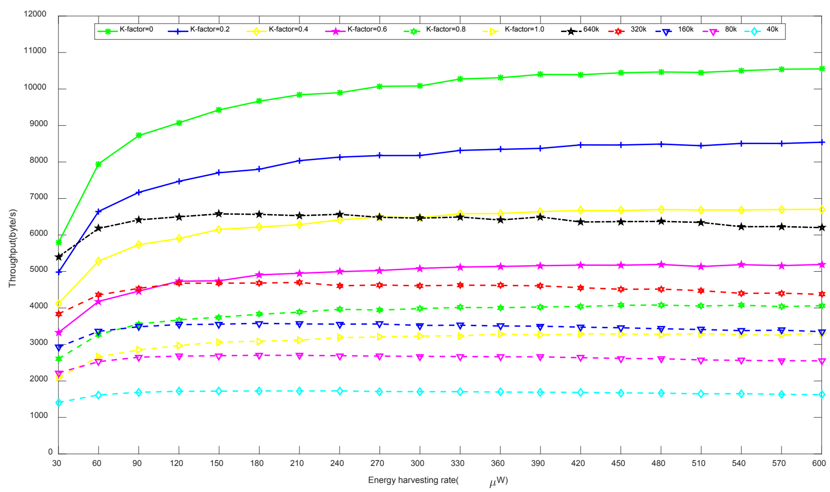
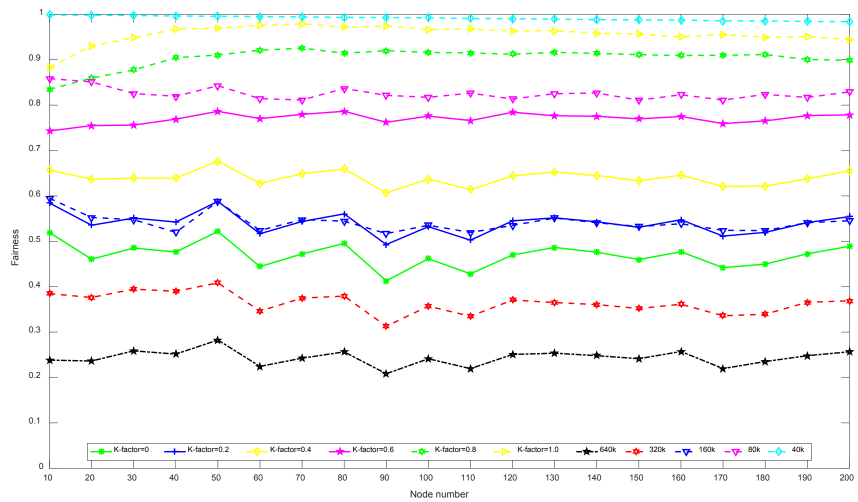


(D)

Figure 5: Throughput performance under different network sizes with (a) randomly spread (b) spread according to regions' area, and different energy harvesting rates with (c) randomly spread (d) spread according to regions' area

From Fig. 5 we can get that the Multi-rate Polling can effectively improve the network throughput compared with PP-MAC (using single uplink rate) and has good scalability both to network sizes and energy harvesting rates. Given a fixed network size n, the throughput of Multi-rate Polling will decrease with the improvement of parameter K. For example, when the K=0, the throughput of Multi-rate Polling is much higher than PP-MAC (using 640 kbps as uplink data rate), while when the K increase to 0.4, the throughput of Multi-Rate Polling and PP-MAC (using 640 kbps as uplink data rate) turns to be similar. The sacrifice of throughput by turning K earns an increase of network fairness, which can be verified through Fig. 6.

From Fig. 6 we can get that the fairness of Multi-rate Polling will increase with the improvement of parameter K. What's more even though the PP-MAC with a lowest uplink data rate (40 kps) can achieve better fairness than Multi-rate Polling. The Multi-rate Polling still has a better overall performance. For example, the throughput of Multi-rate Polling (K=0.4) is similar to PP-MAC (uplink data rate=640 kbps). However, the Multi-rate Polling (K=0.4) performs much better than PP-MAC (uplink data rate=640 kbps) in fairness; the fairness of Multi-rate Polling (K=0.2) is similar to PP-MAC (uplink data rate=160 kbps). However, the Multi-rate Polling (K=0.2) performs much better than PP-MAC (uplink data rate=160 kbps) in throughput.



