Reliable Multicast and Broadcast Mechanisms for Energy Harvesting Devices

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Abstract—The technologies of energy harvesting enable wireless sensors to provide slow but steady transmission rate with very low deployment cost. To efficiently (re)configure settings, transmit data, or update system information to a group of energy harvesting devices, broadcast/multicast schemes should be designed carefully. Currently, two main challenges to reliable broadcast transmission are known as transmission error and energy deficiency. The former comes from non-perfect channel conditions, and the latter is a result of power shortage, causing devices to work abnormally due to energy exhaustion. Considering the two challenges, we propose an erasure-based broadcast scheme for an energy harvesting network to guarantee reliable broadcast transmission. We address the tradeoff between reliability and throughput, and based on this we propose three policies to determine the broadcast period for different performance requirements. Simulation results show that the proposed schemes and policies can significantly improve the performance of broadcast transmission based on energy harvesting characteristics.

Index Terms—energy harvesting, reliable broadcast transmission, erasure code

I. INTRODUCTION

Energy harvesting, a new technique [2] known for its auto-recharging ability of the end equipment, brings great potential in energy-efficient wireless networks. As an addressed technique, energy harvesting features two attractive characteristics: low deployment/maintenance cost and high energy efficiency. Compared to the traditional sensors or devices, which periodically cost expense and human labor on the battery replacement, energy harvesting devices are able to recharge themselves via converting energy from the external environments, such as solar energy or mechanic energy from oscillation or noise [3]. Such self-replenishing ability not only elevates the energy efficiency but reduce the cost to maintain battery power.

Despite the node-level performance optimization issues in energy harvesting node have been carefully studied, the study on the reliable transmission mechanisms still has not been fully considered. In wireless communications, two well-known techniques for reliable transmission are [4] Automatic Repeat reQuest (ARQ) and Forward Error Correction (FEC) [5]. ARQ techniques require feedback information from the receiver. The transmitter retransmits the missing packets upon timeouts or explicit requests from the receiver. When the number of energy-harvesting devices is large, the signaling loading for ARQ to maintain the session for packet retransmission could be large. Besides, feedback messages consume power for uplink transmission, which is larger than packet reception power. If an energy-harvesting device frequently receives the packets broadcast by the base station, the device may suffer from energy shortage soon if it transmits feedback messages for ARQ. Different from ARQ, FEC is based on the use of error correction codes, in which the sender encodes the data using an error-correcting code with redundancy before transmission. The redundancy allows the receiver to recover the errors without retransmission. FEC enables the receiver to correct errors without ACK/NACK feedback overhead, but at the cost of higher forward channel bandwidth. Since employing ARQ technique requires extra energy and overhead to transmit the feedback message, the FEC-based reliable transmission is more suitable for energy harvesting devices. Erasure coding scheme, as a FEC mechanism, can further provide less storage overhead and repair times than strict duplicate given similar performance mean time to failure (MTTF) [6].

In the upcoming future, more energy harvesting devices may spread almost everywhere, serving as sensors or smart meters. To reduce maintaining cost for reconfiguration, these devices should periodically listen to base stations or small cells for broadcast information, such as paging message or system information update. Nevertheless, the legacy broadcast transmission in energy harvesting network confronts the challenge of suspended broadcasting data reception due to exhausted device energy, which is also referred as energy deficiency. To enable highly reliable broadcast transmission, the broadcast scheme should be carefully designed considering the energy harvesting capability of those deployed devices. However, very little existing work considers downlink broadcast issue for energy harvesting devices.

In this paper, we propose an erasure-based broadcast transmission scheme for energy harvesting sensors. The theoretical analysis shows a trade-off between throughput and reliability, based on which we propose three broadcast policies to meet different broadcast requirements. The rest of this paper is organized as follows. Section II is the related work of energy harvesting and reliable broadcast transmission. We introduce
the system model and energy profile in Section III. Section IV presents the proposed broadcast transmission scheme. Section V introduces the performance metrics, and Section VI derives the analysis of the proposed design. Section VII proposes three broadcast policies for different system requirements. The simulation results are shown in section VIII, and Section IX concludes this paper.

II. RELATED WORK

A. Energy Harvesting Sensor Networks

The technology of energy harvesting has attracted increasing attention in the research. Raghunathan et al. analyzed the various design choices and tradeoffs in the design of a solar energy harvesting module [7]. Sudevalayam et al. introduced the basic concepts of an energy harvesting system and discussed the design of sensor network applications and solutions [3]. Seah et al. also provided an overview of energy harvesting technologies and pointed out several research directions [8].

Due to the stochastic nature, the energy harvesting process can be modeled as a stochastic process. In [9], the authors considered that the energy harvesting rate is constant. Hence, the device could harvest a fixed amount of energy in each time slot. In [10, 11], the authors assumed the energy harvesting process is a Bernoulli process that the device could harvest energy with a fixed probability in each time slot. Nevertheless, above models are more tractable for analysis but not realistic. The more refined model is that the amount of harvested energy is dynamic based on the environmental conditions.

The authors proposed a 2-state Markov chain model as the energy harvesting model [12, 13]. In [14, 15], the authors chose the multiple states Markov chain model as the energy harvesting model. In [16–18], the authors assumed that the energy harvesting process follows a stationary and ergodic process. In this paper, we assume the energy harvesting model is a stationary and ergodic process as well.

Kansal et al. proposed the idea of energy-neutral operation [19], which states that the amount of consumed energy should not exceed the amount of harvested energy. The authors supplied theoretical foundations and proposed a duty cycle adaptation scheme to maximize the performance in energy-neutral mode, then followed by much research focusing on the node-level optimization.

Lei et al. modeled the energy harvesting process as a Poisson process, applied a Markov chain model for the state of the battery, and derived the optimal transmission policy for single-hop transmission [10]. Ho et al. proposed a generalized Markovian model that captures the non-stationary of Markovian model by introducing an additional parameter [14]. Medepally et al. analyzed the performance for an energy harvesting node over a single-hop time-varying channel model [11]. Seyedi et al. used 2-state harvesting model to evaluate the average time for energy run-out [12]. Seyedi et al. also discussed the problem of energy efficient transmission strategies for body sensor networks [13]. They formulated this problem as a Markov Decision Process (MDP). Joseph et al. obtained optimal energy management policies which minimize a linear combination of the mean queue length and the mean data loss rate [17]. Sharma et al. extended the work of [17] into [18]. The authors considered a more sophisticated system model with fading channels and effects of leakage and inefficiency in storage.

