An Efficient Clustering Approach to Hierarchical Wireless Sensor Networks

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Abstract. **An efficient utilization and allocation of the limited resources of a wireless sensor network (WSN) in a way that maximizes the information value of the data collected is a significant research challenge. Within this context, this result concentrates on architectural approach as a means of focusing a sensor on obtaining the important data efficiently. Our goal is to facilitate the development of a sensor network and divide all sensors into the distributed clusters. Division is self-organized and fault-tolerant. The fully collision-free TDMA-based MAC protocol is proposed for the inter-cluster communication. As we assume that in each cluster every node is one-hop far away from its neighbours, it is obvious that no routing protocol is needed and it allows using very simple sensor nodes with limited resources, which prolong WSN service life. Along with the upper level, the content here refers to the automatic runtime selection of service implementation and network resources to execute the application specification in a resource-efficient and context-aware case.**

Keywords: **wireless sensor network, clustering, collision-free, hierarchical structure.**

I. INTRODUCTION

With the development of MEMS (micro-electro-mechanical systems), the wireless sensors have become research objects with great capabilities. Wireless sensors are grouped into the network, thus enabling the careful and efficient gathering of objects or environmental data. Wireless Sensor Networks (WSNs) are widely used in environmental monitoring, for example, temperature, humidity, etc., as well as in army/battlefield, disaster, etc [1]. In the above-mentioned fields of interest, sensor nodes are deployed in the unmanned manner. Thus, various protocols such as communication and topology control protocols manage node cooperation and data transfer to the sink. The main function a WSN must support is self-organization. In some cases, self-organization is implemented by structuring a WSN in clusters [2]. In case of clustering, a special node arises in each cluster. The node is called a cluster head (CH), when it maintains cluster functionality. CH can be predefined or may be chosen dynamically from the available nodes.

Grouping nodes into clusters provides the increased network extensibility, as well as routing table minimization because it is not necessary to have a network table in each node. Also, the network topology becomes more stable at the sensor node level. Stability is achieved because sensor nodes maintain their connection to a CH only.

In the paper, a novel clustering scheme is proposed. The scheme is specially designed for the collision-free medium access control (MAC) protocol [3]. Collision-free communication is required in medicine control applications [7]. The applications suffer of data losses caused by collisions on receivers, thus decreasing the overall quality of service or even leading to the vital information loss. Thus, the opportunity of collision-free formation of clusters is demonstrated in the article.

The proposed clustering scheme has been designed for the hierarchical network described in [4], but it is free to use it for another similar hierarchical network.

II. RELATED WORK

Unfortunately, we could not find any clustering collision-free algorithms. Therefore, we will name only a few of them, which are closely related to our problem.

The classical clustering approach – Low-Energy Adaptive Clustering Hierarchy – LEACH [5] and its extension TL-LEACH [6] are mainly aimed at minimizing energy consumption by sensor nodes. Thus, the CH rotation is assumed, and a CH is chosen in terms of minimum energy required for communication. Cluster establishment is performed by broadcasting messages using Carrier Sense Multiple Access (CSMA). For the intra-cluster communication, the Time Division Multiple Access (TDMA) scheme is used – in scheduling neighbouring nodes. Moreover, the Code Division Multiple Access (CDMA) scheme allows each inter-cluster communication to be collision-free to neighbouring inter-cluster communications. However, such an approach uses three medium access techniques that only minimize collisions but not exclude them.

Another clustering scheme approach is described in [7], named Energy Efficient Heterogeneous Clustered (EEHC) scheme. Clusters are formatted within k-hops from a CH. CHs are selected randomly with probability p. The algorithm is designed to be used in large networks with minimized energy consumption. The scheme does not work in the collision-free manner – that is sometimes desirable or even necessary.

III. A PROBLEM STATEMENT

Some sensorial data gathering applications require deterministic real-time medium access and the tranfer of data to data aggregation nodes. Mainly, such applications are intended to be used in a network with the two-level architecture. If it is not defined clearly, then with a high probability such a system can be reduced to a two-level system. Consider Fig. 1, where the two-level system architecture is depicted.

The first level is called the sensor node level. At this level, wireless sensor nodes are placed, which in Fig. 1 are depicted as circles with SN abbreviation inside. From the sensor nodes

CH is chosen. Sensors are placed within 1-hop distance from other inter-cluster nodes. The second level is called the gateway level. More powerful nodes are placed there. They are depicted as circles with GW/SN abbreviation inside (see Fig. 1). Gateway does not operate in sensorial tasks but performs cluster data aggregation. Then aggregated data from one cluster is routed among other gateways and delivered to some central data storage unit / central computer for the analysis. Inter-gateway communication is performed by TCP/IP.

