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CHEARP: Chord-based Hierarchical Energy-Aware Routing Protocol for Wireless Sensor Networks

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Abstract. Wireless Sensor networks (WSNs) are mostly deployed in hostile environments, where nodes may do not have any information about their location. Hence, the designed routing protocols and applications have to function independently from the nodes location. Moreover, extending lifetime in such networks is a critical and challenging issue, since they consist of miniaturized energy-constrained devices. The motivation of this paper is to design an energy efficient location-independent routing protocol for data delivery in WSNs. Therefore, a Chord-based Hierarchical Energy-Aware Routing Protocol (CHEARP) is developed with the focus on preserving the energy consumption. In contrary to the existing DHT-based protocols that interconnect nodes independently of their physical proximity, this paper proposes an approximate logical structure to the physical one, where the aim is to minimize the average paths' length. Simulation results show that the proposed solution reduces the transmission Load, minimizes the transmission delay, and extends the network longevity.

Keywords: Wireless Sensor Networks, Peer-to-Peer Systems, Chord, DHT, Energy-Efficient, Clustering, Data Communication.

1. Introduction

Wireless Sensor Networks (WSNs) [6] have attracted significant interest in today's human life through their major impact and useful support in the construction of intelligent environments. In fact, new applications are continuously developed in order to meet different requirements and purposes of different fields, including healthcare, industry, environmental monitoring and military domain. However, in WSNs researchers do not only interest to develop new services and applications, but also, to extend the network lifetime [16] and to make the developed applications operational as long as possible. The energy is the most delicate resource in sensor devices due to the limited capacity of the equipped batteries that can be expensive and even impossible to renew, particularly in hostile environments, such as battlefields. Therefore, it is strongly recommended that any designed application for WSNs should be power-efficient to overcome this limitation of energy and to increase the network longevity. In addition, transferring the collected data to the sink represents a core task for any WSN application. For this reason, plenty of research projects are being done, and many mechanisms and routing techniques are ongoing in order to optimize the power consumption of sensor nodes [1] [18]. Applying DHT (Distributed Hash Tables) over WSNs becomes an active branch and provides promising assets to meet WSNs problems [9]. The DHT-based routing solutions achieve better performances in terms of scalability, self-organization, decentralization, network lifetime, fault tolerance and latency [2]; besides that, they guarantee data delivery in a limited time. However, the DHT-based routing schemes build a virtual overlay under a physical network topology, where nodes are connected independently of their physical proximity in the network. Hence, two virtual neighbors in the logical space with two close logical identifiers may be far apart and could not be physical neighbors in the underlying network. In this case, a logical hop transmission in a DHT-routing protocol may go through a several physical hops that may cost many transmission packets and a huge amount of energy consumption, which is unsuitable for energy constrained environments such as WSNs. In this paper, the advantages of DHTs are exploited in favor of WSNs, while the divergence problem of the virtual overlay and the underlying network is faced. Hence, we develop a Chord-based Hierarchical Energy-Aware Routing Protocol (CHEARP) for WSNs, which aims to ensure that two neighbor nodes in the physical network are also neighbors in the virtual overlay. In fact, Chord was introduced to accelerate the lookup and to locate efficiently the node that stores the required data. In the proposed solution, we take the benefits of these two characteristics and the other assets of Chord protocol to accelerate the routing process and to locate efficiently the nodes that are connected to the sink (SCH). This allows to relay the sensed data efficiently in a finite time, while consuming few amount of energy. In this work, the network is organized in a two-tier hierarchical structure, in which only cluster-heads perform routing tasks using a same routing policy of Chord protocol.

The remainder of this paper is structured as follows. The next Section provides a brief overview of Chord protocol and points out the problem statement. Section 3 presents a review of some relevant DHT-based routing solutions. Section 4 describes in details the proposed protocol. Section 5 discusses the performance analysis results. Finally, Section 6 summarizes and concludes this paper.

2. Preliminaries

2.1. Brief View of Chord Protocol

Chord [17] is one of the first and most popular protocols for structured peer-to-peer (P2P) systems, designed to address the issue of lookup in dynamic P2P overlays. It assigns for both peers and resources, unique identifiers in the $m - bit$ key space, using the same hash function, where m represents the identifiers' length. The peers in Chord overlay are organized in $one - dimensional$ virtual ring of modulo 2^m size (from 0 to 2^{m-1}), following the ascendency order of identifiers so that the previous node ID is always lower than its successor, moving in one direction in clockwise. The Peers' identifiers and objects' keys are generated by hashing the peers' IP addresses and data, respectively. To store a pair of $key/value$ of any distributed resource, Chord uses a hash function for generating the resource's key. This latter indicates the node where the pair of $key/value$ will be maintained. Then, the key will be mapped onto the first node whose identifier is equal or follows it in the identifier space.

Chord introduces two variants of lookup schemes; the first one is simple but slow, whereas the second holds additional information but accelerates lookup. In the simple key location scheme, nodes require only to know their immediate successors in the ring. Thus, looking for a given key involves passing through the successors around the ring until finding the node that stores the key. To accelerate lookup, a scalable key location scheme requires each node to maintain a routing table, called finger table, constructed so that the i^{th} entry of the nodes n includes a pointer to the successor of node $n + 2^{i-1}$ in the Chord ring. In other words, in an $m - bit$ identifier space, a finger table includes up to m entries. The first finger in the routing table of a given node represents its immediate successor, and each entry in the table maintains information about the identifier, the IP address, and the port number of the concerned finger. Hence, queries for a researched key are forwarded to the node with the largest identifier that is equal to or precedes the key.

