Traffic-based, mobility-aware clustering for IEEE 802.15.4a UWB networks

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***Abstract*—This work presents a traffic-based, mobility-aware clustering algorithm tailored for application scenarios typical of low data rate IEEE 802.15.4a networks and characterized by a hierarchical network organization. The proposed algorithm adapts to emerging traffic and mobility patterns in the network by selecting as clusterheads nodes that are the intended destinations for a large number of packets, and by associating to the same cluster nodes that send packets to the same destination. The performance of the proposed algorithm is compared by computer simulations with both a non-clustered approach and a clustering algorithm aiming at energy efficiency maximization, in a network of UWB nodes compliant to the 802.15.4a physical layer. Simulation results show that the proposed clustering algorithm improves both network throughput and energy efficiency in hierarchically organized low rate UWB networks.**

I. Introduction

The IEEE 802.15.4a standard, based on Impulse Radio UWB, has been proposed as a potential solution for the deployment of sensor networks in a wide range of application scenarios [1]. The 802.15.4a standard is appealing in particular for application scenarios dealing with security operations, disaster recovery and firefighting, due to the positioning capabilities made available by the UWB technology [2].
Such scenarios are usually characterized by a hierarchical organization of people in teams governed by team leaders, leading to peculiar traffic and mobility patterns, quite different from those traditionally assumed in the analysis of ad-hoc networks. It can in fact be expected that the organization in teams would lead to a predominance of intra-team traffic, as well as to common mobility patterns for members of the same team. The deployment of an efficient communications network in such application scenarios should thus take into account traffic and mobility characteristics. In this view, this paper focuses on network organization, by proposing an energy-efficient, traffic-based clustering algorithm robust to node mobility .
The goal of a clustering algorithm is to partition the network in a set of subgroups (clusters) in order to improve network performance. A large number of different approaches was proposed in order to solve the clustering problem. A possible classification of the clustering algorithms is the following one:

- topology-based clustering algorithms;
- metric-based clustering algorithms.

In this work the main solutions proposed in the literature for each of the two classes are discussed, and a novel metric-based clustering algorithm based on similarities in mobility and traffic patterns between network nodes is proposed. The algorithm is then evaluated in terms of throughput and energy efficiency by means of computer simulations.
The paper is organized as follows. Section II reviews and discusses existing solutions for clustering in wireless ad-hoc networks. Section III presents a novel scheme for clustering in low rate UWB networks, while Section IV presents simulation results. Finally, Section V draws conclusions.

II. Previous work

A. Topology-based clustering algorithms

Topology-based clustering algorithms determine the composition of each cluster according to the position and other topology-related characteristics of the nodes in the network. Algorithms belonging to this class group nodes that are either within a given physical distance or within a logical distance (e.g. a maximum number of hops), or according to their connectivity degree. They mainly differ in the actual procedure for cluster formation and in the information exchanged by nodes.

Adaptive clustering: The clustering algorithm proposed in [3], as a slight evolution of previous work on lowest ID clustering by the same group presented in [4], was among the first proposing clustering on the basis of node topology. The algorithm does not apply any specific criterion in the selection of the cluster-heads: node IDs are used to avoid loops in the cluster formation. The algorithm is completely distributed, and leads to a partition of the network in non-overlapping clusters. Nodes belonging to the same cluster in the final network partition are at most at two hops distance. The algorithm proposed in [3] has its main advantage in simplicity. On the other hand, it does not guarantee any specific common property to nodes belonging to the same cluster, since ID, physical position and transmission range are the only parameters used in the cluster formation. As a result, the stability of the clusters can be quite low, especially in presence of mobility.

Degree-based clustering: Hop distance is not the only topology-related parameter proposed as a basis for node clustering. An alternative solution to distance-based clustering is

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described in [4]. The algorithm is based on the degree of connectivity of nodes in the network. The goal of adopting the degree as the criterion for clusterhead selection is to reduce the number of clusterhead changes by choosing clusterheads that are well connected with other nodes in the network. Unfortunately under high mobility conditions the rapid variations in topology lead to frequent reselections of the clusterhead, especially for topology scenarios where several nodes have similar connectivity [4]. In these conditions, in fact, even a single link failure/creation can lead to a clusterhead switch.

