Central or Distributed Energy Storage for Processors with Energy Harvesting

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***Abstract*—We consider an interconnected distributed computer system with multiple computation centres (CC) that operate with energy harvesting to improve sustainability. The intermittent energy harvesting is matched with steady demand from the CCs using energy storage (ES), e.g. batteries. Based on energy leakage from batteries, and power losses over transmission lines, we examine whether a centralised or distributed ES system provides the solution that offers the smallest response time to a fixed workload of computer jobs using the Energy Packet Network (EPN) modelling paradigm.**

***Index Terms*—Energy Harvesting; Distributed Computer System; Energy Packet Network**

I. INTRODUCTION

The massive increase in energy consumption by ICT [1] has induced much research in using energy harvesting [2], [3], [4], [5] as a means of reducing the resulting environmental impact. Such techniques, together with optimisation [6], [7] and learning [8] can be used to judiciously store and dispatch energy in complex systems such as Cloud servers, autonomous wireless sensor nodes, and within computer chips and boards. In this context, a convenient paradigm is to consider that harvested energy, just as computer jobs or data packets, consists of discrete entities that arrive at intermittent random intervals to the system that needs electrical power to operate [9], [10], [11]. This leads to the "energy packet network" (EPN) model and related prototype implementations [12], [13], [14].

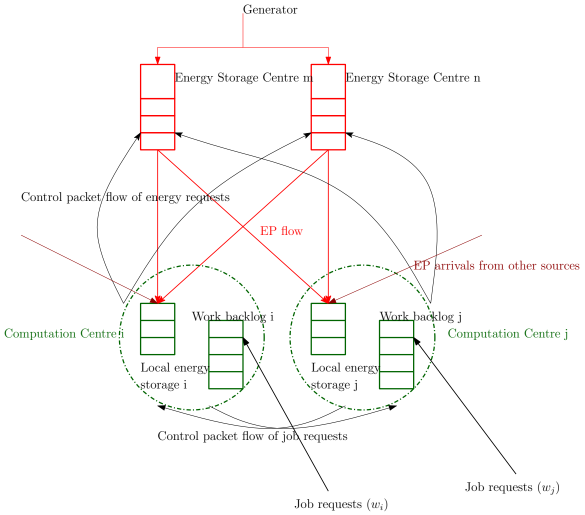

Fig. 1. Model where both energy and jobs are distributed on demand between computation centres.

In the EPN approach the discrete representation of energy in energy packets (EPs) is accompanied by a discrete representation of data packets (DPs) and discrete units of computational work (jobs). An energy storage unit is represented as a queue whose server is the output point of the battery or energy store, while its input is the stochastic flow from an energy harvesting unit or the intermittent flow from a generator. A computational server is represented as a queue of jobs with a service station containing one or more servers (e.g. a multiprocessing computer), and a router is a queue of packets with a server that forwards DPs to other nodes in the network. The queueing formalism of G-networks [15] is a good fit for this type of system: the conjunction of a job (i.e. a unit of computational execution) and an EP, together result in the execution of the job and the "consumption" of the EP. DPs can be used to exchange commands between units, so a DP may trigger the transfer of a job to another server, or it may request the transfer of an EP towards some server that requires energy, and so on. The EPs are "ordinary customers" of the G-network where EPs are stored in queues (batteries), the external arrivals of EPs are the energy produced by sources of intermittent energy, and the G-network "triggers" are DPs that signal the requests made by consumers whose energy buffers are being emptied by jobs, which are "ordinary customers" of a different class from EPs. In addition to triggering energy packets from storage centres to computational nodes, DPs may also be used to request new jobs from other computational nodes which have a backlog of available stored energy. Since intermittent sources of energy need to be coupled with energy storage for greater efficiency, we first briefly present the EPN model, and then use it to compare a centralised with a distributed architecture for storing and dispatching energy to a set of interconnected computer systems. We show that if all stored energy is shared among all consumers, and energy losses are significant along the connections between energy storage and consuming units (i.e. the computational modules), then a centralised storage facility will be more energy efficient. Also, available data [16], [17] indicate that leakage in a larger centralised energy storage (ES) unit may *smaller* than the sum of leakages from multiple ESs having the same overall capacity..

