Network Clustering and Cluster Control in Energy Harvesting Wireless Video Sensor Networks

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***Abstract*—A novel network clustering and cluster control algorithm is proposed for energy harvesting wireless video sensor networks. For inter-cluster energy balance, video sensor nodes are clustered based on their distance from a base station. For intra-cluster energy balance, a cluster head selects a cluster member with the largest residual battery level as the next cluster head. For minimum energy consumption of a cluster, control parameters for all cluster members in each cluster are decided by joint distortion-energy control model of video sensor nodes. From simulation results, the proposed algorithm is shown to keep both inter-cluster and intra-cluster energy balance, and to enable perpetual operation of energy-harvesting wireless video sensor networks.**

Keywords–wireless video sensor network; energy harvesting; energy balance; joint distortion-energy control model.

I. INTRODUCTION

Wireless video sensor networks (WVSNs) for public security and remote monitoring should monitor and record video without interruption [1]. Because they are expected to be installed in a wireless communication environment without stable power supply, energy harvesting is required for perpetual operation. Also, video sensor nodes should control video quality considering their residual energy while keeping network-wide energy balance to prolong the network lifetime.

There have been studies on energy-efficient clustering of wireless sensor networks to improve the lifetime of sensor networks [2][3]. Clusters were organized based on the energy consumption model of data transmission by sensor nodes and a cluster head (CH) was selected based on the selection history and random model [2]. A reactive sensor network routing protocol, TEEN, was proposed to reduce the number of transmission more appropriately in event-driven applications [3]. There have been efforts to extend the lifetime of video sensor networks based on an energy model of a video sensor node [4][5]. Gurses et al. established the energy model of a video codec and radio frequency (RF) transceivers with the energy control parameters of the bit-rate and compression mode of a video codec [4]. Jang et al. also established the energy models of a video codec and RF transceivers with the energy control parameters of routing paths, bit-rate, and aspect ratio of video codecs [5]. However, these studies did not consider the energy consumption of an image sensor which occupies a large portion of the total energy consumption of a video sensor node. Also, energy harvesting function and the corresponding energy consideration in video sensor nodes were not considered to extend the lifetime of WVSNs.

In this paper, a network clustering and cluster control method is proposed for perpetual operation of energy harvesting WVSNs. Sensor nodes are clustered based on their distances to the base station (BS) for inter-cluster energy balance. A video sensor node with the largest residual battery level is selected as the next CH for intra-cluster energy balance. For minimum energy consumption of a cluster, control parameters for all the video sensor nodes in the cluster are calculated by a CH based on joint distortion-energy (JDE) control method of video sensor nodes [6].

The rest of the paper is structured as follows. In Section II, we propose the energy balanced clustering method and WVSN control protocol for the inter-/intra-cluster energy balance. In Section III, we present simulator results verifying the inter-/intra-cluster energy balance. Finally, we conclude the paper in Section IV

II. ENERGY-EFFICIENT NETWORK CLUSTERING AND CLUSTER CONTROL

A. Energy Harvesting Wireless Video Sensor Networks

Energy harvesting WVSNs consist of several clusters where each video sensor node is equipped with energy harvesting and video sensing and encoding functions. Each cluster consists of one CH and several cluster members (CMs). CH aggregates the video data received from CMs and transmits it to the BS. The energy consumption model of a transceiver in [2] is used for our energy modeling and is shown in Table I where $k, d, \epsilon_{elec}, \epsilon_{amp}$ represent the amount of information generated by the cluster, the transmission distance, the energy consumptions by the transceiver and the amplifier, respectively.

TABLE I. ENERGY CONSUMPTION MODEL OF TRANSCEIVER MODULE. [2]

module	energy consumption model
transmitter	$e_{tx}(k,d) = ke_{elec} + kd^2\epsilon_{amp}$
receiver	$e_{rx}(k) = ke_{elec}$

B. Energy Balanced Clustering

For intra-cluster energy balance, the BS estimates the total energy consumption of each cluster by considering its average distance to the cluster and the cluster size.