B. Metric-based clustering algorithms

Metric-based clustering algorithms determine the composition of each cluster by minimizing a clustering metric. The adopted metric models one or more key system parameters, and the clustering procedure aims at optimizing network performance as a function of the selected system parameters. Algorithms belonging to this class mainly differ in the definition of the metric and the selected system parameters.

Generalized Distributed and Mobility-Adaptive Clustering (G-DMAC): The Generalized Distributed and Mobility-Adaptive Clustering (G-DMAC) algorithm is one of the first attempts to overcome the limitations of the topology-based clustering algorithms. The algorithm, described in [5], aims at reducing the clustering overhead due to reorganization and maintenance of the clusters observed in [3]. In order to do so, the algorithm assumes that each node i is characterized by a weight w_i describing a specific characteristic of the node, and that nodes with higher weight have higher probability of becoming clusterheads. The G-DMAC takes into account mobility by adopting for each node a weight which is inversely proportional to its speed, making still or slowly mobile nodes more suitable to take the role of cluster-heads; however, relationship between mobility patterns of different nodes is not taken into account.

The (α, t) cluster framework: The clustering algorithm proposed in [6] mainly focuses on the reduction of clustering overhead due to mobility. In order to achieve this goal, the (α, t) clustering algorithm adopts a link-depending metric. The goal of the algorithm is in fact to guarantee that nodes belonging to the same cluster have the possibility to communicate along cluster-internal paths that are characterized by a minimum expected path availability α over a time interval of duration at least equal to t seconds.

It is worth noting that the algorithm considers clusters spanning over multihop paths, and as a consequence requires the combination of routing and mobility information.

The main drawback of the algorithm is the need for an accurate mobility model for achieving good estimates of the average path availability. In [6] the authors only evaluate the performance of the algorithm in a scenario where nodes actually move according to the same model used in the determination of the (α, t)-path availability: this is of course a best-case scenario, and no information is provided on the performance of the algorithm when nodes move according to a different mobility model.

Energy-Efficient Unequal Clustering: The main goal of the Energy-Efficient Unequal Clustering (EEUC) algorithm, proposed in [7], is to maximize network lifetime in a sensor network scenario where clusterheads act as relays of all data traffic produced within the cluster towards a network sink. In this scenario clusterheads that are closer to the sink are subject to a higher power consumption, since all the traffic sent by nodes further away from the sink is relayed by a clusterhead close to the sink. In order to balance this inequality in power consumption, the EEUC algorithm introduces a clustering metric based on the position of a node with respect to the sink.

The EEUC protocol leads to very good fairness in energy consumption in the considered scenario, as shown by the simulation results in [7]; unfortunately the scenario is highly specific, and the algorithm is not directly applicable to different application scenarios.

Weighted Clustering Algorithm (WCA): The Weighted Clustering Algorithm (WCA), proposed in [8], is a general-purpose weight-based clustering algorithm. The weight assigned to each node is the result of a weighted sum of four values taking into account different node characteristics or properties. The weight associated to a generic node v is obtained as follows:

$$I_v = c_1 D_v + c_2 P_v + c_3 M_v + c_4 T_v \tag{1}$$

where:

- D_v is a connectivity-related parameter, defined as $D_v = |d_v - M|$, d_v and M being respectively the number of neighbors of v and the preferred size for a cluster, according to a predefined evaluation on the optimal number of nodes per cluster, in terms of intra-cluster access efficiency;
- P_v is the sum of the distances from v to all of its neighbors;
- M_v is a moving average of the speed of node v;
- T_v is the amount of time spent by v while acting as a clusterhead, and models the energy consumption of node v, since it is assumed that clusterheads consume significantly more energy than standard nodes.

The four coefficients $c_1, \cdots, c_4$ can be set to different values according to the network scenario and the desired importance for each of the four node characteristics. Cluster formation is carried out by individuating the N (where N is the desired number of clusters) nodes with lowest weight and electing them as clusterheads, with the constraint of not having two clusterheads within radio coverage.

The WCA algorithm has the advantage of being simple and potentially easy to implement. Unfortunately some of the selected properties included in the weight are not easy to evaluate: as an example, the moving average of the speed M_v can be hard to evaluate without dedicated hardware such as a GPS module. The knowledge of the distances from all neighbors in order to evaluate P_v is not straightforward as well, and requires a significant overhead in terms of ranging.

