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Abstract

Energy harvesting may be needed to operate digital devices in locations where connecting them to the power grid and changing batteries is difficult. However, energy harvesting is often intermittent resulting in a random flow of energy into the device. It is then necessary to analyse systems where both the workload, and the energy supply, must be represented by random processes. Thus, in this paper, we consider a multi-hop tandem network where each hop receives energy locally in a random process, and packets arrive at each of the nodes and then flow through the multi-hop connection to the sink. We present a product-form solution for this N-hop tandem network when both energy is represented by discrete entities, and data is in the form of discrete packets.

Keywords (separated by '-'): Tandem networks - Energy packet network - Renewable energy

Tandem Networks with Intermittent Energy

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Abstract. Energy harvesting may be needed to operate digital devices in locations where connecting them to the power grid and changing batteries is difficult. However, energy harvesting is often intermittent resulting in a random flow of energy into the device. It is then necessary to analyse systems where both the workload, and the energy supply, must be represented by random processes. Thus, in this paper, we consider a multi-hop tandem network where each hop receives energy locally in a random process, and packets arrive at each of the nodes and then flow through the multi-hop connection to the sink. We present a product-form solution for this N-hop tandem network when both energy is represented by discrete entities, and data is in the form of discrete packets.

Keywords: Tandem networks · Energy packet network
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1 Introduction

Energy is one of the primary concerns for digital devices capable of processing and transmitting information such as computers, Internet of Things (IoT) and network nodes (e.g. sensors), as the total electrical energy use by ICT has been approaching 10% of total electricity consumption worldwide [1]. Therefore, many studies investigate the use of energy harvesting to reduce the dependency of such devices on non-renewable energy sources [2]. Harvested energy is also very useful for devices in remote locations such as stand-alone sensors, and in systems which are difficult to reach to change batteries. However, harvested energy is generally intermittent and limited, so that the Quality of Service (QoS) depends on the interaction between energy availability and the workload that the device must process. Since queueing models are useful for the analysis of communication and computing systems, the use of intermittent energy in queueing models was introduced in the "Energy Packet Network" (EPN) paradigm [3] where an energy queue is a battery, while a data or work queue is a usual queue of jobs or packets.

In this paper we present new results using a somewhat different modeling approach introduced in [4] where it is assumed that the sensing process that

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generates packets and the energy harvesting process that collects energy are both much slower than the forwarding (or service times) for the data packets (DP), with further work in [5]. A model with transmission errors, so that several energy packets (EP)s may be needed for a successful DP transmission, is discussed in [6,7]. A two-hop feed-forward network was analysed in [8]. Since tandem systems are of interest in several areas such as production lines, supply chains and optical transmission lines [9,10], in this work, we consider an N-hop tandem network model and present its product-form solution [11,12] for the joint probability distribution of backlog of DPs and EPs. Similar model without external data arrival at each node will also appear in extended form elsewhere [13].

2 N-Hops Tandem Network

The tandem network model shown in Fig. 1 is studied. Each node is assumed to sense traffic as discrete data packets (DP)s, and harvest energy as discrete energy packets (EP)s. The arrival of both DPs and EPs at Node-i are assumed to be independent Poisson processes with rate λ_i and Λ_i, respectively. It is also assumed each node has unlimited energy storage (e.g. battery or capacitor) and data buffer. Energy leakage occurs due to natural discharge characteristic of batteries, and DP loss occurs due to impatience or errors. The leakage rate at node i is μ_i (γ_i) when there are more than one EPs (DPs) at node i, and is μ_i^0 (γ_i^0) when there is just one EP (DP) at the same node.

With current electronic technology, the DP transmission time will be in the nanoseconds, while the constitution of a full DP through sensing of external events, the harvesting of a significant amount of energy, the leakage of an EP and the loss of a DP due to impatience or errors will take much longer time. Thus, we can assume that the DP forwarding times are negligibly small compared to these other time durations.