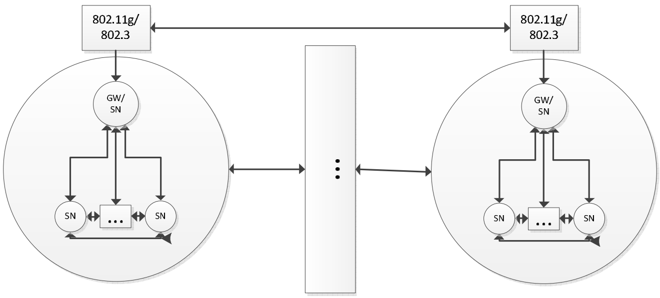

Fig. 1. The architecture of two-level system

In the paper, we propose an approach not only in providing the real-time data gathering and deterministic medium access, but also the collision-free communication between wireless sensor nodes. For that purpose, the novel MAC protocol is used that ensures the collision-free cluster formation and intra-cluster communication. The cluster formation procedure states that all cluster members are configured in the same way for one cluster and in a different way for another. For example, one cluster member nodes use the communication channel with number 1, then another cluster selects for its nodes the communication channel with number 2. Respectively, all nodes are preprogrammed – communication channels are pre-defined. Such a case is shown in Fig. 1. According to manual communication channel separation, one cluster will operate in the frequency range, which is not the same for another cluster. The same principle is applied in the case of more than two clusters. The only limitation is the number of available communication channels.

Unfortunately, such an approach has a significant limitation because each node requires the explicit indication of communication channel number. Such limitation results in the complex network planning and maintaining. Moreover, self-organization and self-healing of a network cannot be achieved in full because of static, hard-coded definition of communication channels of wireless sensor nodes.

To solve the drawbacks, we suggest implementing a clustering algorithm with the dynamic communication channel changing mechanism. The algorithm expands the MAC protocol functionality. The modified MAC protocol performs and controls intra- and inter-cluster connection formation as an additional subtask.

IV. THE PROPOSED CLUSTERING ALGORITHM

The proposed clustering algorithm is designed to be used at the first level of a hierarchical system. At this level, wireless sensor nodes are placed. Communication between each wireless sensor node is established by the collision-free TDAM-based medium access protocol. The protocol possesses self-organising features, which enable cluster establishing. The protocol is fault tolerant if a network changes its configuration.

Intra-cluster 1-hop connectivity between nodes is used because it is necessary to achieve the faster transfer of data from a cluster to a sink (GW). That is why no data routing between sensor nodes is needed. As a result, no routing protocol is needed that helps to prolong network lifetime. Furthermore, smaller latency in data delivery from the sensor node to the sink is ensured in comparison with the data delivery from the one which is n-hop far away.

Each cluster in a network is maintained by its CH. A CH is selected from wireless sensor nodes. The MAC protocol defines an algorithm and its operation in the collision-free manner with a guarantee of only one CH existence in one cluster. After CH selection procedure, it performs cluster maintaining and new member inclusion procedures. MAC protocol defines a procedure of new member inclusion in the collision-free manner. That helps to avoid the negative influence of new potential member request packets on the stabilized inter-cluster communication.

