Asynchronous Clustering of Multihop Wireless Sensor Networks

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Abstract—Node clustering has been widely studied in recent years for Wireless Sensor Networks (WSN) as a technique to form a hierarchical structure and prolong network lifetime by reducing the number of packet transmissions. Cluster Heads (CH) are elected in a distributed way among sensors, but are often highly overloaded, and therefore re-clustering operations should be performed to share the resource intensive CH-role. Existing protocols involve periodic network-wide re-clustering operations that are simultaneously performed, which requires global time synchronisation. To address this issue, some recent studies have proposed asynchronous node clustering for networks with direct links from CHs to the data sink. However, for large-scale WSNs, multihop packet delivery to the sink is required since long-range transmissions are costly for sensor nodes. In this paper, we present an asynchronous node clustering protocol designed for multihop WSNs, considering dynamic conditions such as residual node energy levels and unbalanced data traffic loads caused by packet forwarding. Simulation results demonstrate that it is possible to achieve similar levels of lifetime extension by re-clustering a multihop WSN via independently made decisions at CHs, without a need for time synchronisation required by existing synchronous protocols.

I. INTRODUCTION

Wireless Sensor Networks (WSN) are formed of simple sensing devices with limited battery energy that autonomously operate without being recharged for extended periods of time. Some typical applications are environmental or habitat monitoring and military surveillance, requiring the collection of sensory data to a control centre from a large deployment area.

Energy savings are possible in WSNs via exploiting the similarities in the collected data streams generated by sensors that are geographically close. The correlation of harvested data from sensors in the same locality leads to possibilities to *summarise* the gathered information from multiple sensors in a certain location by producing a single representative data stream. By placing nodes with higher computational power and higher energy stocks at regular locations in the network, a hierarchical structure can be formed, in which such nodes can perform data summarization and reduce the amount of data transferred to the network's data sink. However, WSNs must often be deployed without any infrastructure support and operate in a self-organised manner. Therefore, these data summarization nodes are instead selected from the deployed sensors, which then collect the data traffic in their vicinity. Without human intervention, forming such *clusters* of sensors is to be performed by the network itself: an autonomous

construction of network hierarchy [1]. Each sensor that collects data from a cluster of sensors is called a *cluster head* (CH).

Although the hierarchical structure obtained by node clustering provides energy savings by means of data summarization, CH nodes are responsible for processing the collected data streams from sensors and then relaying the summarised information to a next hop CH, to be delivered to the data sink. Therefore, CH nodes have higher energy consumption rates than ordinary sensors, effectively making them prone to early energy depletion. To prevent this, the CH-role is rotated among network nodes by renewing the set of CHs at regular intervals, which is a process called *re-clustering*.

Many node clustering protocols have been proposed as a means to extend network lifetime in WSN data collection scenarios [1]. These protocols divide the runtime into *time rounds*. Each round starts with a short re-clustering phase followed by a considerably longer data transmission phase in order to obtain a high fraction of time devoted to data delivery rather than topology management. However, protocols based on time-rounds require network-wide time synchronisation, so that nodes can simultaneously engage in this short reclustering phase and perform cooperative operations to elect the new set of CHs. Some recent studies [2] [3] [4] propose *asynchronous clustering* to avoid this requirement, however the proposed protocols assume direct links from CHs to the data sink, and therefore are limited to scenarios in which sensors can reach the sink in a single hop.

In this paper, we present the Asynchronous Clustering Protocol (ACP), designed for multihop WSN data collection scenarios. Sensor nodes dynamically change their transmission ranges to effectively modify the network hierarchy, considering residual node energy levels as well as the unbalanced traffic loads on CHs caused by multihop packet forwarding. In contrast to existing clustering protocols proposed for multihop WSNs, ACP does not require network-wide time-synchronisation [2] [5] [6] [7], estimation of inter-node distances [6], specific network topologies [7], or static estimations of energy consumption levels over multihop paths [7]. ACP is compared with the Unequal Cluster-based Routing (UCR) protocol in multihop WSNs in terms of gains in average throughput at the data sink and network lifetime. Simulation results demonstrate that ACP can achieve similar levels of network lifetime extension, while achieving higher throughput and lower node outage.

