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Provisioning Quality-of-Service to Energy Harvesting Wireless Communications

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***Abstract*— Energy harvesting (EH) is an innovative way to build long-term and self-sustainable wireless networks. However, inconstant EH rate may have an adverse effect on the Quality-of-Service (QoS) of wireless traffic, such as packet delay and error. In this article, we discuss techniques that provide QoS to EH powered wireless communications. A new "dynamic string tautening" method is presented to produce the most energy efficient schedule with substantially lower complexity, compared to convex optimization techniques. The method adapts to the bursty arrivals of wireless traffic and harvested energy, and ensures delay-sensitive data to be delivered by deadline. Comprehensive designs of EH powered transmitters are also discussed, where the EH rate, battery capacity, and deadline requirement can be jointly adjusted to leverage QoS and the cost.**

***Index Terms*— Wireless sensor networks; energy harvesting; Quality-of-Service.**

I. EH IN WIRELESS COMMUNICATIONS

Energy harvesting (or scavenging) is a process of capturing and converting ambient energy into usable electrical energy. A large number of external energy sources have potential to be harvested. They are [1]:

- natural (renewable) energy, e.g., wind, water flow, ocean currents and the sun;
- mechanical energy, e.g., vibration, and mechanical stress and strain;
- thermal energy, e.g., waste energy from furnaces, heaters, and friction;
- light energy, e.g., natural and artificial light;
- electromagnetic energy, e.g., inductors, coils and transformers;
- energy from the human body, e.g., a combination of mechanical and thermal energy naturally generated by people when walking, sitting, climbing and running;
- energy from other sources, such as chemical and biological sources.

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It is reported in [2] that environmental and kinetic energy harvesting (EH) – based on light, thermal and motion – are the most promising techniques. Given a typical transfer efficiency of 10%, the energy that can be harvested in an outdoor daylight environment is about 1 mW/cm^2 [2]. This is at the same order of magnitude that carefully designed ultra-low-power micro-controller circuits typically consume.

In wireless communication systems, environmental EH is a critical component to build self-sustainable networks, such as wireless sensor networks in remote human-unfriendly environments [3]. Reducing carbon footprint, harvesting energy from renewable sources to power wireless transmissions is the key to implement the self-sustainability. On the other hand, Quality-of-Service (QoS), e.g., delay and packet error rate, is crucial to many wireless applications. For example, sensory data are delay critical in bushfire and flood monitoring applications. However, to provide QoS to EH powered wireless transmissions, three critical challenges arise.

The first critical challenge of providing QoS to EH powered wireless transmissions is the unreliable nature of EH. Many EH technologies significantly rely on the environment where the devices are [2]. The energy harvested may fluctuate dramatically with the time. This has strong impact on the reliability/availability of wireless links powered by the energy, and hence the QoS. Existing techniques developed to address the challenge are limited to delay-tolerant (bandwidth-demanding) traffic [4–6]. They are unable to provide QoS to delay-sensitive traffic.

The second critical challenge of providing QoS to EH powered wireless transmissions is to increase the energy efficiency of wireless transmissions. In general, the current energy transfer rate of EH is low, e.g., 15 to 20% for solar [2]. Maximizing the energy efficiency of wireless transmissions is therefore important to make the insufficient energy harvested meet the energy requirement of wireless transmissions, thereby reducing the probability of energy outage and QoS violations. Again, bandwidth-demanding delay-tolerant traffic has been the focus in existing techniques of optimizing the transmission energy efficiency, e.g., the one proposed in [7]. Those techniques cannot apply to delay-sensitive applications, where QoS is required.

Another critical challenge of providing QoS to EH powered wireless transmissions is the energy consumption of wireless circuitry. Part of the consumption is on transmission. Ultra-low-power circuitry has recently been developed to reduce active current, operating voltage, and pin leakage [2]. The current is about 16 mA when transmitting [2]. However, this is still non-negligible, given the low EH level of milliwatts. To save the transmission energy, an "on-off" mode was developed for bandwidth-demanding traffic first in time-invariant channels [8] and then extended to time-varying channels [9, 10]. However, the mode is unable to address the QoS requirement of delay-sensitive traffic. Another part of the circuit power consumption is on signal processing, especially for generating the optimal transmission schedules in delay-sensitive applications. Convex optimization techniques, such as the one proposed in [6], are in general unsuitable due to high search complexity.