The network-level design and analysis have also attracted substantial research efforts. Tacca et al. proposed a cooperative automatic repeat request (ARQ) scheme to enhance the throughput [9]. Medepally et al. studied the cooperative transmission scheme for energy harvesting nodes [16], but the energy harvesting model is different from [9]. Niyato et al. considered the general energy harvesting model and channel state model and presented a queueing model and game-theoretic formulation for performance analysis and optimization [15]. Eu et al. studied the uplink medium access control schemes for wireless sensor networks powered by energy harvesting [20]. They proposed a probabilistic polling protocol achieving high throughput and fairness. J. Yang et al. considered the issue of broadcast transmission with energy harvesting nodes [21]. They assume the transmission nodes are energy harvesting nodes and aim to minimize the transmission complete time. K. Tutuncuoglu et al. investigate the single-link problem with energy harvesting nodes both in transmitter and receiver, and they propose a general framework of utility maximization by power control [22]. In this work, we focus on the design of a reliable broadcast transmission scheme. In the proposed scheme, we apply erasure coding to guarantee the transmission reliability for energy-harvesting devices, and we study how to maximize the throughput and the success probability by configuring the broadcast period and the parameters of the erasure coding. As we know, this topic is not yet well studied by the previous works.

B. Reliable Broadcast Transmission

There are two main methods of dealing with the transmission error: Automatic Repeat reQuest (ARQ) and Forward Error Correction (FEC). Hybrid scheme also exists. Jones et al. introduced the ARQ and the FEC techniques for error control [23]. In addition, they discussed the design issues in broadcaast transmission. Rizzo provided a theoretical description of erasure code [24] and discussed the applications of erasure coding. Hayinga studied two kinds of FEC methods and compared the performance [25]. Byers et al. discussed the implementation issues of erasure codes. They implemented and compared the performance of Tornado codes and Reed-Solomon codes. The advantage of Tornado codes is that it trades a small degradation of decoding inefficiency for improvement to encoding and decoding time [26]. Yuk et al. proposed an adaptive redundancy control method for erasure-based data transmission [27]. They used a continuous time Markov chain for modeling the loss process. With different degrees of packet loss, a sender can adapt the code rate to achieve the required reliability. Lin et al. derived and discussed the performance of erasure code in different parameter settings [28]. They revealed some situations when a whole-file replication is preferred. Wen et al. studied the retransmission scheme and erasure-based redundancy scheme [29] and concluded that the redundancy scheme can achieve better reliability and
energy efficiency when the loss probability is low. However, when the loss probability becomes large, the performance of erasure coding will be largely degraded.

To increase the bandwidth efficiency of reliable broadcast, the network coding scheme has been proposed recently. Nguyen et al. compared the network coding scheme and other broadcast schemes and evaluated the performance [30]. Fujimura et al. studied the performance of network coding and erasure coding in multi-hop scenario [31]. They provided the theoretical analysis and simulations, and concluded that network coding can achieve higher reliability. The network coding scheme is a promising technique; however, the network coding scheme needs feedback information from each receiver, so scalability is a challenge for a network with considerable devices. In view of this, we consider the erasure-coding based reliable transmission in this paper.

In a multi-hop scenario, the intermediate devices have to relay the broadcast traffic to neighboring devices. The tree-based broadcast transmission has widely been used. J.E. Wieselthier et al. proposed an algorithm to determine the minimum-energy tree for broadcast/multicast [32]. M. Čagalj et al. proved the problem of determining minimum-energy broadcast tree is an NP-complete problem [33].

III. System Model

A. General Description

We consider an Energy Harvesting Network, which consists of a base station powered by a fixed power supply and a number of energy harvesting devices deployed around the base station. In our model, the base station always has data present to be transmitted and it periodically broadcasts packets to all devices. Each device directly communicates with the base station, and aim to receive all packets broadcast by the base station, as illustrated in Fig. 1. We assume in each time slot the base station can broadcast at most one data packet. Since transmission may suffer from noise or interference, we assume that the transmission error occurs with a probability $\mu$.

B. Energy Harvesting Model

For the easy of Markov chain modeling, we apply the Bernoulli process as the energy arrival model. In the following context, we apply two tools to analyze the system model, Markov chain model and the proposed approximation model. For the Markov chain model, we apply the Bernoulli process as the energy arrival model for ease of analysis, i.e., we assume in each slot a device has probability $P_H$ to harvest $E_H$ mJ. The approximation model, in contrast, can apply to a stationary and ergodic process with mean $\rho$ mJ/slot.

Hence, our approximation model is capable of applying to several stochastic energy harvesting models. Likewise, the models of Bernoulli process in [10, 11] and the Markovian process in [12–15] belong to the stationary and ergodic process.

C. Energy Consumption and Energy Storage

In this paper, the main power consumption of an energy harvesting device is on receiving broadcast data. Assume that the packet size is fixed and the energy cost of receiving one packet is constant. We then denote the energy consumption of receiving one packet as $E_R$. In addition to the data reception, the devices also need to maintain the system operation or perform signal processing. We define $E_M$ as the amount of energy consumption per time slot to maintain the basic operation.

Next, we discuss the energy storage of energy harvesting devices. We consider that each device equips a rechargeable battery with energy capacity $C$ mJ. Without loss of generality, we also take the leakage effect into account. We assume that $E_L$ is the amount of lost-energy in each time slot due to the leakage effect. With the above definitions, a device costs $E_R + E_M + E_L$ in each busy slot and $E_M + E_L$ in each idle slot, in which a busy slot refers to a slot the device receives a packet, while an idle slot means a slot the device does not receive any data.

IV. Reliable Broadcast Transmission Scheme

A. Challenges of Reliable Transmission in Energy Harvesting Network

To achieve efficiently reliable transmission, the ARQ technique as well as the FEC technique has been widely used for reliable transmission; however, the former technique will be inefficient when the number of receivers becomes large. Furthermore, the ARQ technique demands its receivers to send feedback information, which is comparatively power-consuming than the FEC technique. In addition to packet loss, the energy deficiency is the other challenge in energy harvesting networks. When an effective FEC-based scheme is designed carefully, self-correcting code can be used to eliminate superfluous power waste. In this section, we consider both transmission error and energy deficiency, and apply the erasure coding scheme to resist the bad channel condition. Additionally, the energy-aware receiving scheme and early-termination scheme are also proposed to handle the energy deficiency problem.
B. Transmission with Erasure Coding

To enhance transmission reliability, the erasure-based redundant transmission scheme has been widely used. Erasure coding encodes $N$ original packets into $N + K$ packets. Then the transmitter will transmit the $N + K$ packets. For each receiver, it can reconstruct the original data if it receives at least $N$ out of $N + K$ encoded data packets. We call each correlated $N + K$ packets as a block. We denote the broadcast period $T$ as the interval between two adjacent downlink transmitted packets, and we define the block period as the interval of one block. Thus, the block period is $(N + K)T$.