The paper is organised as follows. First, Sec. II provides a brief review of node clustering protocols in WSNs. Then, Sec. III describes ACP in detail. Performance results are provided in Sec. IV. Finally, Sec. V concludes the paper.

II. RELATED WORK

Node clustering in WSNs has been extensively studied in the past decade [1], with a number of protocols proposed to save limited sensor energy so as to extend network lifetime. The first generation of clustering protocols are designed for networks with direct links between CHs and the network's data sink [8] [9] [10]. The LEACH protocol [8] provides the first example of how a WSN can be autonomously organised to extend its lifetime. To achieve this, the strategy is to equalise the time fraction that different nodes take the load-intensive CH role. Starting with equal energy levels, each node picks a probability value to decide whether to act as a CH, based on the number of times it has recently claimed the CH role. An improved version of LEACH, called M-LEACH, is proposed in [11], in which nodes in a cluster deliver data to the CH over multihop paths and can thus achieve energy savings. Similarly, k-hop forwarding from cluster members towards the CH is included in [9] with simpler sensors that have a fixed radius rather than an adjustable one.

Instead of the received signal strength (RSS) from neighbour CHs, later clustering protocols introduce different metrics for sensors when making a decision on which CH to join. EECS [12] proposes a weighted cost function that takes into account sensor-to-CH and CH-to-sink distances to consider the transmission costs. HEED [5] introduces *average reachability power*, which is the average minimum transmission power to reach a CH from its neighbour nodes. This is used as an estimate of the prospective intra-cluster communication costs if the node chooses to act as a CH.

Residual node energy levels have been considered in clustering protocols to assign the CH role to resource-rich sensors. EEHC [13] is one example, which is designed for networks with direct links to the data sink from CHs. Similarly, HEED [5] takes into account residual node energy levels and uses CH node degrees to uniformly distribute the CHs in the network and provide high connectivity. Similar to HEED, DEEC [14] can provide fairer CH election in terms of energy levels, but all nodes need to know the most recent average node energy in the network. An improvement of HEED is the VCA protocol [15] which uses a voting mechanism to elect the CHs and regular neighbourhood messages to inform neighbour nodes of residual energy levels.

Apart from sensors' residual battery energy, a high traffic load is another factor that leads to early energy depletion. Towards this, some approaches [6] [7] [16] have considered the imbalance in traffic load between different sensors, and as a remedy, clusters of different sizes are formed, i.e. the CH communication range with cluster members. UCS [16] considers powerful nodes pre-deployed in the network to serve as CHs, whereas others, e.g. UCR [6] and EC [7], elect CHs in regular time rounds. These protocols are aimed

at improving network lifetime via elimination of network hot-spots caused by the imbalance in traffic loads on CHs due to multihop forwarding to the data sink. UCR needs to estimate inter-node distances using RSS levels to adjust node transmission ranges. In comparison, EC can provide longer network lifetime; however it relies on estimation of end-to-end packet delivery energy costs in a specific rectangular topology that is divided into virtual regions.

The common mechanism in node clustering in WSNs is that network runtime is divided into time rounds which start with a short re-clustering stage followed by a longer data transmission stage. In order to rotate the load-intensive CH role, nodes periodically perform re-clustering operations at each re-clustering stage to elect a new set of CHs that will serve the network during the next round. Recently, some studies have emphasized the need for a fully asynchronous operation in a self-organized WSN, which does not require time rounds [2] [3] [4]. These asynchronous node clustering protocols are designed for networks with single hops from CHs to the data sink and are not applicable to multihop WSNs, since in such networks it is essential to consider the multihop traffic loads. In contrast, this paper presents an asynchronous protocol specifically designed for multihop WSNs.