Note that upper layer protocols, such as resource reservation protocol (RSVP) at the Transport Layer, have been widely used to provide QoS to traffic flows travelling over networks. QoS is provided by prioritizing traffic flows and adjusting bandwidths at every intermediate (routing/switching) nodes. However, this cannot address the aforementioned three critical challenges that reside on each individual wireless link and are caused by unreliable power sources.

In this article, we present a new method which jointly addresses the three critical challenges and provides QoS to EH powered wireless transmissions. A new "dynamic string tautening" method is developed to produce the most energy efficient schedule with substantially reduced complexity, and ensure delay-sensitive data to be delivered by deadline. Comprehensive designs of EH powered transmitters are also discussed, where the EH rate, battery capacity, and deadline requirement are jointly adjusted to leverage QoS and the cost.

II. QoS Provisioning in EH Communications

In this article, we focus on QoS provision on a single wireless link where the transmitter is powered by environmental EH techniques, as illustrated in Fig. 1. Delay sensitive sensory data arrive at the transmitter in bursts. The energy that the transmitter harvests is also bursty, due to the constantly changing ambient energy source. Our focus on the single-link QoS provision is because it is the key and fundamental issue of EH powered wireless networks. Our results on the single link can be extrapolated to real network topologies and scenarios, as will be discussed in Section IV-B.

Referring to [3], the EH process can be modelled as a discrete sequence, where every element E_i $(i = 0, 1, \cdots, N)$ is the energy (in joules) instantly harvested from ambient sources. We also model the bursty data arrival as a discrete sequence, where every element A_j $(j = 1, \cdots, M)$ is the number of newly arrived packets.

We can similarly model a discrete sequence to represent the strict deadline requirements of the packets, where every element of the sequence D_k $(k = 0, 1, \cdots, K)$ indicates the number of packets that must be delivered so far. If any packet that reaches its deadline but is undelivered yet, it will be discarded by the EH powered transmitter.

Every element of the sequences is tagged with a time stamp, which indicates when the event occurs (i.e., new energy is harvested, new packets arrive, or deadlines are met). E_i, A_j, and D_k are tagged τ_i, t_j, and μ_k, respectively. Of course, these time stamps may not overlap between difference sequences, as the EH process and the data arrival process are unnecessary to be synchronous in practice.

Arranging the time stamps of all the three sequences in an ascending order, we can combine the three sequences into one sequence. The time interval between any consecutive two elements of the combined sequence is referred to as an "epoch". Within an epoch, the status of the three processes of EH, data arrival, and data deadlines does not change. We need to optimize the transmission schedule of each epoch for QoS provisioning, so that the overall optimality of the transmission schedule across the entire EH powered transmission process can be guaranteed.

Clearly, three constraints of generating the optimal transmission schedule arise due to causality.

a. The total number of packets required to be delivered is the number of arrived packets.
b. At any instant, the number of the transmitted packets must be no larger than the number of the arrived packets.
c. The total amount of energy consumed up to a time must be no greater than the energy accumulatively harvested so far.

Modelling the EH powered transmission in such a way reveals that the EH process and the data arrival process have not only the same time sequence nature, but also yield causalities which need to be imposed as constraints to transmission schedules. Existing studies have been extensively conducted to address the problem of QoS provision to bursty data process in the presence of unlimited energy [11]. The similarities between the processes indicate that there is a good opportunity to solve the QoS provisioning problem in EH wireless communications by extending those existing techniques.

In this article, we introduce a feasible transmission schedule which, extended by our recent work [12], is able to provide QoS to bursty traffic adapting to the EH progress. We will confirm the optimality of the schedule, and show its superiority of computational efficiency.

A. QoS Provisioning under Reliable Power Supply

In our recent work [12], we derived the most energy efficient transmission schedule to provide QoS to bursty data, given constant and sufficient power supply. Here, we summarize the conclusion of that work, which will provide the key insight and guidances to design the optimal EH powered transmission schedules, as will be described in Section II-B.