2.2. Problem Statement

The main problem that researchers have to hold in order to develop an energy efficient DHT-based routing protocol for WSNs is how to deal with the divergence between the virtual overlay and the underlying network. To illustrate this problem, an example of Chord topology is shown in Figure 1, where the node $N6$ points to the node $N17$ even though the node $N35$ is closer to it than $N17$, since the ring construction follows the ascending order of identifiers. In case of wired networks, each node can reach any destination through several physical neighbors without influencing the lifetime of the network. However, in case of energy-constraint networks such as WSNs, any virtual hop may cause many physical hops, and hence, many transmission packets, which increases the consumed energy, the end to end delay and the overhead in the network. In this paper, we address these problems and develop CHEARP, a DHT-based energy efficient protocol, which takes the benefits of DHT overlays to be a self-organized and a totally decentralized protocol that suits the random deployed networks, such as WSNs. In the proposed solution, we handle the structure shown in the Figure 1 in such way that the physical structure and the logical overlay are approximated. This allows to guarantee that if two nodes are neighbors in the physical network topology, they will be also neighbors in the virtual overlay.

3. Related Works

The development of routing protocols in WSNs is a subject of many researches. In fact, a myriad of routing protocols are continuously developed with the aim of facing the challenges and the intrinsic constraints of WSNs, in particular, the energy consumption. Since we grant more interest to P2P and DHT-based solutions, in this section, only some DHT-based routing protocols are reviewed.

A survey of DHT-based solutions in WSNs could be found in [9], where the authors study the applicability of DHT over WSNs.

In [3], the authors discuss the application of Chord, a DHT protocol, over WSNs to improve the delivery ratio of the overlay architecture. The proposed scheme introduces CREIDO packets to find out the eventual joining or leaving nodes in order to cope up instantly the network changes by mean of stabilization function. This work focuses only on detecting eventual changes in the Chord network for an instant update of the topology,

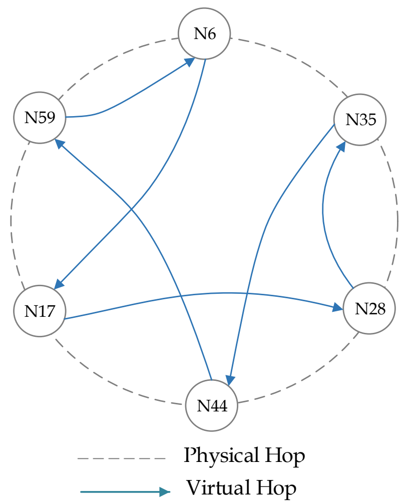

Fig. 1. Illustration of the divergence between physical network topology and the virtual overlay in Chord.

and the authors do not provide any details of the manner in which they apply Chord over WSNs.

The work in [5] consists on a limited energy consumption model for Wireless Sensor Networks, which consists on adapting the Chord protocol for WSNs. The authors organize the random deployed nodes on clusters and elects for each cluster a strongest node in terms of energy as cluster-head. In the developed scheme, the Cluster-heads are interconnected according to Chord topology, and they represent the only nodes that perform data transmission. The solution considers the energy level of nodes and permutes Cluster-heads to save energy. However, it does not consider the physical proximity of nodes.

CLEVER is proposed in [8] as a Cluster-based Energy-aware Virtual Ring Routing protocol [4] for WSNs. It applies a DHT-Virtual Ring Routing protocol for inter and intra cluster communication. In addition, the solution makes a use of clustering mechanism, where the energy powerful nodes are defined as super-peers that take charge of the virtual routing in the network (virtual hops). Besides, for each node is assigned a transmission power considering its energy amount, which seems good for saving energy. However, the super-peers in different clusters could not communicate and require the implication of the weak nodes in each data transmission to perform routing task (physical hops).

The authors in [7] present Coral-based VRR protocol that organizes the network space in multilevel virtual rings. In this work, nodes are categorized according to their residual energy under three classes, namely hyperpeers that represent nodes with a big amount of energy, superpeers that are nodes with more energy than peers, and peers that are nodes having critical energy amount. Indeed, the first Coral-based VRR level in the network regroups all categories of nodes, the second level includes only superpeers and hyperpeers, while the third level includes only hyperpeers. Moreover, this classification of nodes aims to exploit as much as possible the energy powerful nodes in routing. Then, VRR is applied to ensure transmission in each layer, while Coral-based VRR allows transition between the three layers. This technique manages efficiently the network, nevertheless, it shows the same drawback of CLEVER, where two virtual neighbors may be physically far away.

Concisely, from the above reviewed DHT-based solutions, it is noticed that most of DHT-based solutions present the same problem of divergence of the physical and logical neighborhood. We overcome this problem by providing an approximate virtual overlay to the underlying network. More details are given in Section 4

4. Proposed Solution

In this section, the network model considered in this work is described and the details of our proposal are given.

4.1. Network Model

Before giving the details about the principal of the proposed solution, a description of the network model is given. First, we suppose a random deployment environment of WSNs, where sensor nodes are static and organized in clusters according to the physical proximity. Then, a cluster head is elected for each cluster using the objective function, which is given further (Function 2). We consider a scenario of application, where nodes have to sense physical parameters from the zone of interest, and to transmit the collected data to the sink. In this proposal, a Chord-based overlay is built on top of the physical network. Thus, sensors are organized logically in a virtual ring according to the ascending order of their identifiers, as shown in Figure 2. Before the overlay formation, for each node is associated a unique identifier using the same hash function used in Chord protocol. Two kinds of links are distinguished, namely physical and logical. A physical link exists between two nodes if the distance separating them is less than or equal to the maximum radio transmission power ($d(n1, n2) \leq r$), which is supposed to be the same for all the sensor nodes in the network. Whereas, the logical links are defined using Function 1, where for each node n is associated a set of up to m neighbors (fingers). The set of the node n fingers is denoted by $Fingers_n$, the identifiers' length by m, and the identifier of the node n by n_{id}. In this paper $\mathcal{C}$ is considered as the set of clusters, $\mathcal{CH}$ as the set of cluster heads, and a summary of the used notations is given in Table 1.

$$Fingers_n = \{Successor\,[(n_{id} + 2^{i-1})\,modulo\,2^m]\} \qquad (1)$$
$$\textit{With } 1 \leq i \leq m$$

4.2. Network Structuring

Preliminary Phase. This phase succeeds the deployment of sensors in the zone of interest and consists on determining a ring band in the network, defined by external and internal

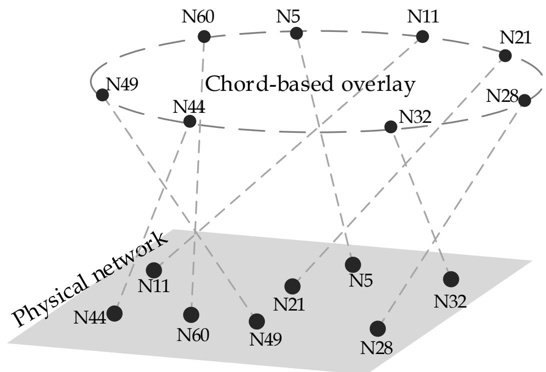

Fig. 2. Example of a Chord-based overlay.