III. ASYNCHRONOUS CLUSTERING PROTOCOL (ACP)

ACP is a node clustering protocol, in which CH nodes make independent decisions to perform re-clustering operations. In contrast to conventional clustering protocols, ACP is not based on time-rounds and synchronised periodic re-clustering operations. When certain criteria are met, CH nodes initiate such operations either within their own clusters or over multiple neighbour clusters, covering a section of the network. Similar to most existing clustering protocols [5] [6] [7], each node i keeps a probability value $P(i)$, called the *CH-probability*, which reflects its likelihood to claim the CH role. ACP updates CH-probability values dynamically, based on three main node variables: (i) residual node energy level $E(i)$, (ii) latest incoming data traffic rate $r_{in}(i)$, and (iii) hop distance $h(i)$ to the sink. Cluster sizes are unequal, which is a strategy to equalise energy consumption rates at nodes.

A. Network Model

ACP is designed for data collection scenarios in large-scale multihop WSNs, which deliver collected sensor data to a network sink situated at a random location in the network area. Each sensor node is attached to a single CH, which collects the data generated by the sensors in its cluster, processes the data streams and summarises them into a single data stream, and then forwards the data packets to a next hop CH towards the data sink. The cluster size of a CH is its transmission range when communicating with cluster members. Cluster sizes are dynamically modified by re-clustering operations, which changes the network hierarchy over time. Data and control packet transmissions between CHs have a range of R , which is computed as outlined in [17].

B. Re-clustering in ACP

ACP has two re-clustering operations¹, ICR and MCR, that enable dynamic change of the CH-roles, as explained next.

1) *Intra-Cluster Re-clustering (ICR)*: ICR is based on the idea that a CH node may prefer to periodically compare its residual energy with those of the nodes in its cluster, and transfer its role to the most suitable one. This is performed in an attempt to balance the CH role, while limiting the transfer operations within individual cluster boundaries. Denoting the set of cluster members of a CH j by $C(j)$, an ICR check² is:

$$\text{Find a member } k \mid E(k) > \theta_{IN} * E(j), \quad k \in C(j), \quad (1)$$

where θ_{IN} is a threshold coefficient, and $E(\cdot)$ denotes node energy. An ICR operation is performed only if the ICR check holds for a member k with the highest residual energy. However, ACP allows a CH to transfer its role to a member node only if that node currently has connectivity to another CH. To ensure this, the following procedure is followed. CH j considers node k as a candidate and checks if k has any CH neighbours other than CH j , by sending a BEACON packet to node k . Upon reception of the BEACON from CH j , if node k does not have another CH neighbour³, then it replies with a BEACON to CH j , which then cancels the ICR and does not transfer its role. Otherwise, node k transmits a BEACON to its best CH neighbour bch (highest RSS) to check whether it is still available as a CH. After later BEACON transmissions from CH bch to node k and then to CH j , the CH role can be transferred only if CH bch is available. This is a policy towards keeping the network connected. Alternative nodes in the cluster are not tried consecutively, in order to keep the ICR as short as possible. This minimizes the data transfer interruption which can be caused by a long series of BEACON transmissions, especially for clusters with many members.

After a confirmation is received from its prospective CH, CH j first announces to its CH neighbours that it is about to transfer its role, with the transmission of a CHCANCEL packet. Neighbour CHs that have picked j as their next hop now check the availability of an alternative next hop CH via a BEACON packet, by going through the list of CHs in a descending order of RSS. CH j also transmits a CHCHANGE to its members, which includes the new CH's ID k and the latest *baseline probability* $p_{h(j)}$ (see Sec. III-C3) computed by CH j . Upon receiving the CHCHANGE, the new CH k first updates its CH probability $P(k)$ by Eqn. 5 using the baseline probability $p_{h(j)}$ received from the former CH j . Other member nodes also update their local copies of the baseline probability. Then, CH k transmits an ANNOUNCE packet with a range of $r(k)$ (see Sec. III-C1); receiving nodes not linked to a CH join CH k . Member nodes outside CH k 's range join a nearby CH with the highest RSS; or if no alternative CH exists, they start a reclustering timer (Sec. III-B2) to become a prospective CH.