Fig. 2 illustrates the operation of erasure coding. At first, the $N$ source data packet will encode into the $N + K$ encoded data packets. The redundant packets are added to enhance the reliability. After transmission, the device correctly received $N'$ packets. If $N' \geq N$, then the device can reconstruct the original $N$ source packets. If the number of packets correctly received is less than $N$, the device cannot reconstruct any packet and the energy consumed for receiving packets is a waste. Such circumstance is called incomplete reception. Fig. 3(a) shows an example of incomplete reception with the parameters $(N, K, T) = (3, 2, 4)$. We find that after the device receives one packet, its energy level drastically decreases. On the other hand, energy leakage and power consumption during signal processing cause only slight decrease of the energy level. The energy may randomly arrive and be harvested by the device. In this block period, the $2^{nd}$ and $4^{th}$ packets are loss due to noise or interference. Moreover, the device cannot receive the $3^{rd}$ packet because its battery power is exhausted. Then the device only correctly receives 2 packets in this block period. Therefore, the transmission is failed in this block and the power is wasted.

C. Energy-Aware Receiving Scheme

As mentioned, either the transmission error or energy deficiency leads to a receiving failure for an energy harvesting device. Erasure coding scheme only deals with the factor of transmission error. To handle the other problem, we propose the energy-aware receiving scheme to determine whether the
device should receive the block packets. The energy-aware scheme introduces an energy threshold $B$. In the beginning of each block, a device examines its own energy. If the device has energy more than the energy threshold $B$, it receives the block of packets; otherwise, it skips this block of packet reception and turn off the receiver for power saving. Obviously, the scheme can efficiently avoid incomplete reception - packet reception is interrupted due to exhausted energy. Fig. 3(b) illustrates the energy-aware receiving scheme. The device turns on its receiver when the energy level achieves the energy threshold at the beginning of each block period. Compare to the Fig. 3(a), the $3^{rd}$ packet can be correctly received in this case and the whole block packets can be reconstructed.

D. Early-Termination Scheme

In a legacy erasure coding scheme, the receiver should receive all the packets in one block, then it decodes the packets. To enhance the energy efficiency, we propose the early-termination scheme. The idea of the early-termination is that if a device already successfully receives enough number of packets to decode the original data packets, it then stops receiving the remains in this block to save power. To implement the early-termination scheme, we can add the checksum value in each broadcast packet, resulting in quick checking of the device whether the received packet is correct. The benefit of early-termination scheme is to improve the energy efficiency. As a result, the device can receive more packets.

Fig. 3(c) illustrates the combination of energy-aware receiving and early-termination schemes. The problem of energy deficiency is avoided because of the energy-aware receiving scheme. The device successfully receives the $1^{st}$, $3^{rd}$ and $4^{th}$ packets in this block, while the $2^{nd}$ packet is lost due to the noise or interference. Since the device has already correctly received 3 packets in this block period, it can skip the $5^{th}$ and save power according to the early-termination scheme.

V. PERFORMANCE METRICS

A. Successful Reception Probability

We define the successful reception probability $P_S$ as the probability that an energy harvesting device correctly reconstructs original packets when a base station broadcasts a block of packets, i.e.,

$$P_S = \frac{\text{The number of correctly reconstructed blocks}}{\text{The number of broadcast blocks}}. \quad (1)$$

This metric indicates the degree of reliability. If we want to achieve reliable transmission, then the $P_S$ should be guaranteed. According to the description of section IV, the device should accurately receive $N$ packets in one block period to reconstruct the original packets. Therefore, the $P_S$ also refers the probability that a device can correctly receive $N$ packets in one block period.

B. Throughput

The throughput $U$ refers to the number of data packets that one device correctly reconstructed per time slot, i.e.,

$$U = \frac{\text{The number of correctly reconstructed packets}}{\text{The number of total time slots}}. \quad (2)$$

Note that the device can reconstruct the original packets if it correctly receives $N$ packets, but it cannot reconstruct anything when the number of receiving packets in one block is below $N$. For an energy harvesting device, the throughput is limited by the amount of its available energy.

C. Energy Cost Per Packet

The amount of harvested energy is quite limited in current harvesting technologies, so the energy efficiency is a crucial metrics. $E_P$ refers that the expected amount of energy to correctly receive one packet, namely,

$$E_P = \frac{\text{Total energy consumption of receiving packets}}{\text{The total number of correctly reconstructed packets}}. \quad (3)$$

This metrics indicates the energy efficiency of the energy harvesting device in broadcast transmission. At the same energy level, the device can receive more data when the $E_P$ is smaller.

Before introducing the analytical model, we summarize the notations in Table I.

VI. ANALYTICAL MODEL

In this section, we evaluate the performance metrics of the proposed broadcast transmission scheme. At first, we evaluate the successful reception probability $P_S$. To derive the $P_S$, we decompose the probability into $P_{S|R}$ and $P_R$. $P_{S|R}$ and $P_R$ are defined as follows:

- $P_{S|R}$: The conditional probability that one block of packets can be correctly reconstructed in the device if it receives the block
- $P_R$: The probability that the device receives a block of packets

From the above definitions, we have

$$P_S = P_{S|R} = P_{S|R} \times P_R. \quad (4)$$

where the first equality in (4) holds because the event $R$ must occur when $S$ occurs.

Firstly, we evaluate the $P_{S|R}$. According to the energy-aware receiving scheme, a device receives a block of packets only when its energy level is equal to or larger than energy threshold $B$. In other words, if the energy threshold $B$ is large, the device decides to receive a block of packets only when it has sufficient energy to receive all packets of the block, and thus the energy deficiency effect can be eliminated. In this way, transmission failure is dominated by the transmission error. Hence we can obtain $P_{S|R}$:

$$P_{S|R} = \sum_{i=0}^{K} \binom{N+K}{i} \mu^i (1 - \mu)^{N+K-i}, \quad (5)$$

where $\binom{N+K}{i} \mu^i (1 - \mu)^{N+K-i}$ is the probability that $i$ packets experience transmission error.