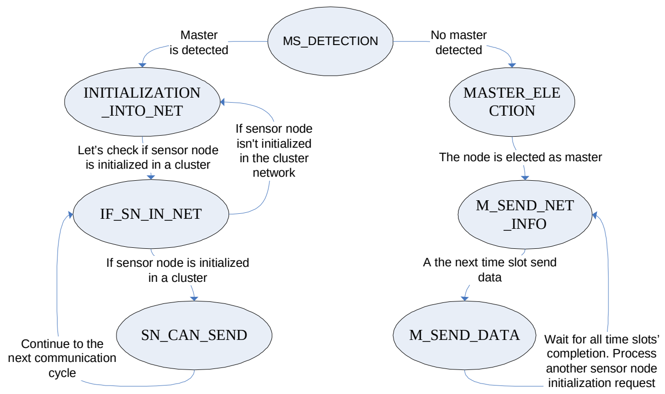

Fig. 2. The original state machine of the collision-free MAC protocol

In case of two-level system, there are some changes in CH selection state [4]. The changes occur because the GW is connected with the SN directly by electrical communication interface. The connection is necessary because of GW inability to work in two-protocol systems simultaneously without adding additional hardware. Such hardware is one sensor node from wireless sensor nodes. According to limitations of a system described in [4], the GW is a line-powered device with unlimited energy source. Thus, the sensor node connected to the GW becomes unlimited in energy resource, too. This feature allows the sensor node to change its state to the CH, with sending a service packet, informing all cluster participants. After sinding the packet, the original CH sends an ACK service packet to confirm the CH change procedure. Then after receiving the ACK packet, a new node switches to CH state with the same network status. Thus, other nodes will not suffer from the CH changing. The only limitation is that the CH change procedure will start only after obtaining the network status information.

In the paper, we try to eliminate one significant system limitation affecting the wireless sensor node deployment and network planning. The fixed communication channel arrangement in all wireless sensor network nodes is discussed in [3, 4]. On the contrary, we suggest specifying only a starting frequency of communication because in the real world wireless sensor nodes may be scattered randomly and their number may also vary trough node breakage. In some cases, it can be a significant obstacle to extend the existing network. Especially, when there are not available nodes with a specific communication channel. Or in other case, it is enough if only a few of cluster sensor nodes will operate to fulfill a task. This leads to the situation that the left nodes become useless. And still they are unavailable for other clusters because of hard-coded communication channels. As a result, they are not suitable for replacement –wireless sensor nodes of neighbouring clusters communicate on different channels.

Of course, the collision-free communication mode remains as a main feature of an enhanced solution. Also, the neighbouring clusters may exist in the radio ranges of each other without limitations. The only requirement is not to impede neighbouring cluster communication and vice-versa. It is achieved by dividing each cluster into its communication channel, but now in the auto mode.

To enable new features, the following MAC protocol modifications have been made:

- all wireless sensor nodes have been programmed to start communication on a common communication frequency;
- between CHs communication for service information exchange;
- a new type of service packet has been implemented. One is for the CH, telling its sensor nodes to switch to another communication channel.

As aforementioned, in the new MAC protocol variation the change is made in the CH detection if it is connected to the infinite supply power or not. Therefore, each sensor node knows if it is a potential CH. This feature is the main in case of a self-clustering procedure. If it is a potential CH, after powering on the sensor node enters MS_DETECTION state (Fig. 2) and starts listening to a defined communication frequency. In such a state, the sensor node waits for a data packet at a current communication frequency for a wait time tw, which is calculated as follows:

$$t_W = t_T * 2 + t_S + t_{ID}, \qquad (1)$$

where t_T is the maximum communication cycle period time, t_S is the maximum sleep interval, t_{ID} is the time calculated from the SN ID number. All these values are known to SNs, but can be changed before programming them. During time $2*t_W$ the sensor node radio receiver is switched on, as well as the countdown timer starts from the same $2*t_W$ time, which is used for sensor node assurance to hear the intra-cluster communication. If during this time interval the sensor node receives the data packet from another node or even the master packet it stops counting down and switches to another communication channel. After the communication channel change, the sensor node continues listening. If for time t_w no communication is heard, the sensor node enters MS_ELECTION phase, where it has a good chance to become a cluster master. Other MAC protocol state machine states remain unchanged. After master selection procedure, a new CH sends the network information data package together with service information. At the next communication TDMA slot, the CH data is transmitted to communication partners in one cluster. TDMA frame ends with the initialization slot, where the uninitialized nodes send their initialization requests to the CH.

Some changes affect the sensor node inclusion into the cluster, too. The sensor node and CH know its potential role. Sensor node is a wireless sensor node that is not connected to the GW. Thus, its potential role is SN-role. In the original MAC protocol, the sensor node could change its state to MS_ELECTION if its CH runs out of power or stops functioning. Now it is unnecessary because if no CH is available for the sensor node in its radio range, it means that it is far away from all CHs or the appropriate CH “died”. If it so, the sensor node cannot deliver its data to a central computer; thus, it becomes useless for a two-level system.

When the sensor node is powered on, it enters MS_DETECTION state. In this state, the sensor node waits for time t_w (Eq. 1). If it receives the packet from another intra-cluster initialized sensor node, it stops the timer and waits for a CH service packet. After the service packet reception, the sensor node analyses the density of a cluster – if it is able to connect to it. If a cluster is too dense or new cluster participant registration is closed, the sensor node switches to another communication frequency, or it switches to a particular communication frequency if the CH has informed about it in its service packet. However, if no master packet is received, the sensor node switches to another communication cluster and enters MS_DETECTION state at once.