Table 1. Notations.

Notation	Description
$\mathcal{C}$	The set of clusters
$\mathcal{CH}$	The set of cluster heads
$\mathcal{CR}$	The set of CH nodes constituting the CHEARP Ring
CHt	A temporary cluster head
$CH2$	A second degree cluster head
CH_{init}	The CH that initiates the ring creation
CH_{succ}	The CH successor in the ring
CH_{pred}	The CH predecessor in the ring
CN	The number of the formed clusters or cluster heads
Dgr	Node degree
$\mathcal{F}$	The set of finger tables
$Fingers$	A finger table of a node
f	A finger of a node
NN	The variable of the cluster nodes' number
i, j	Loop counters
$idCH$	CH identifier
$idN_{i,j}$	Node N identifier
m	Nodes identifiers length
$N_{i,j}$	The j^{th} node in the cluster C_i
r	The transmission range
SCH	A cluster head that is a one hope linked to the sink (*connected cluster head*).

borders as shown in Figure 3. The goal behind is to avoid nodes at the boundary to be elected as cluster-heads in order to do not waste energy in communication since there are no nodes at the external side of the boundary. On the other hand, the ring band is the most suitable part in the network space where the CHEARP ring has to be created. Indeed, the nodes in this part have more possibility to be directly connected to the sink, which makes them the appropriate nodes for the CHEARP ring creation.

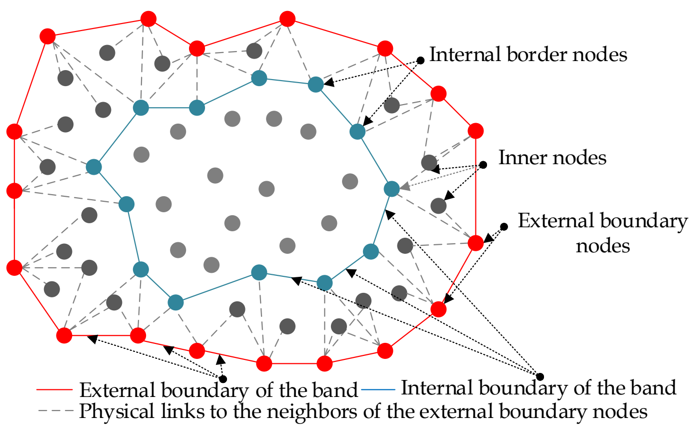

Fig. 3. Example of a random network after the preliminary phase.

The boundary sensor nodes forming the perimeter of the network represent the external borders of the ring band. There exist many algorithms in the literature to this end, such as in [14][19][12]. To determine the inner nodes that belong to the band, each boundary node sends a broadcast message through the network. The nodes that receive the messages will be part of the ring band. The last nodes that receive the broadcast message along the internal side of the network represent the internal borders of the ring band.

Clustering Phase. Based on clustering mechanisms, sensor space is divided into small zones that regroup sensors considering given properties. The authors use a hierarchical structure since it suites the energy-saving issue. This kind of structures is characterized by a division of the network into clusters, where for each cluster is associated a cluster head (CH). The clustering phase in this work is carried out in three steps, namely the creation of basic clusters, the election of cluster-heads and the cluster expansion.

1. ***Basic Clusters Creation***
   There exist several clustering mechanisms in the literature [10][15][13]; for some of them, cluster heads are firstly elected for each cluster. After that, the sub peers integrate the appropriate clusters. While for some others, sub peers belong first to their appropriate clusters, then, CHs are selected for each cluster. In this first step of the clustering phase, the network is structured considering the second class of clustering approaches. The basic clusters could be formed using the physical proximity of the nodes, where nodes that are geographically close form a cluster. At this stage, the authors assume that the network is organized in a set of basic clusters that include only the nodes in the ring band, as illustrated in Figure 4. Basic cluster creation. For each cluster is associated, randomly, a temporary cluster head (CHt). The cluster heads and the second-degree cluster heads ($CH2$) will be elected in the next step, according to important parameters that are defined further.

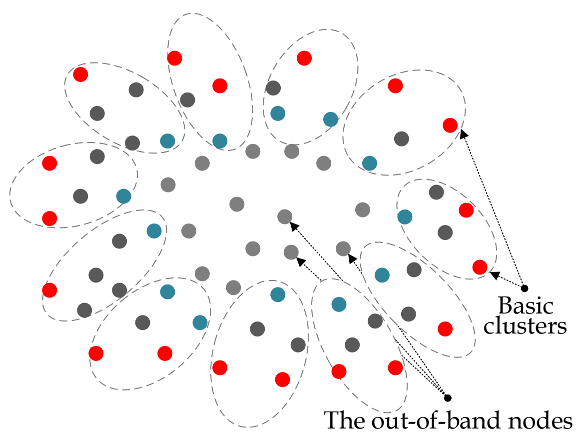

Fig. 4. Basic cluster creation.