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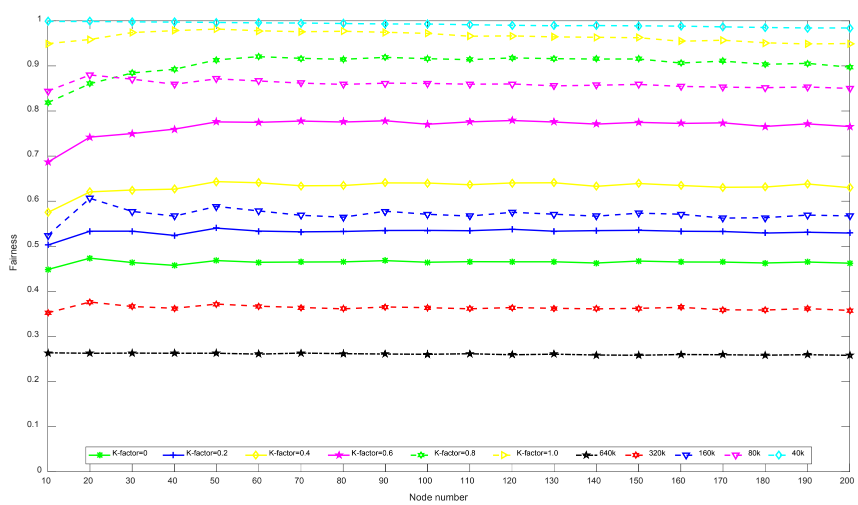

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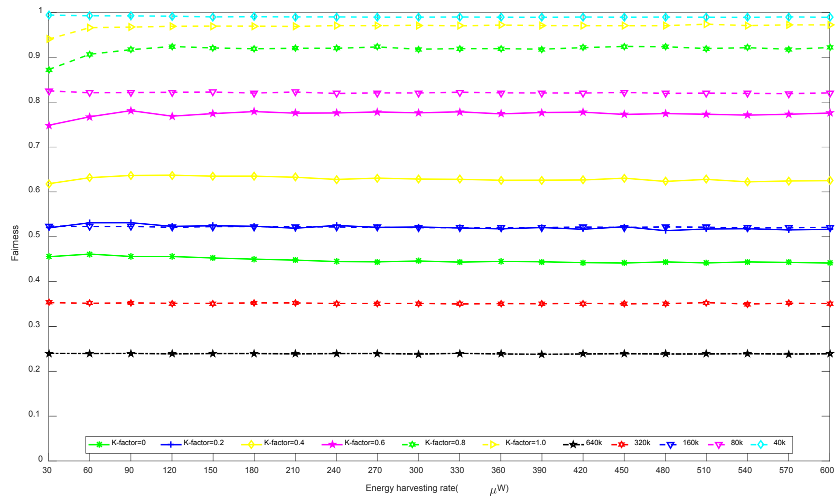
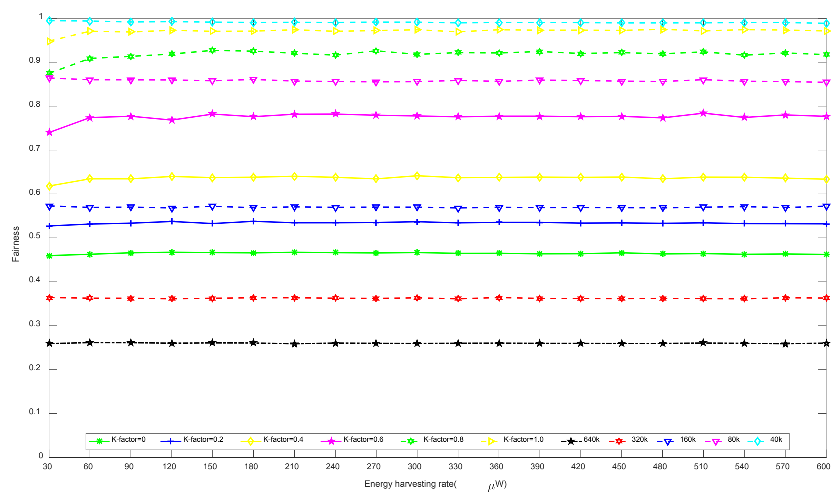


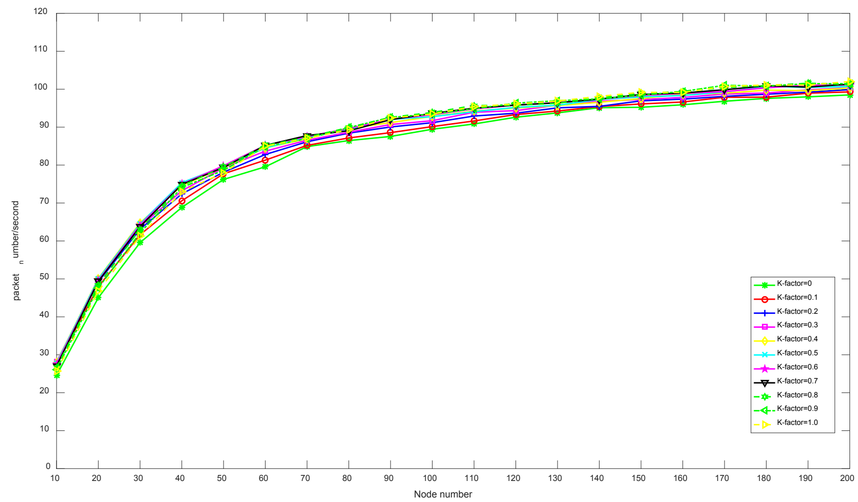
(C)