For the cluster size n, the energy consumption by the cluster head for n rounds is defined as follows:

$$e^{ch}(n, \bar{d}_{bs}) = k(2e_{elec} + \bar{d}_{bs}{}^2\epsilon_{amp}) + e_{proc}, \quad (1)$$

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where $\bar{d}_{bs}$ and e_{proc} represent the average distance between the nodes in the cluster and the BS and the energy consumption required for video sensing and encoding in a CH or a CM, respectively.

The energy consumption by a cluster member is defined as follows:

$$e^{cm}(n, \bar{d}_{ch}) = (n-1)\Big\{\frac{k}{n}(e_{elec} + \bar{d}_{ch}{}^2\epsilon_{amp}) + e_{proc}\Big\}, \quad (2)$$

where $\bar{d}_{ch}$ represents the average distance between the CH and the CMs in the cluster.

Then, the total energy consumption by a cluster is defined as follows:

$$\begin{aligned} e^{tot}(n, \bar{d}_{bs}) &= k(2e_{elec} + \bar{d}_{bs}{}^2\epsilon_{amp}) + ne_{proc} \quad (3) \\ &+ \frac{k(n-1)}{n}\{e_{elec} + (\omega_1 n + \omega_2)^2\epsilon_{amp}\}, \end{aligned}$$

where ω_1 and ω_2 represent the model coefficients. These coefficients model the property of $\bar{d}_{ch}$ growing linearly as the cluster size n.

In conventional studies for sensor networks, the processing energy of a scalar sensor node is negligible compared to the transceiver energy. However, in wireless video sensor nodes, because the bandwidth of sampled data is quite larger than conventional scalar sensors, the processing energy should also be considered for clustering or cluster control. The processing energy in a video sensor node depends greatly on the rate control method of a video codec, and there may exist lots of possible combinations of video sensor node control parameters. Therefore, the processing energy is not considered for clustering, but considered only for cluster control.

In an initialization step, all nodes transmit their ID values, locations, and remaining battery levels to the base station. The number of clusters constructed for the $100 \times 100m^2$ area is chosen to be 5% of the total number of video sensor nodes as in the LEACH [2]. Each cluster is constructed based on the distance between the reference point and the BS with its cluster size proportional to $\bar{d}_{bs}{}^2$. The BS selects the size of each cluster to minimize the total energy consumption of the WVSN based on the total energy consumption of (3). The CH is selected right after the clustering. The clustering results are broadcast to all the nodes. An example of clustering is shown in Figure 1.

Figure 2 shows total cluster energy consumption by cluster size n and $\bar{d}_{bs}$ over n rounds. The time duration, n rounds, is same with the cluster size and is the average time for each node to act once CH when cluster size is n. If $\bar{d}_{bs}$ increases, $e^{tot}(n, \bar{d}_{bs})$ increases as the cluster size n decreases. For smaller cluster size n, because nodes in the cluster are more frequently selected as the CH, $e^{ch}(n, \bar{d}_{bs})$ increases while both $\bar{d}_{ch}$ and $e^{cm}(n, \bar{d}_{ch})$ decrease. However, because the effect by $\bar{d}_{bs}$ is more dominant than that of the cluster size n, the overall cluster energy consumption increases.

C. Video Sensor Network Control Protocol

After clustering by the BS, the CM with the highest remaining battery level in each cluster are selected as the CH of each cluster, and the BS broadcasts the clustering result and the CHs to all the nodes in the WVSN. Based on the received information, the CH selects the distortion-energy control parameters of the cluster for each predetermined time interval T. The control parameters are selected by the JDE control method [6] for the CM with the lowest remaining battery level.

Then, each round of the cluster starts with the selected control parameters and the CH performs time scheduling for time division multiple access (TDMA)-based data transmission and broadcasts the results to CMs. This allows each CM to turn off its transmitter if it is not in its assigned time interval, which results in efficient energy dissipation. The CMs transmit the sensed compressed video data, the identifier, and the remaining battery level after each round to the CH at the allocated time interval. The CH finally transmits the video data received from CMs to the BS. The CH selects the next CH, calculates the distortion-energy control parameters based on the remaining battery levels of CMs, and sends the results to all CMs in the cluster.