In the case of reliable power supply, the EH process/sequence is absent. An epoch is the interval between two consecutive time stamps in the combined sequence of data arrival and deadlines. The important conclusion we draw is that *the most energy efficient transmission schedule only adopts one of the following three policies per epoch i:*

1. *"on" policy, where the transmitter sends at the data rate higher than r_{ee} for the entire epoch i;*
2. *"off" policy, where there is no transmission in epoch i;*
3. *"first-on-then-off" policy, where the transmitter sends at the data rate of r_{ee} for a time period less than the duration of epoch i;*

where r_{ee} is the data rate that maximizes the number of bits to be transmitted using a joule of energy. The number of bits

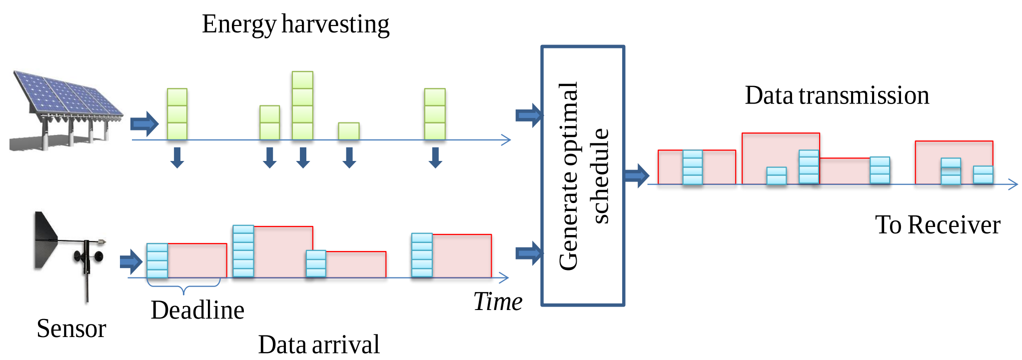

Fig. 1. Illustration on EH powered wireless transmission, where solar panels are used to harvest energy. The transmitter decides the optimal transmission schedule, which adapts to the bursty characteristics of sensory data and EH, and ensures data to be transmitted by their deadlines.

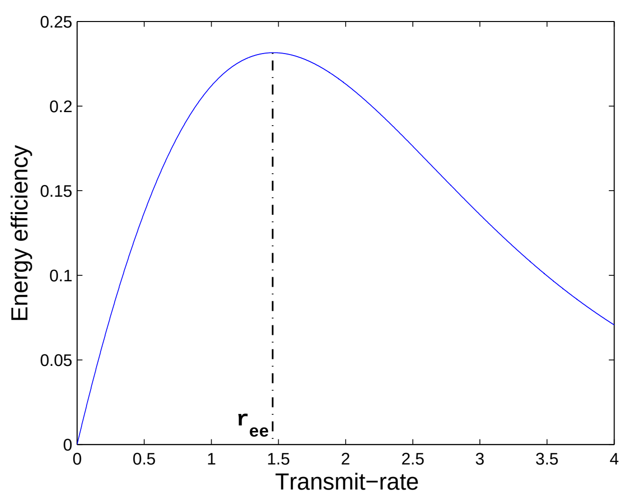

Fig. 2. Bits-per-Joule energy efficiency versus transmission rate r, which is plotted based on Shannon's formulation $P(r) = \frac{1}{|h|^2}\left[\exp(r) - 1\right]$, where $P(r)$ is the power required to transmit the rate of r, and h is the channel coefficient of the link from the transmitter to the receiver.

to be transmitted using a joule is typically quasi-concave [7], as shown in Fig. 2. Therefore, r_{ee} can be efficiently obtained by a simple bi-sectional search.

In the case where a large number of packets reach their transmission deadline, the transmitter should send those packets all the time through until the deadline with the required power; see the "on" policy. In other cases, the transmitter should send deadline-reaching packets with the most energy efficient data rate. Once the transmission completes, the transmitter turns off into a standby state; see the "first-on-then-off" policy. By doing these, the energy consumption of the transmitter is minimized, while the QoS of the bursty data traffic can be guaranteed.

The optimality of the policies in terms of energy efficiency can be rigidly proved through a judicious change of variables, which converts the original, non-convex problem of minimizing the transmit energy into a convex program [13]. The Karush-Kuhn-Tucker (KKT) conditions can be then employed to solve the convex problem and confirm that the policies satisfy the conditions.

The conclusion also indicates that the most energy efficient transmission schedule is event driven. The transmitter switches between the policies only on the arrival of new data bursts or on the data deadlines.

B. QoS Provisioning under EH

In the presence of EH, it can be shown that the most energy efficient policies described in Section II-A still apply. This is because the energy efficiency of transmission is critical to EH powered systems. The key difference is that, in this case, the transmission data rate and duration depend on the availability of energy harvested from external unstable sources.