We define $R_{blk}$ as the number of packets the device receives in one block period when it decides to receive. Since we assume the transmission error probability as a stochastic process following a Bernoulli process with parameter $\mu$, the probability distribution of $R_{blk}$ can then be expressed as

...
Likewise, if failing in receiving and the device stops receiving more packets in this block.

, which states that if the device successfully receives , which states that if the device successfully receives

\[
P(R_{blk} = r) = \begin{cases} 
0, & \text{if } r < \min(N, K+1) \\
\left(\frac{N-1}{N}\right)^r - N(1-\mu)^N, & \text{if } N \leq r \leq K \\
\left(\frac{K}{N-1}\right)^{K(1-\mu)^{r-K}}, & \text{if } K+1 \leq r \leq N-1 \\text{ } E_P, \text{ the expected energy cost per successfully received packet, can then be derived by:} \\
\left(\frac{K}{N-1}\right)^{K(1-\mu)^{r-K}} + \left(\frac{N-1}{N}\right)^r - N(1-\mu)^N, & \text{if } r = N + K + 1 \\
\end{cases}
\]

\[E_P = \frac{E(R_{blk})E_R}{NP_{S|R}}
\]

\[U = \frac{P_S \times N}{(N+K)T}
\]

Next, we derive the throughput \( U \):

\[U = \frac{P_S \times N}{(N+K)T}.
\]

\[A. \text{ The proposed approximation approach}
\]

In this subsection, we provide another approach to derive \( P_R \). By this approach, we can derive \( P_S \) without the need to solve the Markov chain equalities. Here, we denote \( \rho \) as the expected harvested energy per time slot, i.e., \( \rho = P_H E_H \) for the Bernoulli process modeling.

Denote \( T_{thr} \) as the number of slots in a broadcast period that can lead to energy neutrality, i.e., the consumed energy in a block period, \( E_R\hat{E}[R_{blk}] + (N+K)T(E_M + E_L) \), is equal to the consumed energy in a block period, \( (N+K)\rho \). Then we have

\[T_{thr} = \frac{E[R_{blk}]E_R}{(N+K)(\rho - E_M - E_L)}.
\]

When \( T \) is \( T_{thr} \), the expected amount of harvested energy in a block reception period \( (N+K)T \) is just enough to receive a block of packets. Thus, when \( T \) is smaller than \( T_{thr} \), the recharging rate is smaller than the power consumption, and thus the bottleneck of the system throughput is the energy harvesting rate. Since the energy harvesting rate \( \rho \) is independent of \( T \), the throughput values achieved by different \( T \), \( \forall T \leq T_{thr} \) are the same. Moreover, because of \( T \leq T_{thr} \), all harvested energy can be totally consumed on packet reception rather than accumulated in the battery, so the throughput is maximized when \( T = T_{thr} \) and \( (N, K) \) is given. Besides, there is a period reception probability per \( (N+K)T \) slots, but the device needs \( (N+K)T_{thr} \) to harvest enough energy for a block reception. So the probability for a UE to perform its block reception, \( P_R, \) is \( \frac{E[R_{blk}]E_R}{(N+K)(\rho - E_M - E_L)} \).

In contrast, when \( T \) is larger than \( T_{thr} \), a device can harvest more than what it needs, i.e., in each block period \( (N+K)T \) it can harvest more energy than its expected consumed energy \( ((N+K)T(E_M + E_L) + (N+K)E_R) \). In other words, only \( \frac{T_{thr}}{T} \) harvested energy is used for packet reception, and the other \( 1 - \frac{T_{thr}}{T} \) part is stored and accumulated in the battery. Therefore, when \( T > T_{thr} \), the system throughput \( U \) is proportional to \( \frac{T_{thr}}{T} \) (or inversely proportional to \( T \)), and the energy status in the steady state will stay in the capacity \( C \) since the harvested energy keeps accumulated into the battery until the battery capacity is reached. Moreover, when \( T > T_{thr} \), a device always has sufficient energy to receive packets in each block, and thus \( P_R = 1 \) and \( P_S = P_{S|R} \) hold.

From the discussion above, we have

\[P_R = \begin{cases} 
1, & \text{when } T > T_{thr} \\
\frac{T}{T_{thr}}, & \text{when } T < T_{thr}.
\end{cases}
\]
\[ P(E(n+1) \mid E(n)) = \begin{cases} \frac{P(H = E(n+1) - E(n)) + (E_M + E_L)T(N+K))}{E_R}, & \text{if } E(n) < B \\ \sum_{i=0}^{N} P(R_{dk} = i) \frac{P(H = E(n+1) - E(n)) + (E_M + E_L)T(N+K) + E_R)}{E_R}, & \text{if } B \leq E(n) \leq C \end{cases} \] (8)

\[
\begin{align*}
P_S &= P_{S|R}P_R = \begin{cases} P_{S|R}, & \text{when } T > T_{thr}, \\
P_{S|R} \frac{T}{T_{thr}}, & \text{when } T < T_{thr}, \end{cases} \\
U &= \frac{P_S \times N}{(N + K)T} = \begin{cases} \frac{P_{S|R}(N + K)T}{E_{[R_{dik}]E_R}}, & \text{when } T > T_{thr}, \\
\frac{P_{S|R}(N + K)T}{E_{[R_{dik}]E_R}}, & \text{when } T < T_{thr}, \end{cases} \\
K \text{, which justifies our argument that when } T < T_{thr}, U \text{ is constant and it depends on only the energy-harvesting parameters and (N,K) configuration rather than } T. 