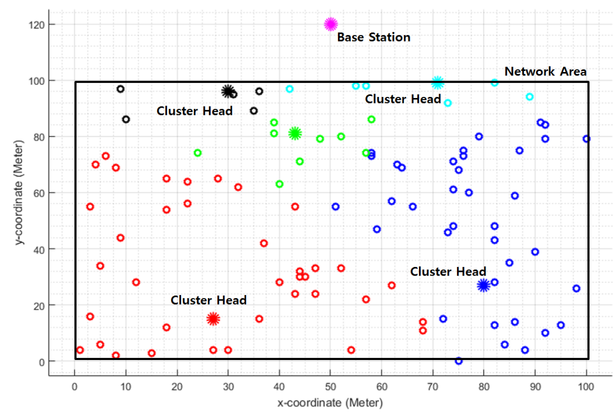


Figure 1. Energy balanced clustering results.

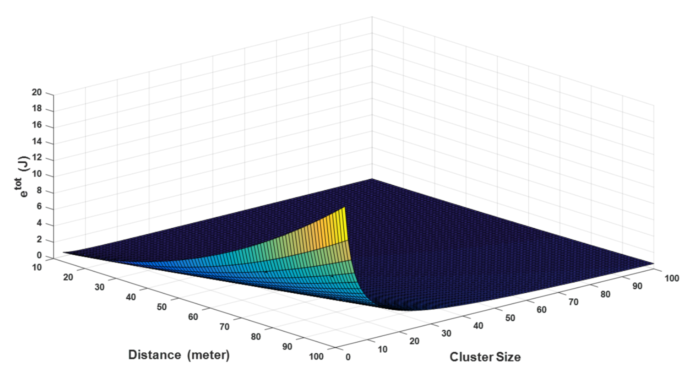
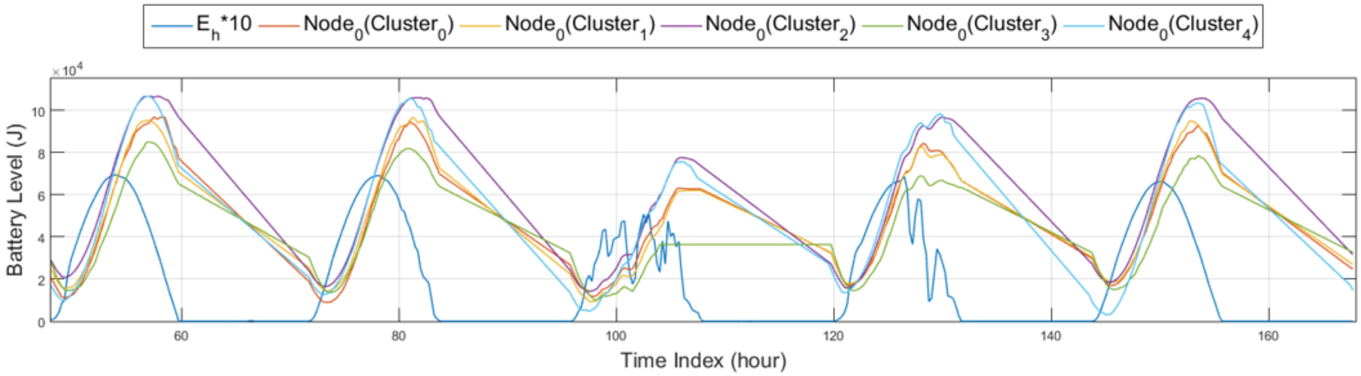