III. TRAFFIC-BASED, MOBILITY-AWARE CLUSTERING

Existing works discussed in Section II highlight the potential benefit of taking into account node mobility in network organization. None of them, however, takes advantage of a specific characteristic of the application scenarios considered in this work, that is the presence of a hierarchical organization external to the communication network.

The presence of such hierarchical organization impacts the network under two main aspects:

1) node mobility patterns - mobility patterns in a network scenario characterized by a hierarchical organization are not described properly by standard mobility models. Group mobility is a more accurate description of the behavior of the nodes in the considered scenario;
2) traffic patterns - Since nodes in the considered scenario are organized in teams, it is also reasonable to expect that a relevant portion of the traffic will be internal to the team, leading to traffic patterns that are not uniformly distributed, as it is traditionally assumed in the analysis of ad-hoc networks.

The algorithm described in this section was intentionally designed in order to take advantage of such emerging traffic and mobility patterns in the network. The main goal in the development of such algorithm is to achieve a network partition resembling the hierarchical organization in teams, in order to optimize network performance and reduce as much as possible inter-cluster routing overhead. Clustering in the proposed algorithm is performed in two steps, described in the following.

A. Clusterheads selection

The number N of clusters to be created is assumed to be an input parameter to the algorithm. Future versions of the algorithm will address the more general approach of including N in the set of parameters to be optimized by the algorithm itself. The evaluation of the optimum number of clusters that best fits the scenario of interest can be achieved using several methods, that typically measure the dissimilarities between the values of the specific parameters of a candidate node and the average values of the exisiting clusters in the network [9]. A comparison with an appropriate threshold will then determine the final number of clusters. These procedures are often iterated starting from different network conditions. The obtained results are finally averaged. For specific scenarios, as the ones characterized by an organization in teams, however, the number and/or cardinality of clusters may be fixed in advance, or must cope with rigid constraints. These aspects will be an interesting subject of future studies. In the present implementation of the clustering algorithm the clusterheads selection procedure is carried out as follows.

1) Evaluate for each node i the number R_i of received DATA packets in the last clustering interval T_c. Received packets are defined as end-to-end packets, including both single hop and multi-hop connections;
2) select the N nodes that received the highest number of packets in the last clustering interval as clusterheads.

Note that there is no specific requirement on the minimum logical distance between clusterheads; the algorithm is in fact designed to detect emerging traffic patterns, irrespectively of the topological characteristics of the nodes.

B. Node association

Nodes that were not selected as clusterheads are associated to a clusterhead during this phase. Node association is carried out using the same criterion adopted during the clusterhead selection phase, that is traffic measurement. The procedure for node association can be described as follows.

1) Evaluate for each node i the number of packets S_i sent to each of the N clusterheads identified during the clusterhead selection phase;
2) for each node i determine the maximum number $S_{i\,MAX}$ among the N values evaluated at step 1.
3) Associate node i to the cluster corresponding to $S_{i\,MAX}$.

The above procedure associates each node i to the cluster held by the node that was the most frequent intended destination among the N clusterheads for the packets sent by the node i. This approach is based on the assumption that if a node belongs to a team, it will send most of its traffic to the team leader, for example in order to report information from scouting and surveillance. As a consequence, the proposed clustering scheme increases routing efficiency by detecting end-to-end traffic patterns and associating nodes that communicate frequently to the same cluster, thus minimizing inter-cluster transmissions.

C. Impact of mobility

Mobility will have a strong impact on the node association procedure described in Section III-B. As already stated at the beginning of the section, it is expected that the application scenarios considered in this work will lead to a strong correlation not only in the traffic patterns of nodes belonging to the same team, but also in the mobility patterns of the same nodes. The proposed node association procedure will inherently take into account the mobility correlation aspect, as nodes that show different mobility patterns will often fall out of physical connectivity, thus leading to a low probability of being associated to the same cluster. The impact of correlation in both mobility and traffic patterns on the performance of the proposed algorithm will be evaluated in future research activities.

D. Required data structure

Algorithm operation requires that the number of packets exchanged between any pair of nodes is collected and transferred to a node in charge of selecting the N clusterheads. Such data can be organized in a matrix, as shown in Table I. Note that although in this phase the algorithm is centralized, the procedure can be distributed among nodes in the network, for example by means of periodic packet exchange between neighboring nodes.