¹A CH and its cluster can participate in either ICR or MCR at a time.

²ICR checks are limited to individual cluster boundaries, which avoids excessive control packet exchange over the whole network.

³The neighbour CH with the highest RSS is discovered via CHSIGNALS, see Sec. III-D3.

2) *Multi-Cluster Re-clustering (MCR)*: MCR refreshes the cluster structure over a wider area than a single cluster's coverage area. The operation is aimed at reducing the energy imbalance across multiple clusters. In contrast to ICR, MCR is an election-based scheme. Each node that participates in MCR (not necessarily every node in the network, as opposed to synchronous protocols) engages in a competition to become a CH by setting a timer called the *re-clustering timer* T_R . This timer is shorter if the CH-probability is higher: at a node i , $T_R = (1 - P(i))T$, where T is a system constant.

With periodic CHHELLO packet exchanges (see Sec. III-D2), each CH node j monitors the standard deviation of node energy in its cluster and calculates the average $\overline{\sigma_E}(j)$ of the standard deviation values collected from its CH neighbours. If this average is more than a certain level of the standard deviation σ_0 of the initial node energy levels of the network⁴, then CH j concludes that the energy balance across the region covered by neighbouring CHs is deteriorating. This is given by:

$$\overline{\sigma_E}(j) > \theta_{STD} * \sigma_0, \quad (2)$$

where θ_{STD} is a decision threshold coefficient. When the criterion in Eqn. 2 is met, an MCR is initiated by CH j which triggers its neighbouring CHs via a RECLUSTERCH packet to get involved. Each neighbour CH, including CH j then transmits a RECLUSTER packet to their members, indicating that an MCR has started. All involved CHs, their member nodes, as well as any other nodes in range that are not attached to a CH, update their CH probability values by Eqn. 5 using the baseline probability value recorded in the packet, and then set their re-clustering timers. Upon expiry of re-clustering timers, nodes transmit ANNOUNCE packets and notify their neighbour nodes of the formation of new clusters. If a node receives an ANNOUNCE before its timer expires, it ceases to participate in the election. Successful nodes become a CH and send ACCEPT packets to those nodes from which a JOIN has been received, and confirm those nodes' cluster membership.

C. ACP Fundamentals

In this section, the analytical basis that enables successful cluster updates via the ICR and MCR operations is presented. First, the CH-probability and its relation with cluster sizes and hop distances to the data sink are explained. Then, the concept of *baseline probabilities* is introduced as a way to balance multihop traffic loads on CHs.

1) *CH-probability and cluster sizes*: ACP makes a relation between a node i 's CH-probability $P(i)$ and the size of its cluster when node i becomes a CH. The *cluster size* of CH i is defined as the transmission radius denoted by $r(i)$ that CH i uses to communicate with its cluster members. The $P(i) \Leftrightarrow r(i)$ relation is a result of the fact that CH nodes are chosen by an election mechanism in which each node i transmits an announcement packet to declare its CH role within a range of $r(i)$. The announcement packet effectively notifies other nodes

⁴ σ_0 is a value pre-set at each node at deployment time.

that they cannot become a CH since they are within node i 's prospective cluster boundary. Similar election mechanisms have been used in previous protocols [6] [7].