The state of node $i \in \{1, \dots, N\}$ at time t can be represented by the pair (x_i^t, y_i^t) where the first variable represents the backlog of DPs at the node, while the second variable is the amount of energy (in EPs) available at the same node. As with the single node model we must have $x_i^t \cdot y_i^t = 0$ since if there is both an EP and a DP at a node, the transmission occurs until either all DPs or all EPs are depleted at node i. Thus the state of a node may be represented by a single variable $n_i^t = x_i^t - y_i^t$. If:

- $n_i^t > 0$, then node i has $n_i^t = x_i^t$ DPs waiting to be forwarded, but it does not have the EPs at that node to start the transmission from that node,
- $n_i^t < 0$, then node i has a reserve of $-y_i^t$ EPs, but does not have any DPs to transmit,
- $n_i^t = 0$, then node i does not have any DP and EP in their respective buffers.

The tandem network is then represented by the vector of positive, negative or zero integers: $\bar{n}^t = (n_1^t, \dots, n_N^t)$, $t \geq 0$, and $\bar{n}$ denotes a particular value of the vector, so that we study the probability $p(\bar{n}, t) = Prob[\bar{n}^t = \bar{n}]$.

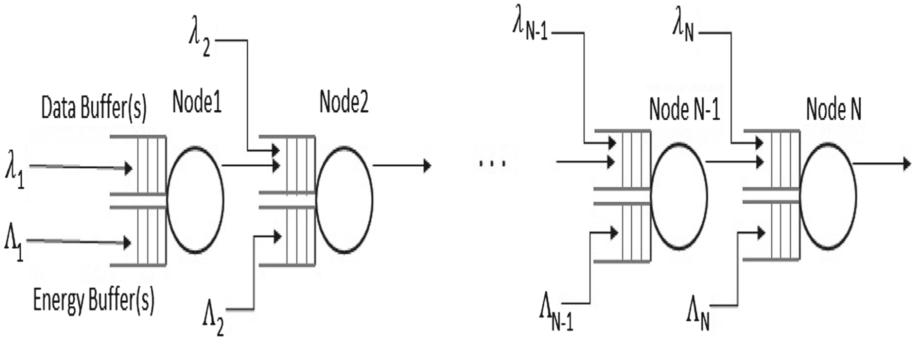

Fig. 1. Tandem network comprised of several store-and-forward layers that forward data packets (DPs) to the devices that collect the data and monitor the sources of the data.

Let $\bar{e_i} \triangleq (0, 0, \cdots, 1, \cdots, 0)$ be a vector whose i^{th} element is 1 and other $N-1$ elements are 0. The equilibrium equations for the steady-state probability distribution $\pi(\bar{n})$ for this system are:

$$\pi(\bar{n}) \sum_{i=1}^{N} [\lambda_i + \Lambda_i + \gamma_i \delta_{n_i>1} + \gamma_i^0 \delta_{n_i=1} + \mu_i \delta_{n_i<-1} + \mu_i^0 \delta_{n_i=-1}] \tag{1}$$

$$= \sum_{i=1}^{N} [\pi(\bar{n} + e_i)(\gamma_i \delta_{n_i>0} + \gamma_i^0 \delta_{n_i=0} + \Lambda_i \delta_{n_i<0} \delta_{i \neq N} + \Lambda_N \delta_{i=N})] \tag{2}$$

$$+ \sum_{i=1}^{N} [\pi(\bar{n} - e_i)(\mu_i \delta_{n_i<0} + \mu_i^0 \delta_{n_i=0} + \lambda_i \delta_{n_i>0} \delta_{i \neq N} + \lambda_N \delta_{i=N})] \tag{3}$$

$$+ \sum_{j=1}^{N-1} \sum_{i=j}^{N-1} [\pi(\bar{n} - \sum_{k=j}^{i+1} e_k) \lambda_j \prod_{k=j}^{i} \delta_{n_k \leq 0} (\delta_{1+i=N} + \delta_{n_{i+1} \geq 1} \delta_{1+i \neq N})] \tag{4}$$

$$+ \sum_{j=1}^{N-1} \sum_{i=1}^{j} [\pi(\bar{n} + e_i - \sum_{k=1}^{N-j} e_{i+k}) \Lambda_i \delta_{n_i \geq 0} (\delta_{N-j \leq 1}. \tag{5}$$

$$. + \delta_{N-j \geq 2} \prod_{k=1}^{N-j-1} \delta n_{i+k} \leq 0)(\delta_{i=j} + \delta_{n_{N+i-j} \geq 1} \delta_{i \neq j})]$$