An enhanced MAC protocol with the clustering algorithm state machine can be developed from the original one. Consider Fig. 3, where the enhanced state machine is shown.

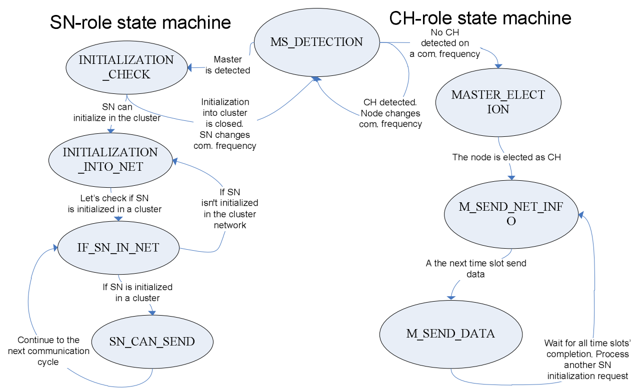

Fig. 3. The changed state machine of the collision-free MAC protocol

Though each wireless sensor node knows its potential role in the wireless sensor network in general and in a cluster in particular, the state machine is divided into two parts. One part is dedicated to the sensor node, while the other is dedicated to a potential CH node.

A new state has been added to a state machine in the SN-role part – INITIALIZATION_CHECK – where the sensor node checks if it is able to initialize in the cluster;

The sensor node enters the state only after MS_DETECTION, when a CH is detected. If the checking procedure ends with a positive result, i.e., initialization is open, then the sensor node enters INITIALIZATION_INTO_NET state. And the further steps till the data packet is sent are performed as in the original MAC protocol [3]. If the checking procedure ends with a negative result, and the sensor node cannot be initialized in the cluster, then the sensor node changes a communication frequency. Communication frequency can be changed according to the full cluster CH service packet information about free-to-join clusters, or by changing communication frequency by the frequency counter incrimination. Thus, switching to the next frequency is performed.

In the point of CH-role state machine part, a new loop in MS_DETECTION has been added. According to a new loop, MS_DETECTION state has been modified. A new procedure has been added – CH detection on a particular communication frequency. If a CH is detected, a potential CH changes its communication frequency by incrementing a frequency counter. Thus successive communication frequencies become checked. It helps not only to form a cluster with collision-free communication and without negative influence on other clusters, but also enables a network self-healing feature. When a certain CH “dies”, another CH can take its place simply by adding it to the same place, where the out-of-service CH worked. If a CH is not found, the potential CH changes its state to MASTER_ELECTION state. And further MAC protocol operations are the same as in the case of the original MAC protocol [3].

As aforementioned, changes are made in GWs, too. GW, as it is in the original approach [3], is a device that communicates in two-protocol stacks. They are TCP/IP and originally developed collision-free self-organising wireless sensor network protocol. They carry out quite a simple task of data aggregation in a cluster and delivery to a control computer via TCP/IP network using Wi-Fi or Ethernet medium. Moreover, all GWs have a link between them via the upper levels of routers. This connection allows GWs to communicate between them and exchange the service information. In the modified approach, the service information is the data about GW-specific CH and cluster parameters. The parameters are the following: network density, cluster task (-s), communication frequency information. Based upon this information, a CH includes it in a service packet, thus informing a new sensor node about available clusters and their communication frequencies. Thus, sensor nodes that are new in the network can fast find an appropriate cluster to join it.

V. CONCLUSIONS

In the paper, a self-organising clustering approach for two-level systems has been discussed. A novel approach has been presented that is based on a newly developed collision-free MAC protocol. The protocol is changed, thus gaining a self-clustering feature. While the changed MAC protocol still supports the collision-free communication, it has become more flexible for its use in real-life applications. A two-level wireless sensor network planning procedure has been reduced to a GW placement and sensor node scattering near each GW. Moreover, a self-healing feature has been added to the MAC protocol. The feature allows replacing the out-of-order GW or/and the CH simply by adding the properly operating one. Moreover, the changed MAC protocol is shown with the help of the state machine in the article.