The $P(i) \Leftrightarrow r(i)$ relation is derived such that there is a high probability to have at least one other node within the range $r(i)$, given the node density conditions. In doing so, the aim is for sensors to have a high chance to locate other CHs in their locality. This corresponds to the average number of CHs in a given area, which can be modelled by the Poisson pdf using the average uniform node deployment density σ . Defining node i 's announcement boundary by a circular radius $r(i)$, the probability that there is at least one CH node within this circular boundary is given by:

$$\text{Prob}\{\mathbf{n} \geq 1\} \approx 1 - e^{-\sigma P(i) \pi r(i)^2}, \quad (3)$$

$$r(i) \approx \sqrt{\frac{2 \ln 10}{\sigma P(i) \pi}}. \quad (4)$$

where $\sigma P(i)$ is the average CH density in the local area, and Eqn. 4 is derived by setting Eqn. 3 to 99%.

2) *CH-probability and hop distances to the sink*: The variables $P(i)$ and $r(i)$ are related with node i 's hop distance $h(i)$ to the sink, in order to capture the effect of multihop data forwarding imbalance in a large-scale WSN. The CHs that are closer to the sink have higher data forwarding loads, which suggests that they should ideally have smaller cluster sizes so that (1) the additional load from cluster members is less, and (2) more clusters can share the high load. Therefore, ACP strives to avoid network hot-spots by adjusting the cluster size $r(i)$ according to the hop distance $h(i)$. This is possible by associating $h(i)$ with a dynamic variable, called the *baseline probability*, $p_{h(i)}$, which depends on the traffic loads in node i 's neighbourhood. ACP relates the CH probability $P(i)$ to the baseline probability $p_{h(i)}$ as follows:

$$P(i) = p_{h(i)} \frac{E(i)}{\mathcal{E}_{\max}(i)}, \quad (5)$$

where $\mathcal{E}_{\max}(i)$ is the maximum residual node energy among the neighbours of node i (including its own energy). The energy proportion makes sure that higher energy nodes have a better chance to become a CH.

3) *Capturing the effect of multihop traffic load imbalance via 'baseline probabilities'*: Forwarding data flows hop by hop towards the sink causes increasing loads on the set of CHs at decreasing hop distances. Hence, denoting L_x as the average per-CH load at hop x , we have $L_1 < \dots < L_K$. In a large-scale WSN with many nodes, approximately circular bands of regions of almost equal widths around the sink are formed [18], where each region encloses the locations where nodes at a particular hop distance to the sink are found. Denoting the largest hop distance to the sink as K , the total average data traffic forwarded by CHs at hop x is $L_x \approx \sum_{j=i}^K (2j-1)at = (K^2 - i^2 + 2i - 1)at$, where t is the average sensor data traffic rate, a represents the area of the inner-most region, and $(2x-1)a$ approximates the area of the region at hop x .

For an equal distribution of load on CHs across the network, the number of CHs in a hop distance region must be higher if the forwarded traffic rate by that region is higher. As such, consider two regions R_1 and R_2 with areas of A_1 and A_2 , data loads of L_1 and L_2 served by n_1 and n_2 CHs, respectively. The corresponding CH probabilities are $p_1 = \frac{n_1}{\sigma A_1}$ and $p_2 = \frac{n_2}{\sigma A_2}$. In order to have the same load per CH and thus have energy equalisation between the two regions, we must ensure $\frac{L_1}{n_1} \approx \frac{L_2}{n_2}$. Hence, we have $p_2 \approx \frac{L_2}{L_1} \frac{A_1}{A_2} p_1$, and the baseline probability of hop distance x can be represented in terms of the baseline probability of the inner-most region, as:

$$p_x = \frac{L_x}{L_1} \frac{A_1}{A_x} p_1 = \frac{K^2 - x^2 + 2x - 1}{(2x - 1)K^2} p_1. \quad (6)$$

Setting a large p_1 leads to having more CHs in the network. Based on Eqn. 6, the total number of CHs in the network is approximately $M = \sum_{j=1}^K (2j-1)ap_j\sigma = \sigma\pi R^2 p_1 \sum_{j=1}^K \frac{K^2 - j^2 + 2j - 1}{K^2}$, where R is the CH-to-CH transmission range. Denoting $\sum_{j=1}^K \frac{K^2 - j^2 + 2j - 1}{K^2} = C$, we have $p_1 = \frac{M}{C\sigma\pi R^2}$.