We define the time stamps of the combined time sequence of the EH, data arrival and deadline processes, as a unified timeline $\{\sigma_0, \sigma_1, \cdots, \sigma_{N+M+K}\}$ (as described earlier in Section II). Epoch i is the interval from σ_{i-1} to σ_i with the duration of $L_i = \sigma_i - \sigma_{i-1}$. The construction of the unified timeline is due to the fact that the most energy efficient policies are event driven, as pointed out in Section II-A. On the other hand, EH is an event that can activate switching policies. For example, when the transmitter runs out of energy, it stays "off" even if there are data to transmit. Once new energy is harvested, the transmitter should turn "on" and proceed with either Policy 1 or 3.

Given the unified timeline, we can derive that the optimal transmission schedule based on harvested energy should comply with the following rule [13, 14]:

In the optimal transmission schedule, the transmission data rate only changes at the instant when the data causality, deadline, or energy causality is met with equality. To be specific, the rate change happens after the epoch where

a. *there are no undelivered data, or*
b. *the transmitter runs out of energy, or*
c. *all deadline-approaching data are delivered.*

We note that at any instant, the number of delivered packets must not be larger than the number of the packets that have arrived so far due to causality. Also note that transmissions are interrupted if the transmitter runs out of energy, and will not be resumed until sufficient energy is harvested. In this case, data

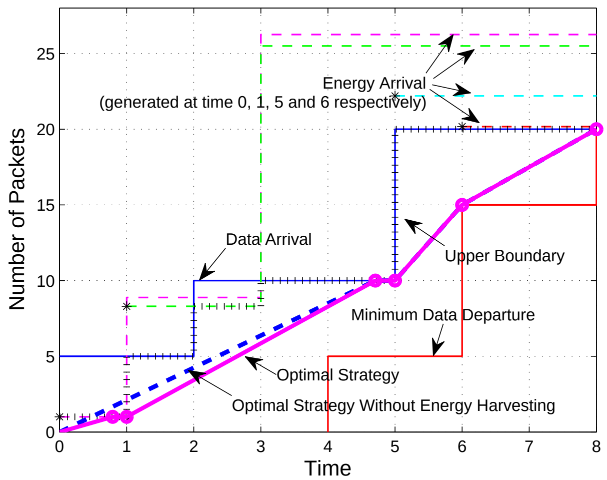

Fig. 3. An illustrative example of the proposed "string tautening" method and the achieved optimal transmission schedule, which is the most energy efficient to provision QoS to EH wireless communications.

whose deadlines are within the transmission interruptions are dropped. Proper designs of the transmitter, including the EH rate and batter capacity, adapting to the data arrival process and the QoS (to be specific, delay) requirement are able to reduce the dropped data to lower than a required level. Details will be discussed in Section III.

The optimality of the rule can be confirmed, because the rule was derived by first formulating the optimization problem to minimize the energy consumption under the constraints of inconstant EH rate, bursty data arrival, and strict data deadlines. We then write the Lagrangian of the constrained optimization problem, and finally solve it with the KKT optimality conditions.

Following the rule, a computationally efficient algorithm with a temporally linear complexity can be developed to find the optimal transmission schedule that provides QoS to delay-sensitive, bursty data in EH systems.

Our new algorithm can be visualized as "string tautening", which has a distinguished feature of changing feasible solution regions imposed by the dynamic EH process. In other words, the current direction of tautening the string depends on the past directions during a process of determining the optimal transmission schedule. The reason is because the past transmission data rates, indicated by the past tautening directions, affect the current energy level in the battery, which in turn determines the current direction to tauten the string. In contrast, existing "string tautening" methods have fixed solution regions [15], and therefore cannot address the dynamic EH problem.

Fig. 3 illustrates our proposed "string tautening" process, where, at any instant, the data arrival curve plots the amount of data generated for transmission and the deadline (minimum data departure) curve plots the amount of data reaching their deadline. There are a number of EH curves. They are produced sequentially, one curve each time the conditions in the optimal rule are met. Each EH curve plots the maximum amount of data that can be transmitted at future instants, given the energy harvested and the data transmitted so far.

A closed feasible solution region is presented. The deadline curve provides the lower boundary of the feasible solution region. The (dotted) upper boundary of the region is provided by the lower of the data arrival curve and the dynamic EH curves, so that the optimal transmission schedule can satisfy both causalities of data and energy, as well as the deadline requirements (i.e., QoS).

It is also possible that there are multiple closed solution regions in a single optimal transmission schedule, but not shown here. In this case, the upper boundary curve crosses and becomes underneath the lower boundary during some periods of the transmission schedule. No transmissions will take place during the periods due to insufficient energy, as noted earlier. The periods become infeasible solution regions.