A. The EPN Model

Consider the EPN schematically shown in Figure 1 consisting of N computation centres (CC) C_1 ,..., C_N, and M ESs S_k replenished by intermittent renewable energy sources at rate λ_k in watts, $k = 1, \ldots, M$. A job on C_i is executed in average time μ_i^{-1} seconds with one EP of energy. This allows us to establish a relation between computational work and energy consumption; it is easy to generalise this to jobs that may require multiple EPs differently in different processors by simply having jobs at C_i return probabilistically multiple times to C_i before leaving it for another CC. Note that EPs are given in energy units (e.g. joules) while the energy flows or rates in EPs per unit time correspond to *power*. Each computation centre also has local energy storage that is connected to the S_k. The parameter η_k denotes the energy loss rate by leakage at S_k. After completing a work step at C_i, the job either goes to some other C_j with probability $P(i, j)$ or finishes and finishes work, hence leaves the system, with probability $1 - \sum_{l=1}^{N} P(i, l)$. As it does its work, C_i requests energy for future work from S_k with probability $p(i, k)$; with probability $1 - c(k, i)$ this request is rejected, while with probability $c(k, i)$ an EP is sent from S_k to C_i, resulting in the probability $q(k, i) = p(i, k)c(k, i)$. Note that $p_i = \sum_{k=1}^{N} p(i, k) \leq 1$ because C_i will not necessarily request an EP for each EP it consumes. Also, energy loss will occur during energy transmission between S_k and C_i, at a rate $\delta(k, i) = \delta * d(k, i)$ proportional to the physical distance $d(k, i)$ between them. Hence S_k will send not one EP, but $(1 + \delta(k, i))p(i, k)c(k, i)$ EPs/unit-time to the requesting CC to compensate for losses. Thus S_k's total energy transmission rate is $\sum_{i=1}^{N}(1+\delta(k, i))\rho_i h_i \mu_i c(k, i)p(i, k) \leq \Lambda_k$ where Λ_k is the maximum EP rate (watts) at which S_k can provide power. Furthermore, based on experimental data [18] we assume that C_i consumes energy at a rate $\rho_i\alpha_i + \pi_i$ where ρ_i is the probability that the CC is busy processing jobs, i.e. its utilisation rate, and α_i, π_i are constants. Applying G-Network theory [19], [20], if h_i is the probability the local energy storage at C_i is non-empty, and Q_k is the probability that S_k contains at least one EP. Assuming all job and EP arrivals are Poisson and service rates are exponential, G-network theory [15] allows us to write:

$$\rho_i = \frac{w_i + \sum_{j=1}^{N} h_j\rho_j\mu_j P(j, i)}{\mu_i h_i}, \quad R_i = \frac{\frac{1}{\mu_i}}{1 - \rho_i}$$

$$h_i = \frac{\gamma_i + \rho_i\mu_i h_i \sum_{k=1}^{M} Q_k q(k, i)}{\rho_i\alpha_i + \pi_i},$$

$$Q_k = \frac{\lambda_k}{\sum_{i=1}^{N} \rho_i\mu_i h_i q(k, i)(1 + \delta(k, i)) + \eta_k}.$$

where R_i is the average job response time at C_i.

II. CENTRALISED OR DISTRIBUTED STORAGE

Assume now that all N CCs have identical parameters and receive identical workload, and that the local power supply in watts at the CCs γ_i is negligible small $\gamma_i << \lambda_i$. Under these conditions we would like to compare the two systems in Figure 2, to determine whether we should have a single *centralised* ES storing receiving energy and distributing it to the CCs, or whether it is preferable to have M identical *distributed* ESs shared by all CCs. We assume that all CCs have identical processing rate μ. The ESs each receive energy at rate λ and have leakage at rate η in watts. If the ESs accept to deliver the energy request by the CCs and provide them with energy when they have it, then $c(k, i) = 1$, so that $\sum_{k=1}^{M} p(i, k)c(k, i) = p_i$ even when $M = 1$. Because the CCs are identical we take $P = \sum_{j=1}^{N} P(j, i)$, $p_i = p$. For both the centralised *and* distributed case we have:

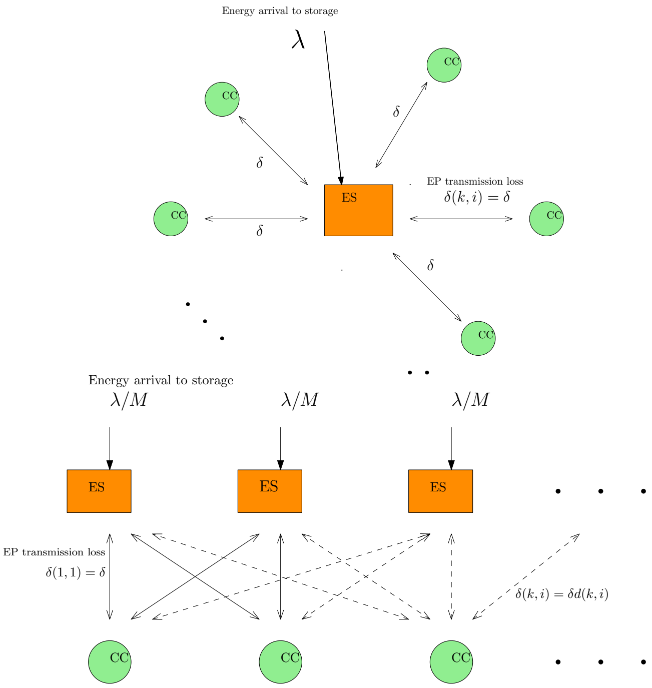

Fig. 2. Centralised system architecture when N CCs share a single ES (top) with power connections of equal unit length experiencing the same energy transmission loss rate $1.\delta$, compared to the Distributed Case (bottom) when CCs share M identical ESs with energy transmission loss rate $\delta(k, i) = \delta d(k, i)$ in watts proportional to the distance $d(k, i)$ of C_i from each S_k.

$$\rho = \frac{w + \rho\mu h P}{\mu h}, \quad h = \frac{\gamma + \rho\mu h Q p}{\rho\alpha + \pi}.$$

As a consequence we have the following results:

Lemma 1 Both for the system that uses a single centralised ES or M distributed ESs, as long as all of the CCs are identical with identical workload w then:

$$\rho h = \frac{w}{\mu(1 - P)}, \quad h = \frac{\gamma}{\pi} + \frac{w[Qp - \frac{\alpha}{\mu}]}{\pi(1 - P)}. \qquad (1)$$

which *only* depends on the individual arrival rate of jobs w to each CC, the job service rate μ, and p, P, π, α.

Lemma 2 Since jobs visit on average $1/(1 - P)$ CCs before completion, with N identical CCs the average response time for jobs in the system is $R^* = (1/\mu)[(1 - P)(1 - \rho)]^{-1}$. R^* is an increasing function of ρ. By *Lemma 1* ρ is a decreasing function of h, and h is an increasing function of Q, it follows that as Q increases, R^* decreases.

Now assume that for the centralised case, all CCs are at the same distance $d = 1$ of the ES; the probability that the *centralised* ES unit contains at least one EP is:

$$Q_c = \frac{\lambda_c}{N\mu p\rho_c h_c(1+\delta)+\eta_c} = \frac{\lambda_c}{Np\frac{w}{1-P}(1+\delta)+\eta_c},$$

while for each distributed ES it is:

$$Q_d = \frac{\lambda_d}{\frac{N}{M}\mu p\rho_d h_d(1+\delta_d)+\eta_d} = \frac{M\lambda_d}{Np\frac{w}{1-P}(1+\delta_d)+M\eta_d},$$

where we assume that all CCs make energy requests to all ESs equally, and δ_d is the average energy transmission loss rate from ESs and CCs in the decentralised organisation. Thus:

$$\frac{Q_c}{Q_d} = \frac{\lambda_c}{M\lambda_d}\frac{Np\frac{w}{1-P}(1+\delta_d)+M\eta_d}{Np\frac{w}{1-P}(1+\delta)+\eta_c}$$

This proves the following result.

Theorem If the total harvested power supply in the centralised and distributed systems are identical $\lambda_c = M.\lambda_d$:
- If the transmission losses are the same in both cases $\delta = \delta_d$, and the centralised system leakage is *less* than the overall storage leakage rate of the distributed system $\eta_c < M.\eta_d$, then $Q_c > Q_d$ and $R^*_c \leq R^*_d$. Hence *at equal power the centralised system delivers lower response time*.
- More generally for an equal amount of harvested power in both cases, $R^*_c \leq R^*_d$ if and only if:

$$\delta_d - \delta \geq \frac{\eta_c - M\eta_d}{Np\frac{w}{1-P}}, \quad (2)$$

which only depends on the leakage and transmission losses, the number M of ESs and N of CCs, on the workload, and the probability p that the CCs make a request for energy to the ESs after processing each job.

III. CONCLUSIONS

We study the choice of centralised or distributed energy storage in multi-computer system, when energy flows intermittently to ESs from energy harvesters, computer jobs arrive intermittently to CCs which need energy from the ESs, and computer jobs circulate among CCs till completion. Assuming identical total energy flows and computer job flows into the system, we show that the average job response times will depend on ES energy leakage and transmission loss parameters, and make optimum choices between a large or several smaller (in total equivalent) ESs.

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