\text{To sum up, we can observe that there is a trade-off between reliability and throughput: } P_R \text{ linearly increases with } T \text{ and reaches 1 when } T > T_{thr}, \text{ while } U \text{ keeps constant when } T \leq T_{thr} \text{ and is inversely proportional to } T \text{ when } T > T_{thr}. \text{ Considering the two cases for } T < T_{thr} \text{ and } T > T_{thr}, \text{ we can find that } T_{thr} \text{ is the optimal } T \text{ given (N,K) and other system parameters, i.e., selecting } T \text{ as } T_{thr} \text{ reaches both the maximal throughput and the maximal successful probability } P_S. \text{ Thus, we consider the } T_{thr} \text{ as the } T \text{ for different sets of } (N,K), \text{ and we reduce the original } (N,K,T) \text{ optimization problem into a } (N,K) \text{ optimization problem. Consider } U \text{ and } P_S \text{ for different } (N,K) \text{ given } T = T_{thr}, \text{ we have}
\end{align*}
\]

\[
\begin{align*}
P_S &= P_{S|R} = \sum_{i=0}^{K} \binom{N + K}{i} \mu^i(1 - \mu)^{N+K-i}, \\
U &= \frac{P_{S|R}}{E_{[R_{dik}]E_R}} \frac{N + K}{E_{[R_{dik}]E_R}}. 
\end{align*}
\] (16)

\section{VII. Broadcast Polices}

In an energy harvesting network, devices have different capabilities of harvesting energy due to different locations, distinct energy harvesters, or various severity of transmission error. Hence, we denote \( \rho_j \) and \( \mu_j \) as the expected amount of arrival energy per slot and transmission error probability of device \( j \) respectively. Assume that all devices have the same energy capacity \( C \), where \( C \gg B \). At first, we determine the parameters \( (N,K) \) of erasure coding. The parameter settings should guarantee that each device can successfully receive packets when it turns on the receiver, or \( P_{S|R} \) approaches to 1. Hence, the parameters \( (N,K) \) are satisfied that

\[
\min_j \sum_{i=0}^{K} \binom{N + K}{i} \times (\mu_j)^i(1 - \mu_j)^{N+K-i} > 1 - \delta
\]

broadcast period \( T \) value to satisfy different system requirements.

\subsection{A. Reliability-First Policy}

The goal of the reliability-first policy is to ensure that successful reception probability \( P_S \) of each device is higher than \( 1 - \delta_r \), where \( \delta_r \) is a very small positive value. After satisfying the requirements, the throughput \( U \) should be as high as possible. We formulate the policy as an optimization problem:

\[
\begin{align*}
\{ \max_{T \in \mathbb{N}} \sum_j U_j(T) \mid & \text{subject to } P_{S_j}(T) > 1 - \delta_r, \forall j \\
& \text{Threading-First Policy}
\end{align*}
\] (17)

\text{Theorem 1. Problem in (17) has solution } T^* = T_{RF} = \max_j \{ T_{thr_j} \} = \max_j \{ \frac{E_{[R_{dik}]E_R}}{(N + K)\rho_j - E_{M} - E_{L}} \}.

\text{Proof.} We prove the theorem by the following inequalities:

\text{i. } T_{RF} \geq \max\{T_{thr_j}\}:

To satisfy (17), \( T_{RF} \) must be larger than \( T_{thr_j}, \forall j \) according to (14). Hence, we can obtain that

\[
T_{RF} \geq T_{thr_j}, \forall j
\]

\Rightarrow T_{RF} \geq \max\{T_{thr_j}\}

\text{ii. } T_{RF} < \max_j \{ T_{thr_j} + 1 \}:

To maximize the total throughput, the \( T_{RF} \) should be as small as possible. Hence, we get \( T_{RF} = \min\{T \mid T \geq T_{thr_j}, \forall j\} \Rightarrow T_{RF} < \min\{T \mid T \geq T_{thr_j} + 1, \forall j\} \Rightarrow T_{RF} < \max_j \{ T_{thr_j} + 1 \}.

According to i. and ii. and \( T_{RF} \in \mathbb{N} \), we get \( T_{RF} = \max_j \{ T_{thr_j} \} = \max_j \{ \frac{E_{[R_{dik}]E_R}}{(N + K)\rho_j - E_{M} - E_{L}} \} \).

\section{B. Throughput-First Policy}

The packet loss is not very critical to some applications, such as the real-time video streaming and the voice transmission. Therefore, we propose the throughput-first policy for such applications. We can find that the upper bound of throughput \( U \) is \( P_{S|R} \frac{N + K}{E_{[R_{dik}]E_R}} \) by (15). We define normalized throughput \( \hat{U}_j \) as the ratio of \( U_j \) to \( P_{S|R_j} \frac{N + K}{E_{[R_{dik}]E_R}} \). The aim of throughput-first policy is to guarantee that \( \hat{U}_j \) is larger than \( 1 - \delta_u, \forall j \), where \( \delta_u \) is a very small and positive scalar. It indicates that the throughput of each device approaches to the upper bound. We formulate the policy as follows:

\[
\begin{align*}
\{ \max_{T \in \mathbb{N}} \sum_j P_{S_j}(T) \mid & \text{subject to } \hat{U}_j(T) > 1 - \delta_u, \forall j \\
& \text{Throughput-First Policy}
\end{align*}
\] (18)
Definition 2. We define the normalized throughput $\hat{U}_j$ of device $j$ as follows: $\hat{U}_j = \frac{U_j}{P_S(r_j, N_j, E_{Mj}, E_{Rj})}$. 

Theorem 2. The solution of (18) is $T_{TF} = \min_j [T_{thr_j}] = \min_j \left[ \frac{E[R_{th_ij}]}{E_{Rj}((N_j - E_{Mj} - E_{L})r_j)} \right]$. 

Proof. We prove the theorem by the following inequalities: 
\[ i. \ T_{TF} \leq \min_j \{T_{thr_j}\}; \]
\[ ii. \ T_{TF} > \max \{T\mid T \leq T_{thr_j}, \forall j\}. \]
To satisfy (18), $T_{TF}$ must be smaller than $T_{thr_j}, \forall j$ according to (13). Hence, we obtain $T_{TF} \leq T_{thr_j}, \forall j$ (19). 

To maximize the reliability, the $T_{TF}$ should be as large as possible. Hence, we get 
\[ T_{TF} = \max \{T\mid T \leq T_{thr_j}, \forall j\}. \]
\[ \Rightarrow T_{TF} > \max \{T\mid T \leq T_{thr_j} - 1, \forall j\}. \]
\[ \Rightarrow T_{TF} > \min_j \{T_{thr_j} - 1\}. \]

According to i. and ii. and $T_{TF} \in \mathbb{N}$, we obtain $T_{TF} = \min_j [T_{thr_j}] = \min_j \left[ \frac{E[R_{th_ij}]}{E_{Rj}((N_j - E_{Mj} - E_{L})r_j)} \right]$. 