TABLE I
EXAMPLE OF EXCHANGED TRAFFIC MATRIX USED IN THE TRAFFIC-BASED CLUSTERING ALGORITHM

Node IDs	**1**	**2**	**3**	**4**	$\cdots$	$\mathrm{N_{nodes}}$
1	0	35	15	55	$\cdots$	44
2	22	0	$\cdots$	$\cdots$	$\cdots$	$\cdots$
3	30	$\cdots$	0	$\cdots$	$\cdots$	$\cdots$
4	41	$\cdots$	$\cdots$	0	$\cdots$	$\cdots$
$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$
$\mathrm{N_{nodes}}$	34	22	15	54	$\cdots$	0
Sum	195	104	99	144	$\cdots$	113

E. Mapping on the IEEE 802.15.4a MAC

The procedure described above is independent on the underlying MAC protocol, the only requirement being that the MAC must guarantee the capability for a node of receiving packets from all nodes in radio connectivity. It is however important to analyze how the resulting network partition can be mapped on the MAC.
The IEEE 802.15.4a MAC organizes the devices in Personal Area Networks (PANs), each PAN being controlled and managed by a PAN coordinator. The PAN coordinator has the role of managing the access to the wireless medium of nodes associated to the PAN. It is straightforward to associate the role of clusterhead to the role of PAN coordinator: in this case the proposed clustering scheme is intrinsically adopted as the network formation algorithm, starting from an initial situation where all nodes are part of the same PAN. Once nodes are organized in different clusters and thus in different PANs, energy consumption can be reduced by assigning to each cluster a different part of the available radio resource. Given the characteristics of the underlying MAC, this can be achieved in two ways:

- Assignment of different Time Hopping codes to each cluster/PAN
- Assignment of different frequency bands to each cluster/PAN.

The latter approach is more efficient, since it completely avoid mutual interference between different clusters. On the other hand, inter-cluster communications can be more difficult, since the hardware specifications defined in the IEEE 802.15.4a MAC do not foresee the capability of listening to multiple channels at the same time. A potential solution to this issue is the adoption of the concept of active part of the frame defined in the 802.15.4a MAC. A PAN coordinator can in fact decide to reserve part of the frame, only allowing devices associated to the PAN to transmit in the remaining part of the frame, known as active part. The PAN coordinator can then use the reserved part of the frame to switch to the frequency selected by another cluster/PAN, in order to act as a gateway between the two clusters.

IV. PERFORMANCE EVALUATION

The proposed clustering algorithm was analyzed by simulation, by using a simulator developed in the framework of the OMNeT++ simulation environment [10]. The performance of the protocol was compared with the one achieved by a system with the same characteristics but without clustering, and with the performance observed for the WCA clustering algorithm proposed in [8] and configured so that the only relevant parameter is residual energy of each node. This configuration was achieved by using the weighted sum in Eq. (3) with $c_1 = c_2 = c_3 = 0$, and $c_4 = 1$.
The algorithms were compared in a simulation scenario characterized by the presence of $N_{nodes} = 16$ nodes, to be divided in $N = 4$ PANs in an area of size of $100x100\,m^2$. The N_{nodes} were hierarchically organized in 4 teams of 4 nodes each, showing the following behavior in terms of traffic and mobility. Traffic characteristics were defined as follows:

- At each connection request, the source node selected with probability η a specific predefined node, and with probability $1 - \eta$ a randomly selected node;
- The predefined target node for each transmitting node was set so that each team leader was the preferred target of the three remaining nodes composing the team.

Mobility was characterized taking into account the group-like behavior of each team as well. Nodes belonging to the same team formed a group that moved according to the Kerberos group mobility model described in [11].
The channel was modeled using the IEEE 802.15.4a in the Indoor LOS scenario (CM1 [12]). Both thermal noise and interference were taken into account, the latter by means of an implementation of the Pulse Collision interference model [13]. A complete list of simulation settings is reported in Table II. Results in terms of throughput and residual node energy are presented in Figure 1 and 2, respectively. Figure 1 shows that throughput is increased compared both to the case of a non-clusterized network and to the case of the WCA, mainly thanks to reduction of dropped packets due to changes in connectivity within a cluster. Figure 2 shows that by taking into account traffic and mobility in the creation of clusters energy efficiency is increased as well, leading to a higher percentual residual energy at the end of the simulation time for the proposed algorithm compared to the other solutions. This result is achieved by means of a decrease in inter-cluster communications and in packet retransmissions due to path disruption caused by node mobility.