4) *Network initialisation*: The first step of network initialisation is the discovery of node hop distances to the data sink by a single packet INIT from the sink that is flooded in the network by all nodes with the CH-to-CH transmission range R [17]. Each time this packet is forwarded, an acknowledgement packet ACK is sent back by receiver nodes. Those nodes that forward INIT packets, but consistently do not receive any ACKs back, prepare a HOPNOTIFY packet and unicast it to the sink through the discovered shortest path. The sink collects all HOPNOTIFY packets, determines the largest hop distance value K , and estimates the baseline probability p_1 of the inner-most region. Then, it disseminates K and p_1 to network nodes by flooding a SET packet.

The second step is the calculation of the initial baseline probabilities, as outlined in Sec. III-C3. Upon reception of SET, each node i computes $p_{h(i)}$ by Eqn. 6 and its initial range by $r(i) = \sqrt{\frac{2 \ln 10}{\sigma p_{h(i)} \pi}}$. After a single exchange of HELLO messages, the initial CH-probability $P(i)$ is computed by Eqn. 5. Then, the re-clustering timer (see Sec. III-B2) is set by $t_R(i) = (1 - P(i))T$, and nodes send ANNOUNCE packets when their timers expire. Finally, such nodes become CHs, whereas receiving nodes join the elected CHs.

D. Neighbourhood Packet Exchanges

The operation of ACP is based on the exchange of periodic feedback packets from neighbour nodes. Besides node-specific values, such as node ID and hop distance to the sink, each periodic packet contains some information required to update energy statistics. ACP has three neighbourhood packet types: HELLO, CHHELLO, and CHSIGNAL⁵.

⁵Nodes have their own timers that control the periodic transmission of these packets and node timers are not necessarily synchronised.

1) *HELLO packets*: Each node i transmits a periodic HELLO packet with a transmission range of $r(i)$, containing the residual energy level information, $E(i)$. Node i collects HELLO packets from the set of its neighbours and updates the following local statistics: (i) local energy average $\mathcal{E}(i)$, (ii) standard deviation of local residual node energy levels $\sigma_{\mathcal{E}}(i)$, and (iii) maximum local residual node energy level $\mathcal{E}_{max}(i)$.

2) *CHHELLO packets*: Each CH node i periodically transmits additional neighbourhood packets called CHHELLO to its neighbour CHs once in every CHHELLO time period, with the range R . CH nodes need not be synchronised. The exchange of CHHELLO packets provides co-ordination between neighbouring CHs and clusters, e.g. the baseline probability p is updated according to changing traffic loads on CHs and the dynamicity of the set of CHs (see Sec. III-E1).

The CHHELLO packet contains information on: (i) hop distance to the sink $h(i)$, (ii) baseline probability $p_{h(i)}$, (iii) the most recent traffic load $L(i)$ on the CH, and (iv) the standard deviation of local residual node energy levels $\sigma_{\mathcal{E}}(i)$. CH i updates the average $\overline{\sigma_{\mathcal{E}}}(i)$ of the standard deviation values collected from neighbour CHs, which is used in re-clustering operations as an indicator of the energy variation over multiple clusters, as explained in Sec. III-B2.

3) *CHSIGNAL packets*: CH nodes periodically exchange CHSIGNAL packets to update their next hops to the sink. Each CHSIGNAL contains energy and hop distance information. These packets are also used for nodes to track the existence of CHs in their vicinity, hence, in contrast to CHHELLOs, they are received by not only CHs but also ordinary sensor nodes.

E. Update of Protocol Variables

Protocol variables are updated based on the information received from neighbourhood packets.