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Romāns Taranovs, Valerijs Zagurskis, Gundars Miezītis. Efektīvā klasteros sadalīšanas pieeja hierarhiskiem bezvadu sensoru tīkliem
Efektīvā limitēto resursu izmantošana un izdalīšana bezvadu sensoru tīklos veidā, kas maksimizē savāktu datu informācijas vērtību, ir liela pētīšanas problēma. Šinī kontekstā pētījuma rezultāti koncentrējās uz arhitektūras pieeju, kā rīkiem efektīvai svarīgu datu ieguvei no sensoru mezgliem. Mērķa sasniegšanai mēs piedāvājām sadalīt visus tīklā pieejamos bezvadu sensoru mezglus klasteros. Rakstā ir piedāvāta pieeja automātiskai bezvadu sensoru mezglu sadalīšanai klasteros. Ir parādīta tās atšķirība no oriģinālās pieejas, kur katrs bezvadu sensoru mezgls bija konfigurēts un tam bija uzstādīta komunikācijas frekvence. Rakstā ir pieradīts, ka modificēta pieeja ir daudz izdevīgāka par statisko. Tad palielinās bezvadu sensoru tīkla paš-organizācijas īpašības, kuru rezultātā tīkls paliek vieglāk uzstādāms un pārvaldāms, pat cilvēkiem bez īpašām, specifiskām zināšanām. Kā arī parādās jaunā īpašība – bezvadu sensoru tīkla pašārstēšanās. Kad bojāta klastera mezglus var viegli aizvietot ar jaunu mezglu ieslēgšanu tīklā bez īpašas viņu priekš-konfigurēšanas. Tas ir, komunikācijas sākumā parametri ir vienādi visiem mezgliem. Pie tam bezsadursmju TDMA-bāzē vides piekļuves protokols (MAC) paliek, respektīvi, paliek hierarhiska bezvadu sensoru tīkla izmantošanas iespēja kritiskos lietojumos, kur ir nepieciešams nogādāt vairāk derīgu datu par determinētu laiku. Bezvadu sensoru mezgli klasteros paliek viena lēciena attālumā viens no otra, kas liecina par maršrutēšanas protokola neizmantošanu. Katrs mezgls var būt sasniedzams citam mezglam, sūtot datus apraides veidā. Protokolu steka minimizēšana ļauj samazināt sistēmas programmas sarežģītību, kas samazina papildus barošanas enerģijas nepieciešamību. Rezultātā no baterijām baroti bezvadu sensoru mezgli var strādāt ilgāk bez aizvietošanas. Kopā ar augšējo vārteju līmeni tiek piedāvāta viegla un dinamiski pārkonfigurējama bezvadu sensoru tīkla struktūra.

Роман Таранов, Валерий Загурский, Гундарс Миезитис. Эффективный подход к самокластеризации в иерархической беспроводной сенсорной сети
Эффективное использование и выделение ресурсов для беспроводных сенсорных сетей в виде, что максимизирует качество собранной информации является огромной исследовательской проблемой. В данном контексте результаты исследования концентрируются на архитектурных подходах как к средствам для эффективного получения данных из беспроводных сенсорных узлов. Для достижения цели мы предлагаем разделить всю сеть на кластеры их беспроводных сенсорных узлов. В работе предлагается подход к автоматическому разделению беспроводных сенсорных узлов на кластеры. Показано отличие от оригинального подхода, где каждый сенсорный узел предварительно программировался и настраивался для коммуникации на определённо выделенном коммуникационном канале. В работе показываются различия между двумя подходами и доказывается превосходство модифицированного динамического подхода над статическим. Когда увеличиваются свойства самоорганизации беспроводной сенсорной сети, в результате чего сеть становится легче устанавливающийся и управляемой, даже для людей без специфических знаний. А также появляется новая особенность сети –самолечение, когда узлы повреждённого кластера могут быть легко заменены новыми узлами их включением в сеть, без особенного конфигурирования их. Что означает, что начальные параметры коммуникации для всех беспроводных узлов одинаковы. При чём, бесколлизионный, основанный на TDMA подход к MAC протокол сохраняется как основная особенность внутрикластерной коммуникации. В следствии чего остаётся возможность использования сети для критических к данным приложений, а также для приложений, где необходимо гарантировать скорость коммуникации. Все узлы каждого кластера остаются на расстоянии одного хопа друг от друга, что позволяет не использовать маршрутизацию. Каждый узел может достичь другого широковещательным сообщением. Уменьшение стека протоколов позволяет уменьшить программную сложность, что уменьшает требования к использования энергии питания. В результате, беспроводные сенсорные узлы питаемые от батарей смогут работать дольше без их замены. Вместе со вторым уровнем маршрутизаторов предложен способ динамической переконфигурации структуры беспроводной сенсорной сети.