Seven epochs are demonstrated in the figure. Different transmission policies are adopted across the epochs, as highlighted in the figure. In the first epoch between time 0 and 1, the "first-on-then-off" policy is adopted, and the slope of the string is the most energy efficient transmission rate r_{ee}, as specified in the policy. In the next three epochs until time 5, the policy is also adopted throughout the epochs, with the most energy efficient transmission rate. In the last two epochs, the "on" policy is separately adopted, and the slope of the string is chosen as such that the deadlines can be met.

It is worth pointing out that every EH curve is always underneath the previous ones, as shown in the figure. One reason is that the previous curves cannot foresee the future transmissions due to causality. Another reason is that every EH curve gives a tight energy budget based on the energy consumed so far. New transmissions will only get the budget tighter. The conclusion we can draw is that the optimal transmission schedule is able to leverage the current transmission rate, as well as the energy saved for future use.

For comparison purpose, we also plot the most energy efficient transmission schedule in the case of constant and sufficient power supply, employing [12]. We can see that the optimal transmission schedule in this case is in general above the one we developed for EH communications. This is because, in the presence of sufficient power supply, the upper boundary of the feasible solution region for the optimal schedule is provided solely by the data arrival curve, and therefore the region is larger than the one in the EH case. However, this optimal schedule does not apply to the EH case, because the string can cross and go beyond the EH curves, invalidating the schedule, as demonstrated in Fig. 3 when the time is 1.

III. Designing EH Transmitters with Guaranteed QoS

So far, we have discussed the most energy efficient schedule to guarantee the deadlines of EH wireless transmissions, given any configuration on data arrival rate, EH capability, and battery capacity. However, a substantial amount of packets may still be dropped at the transmitter under a poor configuration, for example, excessively small battery or high data arrival. A joint and holistic design of the data arrival, EH capability, and battery capacity is required to balance the deadline requirement and the tolerable packet drop rate.

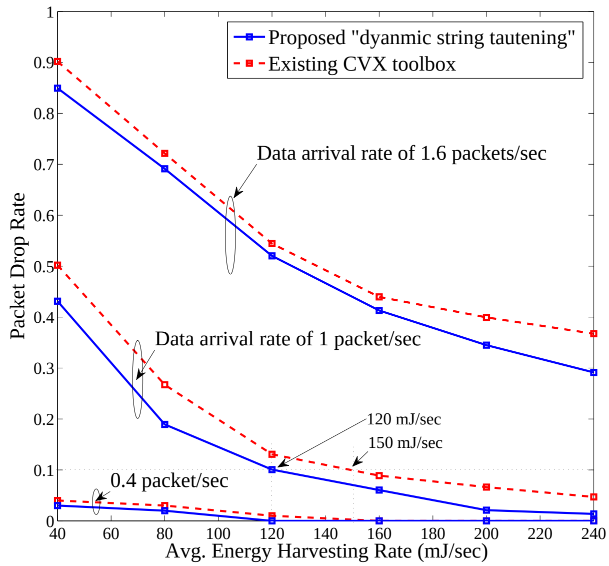

Fig. 4. EH rate versus packet drop rate, where we assume the transmitter has unlimited battery capacity, the average data arrival rate is 0.4, 1.0, and 1.6 packets/sec, and the deadline is 2.5 seconds for every packet.

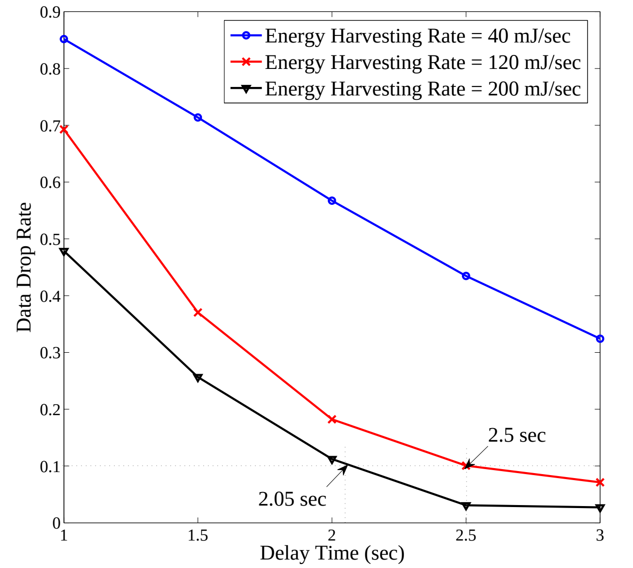

Fig. 5. Delay requirement versus packet drop rate of our proposed "string tautening" scheme, where we assume the transmitter has unlimited battery capacity and the data arrival rate is 1 packet/sec.