Theorem 1. Let:

$$v_1 = \lambda_1, \tag{6}$$

$$v_{i+1} = \lambda_{i+1} + \sum_{j=1}^{i} \lambda_j \prod_{k=j}^{i} \frac{\Lambda_k}{\Lambda_k + \gamma_k}. \tag{7}$$

and the conditions

$$v_i - \gamma_i = \Lambda_i - \mu_i, \tag{8}$$
$$\mu_i^0 = v_i + 2\mu_i, \tag{9}$$
$$\gamma_i^0 = \Lambda_i + 2\gamma_i. \tag{10}$$

are satisfied, then the steady state probability distribution:

$$\pi(\bar{n}) = \prod_{i=1}^{N} \pi_i(n_i), \tag{11}$$

where $\bar{n} = (n_1, n_2, \cdots, n_N)$ and

$$\pi_i(n_i) = \begin{cases} P_i, & \text{if} n_i = 0 \\ \frac{1}{2} P_i (\frac{v_i}{\Lambda_i + \gamma_i})^{n_i}, & \text{if } n_i \geq 1 \\ \frac{1}{2} P_i (\frac{\Lambda_i}{v_i + \mu_i})^{-n_i}, & \text{if } n_i \leq -1 \end{cases}$$

where the normalising constant P_i is:

$$P_i = (1 + \frac{v_i}{2\mu_i} + \frac{\Lambda_i}{2\gamma_i})^{-1}. \tag{12}$$

Equation 8 indicates that the net inflow of DPs, after removal of those that time-out, should be the same as the total inflow of EPs minus the loss of EPs due to leakage. The product-form solution of the joint probability distribution enables the rigorous computation of all the performance metrics (throughput, average backlog of DPs, energy efficiency, average response time) for such systems operating with intermittent energy.

Proposition 1. The steady-state arrival rate of DPs to Node 1 is obviously $\alpha_1 = \lambda_1$, and for Node i, $i > 1$:

$$\alpha_i = v_i. \tag{13}$$

Proposition 2. The DP throughput of Node-i in steady-state is:

$$o_i = \sum_{n_i > 0} \pi(n_i) \Lambda_i + \sum_{n_i < 0} \pi(n_i) v_i \tag{14}$$
$$= \frac{v_i \Lambda_i}{\Lambda_i + \gamma_i}. \tag{15}$$

Proposition 3. The average backlog of DPs waiting at Node-i in steady-state is:

$$<n_i> = \sum_{n_i > 0} n_i \pi(n_i) \tag{16}$$
$$= \frac{v_i}{\mu_i} \frac{\gamma_i}{\gamma_i + \mu_i}. \tag{17}$$

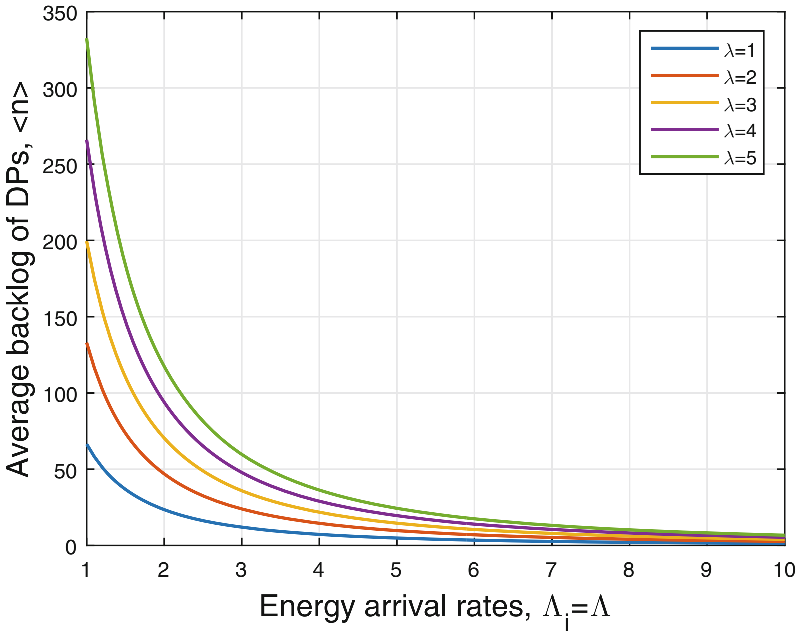

Fig. 2. The total average backlog of DPs at all of the $N = 5$ units, versus the arrival rate of EPs. We see that the values of N, Λ and λ impact the DP backlog time significantly. Note that the total energy arrival rate to the system is $N\Lambda$.