2. ***Cluster Heads Election***
   After the formation of basic clusters, the election process of cluster-heads is executed as shown in Algorithm 1. The nodes are chosen to be cluster-heads considering their degrees, which are calculated using the Function 2. Each node N_i calculates its degree Dgr_i based on its residual energy level E_i, its connectivity rate C_i, defined as the number of its neighbors, and its signal strength to the sink P_i. The degrees are sent to the temporary cluster heads $CHts$ that were selected before. The nodes, whose Dgr values are the highest in each cluster, are elected to be cluster-heads and establish connections with the nodes of their clusters.

$$F : Dgr_i = E_i * C_i * (|P_i| \vee 1) \tag{2}$$

   The degrees of nodes are defined in the Function 2 in such a way that we promote nodes connected to the sink with a good signal strength (a non-null P_i), a good level of energy and that have more neighbors. The logic operator OR inclusive ($\vee$) allows to avoid a null value of Dgr when a given node N_i is not connected to the sink ($P_i = 0$). Thus, if a node is connected to the sink, its degree will be defined as $E_i * C_i * (P_i + 1)$; else, it will be defined as $E_i * C_i * 1$. The elected CHs supervise their clusters and handle the data transmission from their nodes to the sink. While the second-degree cluster-heads take charge of the data aggregation mechanism to save more energy.

Algorithm 1 *Cluster heads election*

Input: *$\mathcal{C}$: The set of clusters*
Output: *$\mathcal{CH}$: The set of cluster heads*

```
begin
for i = 1 to CN do
    for j = 1 to NN_i do
        CHt_i sends broadcast message to the nodes of cluster C_i
        Calculation of Dgr(N_{i,j})
        Sending Dgr(N_{i,j}) to CHt_i
    end for
    CHt_i selects the highest degree Dgr and returns the corresponding CH_i
    CHt_i selects randomly the second highest degree and return the corresponding CH2_i
end for
end
```

3. ***Cluster Expansion***
Once the step of CH election is completed, in the last step (cluster expansion), the elected CHs extend the clusters by sending a multi-hop diffusion messages so that nodes that did not belong to the band join any cluster and be a part of the hierarchical structure of the network, as shown in Figure 5.

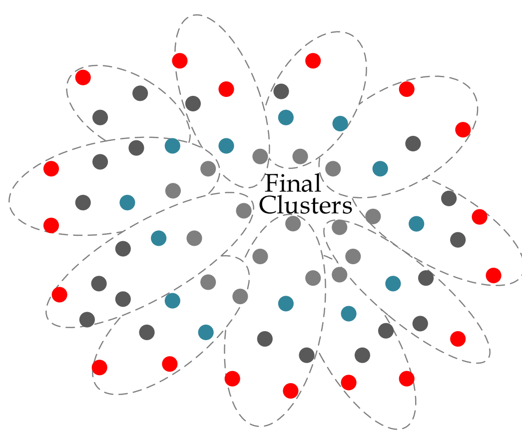

Fig. 5. Cluster Expansion.

As it was previously mentioned, the basic cluster creation includes only the nodes in the ring band that includes effectively the border nodes. Hence, after the basic cluster creation, each border node belongs to one of the created basic clusters. In the next step of clustering phase, a cluster-head is elected for each basic cluster as it is shown in the cluster heads election sub-section. The last step of clustering phase is the cluster expansion that aims to integrate nodes that are not part of the band, i.e. the nodes that are not part of the basic clusters, into the appropriate ones. To do so, each cluster-head (CH) sends a multi-hop broadcast message through the network. The nodes that already belong to one of the basic clusters (including the border nodes) are not interested in the message hence they ignore it. However, the nodes that are outside the band and that did not integrate any cluster, could now belong to one of the basic clusters. The broadcast messages are sent in multi-hop in order to reach nodes that probably could not be reached by cluster-heads. In this case, the connection is ensured by the intermediate nodes of the same cluster.

4.3. Network Routing

Ring Topology Construction and Nodes Re-identification. To approximate the overlay structure to the physical topology, CHEARP protocol proceeds by re-identifying the nodes at the overlay construction step as resumed in Algorithm 2. The first node that initiates the CHEARP ring determines the distances that separate it from other CHs in its vicinity, using the signal strength, and points at the successor node that have the shortest distance. After that, using the source node id, the successor pointer calculates its new id. This procedure continues until the formation of the CHEARP ring is completed. The proposed re-identification mechanism allows to obtain a logical structure (CHEARP ring) close to the physical one. Indeed, the CHs identifiers are substituted after being part of the CHEARP ring, where each new CH identifier is based on the previous CH identifier (the predecessor of the current CH). Hence, this solution guarantees that:

- Each direct successor is the closest in the physical network and in the overlay too;
- $\forall\, CH_i \in \mathcal{CR},\ idCH_{i-1} < idCH_i$.

This allows to shorten the length of paths, which minimizes the transmission response time, reduces the amount of dissipated energy in the network, and hence, extends the network longevity.

Construction of Finger Tables. This step succeeds the CHEARP ring creation phase, and consists on the rooting tables construction. As in the basic Chord, each node in the ring calculates its own finger table using the Function 1. The Algorithm 3 illustrates the way in which these tables are formed.

Data Communication.

1. ***Connection initialization phase***
   After the formation of clusters and cluster-heads, connection phase has crucial importance, since it involves the interconnection of the network to the sink. As shown in Figure 6, once the clusters and cluster-heads are elected, the base station sends a

broadcast hello message, including its address, in the network. Since the ring in the CHEARP protocol includes only cluster-heads in routing, the latter nodes are the only ones that are interested in the message sent by the sink. Then, the cluster-heads send back a response message, including their identifiers. After that, the sink will be aware about the cluster heads that could reach it, which is denoted by $SCHs$. In the next step, the sink sends another packet to only the SCH nodes, containing the set of the interconnected SCH identifiers. Then, each SCH relays the packet to its CH neighbors, except of those figured in the packet. Each CH do the same until all the CHs receive the SCH table. Hence, CHs that are not $SCHs$ hold another information besides the routing table, which consists on the table of the $SCHs$. The redundant $SCHs$ ensure the connection availability to the sink and ensure the load sharing.