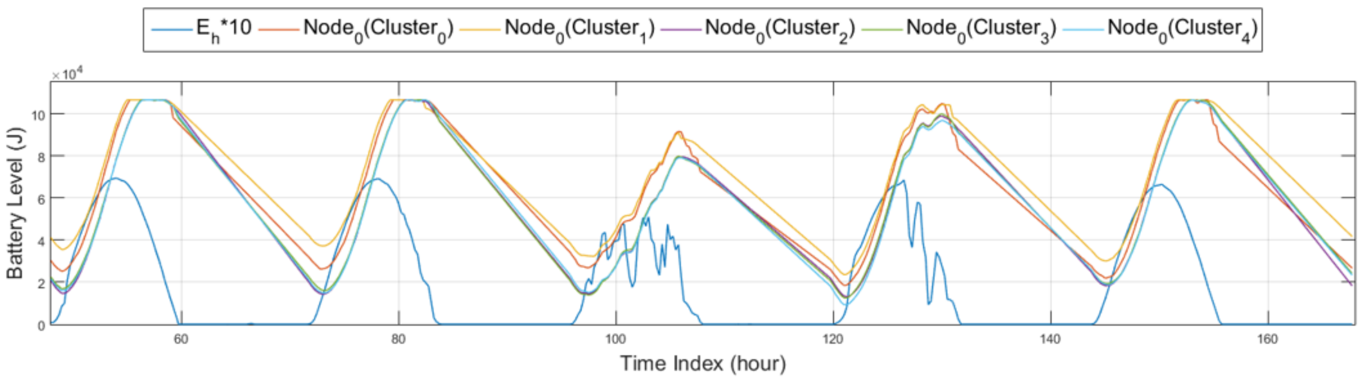
Figure 2. Total energy consumption e^{tot} during n rounds

III. EXPERIMENTAL RESULTS

A simulator is designed to evaluate the sustainability of WVSNs and the inter-/intra-cluster energy balance. Ranges of control parmeters for the JDE control of CMs, such as the operating frequency f of a video sensor node, the quantization parameter q_p and the frame rate r_M of a video codec, are summarized in Table II. Figure 1 shows the clustering results of video sensor nodes randomly distributed in $100 \times 100m^2$ area.



(a) equal sized clustering



(b) energy balanced clustering

Figure 3. Battery level of CM 0 of each cluster, E_h: harvesting energy.

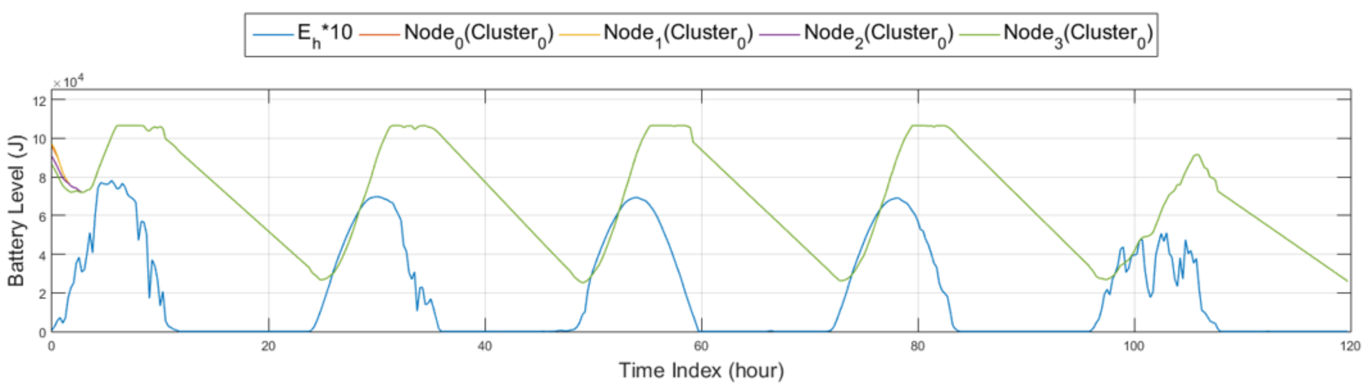


Figure 4. Evaluation of intra-cluster energy balance.