1) *Baseline probability values*: CH nodes refine their baseline probability values, to balance the load on CHs, according to the latest network conditions, via the periodic CHHELLOs.

Let the set of CHs at hop distance x to the sink be S_x . CHs in S_i can receive CHHELLO packets from other CHs in S_{i-1} , S_i and S_{i+1} , provided that there are some neighbour CHs in these sets. To equalise the traffic loads on individual CHs,

$$p_{i_{new}} \approx \frac{L_i}{L_{i-1}} p_{i-1}, \quad p_{i_{new}} \approx \frac{L_i}{L_{i+1}} p_{i+1}, \quad (7)$$

must hold, where $p_{i_{new}}$ is the new value to be assigned to p_i . Due to dynamically changing traffic loads on CHs, the two objectives in Eqn. 7 may be in conflict, as they may separately and simultaneously force p_i to decrease or to increase. In order to have a unified update rule, the effects of S_{i-1} and S_{i+1} are scaled to be proportional to the corresponding number of neighbour CHs, namely N_{i-1} and N_{i+1} . Hence,

$$\begin{aligned} p_i &= \sum_{k=i-1}^{i+1} \frac{\overline{L}_k}{\overline{p}_k} \left(\frac{N_k}{N_{i-1} + N_i + N_{i+1}} \right) \\ &= \frac{N_i \overline{p}_i + N_{i-1} \overline{p}_{i-1} \frac{\overline{L}_i}{\overline{L}_{i-1}} + N_{i+1} \overline{p}_{i+1} \frac{\overline{L}_i}{\overline{L}_{i+1}}}{N_{i-1} + N_i + N_{i+1}}, \quad (8) \end{aligned}$$

where $\overline{p}_{i-1}$, $\overline{p}_i$, $\overline{p}_{i+1}$ are the average baseline probability values collected by a CH in S_i from its CH neighbours in S_{i-1} , S_i , S_{i+1} , respectively.

Each CH node in S_i first extracts the information on the advertised traffic loads and the baseline probabilities from received CHHELLO packets, and also monitors N_{i-1} , N_i , and N_{i+1} . Then, the average load values $\overline{L}_{i-1}$, $\overline{L}_i$, and $\overline{L}_{i+1}$, as well as the averages $\overline{p}_{i-1}$, $\overline{p}_i$, and $\overline{p}_{i+1}$ are computed. Finally, the baseline probability is updated by Eqn. 8.

2) *CH-probability and transmission range*: Whenever a CH i computes a new value for its baseline probability $p_{h(i)}$, CH i also updates its CH-probability $P(i)$ using Eqn. 5. Then, with the new value of $P(i)$, CH i updates its transmission range $r(i)$ using Eqn. 4. As explained in Sec. III-E1, CH nodes periodically refresh these variables based on received CHHELLO packets. All other nodes perform these updates only during re-clustering operations.

IV. PERFORMANCE EVALUATION

The performance of ACP is compared with that of a synchronous node clustering protocol, UCR [6], which is also designed for large-scale WSNs with multihop data delivery to a data sink. Similar to UCR, an ideal MAC layer and error-free communication links are assumed. In both protocols, the CH-to-CH range R is calculated as in [17] to boost connectivity. Packet sizes are picked according to the carried information, as listed in Table I, where the first four rows are for ACP, the next three rows are for UCR, and the last two rows are for the common packet types.