C. Eclectic Policy

The eclectic policy takes both throughput and reliability into account and maximizes the sum of the eclectic utility, which is the weighted product of $\hat{U}$ and $P_S$. The upper bound of $\hat{U}$ and $P_S$ are 1 and the lower bound of $\hat{U}$ and $P_S$ are 0. When the broadcast period $T$ equals to $T_{thr_j}$, the $P_S$ and $\hat{U}_j$ will approach to 1. In this case, the eclectic utility of device $j$ achieves the maximum. On the other hand, when $T > T_{thr_j}$ or $T < T_{thr_j}$, the eclectic utility of device $j$ will decrease. The goal of eclectic policy is to maximize the total eclectic utility. To generalize our analysis, we introduce a weighting coefficient $\alpha$ into the eclectic utility. The $\alpha$ implies the importance between throughput and reliability. We formulate the optimization problem as follows:

$$\max_{T \in \mathbb{N}} \sum_j P_S_j(T)^\alpha \times \hat{U}_j(T) \times (1-\alpha), \text{ where } 0 < \alpha < 1.$$ (19)

Definition 3. We denote the $T_E$ as the solution of problem in (19).

Definition 4. We define the eclectic utility of device $j$ as 
$$P_S_j(T)^\alpha \times \hat{U}_j(T) \times (1-\alpha).$$

Theorem 3. \[ \min_j [T_{thr_j}] \leq T_E \leq \max_j [T_{thr_j}] \]

Proof. Let $u(T) = \sum_j P_S_j(T)^\alpha \times \hat{U}_j(T) \times (1-\alpha)$. We prove the theorem by the following inequalities:

\[ i. \ T_E \geq \min_j [T_{thr_j}] \]
\[ \text{Assume that } T_E < \min_j [T_{thr_j}], \text{ then } u(T_E) = \sum_j P_S_j(T_E)^\alpha \times \hat{U}_j(T_E) \times (1-\alpha) < \sum_j P_S_j(T_E)^\alpha = u(T_E + \varepsilon), \text{ where } \varepsilon \text{ is a positive number}. \]

Contradiction. Hence, $T_E \geq \min_j [T_{thr_j}]$.

\[ ii. \ T_E \leq \max_j [T_{thr_j}] \]
\[ \text{Assume that } T_E > \max_j [T_{thr_j}], \text{ then } u(T_E) = \sum_j P_S_j(T_E)^\alpha \times \hat{U}_j(T_E) \times (1-\alpha) < \sum_j P_S_j(T_E)^\alpha = u(T_E - \varepsilon), \text{ where } \varepsilon \text{ is a positive number}. \]

Contradiction. Hence, $T_E \leq \max_j [T_{thr_j}]$.

According to i. and ii., we derive that $\min_j [T_{thr_j}] \leq T_E \leq \max_j [T_{thr_j}]$. 

---

**TABLE I**

THE NOTATION IN ANALYTICAL MODEL

<table>
<thead>
<tr>
<th>Notation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$</td>
<td>The expected amount of arrival energy per slot</td>
</tr>
<tr>
<td>$E_H$</td>
<td>The amount of energy harvested per slot in the Bernoulli model</td>
</tr>
<tr>
<td>$E_R$</td>
<td>The amount of energy consumption to receive one packet</td>
</tr>
<tr>
<td>$E_M$</td>
<td>The amount of energy consumption per slot to maintain the basic operation</td>
</tr>
<tr>
<td>$E_L$</td>
<td>The amount of energy loss from battery per slot due to leakage</td>
</tr>
<tr>
<td>$E_P$</td>
<td>The expected energy cost for a successful packet reception</td>
</tr>
<tr>
<td>$R_{th}$</td>
<td>The number of packet receptions to receive packets in a block period</td>
</tr>
<tr>
<td>$H_{th}$</td>
<td>The ratio of total harvested energy to total arrival energy</td>
</tr>
<tr>
<td>$B$</td>
<td>The energy threshold of energy-aware receiving scheme</td>
</tr>
<tr>
<td>$C$</td>
<td>The energy capacity of rechargeable battery</td>
</tr>
<tr>
<td>$N$</td>
<td>The number of source data packets in a block</td>
</tr>
<tr>
<td>$K$</td>
<td>The number of redundant packets in a block</td>
</tr>
<tr>
<td>$T$</td>
<td>Broadcast period</td>
</tr>
<tr>
<td>$U$</td>
<td>Throughput</td>
</tr>
<tr>
<td>$\mu$</td>
<td>The transmission error probability</td>
</tr>
<tr>
<td>$P_H$</td>
<td>The probability a device harvest $E_H$ mJ energy in a slot time (for the Bernoulli model)</td>
</tr>
<tr>
<td>$P_S$</td>
<td>Successful reception probability</td>
</tr>
<tr>
<td>$P_R$</td>
<td>The probability that the device decides to receive a block of packets</td>
</tr>
<tr>
<td>$P_{S</td>
<td>R}$</td>
</tr>
</tbody>
</table>
Note that it is a simple integer programming problem to find the $T_E$, and many existing integer programming approaches can be applied. A straightforward expression to describe the theorem is that if the broadcast period $T$ is larger than $T_{RF}$, then the throughput will be degraded and the reliability cannot be further improved, and vice versa. Thus, the possible range of $T_E$ is between $T_{RF}$ and $T_{TF}$.

VIII. SIMULATION RESULTS AND DISCUSSIONS

A. Performance Comparisons in Different Schemes

To verify our theoretical model, we use Matlab to develop an event-driven simulator, applying Bernoulli process as our energy-harvesting model similar to [10, 11]. In each time slot, a device has probability $P_H$ to harvest energy $E_H$ mJ, and probability $1 - P_H$ to harvest 0 mJ for the environment. The simulation settings are listed in Table II.