Algorithm 2 *Ring creation and nodes re-identification*

Input: $\mathcal{CH}$: *The set of cluster heads*
CH_{init}: *The initial* CH
m: *The identifiers length*
Output: $\mathcal{CR}$: *CHEARP Ring*

begin
$CH1 \leftarrow CH_{init}$
$\mathcal{CR} \leftarrow CH_{init}$
$\alpha \leftarrow m$
$\beta \leftarrow 1$
while $\mathcal{CH} \neq \emptyset$ ***do***
  if $cardinality(\mathcal{CH}) = 1$ ***then***
    $\mathcal{CH} \leftarrow \mathcal{CH} - CH_{init}$
    $\mathcal{CR} \leftarrow \mathcal{CR} + CH1$
  end if
  for $i = 1$ *to* CN ***do***
    for $j = 1$ *to* NN_i ***do***
      $idN_{i,j} \leftarrow idCH_{init} + j$
    end for
  end for
  $\beta \leftarrow \beta + 1$
  CH_i *sends a request message to its* CHs *neighbors*
  if $N \in \mathcal{CH}$ ***then***
    N *sends a reply message containing the distance that separates it from* CH_{init}
  else
    N *drops the message*
  end if
  CHt_i *selects the minimal distance and points to the corresponding* CH_{succ}
  $\mathcal{CH} \leftarrow \mathcal{CH}$ - CH_{init}
  $\mathcal{CR} \leftarrow \mathcal{CR}$ + CH_{succ}
  $idCH_{pred} \leftarrow idCH_{init}$
  $CH_{init} \leftarrow CH_{succ}$
  $idCH_{init} \leftarrow (idCH_{pred})^{\alpha\beta}$
end while
end

Algorithm 3 *Creation of finger tables*

Input: $\{idCH\}$: *The set of* CHs *identifiers*
m: *The identifiers length*
r: *The transmission radius*
Output: $\mathcal{F}$: *The set of finger tables*

```
begin
for i = 1 to CN do
    F_i ← ∅
    Fingers_i ← ∅
    for j = 1 to m do
        f_{i,j} ← Successor ((idCH_i + 2^{l−1}) mod 2^m)
        if Dist(CH_i, f_{i,j}) ≤ r then
            Fingers_i ← Fingers_i + f_{i,j}
        end if
    end for
    {F} ← {F + Fingers_i}
end for
end
```

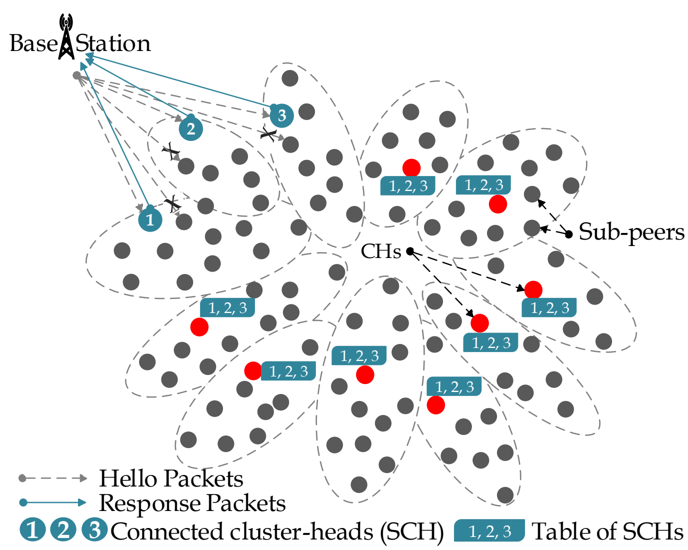

Fig. 6. CHEARP initialization Phase.

2. ***Data delivery phase***
In order to project the Chord basic objectives to the proposed solution, the $SCHs$ are identified as the unique keys that all the sensor nodes are looking for in order to transmit the collected data to the sink. By exploiting the routing strategy of the basic Chord, CHEARP protocol provides data transmission in an average of $O(logn)$ hops

[2], where n represents the number of nodes in the ring. In this section, a description of how the packets are routed by CHEARP is given as follows:

– ***Intra-cluster routing:*** the communication inside each cluster is in multi-hops. Subpeers send data to the $CH2$ for eventual aggregation, then the $CH2$ relays the data to the CH, where they will be transmitted to the sink.
– ***Inter-cluster routing:*** the communication inter-cluster is in multi-hops, following the routing policy of the basic Chord. When a CH receives data from its subpeers, via the second-degree $CH2$, it selects randomly one SCH among the $SCHs$ set as a key to look for. Hence, the given CH checks in its finger table, the CH with the largest closest identifier to the key and relays the data to it. In this way, the data are passed around the CHEARP ring through the successor pointers until achieving the random selected SCH (the requested key), which takes in charge the transmission of the data to the sink.

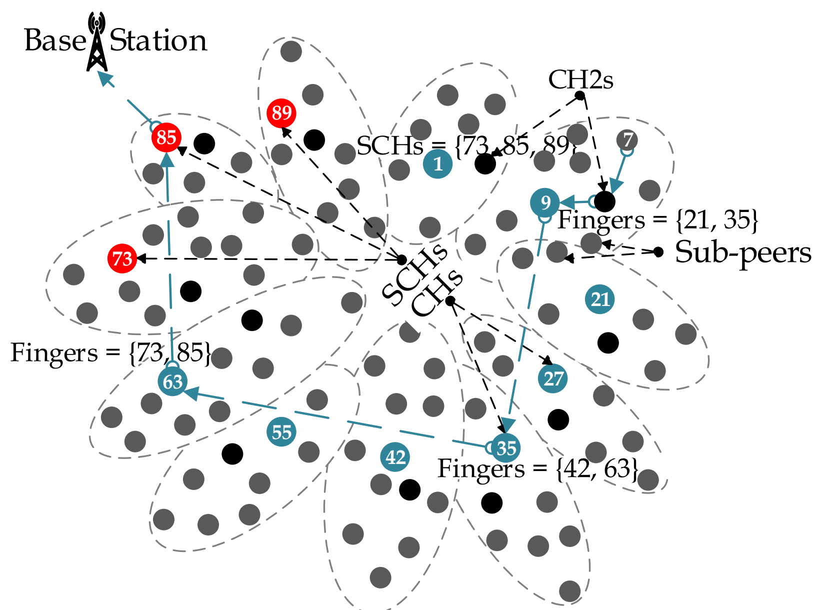

Fig. 7. Example of routing in CHEARP.