Proposition 4. The energy efficiency of Node-i can be defined as:

$$\eta_i = 1 - \frac{\mu_i}{\gamma_i + \Lambda_i}. \tag{18}$$

Proposition 5. The effective average response time (T_i) of Node-i in steady-state can be calculated as:

$$\frac{<n_i>}{v_i} = T_i(1 - l_i) + \frac{l_i}{\gamma_i} \tag{19}$$

$$T_i = \frac{\frac{<n_i>}{v_i} - \frac{l_i}{\gamma_i}}{1 - l_i} \tag{20}$$

$$T_i = \frac{1}{\Lambda_i}[\frac{\gamma_i}{\mu_i}\frac{(\Lambda_i + \gamma_i)}{(\mu_i + \gamma_i)} - 1] \tag{21}$$

where $l_i = \frac{(v_i - o_i)}{v_i}$.

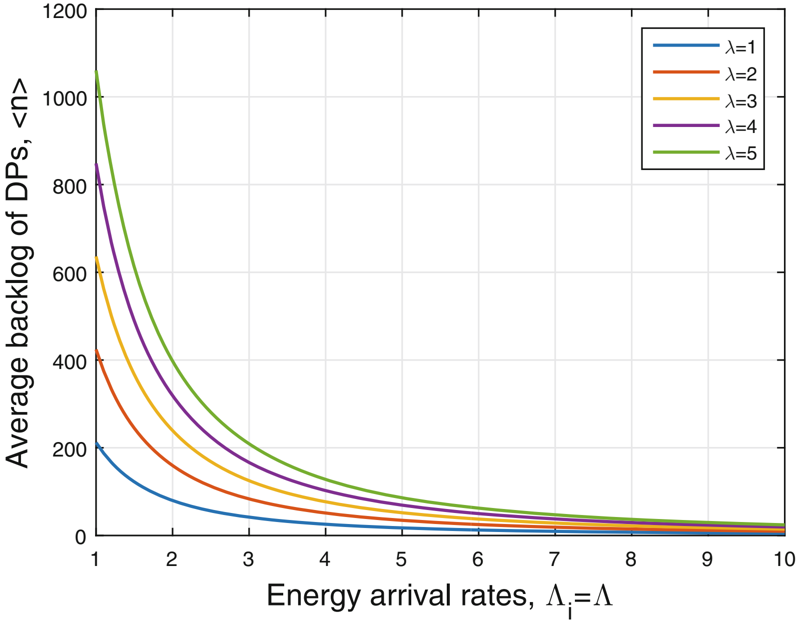

Fig. 3. The total average backlog of DPs at all of the $N = 10$ units, versus the arrival rate of EPs. We see that the values of N, Λ and λ impact the DP backlog time significantly. Note that the total energy arrival rate to the system is $N\Lambda$.

3 Conclusions

This paper introduces a mathematical model of a tandem network of very fast digital devices (i.e. having negligible service time) with limited and intermittent energy sources. The system times are determined by the speed at which energy is harvested and the speed at which data enters into the network. The nodes also suffer from EP losses due to battery leakage and some DP losses due to time-outs or due to the lack of energy in the system. We have explicited the conditions under which this model has product form solution, and presented the product form, jointly for both the EP "queues" (i.e. batteries) and the DP buffers at each of the nodes. Numerical results illustrate the usage of the model. In Figs. 2 and 3 we show the average backlog of DPs for different energy and data arrival rates, and different numbers of nodes N. We set identical values at all units $\Lambda_i = \Lambda$, $\lambda_i = \lambda$. Other parameters are $\gamma_i = 0.1\lambda_i$, $N = 5$ (Fig. 2) and $N = 10$ (Fig. 3), respectively. As one would expect, when the EP arrival rate increases, the average DP backlog decreases significantly since DPs are more rapidly transmitted. More nodes in tandem networks will result in higher overall packet backlogs since the net inflow of DPs will be higher.

In future work, the model can be generalized to time-varying data and energy arrival rates at each node, and dependent inter-arrival times.

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