To demonstrate this, simulations are carried out, where we assume the circuit power consumption $\rho = 30$ mW. The transmit power is optimally achieved by using the new "string tautening" method, as described in Section II. We also assume the gain of the wireless channel $|h|^2$ to be -20 dB during the optimal transmission. In practice, the channel may vary with the time. Our optimal schedule also applies to the time-varying case. Details will be discussed in Section IV.

In the simulations, the data arrival and the EH are modelled as two independent Poisson processes. The average data arrival rate is 1 packet/sec (unless otherwise specified), and the average EH rate ranges from 40 to 240 mJ/sec. It is worth mentioning that the optimal rule/schedule is general, and is applicable to any stochastic processes of data arrival and EH.

For comparison purpose, we also simulate the use of standard convex optimization techniques, specifically, the interior point method, to generate the optimal transmission schedule. The interior point method is effective and has been extensively used to solve optimization problems with convex structures like the one discussed in this paper. The method has been implemented in MATLAB CVX toolbox.

We note that the standard interior point method is able to produce the exactly same optimal schedule in the case where reliable and sufficient power supply is available, as described in Section II-A. However, the standard method requires a substantially higher computational complexity and sequentially higher circuit power consumption, than our "string tautening" method. This is because the interior point method requires matrix operations, high-order multiplications and repeated iterations. It has typically a polynomial complexity higher than $\mathcal{O}(G^3)$ (where G is the number of epoches). In contrast, our "string tautening" method only requires linear complexity $\mathcal{O}(G)$ to adjust the direction of the "string", as shown in Fig. 3. In the case of EH, the higher circuit power consumption of the standard convex optimization methods would reduce the number of packets that can be optimally transmitted each time due to limited energy, and compromise QoS.

A careful design of the EH rate, adapting to the data arrival, is critical to leverage traffic QoS (i.e., the delay and the packet drop rate), as well as the cost of the transmitter. Fig. 4 plots the average packet drop rate with the growth of the EH rate. We can see that the growth of the EH rate is critical to reducing the packet drop rate, especially when the data arrival rate is high. When the data arrival rate is 1.6 packets/sec, increasing the EH rate from 40 mJ/sec to 240 mJ/sec is able to reduce the packet drop rate from 85% to 29%.

Our "string tautening" method described in Section II-B has substantially lower packet drop rates than the CVX programs. For a data arrival rate of 1 packet/sec and an EH rate of 80 mJ/sec, our method is able to achieve a packet drop rate of 19%, while the CVX incurs a packet drop rate of 28%. The reason is that the proposed method consumes much less energy to produce the optimal schedule than the CVX. As a result, more energy can be saved to transmit data and reduce the packet drop rate.

Our "string tautening" method is also able to relieve the requirement of EH. Consider a target packet drop rate of 10% for the data arrival rate of 1 packet/sec. By the figure, we can design the required EH rate to be 120 mJ/sec for our "string tautening" method, while the CVX based transmitter is required to harvest 150 mJ/sec energy on average. Typically, the EH rate is proportional to the size of energy collector, e.g, solar panel. As a result, our method can be equipped with a much lighter (by up to 25%) and therefore cheaper EH devices.

A realistic deadline requirement is important to alleviate the packet drop rate. Fig. 5 shows the average packet drop rate

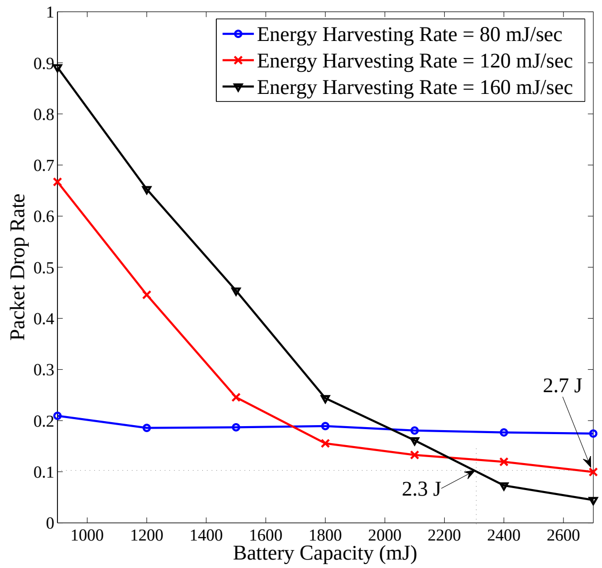

Fig. 6. Battery capacity versus packet drop rate of our proposed "string tautening" scheme, where the data arrival rate is 1 packet/sec and the deadline requirement is 2.5 seconds.