An example of routing in CHEARP protocol is given in Figure 7, where a data transmission is supposed from the node $N7$. The latter sends the data packet to the appropriate $CH2$ in its cluster for eventual data aggregation. Then, the $CH2$ sends the packet to the cluster head $N9$ that takes in charge the data transmission. First of all, $N9$ selects randomly one SCH key among the SCH list, for example $N85$. After that, the query will be resolved as follows. $N9$ picks out in its finger table the successor with the closest identifier to $N85$, which is $N35$. This latter points to the finger $N63$ that owns the largest identifier, and next, $N63$ finds out in its finger table an entry to the key $N85$ and relays the data packet to it. Finally, $N85$ transmits the data to the sink.

4.4. Network Updates

To maintain the correctness of the network topology in this work, the basic Chord functions are taken back while providing the necessary modifications.

Joining Process. The CHEARP ring includes only cluster heads. New sensors may integrate the ring, if they satisfy the required conditions during the updating phase. However, they have first to belong to any cluster in the sensor space. To join one of the clusters, a new sensor broadcasts a joining request. The sensor nodes in its vicinity could respond with a joining reply, containing the necessary information about the CH and the $CH2$ of the appropriate cluster. By this way, the new node will join the first node that replays its request, and integrates the same cluster. The new node could replace the current CH if its energy level is higher.

Leaving Process. The network updates for leaving process depends on whether the leaving node is a CH or a subpeer. In the case of subpeer, the node failure does not influence the network topology and the table correctness. However, if the node that leaves the network is a CH, it becomes mandatory to cope up the network changes in order to maintain the network availability and correctness. A failure is detected by physical neighbors as the same as basic Chord, using the function $check - predecessor()$ [17]. If a predecessor of the current node does not response, the current node turns its predecessor to $null$. Since each node in CHEARP ring holds up to $m\ entries$ in its finger table, if the node's successor fails, another finger could be chosen. To distribute the energy consumption over the nodes in CHEARP, we proceed by the distribution of the cluster head role among the ring band nodes in each cluster. Each CH node checks periodically its instant energy level, if it fits under the fixed threshold ($2/3$ of its initial energy), the re-election processes is triggered, and the CH leaves the ring and becomes subpeer. The new elected CHs and the old one permute their identifiers to keep correct the finger tables of the other CHs in the CHEARP ring. As it have been motioned in the preliminary phase of CHEARP, a node could be cluster head if only it belongs to the ring band. Thus, only inner nodes are concerned by the re-election of the new CH.

5. Performance Analysis

5.1. Radio Energy Model

Many energy models have been proposed in the literature, we use for our analysis the model discussed in [11], which is the first order radio model for energy dissipation. According to this, the transmission and the reception energy costs expended for the transfer of an $l - bit$ data message between two nodes over a distance of $d - meter$ are given, respectively, by Equations 3 and 4.

$$E_T(l, d) = l * E_{elec} + l * E_{amp} * d^2 \quad (3)$$

$$E_R(l) = l * E_{elec} \quad (4)$$

Where, $ET(l, d)$ in Equation 3 and $ER(l)$ in Equation 4 denote, respectively, the total energy consumed in the source node transmitter and in the destination node receiver. The parameter E_{elec} represents the required electronic energy to run the transmitter or the receiver circuit. While, E_{amp} characterizes the energy dissipated by the transmitter amplifier.

5.2. Simulation Environment and Parameters

To position the efficiency of the CHEARP protocol, extensive simulation experiments are conducted under Matlab/Simulink environment, and the obtained results versus the recent DHT-based routing protocol: CLEVER [8] are likened. In this regard, a random deployed network of $100 - 500$ nodes is considered on a squared size field of $500 * 500\ m^2$, which means that the abscissa (horizontal) and ordinate (vertical) coordinates of each sensor are randomly selected between 0 and the maximum value of the space dimension. For each node is assigned a transmission range equals to $150\ m$ and an initial energy value of $2\ j$, while the energy values of E_{elec} and E_{amp} are respectively set to $50\ nj$ and $0,0013\ pj$. The summary of simulation parameters used in this model is given in Table 2.

Table 2. Simulation Parameters Value.

Parameter	**Value**
Sensor field	$500 * 500\ m^2$
Network size	$100 - 500\ nodes$
Packet size	$4000\ Bits$
Initial energy	$2\ j$
E_{elec}	$50\ nj$
E_{amp}	$0.0013\ pj$
Node's transmission range	$150\ m$

5.3. Simulation Results

The subsequent sections illustrate the performance evaluation of CHEARP protocol compared to CLEVER. We grant more interest, particularly, to four important performance metrics, namely the transmission load, the end-to-end delay, the average dissipated energy and the network lifetime. The transmission load is measured as the number of packets in function of transmission frequency (number of transmissions per second) and the number of nodes. The end-to-end delay measures the time (S) that takes a transmission to achieve the destination. The average energy dissipation determines in joules the amount of depleted energy of nodes during the network operations.