TABLE II. EXPERIMENTAL ENVIRONMENTS.

distortion-energy	$f(MHz)$	q_p	$r_M(fps)$
control parameters	200-1,400	30-45	1-30
time unit for encoding control	900 sec		
energy harvesting	battery capacity	solar panel size	
parameters	106,560J	600 cm^2	
video sequence	hall monitor	CIF (352 x 288)	

Figure 3(a) and Figure 3(b) show the battery levels of CM 0 of each cluster after equal sized clustering and the proposed energy balanced clustering methods, respectively. Although inter-cluster energy imbalance exists in equal sized clustering and operation halt of node 0 in cluster 3 due to the failure of the JDE control, operation halt and energy imbalance is decreased in proposed energy balanced clustering. Figure 4 shows the battery level for cluster members in cluster 0. Although there is difference in the battery levels between CMs in the initial phase, the difference decreases as the proposed cluster control goes on. This is because the proposed cluster head selection selects the next CH considering the remaining battery levels of CMs. The resulting inter-/intra-cluster energy balance enables

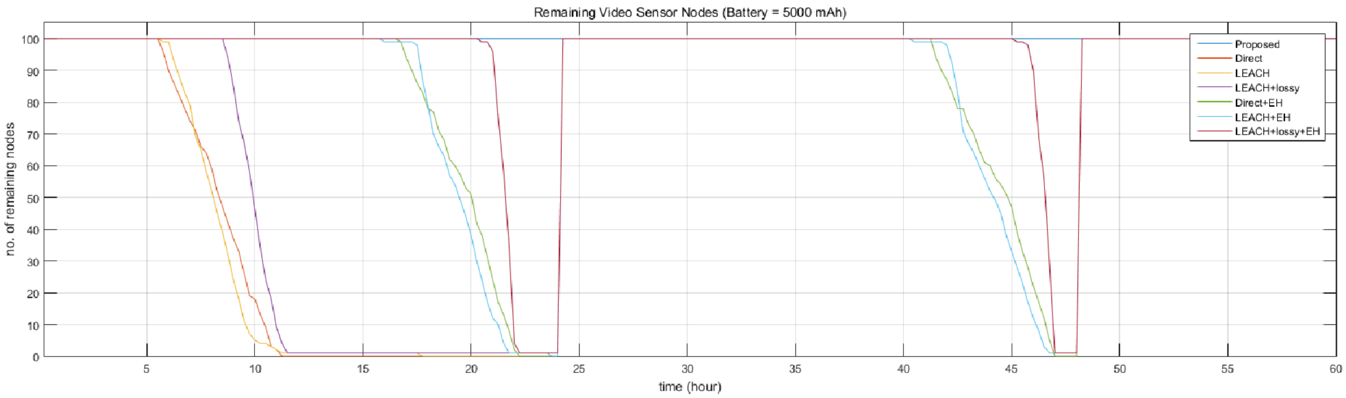


Figure 5. The number of operating CMs.

the perpetual operation of the cluster and the WVSNs.

Figure 5 shows the number of operating CMs for the proposed and the conventional clustering methods. *Direct* and *LEACH* represent the direct transmission without clustering and the clustering method by Heinzelman [2]. Suffixes *lossy* and *EH* represent additive functions, data compression and energy harvesting, respectively. Without EH, CMs die faster due to battery underflow and will not survive because they only use the initially charged energy. With EH, because the conventional clustering method does not consider the amount of harvested energy and the remaining battery level, CMs die during nighttime. However, since the proposed method controls the CMs with the JDE method which predicts the amount of harvesting energy and controls the energy consumption periodically, the CMs can operate perpetually day and night.

IV. Conclusions

A network clustering and cluster control algorithm is proposed for inter-/intra-cluster energy balance in energy harvesting WVSNs. Based on a ten-day simulation, the proposed distance based clustering, energy level based CH selection, and the cluster control by JDE control of video sensor nodes are shown to enable perpetual operation of energy harvesting WVSNs. The optimum number of clusters and the dynamic clustering should be investigated further for general energy harvesting WVSN applications.

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