with the growth of the deadline. We can see that, given a target packet drop rate of 10%, a deadline requirement of 2.5 seconds can be satisfied by employing an EH rate of 120 mJ/sec. In contrast, a deadline requirement of 2 seconds requires a substantially higher EH rate of 200 mJ/sec. In other words, the required EH rate can be reduced by 40%, by increasing the deadline by 25%. The cost of the EH devices decreases substantially.

A proper design of battery capacity is also crucial, adapting to the EH rate and deadline requirement. Fig. 6 plots the packet drop rate with the battery capacity. It is interesting to see that the curves of different EH rates intersect with each other. The higher the EH rate is, the more the packet drop rate changes with the battery capacity. The reason is that, when the battery is small, a high EH rate will lead to energy overflow. The overflown energy cannot be used for transmissions, and therefore is wasted. With the growth of the battery, the probability of the energy overflow decreases. More energy can be collected for transmissions, and the packet drop rate can be significantly improved.

Consider the target packet drop rate of 10%. We can design by checking the figure that the required battery is 2.3 J for the EH rate of 160 mJ/sec, and 2.7 J for the EH rate of 120 mJ/sec. It is noted that in the case of the EH rate of 80 mJ/sec, the target packet drop rate cannot be achieved by enlarging the battery. The achieved packet drop rate stops decreasing, when the battery is larger than 1.5 J. This is because the harvested energy is so small, and a battery of 1.5 J is sufficient to store the energy. However, the energy is insufficient to transmit the data, and the packet loss is high.

IV. Other Considerations on Practical Implementations

In this section, we discuss the practical implementation aspects of the new "dynamic string tautening" method. The communication protocols running on each EH powered link, and connecting multiple links into a network, are described, due to their importance in real implementations.

A. Communication Protocol

Communication protocols are another key aspect of designing EH wireless communication systems, as mentioned in Section I. It enables the receiver to report $|h|^2$ which is necessary for the transmitter to generate the energy efficient transmission rate and schedule, as discussed in Section II-B. An adequate communication protocol is also important in many practical cases where the wireless channel fluctuates with the change of the environment and temperature.

Given the limited energy of the EH wireless systems, the protocol can be designed such that timeslots are preallocated for the receiver to update the transmitter with the channel gain $|h|^2$. The EH powered transmitter is aware of the preallocated timeslots. It switches from the transmit mode or the sleeping mode to the receive mode at the timeslots, and will resume transmissions or return to sleep after that. The interval between two consecutive timeslots is less than the coherence time of the channel; i.e., the channel gain is stable during the interval. By this means, the energy that the transmitter requires to receive the channel updates can be substantially reduced, compared to maintaining a standby receive channel.

Given the protocol, the optimal transmission schedule described in Section II-B can be generated by puncturing out the preallocated timeslots, constructing a new timeline, and carrying out "string tautening" over the new timeline. The data arrivals within a preallocated timeslot are aggregated to the timepoint where the beginning and the end of the preallocated timeslot join in the new timeline. So are the energy harvested and the deadlines reached within the timeslot. The rest "string tautening" operations are as described in Section II-B.

The protocol can be further extended to enable the interval between preallocated timeslots to change (by half or double), adapting to the varying wireless channel. This can be implemented by the receiver adding one more bit into the channel updates to indicate the interval until the next channel reporting timeslot. This allows the interval to fast converge to the coherence time of the time-varying channel.

The protocol can also be extended to enable the real-time adjustment of the data deadlines, adapting to the EH level and the packet drop rate. Specifically, the transmitter can decide to increase or decrease the deadline of every packet based on the current packet drop rate. This can be done by enabling the receiver to report the packet drop rate along with the channel updates. As a result of these extensions, the packet drop rate can be stabilized.

B. Extrapolation to large-scale networks

To extrapolate EH powered transmissions to a real network, the key challenge is the design of the EH powered wireless receivers. This is because limited harvested energy can hardly afford continuous reception and decoding. To address the challenge, we can preallocate periodical timeslots to every pair of transmitter and receiver. The receiver only wakes up and receives during the timeslots, and is in a sleeping mode in the rest of time. The transmitter schedules its transmissions only within the timeslots. In this case, the optimal transmission schedule can be generated in a similar way, as described in Section IV-A. Specifically, the transmitter punctures out the time periods that the receiver is in the sleeping mode, constructs a new timeline, and carries out the "dynamic string tautening" over the timeline. A careful design of the timeslot preallocation is important, which affects the QoS and packet drop rate, as well as the energy consumption of the transmitter and receiver.