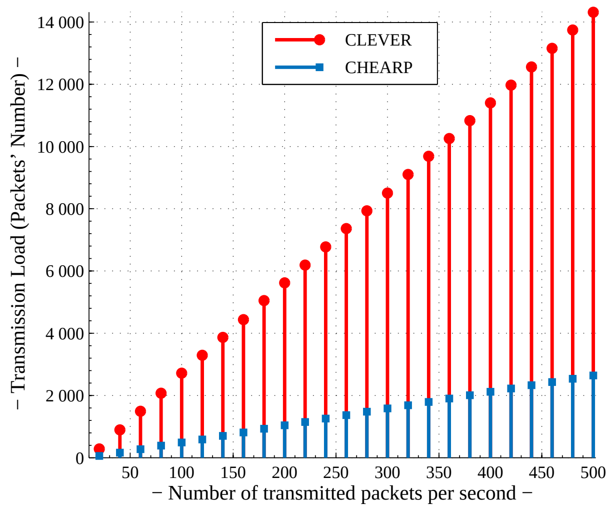

Fig. 8. The impact of transmission frequency on transmission load.

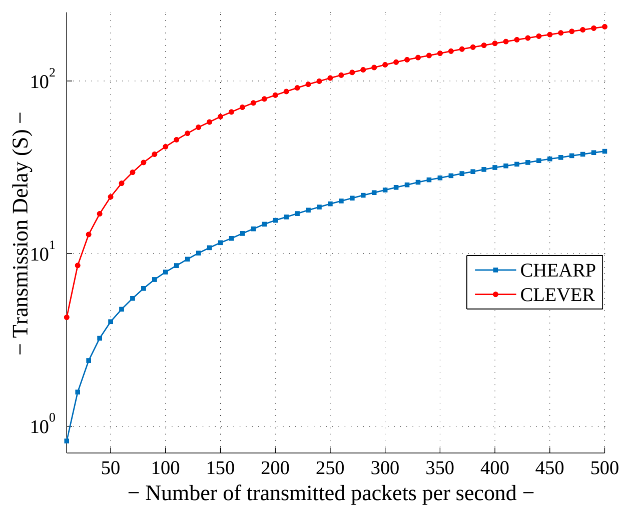

Fig. 9. The impact of transmission frequency on end to end delay

Transmission Frequency Impact. The transmission load of both CHEARP and CLEVER protocols in function of the transmission frequency is depicted in Figure 8. The results are obtained as the number of transited packets in the network versus the transmission frequency ranging from 10 to 500 packet/s. From this figure, CHEARP reveals good results compared to CLEVER. This is justified by the consideration of physical proximity of CH nodes that CHEARP provides. In fact, the proposed protocol shortens the transmission path, since the virtual successor is exactly the physical one, which reduces the

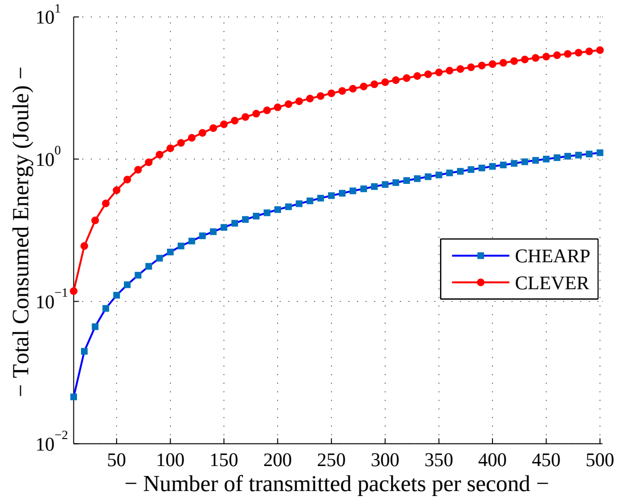

Fig. 10. The impact of transmission frequency on dissipated energy

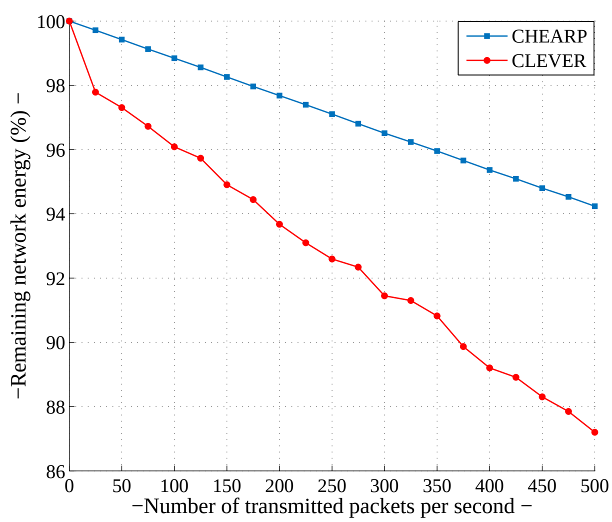

Fig. 11. The impact of transmission frequency on network lifetime

number of visited nodes during transmissions, and hence, the number of transited packets in the network. However, a virtual successor in CLEVER could be reached through several physical hops, which increases drastically the number of transmitted packets in the network, and consequently, the transmission load.

The performance of CHEARP and CLEVER in terms of packet transmission delay are compared in the Figure 9. The obtained results demonstrate clearly that CHEARP outperforms CLEVER with a tolerable increase in front of the excessively high transmission frequency values. Even the use of hierarchical structure and the minimization of the virtual path length, CLEVER shows higher values of end-to-end delay compared to CHEARP due to the high number of packets transmitted through several physical successor nodes before reaching the destination. In contrast, CHEARP allows reaching the destination in short delays, thanks to the approximate physical overlay that it uses.

Figure 10 and Figure 11 compare respectively, CHEARP and CLEVER, in terms of average dissipated energy and network lifetime, where CHEARP proves once more its efficiency against CLEVER. As depicted in Figure 10, CLEAVER consumes more energy than CHEARP since it involves many physical successor nodes in data transmission, which decreases the network lifetime.