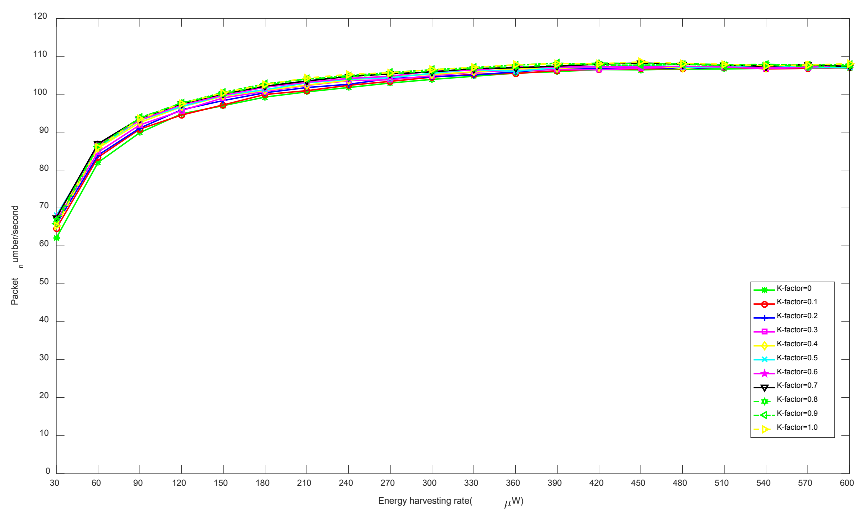
(D)

Figure 6: Fairness performance under different network sizes with (a) randomly spread (b) spread according to regions' area, and different energy harvesting rates with (c) randomly spread (d) spread according to regions' area

To figure out why the Parameter K can effectively achieve the trade-off between the network throughput and fairness. We illustrate the average data packet number (packets/s) successfully received by sink under different K in Fig. 7.



(A)



(B)

Figure 7: The average data packet number (packets/s) successfully received by sink under different network sizes (a) and energy harvesting rates (b)

From Fig. 7 we can get that the average data packet number (packets/s) successfully received by the sink does not present a visible change under different parameter K. With the improvement of K, the network will increase the channel access priority of nodes in low uplink data rate regions. Fig. 8 shows the average throughput of per node in different regions under different values of K. When K grows up, the ratio of low data rate packets will increase, and the average throughput of per node in different regions will become more balanced, which leads to an improvement of network fairness and debasement of network throughput.

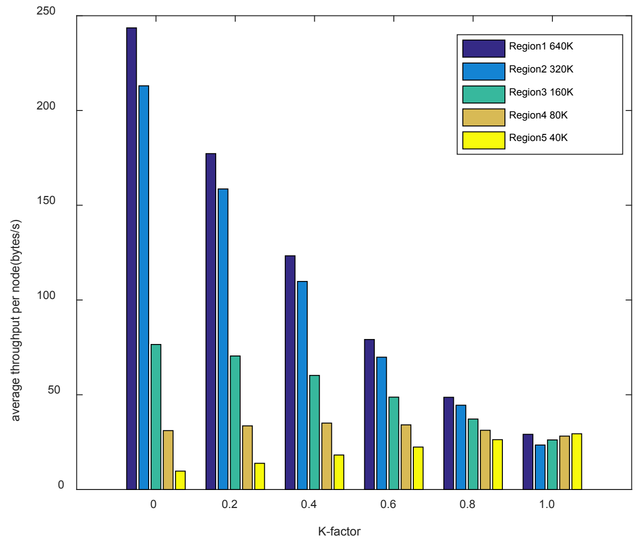


Figure 8: Average throughput of per node under different K value

5 Conclusion

In this paper, we first gave an analysis of the backscatter link budget and the relationship between the sink receiver sensitivity and the uplink data rate. After that, we proposed Multi-rate Polling, a medium access protocol used in single-hop Energy Harvesting Backscatter Wireless Networks. Multi-rate Polling takes the sink receiver sensitivity into account and assigns backscatter nodes with different uplink data rates to maintain the packet reception ratio and improve the overall network performance. Then we introduce a parameter K used in Multi-rate Polling to achieve the trade-off between network throughput and fairness so that Multi-rate Polling can be used in different scenarios which have different emphases on throughput and fairness. The simulation result shows that Multi-rate Polling outperforms other protocols and is suitable for EHBWN.

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