V. Conclusions and Future Work

In this article, we addressed the issue of providing QoS to EH powered wireless communications. A new "dynamic string tautening" method was developed to produce the most energy efficient schedule, adapting to the bursty arrival of traffic and energy. The method ensures delay-sensitive data to be delivered by deadline, meanwhile substantially reducing the complexity and circuit power consumption. Using the "string tautening" method, designs of EH powered transmitters were discussed. The EH rate, battery capacity, and deadline requirements can be jointly designed to leverage QoS and the energy requirement.

The future directions of the work include

a. Extrapolation of the optimal QoS schedule to large-scale EH powered networks, where careful designs of a sleeping mode are required for the transceivers;
b. Upper layer adaptation to the EH powered transmissions, including routing, prioritization, and QoS provision over EH powered wireless networks; and
c. EH processes with multiple (discrete and/or continuous) power sources, and their impact on QoS.

References

[1] C. Knight, J. Davidson, and S. Behrens "Energy options for wireless sensor nodes," *Sensors*, no. 8, pp. 8037-8066, 2008.

[2] M. Raju and M. Grazier, "Energy harvesting ULP meets energy harvesting: A game-changing combination for design engineers," *Texas Instruments*, White Paper, April 2010.

[3] D. Gunduz, K. Stamatiou, N. Michelusi, and Zorzi, M., "Designing intelligent energy harvesting communication systems," *IEEE Commun. Mag.*, vol. 52, no. 1, pp. 210-216, January 2014.

[4] K. Tutuncuoglu and A. Yener, "Optimum transmission policies for battery limited energy harvesting nodes," *IEEE Trans. Wireless Commun.*, vol. 11, no. 3, pp. 1180–1189, Mar. 2012.

[5] J. Yang and S. Ulukus, "Optimal packet scheduling in an energy harvesting communication system," *IEEE Trans. Commun.*, vol. 60, no. 1, pp. 220–230, Jan. 2012.

[6] O. Ozel, K. Tutuncuoglu, Y. Jing, S. Ulukus, and A. Yener, "Transmission with energy harvesting nodes in fading wireless channels: Optimal policies," *IEEE J. Sel. Areas Commun.*, vol. 29, pp. 1732–1743, 2011.

[7] G. Miao, N. Himayat, and G. Li, "Energy-efficient link adaptation in frequency-selective channels," *IEEE Trans. Commun.*, vol. 58, no. 2, pp. 545-554, Feb. 2010.

[8] J. Xu and R. Zhang, "Throughput optimal policies for energy harvesting wireless transmitters with non-ideal circuit power," *IEEE J. Sel. Areas Commun.*, vol. 32, no. 2, pp. 322–332, Feb. 2014.

[9] Q. Bai, J. Li, and J. Nossek, "Throughput maximizing transmission strategy of energy harvesting nodes," in *Proc. IWCLD*, 2011.

[10] O. Orhan, D. Gunduz, and E. Erkip, "Throughput maximization for an energy harvesting system with processing cost," in *Proc. ITW*, 2012.

[11] X. Wang and Z. Li, "Energy-efficient transmissions of bursty data packets with strict deadlines over time-varying wireless channels," *IEEE Trans. Wireless Commun.*, vol. 12, no. 5, pp. 2533–2543, May 2013.

[12] Z. Nan, X. Wang, and W. Ni, "Energy-efficient transmission of delay-limited bursty data packets under non-ideal circuit power consumption, in *Proc. of ICC*, Sydney, Australia, Jun. 10-14, 2014.

[13] X. Chen and X. Wang, "Energy-harvesting powered transmissions of delay-limited data packets," in *Proc. Globecom*, Austin, TX, Dec. 2014.

[14] X. Chen, X. Wang, and Y. Sun, "Energy-harvesting powered transmissions of bursty data packets with strict deadlines," in *Proc. ICC*, Sydney, Australia, Jun. 2014.

[15] M. Zafer and E. Modiano, "A calculus approach to minimum energy transmission policies with quality of service guarantees," in *Proc. INFOCOM*, vol. 1, pp. 548–559, 2005.