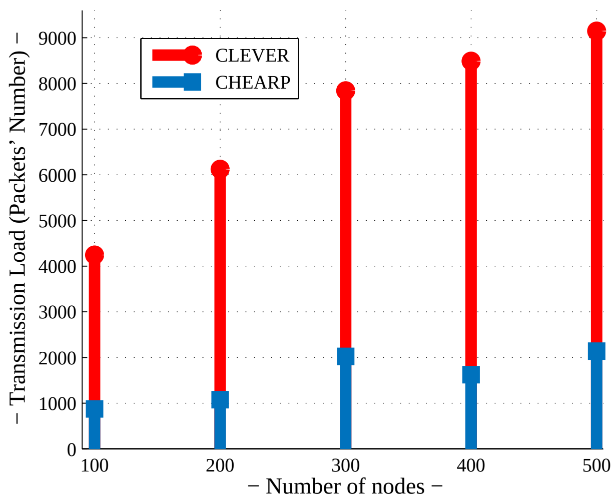

Fig. 12. The impact of network scalability on transmission load

Network Scalability Impact. In the Figures 12, 13, 14 and 15, the authors measure respectively, all of the transmission load, end-to-end delay, dissipated energy as well as the network lifetime, in function of the network size, that ranges from 100 to 500 nodes, where the transmission frequency is fixed at 200 $packets/s$. From these figures, it is noticed that CLEVER generates an increase in terms of load transmission, transmission delay and energy consumption compared to CHEARP. This is due to the lack of the number of transmitted packets through several intermediate sensor nodes (physical hops) before reaching the destination. Besides that, it is noticed that the percentages of the total remaining energy of both CLEVER and CHEARP are almost very close despite the increase of network size, since the total energy of the network increases with the increase of the number of nodes. Hence, even if increasing network size increases the path length, for a same value of transmission frequency, the dissipated energy, in function of network size increase, increases lightly. Through the obtained results, the proposed CHEARP protocol proves its effectiveness as a DHT-based routing solution for WSNs.

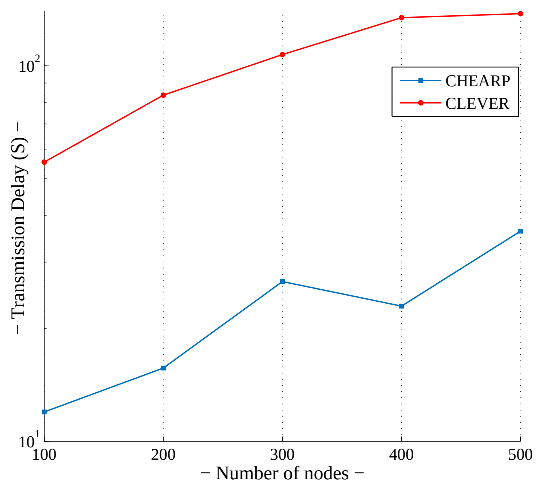

Fig. 13. The impact of network scalability on end to end delay

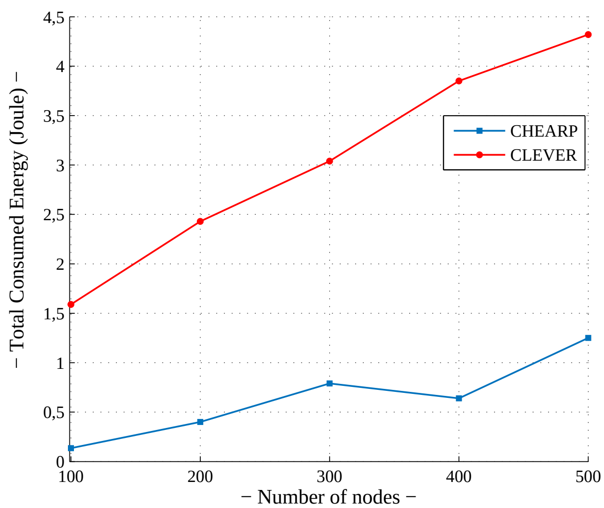

Fig. 14. The impact of network scalability on dissipated energy

6. Conclusion and Future Works

This paper presents a Chord-based Hierarchical Energy-Aware Routing Protocol (CHEARP), which addresses the energy consumption issue in WSNs. In this regard, the proposed solution takes benefits of distributed hash tables, and hierarchical structures to build a hybrid energy aware protocol. Indeed, the proposed protocol copes up the independence between the virtual overlay of the DHT and the physical network topology by re-identifying nodes

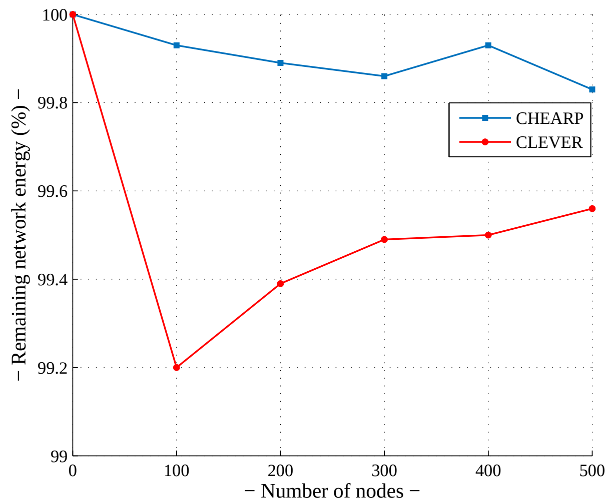

Fig. 15. The impact of network scalability on network lifetime.

during the virtual ring construction. Hence, the proposed solution approximates the two structures and constructs a kind of physical ring, in which CHEARP guarantees for each node, the same set of physical and virtual neighbors. Besides, the proposed protocol suits well the randomly deployed networks, where only a part of sensor nodes could reach the sink. By handling only the identifiers of the interconnected nodes to the sink, any node in the network could transmit the data packets to the sink, following routing principal similar to basic Chord. Furthermore, CHEARP is compared to another DHT-based routing protocol, CLEVER, through which we prove the effectiveness and the good results that CHEARP reveals. In other words, the proposed protocol and its approximate strategy get to reduce the routing path (hop count), which decreases the transmission load and the end-to-end delay, and hence it minimizes the dissipated energy and extends the network longevity, which is the main purpose of this work.

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