<table>
<thead>
<tr>
<th>Notation</th>
<th>value</th>
<th>Notation</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N$</td>
<td>3</td>
<td>$B$</td>
<td>250 mJ</td>
</tr>
<tr>
<td>$K$</td>
<td>2</td>
<td>$E_R$</td>
<td>40 mJ</td>
</tr>
<tr>
<td>$\mu$</td>
<td>0.1</td>
<td>$E_L$</td>
<td>0.5 mJ</td>
</tr>
<tr>
<td>$P_H$</td>
<td>0.3</td>
<td>$E_M$</td>
<td>0.5 mJ</td>
</tr>
<tr>
<td>$C$</td>
<td>2000 mJ</td>
<td>$E_H$</td>
<td>20 mJ</td>
</tr>
</tbody>
</table>

Fig. 4 shows respectively the $P_S$, $U$ and $E_P$ for different schemes. We can see in the energy-aware and early-termination scheme, we show the simulation results and the theoretical values from the Markov chain model and the approximation approach respectively. We can see the simulation results and the theoretical values match perfectly with each other, which justifies that the proposed approximation approach is available to evaluate the performance when $C$ is sufficiently large. Fig. 4(a) shows the successful reception probability $P_S$ for different broadcast period $T$. The $P_S$ increases as the broadcast period $T$ increases. The reason is that with longer broadcast period $T$, a device has higher probability to harvest sufficient energy to receive a block of packet successfully. By theoretical examination, we get $T_{thr} = 5.35$. When $T$ is larger than $T_{thr}$, the successful reception probability $P_S$ approaches to 1. We can see the minimal $T$ to reach 100% $P_S$ is reduced from 8 to 6.35 when we apply the early-termination scheme. Fig. 4(b) shows the throughput $U$ as a function of broadcast period $T$. We observe that when $T < T_{thr}$, the throughput $U$ of the energy-aware receiving scheme is at the same level. In contrast, when $T > T_{thr}$, the throughput drops as the increase of $T$, which indicates that the throughput is dominated by the downlink broadcast rate rather than the energy harvesting rate when $T > T_{thr}$. Moreover, we can see that the throughput can be significantly improved by apply both energy-aware and early-termination schemes. The former eliminates the situation of incomplete reception, while the latter reduces the expected energy to receive a block of packets compared to the baseline scheme. Fig. 4(c) presents the energy cost per packet $E_P$ as a function of broadcast period $T$. As we can see, the early-termination scheme reduce the average energy consumption to receive a block of packets, so it shifts down the average $E_P$ for all $T$ values. In contrast, energy-aware receiving scheme helps eliminate the situation of incomplete reception, which occurs only when $T$ is smaller than $T_{thr}$. Note that if we do not apply energy-aware scheme (i.e., the original scheme and the early-termination only schemes), a device will exhaust its harvested energy in incomplete reception. Therefore, when $T$ is small, a device in the two schemes will frequently waste energy in incomplete reception, and thus cause very large $E_P$ when $T$ is small.

B. $(N,K)$ optimization for homogeneous energy-harvesting devices

In this subsection we consider fixed energy-harvesting parameters, i.e., each device has homogeneous characteristic in $\mu$ and $\frac{E_{SE} - E_L}{P_H}$. Fig. 5 shows performance metrics for different combinations of $(N,K)$ when $T$ is set as $[T_{thr}]$. Fig. 5(a) shows that given the error probability $\mu$ and $T = [T_{thr}]$, and Fig. 5(b) shows the maximum throughput for different $(N,K)$ combinations. Compared Fig. 5(a) and Fig. 5(b), we can find that those $(N,K)$ sets with $P_S$ close to 1 achieve similar throughput, which is the maximal throughput decided by the energy-harvesting rate. This result justifies our argument that when all $(N,K)$ pairs that reaches $P_S \rightarrow 1$ can reach both the maximal throughput and the maximal $P_S$ by setting $T$ as $T_{thr}$. Note that there is some difference between these maximal throughputs achieved by different $(N,K)$. The reason is that to reach an optimal throughput, the $T$ should be set as $T_{thr}$, but in reality $T$ should be an integer and thus leads to the throughput for different $(N,K)$ settings.

Fig. 5(c) shows the selection of $T$ (set as $[T_{thr}]$ for different $(N,K)$ combinations. Observe that we can make derive small $T_{thr}$ by applying small $N$ accompanied with large $K$ much larger than $N$, which is because $T_{thr}$ is proportional to $N + K$. Fig. 5(d) shows the $E_{RF}$ for different $(N,K)$ combinations. Fig. 5(e) shows the average time for a block of packet to be successfully received, which can be derived by $D = TE(R_{blk})$. Fig. 5(f) shows the block period $(N+K)T_{thr}$ for different $(N,K)$ settings. We can see small packet delay can be achieved by setting small $N$ and $K \gg N$, and it may be a good configuration for the base station to transmit delay-sensitive data to energy-harvesting devices. However, as the price of shorter delay, the base station takes much more resources in transmitting redundant packets ($\frac{K}{N+K}$).

C. The Effect of Energy Threshold

Fig. 6 illustrates the effect of energy threshold $B$. In this figure, the broadcast period $T = 4$ is chosen, where $T$ is smaller than $T_{thr}$. It implies that the harvested energy is insufficient to receive each block of packets. We can observe that the probability $P_{S|R}$ increases when $B$ increases, because higher energy threshold $B$ guarantees more opportunities to receive packets in one block period. When $B$ is large enough to eliminate the effect form incomplete reception, the $P_{S|R}$ is then dominated by only transmission error rather the
incomplete reception, and thus $P_{S|R}$ comes to converge to a steady state regardless the value of $B$.

On the other hand, as $B$ increases, $P_R$ drops from 1 and then converges $\frac{1}{T_{thr}}$ when $B$ is large, as introduced in (13). Note that when $B$ is large, the effect of incomplete reception is eliminated and thus the equality $P_S = P_{S|R}P_R$ holds.

**D. The Effect of Energy Capacity**

To evaluate the energy loss due to limited battery energy capacity, we define the effective harvesting ratio $H_{eff}$ as $H_{eff} = \frac{\text{Total amount of harvested energy}}{\text{Total amount of arrival energy}}$. An energy harvesting device will have better performance when it has larger energy capacity to store more energy. In section VI, we derive the performance metrics under the infinite large energy capacity. Yet, while the energy capacity is finite, we introduce the effective harvesting ratio $H_{eff}$ into our analysis. We set $T = 4$ and $B = 180$, and the other parameters follows Table II. Figs. 7(a) and 7(b) illustrate the effect of energy capacity $C$. Observe that both $P_R$ and $H_{eff}$ converges when the energy capacity $C$ is large. Moreover, the difference between the ideal case ($H_{eff} = 1$ for sufficiently large $C$) and the simulation result is only 1%, which suggests that our analysis for large $C$ can be applied to approximate the performance of a realistic case with limited capacity.

Fig. 4. Performance metrics v.s. broadcast period $T$ in different devices.