TABLE I
ACP, UCR, AND COMMON PACKET SIZES (BYTES)

Packet	Size, Content	Packet	Size, Content
BEACON	64, -	RECLUSTERCH	64, -
RECLUSTER	96, $p_{h(i)}$	CHCHANGE	80, New CH ID
CHCANCEL	64, -	CHSIGNAL	112, $h(i)$, $E(i)$
HELLO	96, $E(i)$	CHHELLO	176, $p_{h(i)}$, $L(i)$, $\sigma_{\mathcal{E}}(i)$, $h(i)$
FINALHEAD	64, -	CHADV	64, -
COMPETE	128, $E(i)$, $r(i)$	CHBEACON	128, $E(i)$, distance to sink
QUITELECTION	64, -		
ANNOUNCE	96, $r(i)$	JOIN	64, -
ACCEPT	64, -		

A. Energy Consumption Model

The energy consumption model is adopted from prior studies [8] [10] [13], given by Eqn. 9 below, which computes the transmission energy of l -bits to a receiver node that is x metres apart. The distance x in Eqn. 9 is the transmission range that a node uses within a cluster, e.g. $x = r(i)$ from a CH i towards a cluster member or from i 's cluster members towards i . For inter-cluster communications, CHs use a range of $x = R$.

$$E_{Tx} = \begin{cases} l(e_t + \epsilon_{fs} x^2)J & \text{if } x \leq d_{Th} \\ l(e_t + \epsilon_{mp} x^4)J & \text{if } x > d_{Th} \end{cases}, \quad (9)$$

$$E_{Rx} = l.e_r, \quad E_{Proc} = l.E_{bit} \quad (10)$$

The model differentiates between multi-path fading and free-space conditions. Considering a distance threshold of $d_{Th} = 87m$, free-space conditions are applied with $\epsilon_{fs} x^2$

when $x \leq d_{Th}$, where $\epsilon_{fs} = 10 \text{ pJ/bit/m}^2$. Otherwise, “multi-path” fading conditions are in place with $\epsilon_{mp}x^4$, where $\epsilon_{mp} = 0.0013 \text{ pJ/bit/m}^4$. The transmission and reception energy consumption constants are $e_t = e_r = 50 \text{ nJ/bit}$. The per-bit processing energy $E_{bit} = 5 \times 10^{-9} \text{ J/bit}$ with a standard deviation of 10^{-9} J/bit among network nodes.

B. Results

Presented performance results are averages of 10 randomly deployed networks in an area of $400m \times 400m$, where the data sink is located at the centre. The initial CH density is 10% for both protocols. Sensors with 10 different data generation rates in $[0.5 \text{ } 5] \text{ Kbps}$ are considered. The initial average node energy level is $2J$ with a standard deviation of $0.25J$.

As in UCR, performance results are generated by MATLAB simulations. The unit-time period is the average link transmission time for a control packet of 200 bytes, corresponding to approximately 0.3 msec for a 6 Mbps transmission rate. Time periods are multiples of the unit-time, i.e. HELLO= 40, CHHELLO= 80, CHSIGNAL= 50, $T_R = 1$. An ICR check is performed after a period of $T_{IN} = 100$, following a successful ICR. Decision threshold coefficients for ICR and MCR are arbitrarily chosen as $\Theta_{IN} = 1.25$ and $\Theta_{STD} = 1.25$.

Figure 1 illustrates the performance comparison of synchronous (UCR) and asynchronous (ACP) node clustering in multihop WSNs with respect to network lifetime, average data throughput at the sink, and node outage, for networks with various number of nodes. It is observed that an asynchronous protocol can achieve similar levels of network lifetime, while reducing the fraction of time (outage) when nodes are disconnected from the data sink and increasing the average data throughput at the sink, thanks to the exchange of neighbourhood messages and timely update of clusters at local areas.

Fig. 1. Performance comparison of UCR and ACP.

V. CONCLUSION

In this paper, it is shown that when adapting the network hierarchy to dynamic traffic load conditions in a clustered multihop WSN, network-wide node synchronisation is not a necessity. Similar benefits, as achieved by synchronous clustering, can be obtained in terms of extension of network lifetime. Furthermore, making independent and local re-clustering decisions at cluster head nodes provides higher node connectivity to the network’s data sink and higher data throughput at the sink, as compared to engaging all network nodes in re-clustering operations simultaneously. Hence, asynchronous

node clustering is a promising technique towards achieving fully self-organised wireless sensor networks.

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