Fig. 6. The probability of $P_{S|R}$, $P_R$ and $P_S$ with respect to the energy threshold $B$. 
Fig. 5. Performance metrics for different \((N, K)\) combinations

(a) Successful reception probability \(P_S\)

(b) throughput \(U\)

(c) Selected \(T\) (\(\lceil T_{thr} \rceil\))

(d) Expected number of receiving packet per block \(E(R_{blk})\)

(e) Expected delay \(D\)

(f) Block Period \(T_B\)
The Broadcast Policies in Energy Harvesting Network

In this subsection, we apply different broadcast policies in an energy harvesting network. For tractable analysis, in this evaluation we consider only 3 energy harvesting devices, whose energy-harvesting parameters are listed in Table III. The other parameters follow Table II. With the value of $\alpha = 0.5$ in eclectic policy, we obtain $T_{th_1} = 5.31$, $T_{th_2} = 6.44$ and $T_{th_3} = 7.12$ by (12). According to the three broadcast policies, we get the theoretical value $T_{TF} = 5$, $T_E = 6$ and $T_{RF} = 8$. Fig. 8(a) plots successful reception probability $P_S$ versus broadcast period $T$ in different devices. We can find that the $P_S$ of each device achieves maximum when the broadcast period $T \geq 8$. However, the throughput $U$ will decrease when $T > 8$. Therefore, the simulation results also indicate that $T_{RF} = 8$. Fig. 8(b) plots throughput $U$ versus broadcast period $T$ in different devices. We observe that the throughput of each device achieves maximum when the broadcast period $T \leq 5$. Because the successful reception probability $P_S$ will decrease when $T < 5$, we obtain $T_{TF} = 5$, which matches with the theoretical value as well. Fig. 8(c) plots eclectic utility versus broadcast period $T$ for all devices. The goal of eclectic policy is to maximize the sum of eclectic utility. According to Fig. 8(c), we can observe that the sum of eclectic utility reaches the maximum when $T = 6$. The simulation results and the theoretical analysis are also in correspondence.

E. The Broadcast Policies in Energy Harvesting Network

In this subsection, we apply different broadcast policies in an energy harvesting network. For tractable analysis, in this evaluation we consider only 3 energy harvesting devices, whose energy-harvesting parameters are listed in Table III. The other parameters follow Table II. With the value of $\alpha = 0.5$ in eclectic policy, we obtain $T_{th_1} = 5.31$, $T_{th_2} = 6.44$ and $T_{th_3} = 7.12$ by (12). According to the three broadcast policies, we get the theoretical value $T_{TF} = 5$, $T_E = 6$ and $T_{RF} = 8$. Fig. 8(a) plots successful reception probability $P_S$ versus broadcast period $T$ in different devices. We can find that the $P_S$ of each device achieves maximum when the broadcast period $T \geq 8$. However, the throughput $U$ will decrease when $T > 8$. Therefore, the simulation results also indicate that $T_{RF} = 8$. Fig. 8(b) plots throughput $U$ versus broadcast period $T$ in different devices. We observe that the throughput of each device achieves maximum when the broadcast period $T \leq 5$. Because the successful reception probability $P_S$ will decrease when $T < 5$, we obtain $T_{TF} = 5$, which matches with the theoretical value as well. Fig. 8(c) plots eclectic utility versus broadcast period $T$ for all devices. The goal of eclectic policy is to maximize the sum of eclectic utility. According to Fig. 8(c), we can observe that the sum of eclectic utility reaches the maximum when $T = 6$. The simulation results and the theoretical analysis are also in correspondence.

TABLE III

| The energy harvesting parameters of each device |
|---|---|---|---|
| device | $P_H$ | $E_H$ | $\mu$ |
| device 1 | 0.3 | 20 | 0.10 |
| device 2 | 0.5 | 10 | 0.07 |
| device 3 | 0.6 | 8 | 0.12 |

IX. Conclusions

Energy harvesting is a promising technique for energy efficient and low deployment cost communications. To reduce cost on reconfiguration, system information update, and downlink data transmission for numerous devices, an efficient and robust design for broadcast transmission in energy harvesting networks becomes quite essential. Although the node-level performance optimization issues have been further studied, little attention is paid to the study on reliable downlink broadcast/multicast transmission mechanisms. In this paper, we propose a downlink broadcast scheme for energy harvesting networks. To eliminate the extra energy consumption, we employed the erasure-based FEC scheme to handle the transmission error. Furthermore, energy-aware receiving scheme and early-termination schemes are proposed to cope with the problem of energy deficiency. Through the theoretical analysis, the trade-off relationship between reliability and throughput is clearly shown. Based on this observation, we proposed three broadcast policies to determine the most suitable broadcast period $T$ for different system requirements: the throughput-first policy achieves maximum throughput, the reliability-first policy guarantees the successful reception probability of each device, and the eclectic policy compromises between the throughput and the corresponding reception success probability. To conclude, we address the two main challenges of reliable broadcast transmission in energy harvesting network, and propose a system design and a comprehensive analysis. The simulation results are in line with the theoretical analysis.

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Fig. 8. Performance metrics v.s. broadcast period $T$ in different devices.

Guan-Yu Lin is now a PhD student in the department of Electrical Engineering of National Taiwan University. He received the B.S. degree in the department of Electrical Engineering at National Taiwan University. The interested topic is to evaluate the system performance and design protocols for 4G communication systems. Also, he is interested in applying game-theoretical approaches to address problems in wireless communication systems.

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Rath Vannithamby received his BS, MS, and PhD degrees in EE from the University of Toronto. Dr. Vannithamby leads and manages a team responsible for 4G/5G cellular research in Intel Labs. Prior to joining Intel, he was a researcher at Ericsson responsible for 3G research. Dr. Vannithamby is a Senior Member of IEEE. He has published over 40 scientific articles and has over 100 patents granted/pending. He has authored chapters of three books. He is a co-editor of a book “Design and Deployment of Small Cell Networks” to be published by Cambridge Press in 2014. He has served as a Guest Editor for EURASIP JWCN Special Issue on RRM for 3G+ Systems. He was a TPC track-chair for PIMRC’11. He is currently an editor for the Journal of IEEE Communications Surveys and Tutorials, and also for a new IEEE Journal on Internet of Things. He is a co-chair for two ICC 2014 workshops: ”5G Technologies” and ”M2M Communications for Next Gen IoT”. He is a co-chair for GC 2015 Industry Forum. He has given keynote speeches in major wireless communication conferences including Globecom’10 Broadband Wireless Access workshop. He has also served on TPC for major IEEE wireless communication conferences including ICC, GC, VTC, WCNC, and PIMRC. His research interests are in the area of 5G networks, energy efficiency, QoS, cross-layer techniques, cognitive radio, and machine-to-machine communications.

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