V. CONCLUSION

This work proposed a novel solution for network organization and clustering in IEEE 802.15.4a networks adopted in surveillance and disaster recovery operations. The proposed clustering algorithm follows a metric-based approach, adopting end-to-end traffic measurement as the key metric, in order to detect specific traffic patterns that can emerge in the network, given the highly hierarchical organization of the entities forming the network in the considered application

TABLE II
SIMULATION SETTINGS

Parameter	Value(s)
Area	100x100 m^2
Number of nodes N	16
Network topology	Random node positions
Number of runs	10
Simulation time	6000 s
User bit rate	20 kb/s
Transmission rate	966 kb/s
Transmission power	36.5 μW (FCC limit for Bandwidth $\cong$ 0.5 GHz)
Packet traffic model	CBR
DATA packet length	258 bits (+ 64 bits for Sync trailer)
Physical layer settings	Number of pulses per bit $N_s = 4$, Symbol time $T_s = 258.8ns$, Pulse duration $T_m = 2ns$, Reed Solomon (55,63) FEC
Access strategy	Pure Aloha
Oriented traffic probability η	0.9
Kerberos grouping factor ρ	0.5
Kerberos max speed	2 m/s

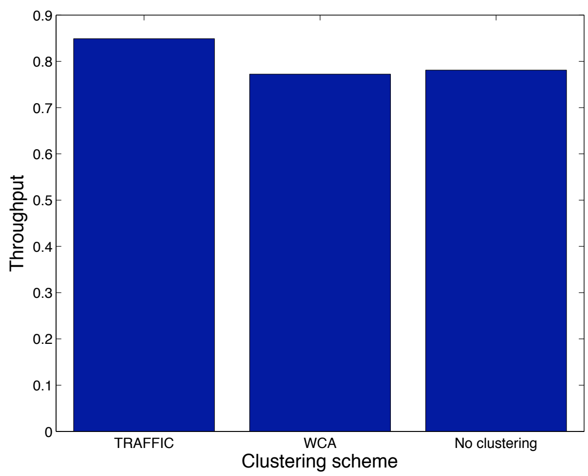

Fig. 1. Throughput for the two considered clustering algorithms (Traffic-based and WCA) vs. no clustering.

scenarios. The procedures for clusterhead selection and node association to the clusterheads were defined, and the required data structure for the execution of the two procedures was identified. Finally, the possibilities of combining the proposed clustering scheme with the characteristics for the IEEE 802.15.4a MAC were analyzed, highlighting potential solutions for implementing the desired network resource partition while guaranteeing end-to-end network connectivity.
The proposed clustering algorithm was analyzed by means of simulations. The performance of the traffic-based approach was compared with a reference solution not adopting network

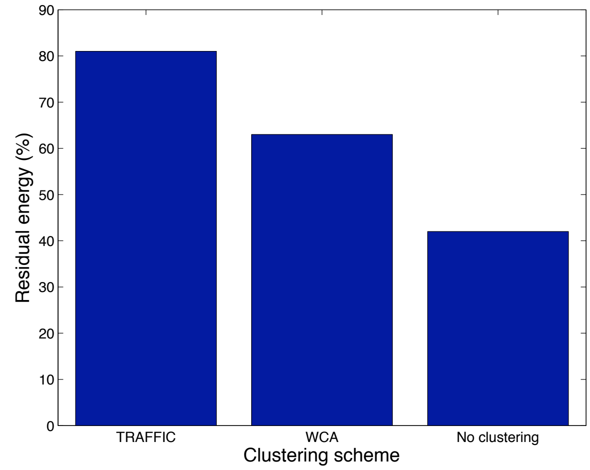

Fig. 2. Percentual residual energy for the two considered clustering algorithms (Traffic-based and WCA) vs. no clustering.

clustering and with the performance of the metric-based WCA clustering algorithm proposed in [8], configured in order to determine network partition on the basis of residual node energy. Simulation results show that in a network scenario characterized by group-oriented traffic and mobility patterns the proposed protocol can provide a significant increase in network lifetime, expressed by the average residual energy, while guaranteeing a higher throughput thanks to the reduction of multi-hop, inter-cluster connections. The complete definition of the message exchanges between nodes in order to implement the proposed scheme in a distributed fashion will be addressed in future research work.

ACKNOWLEDGMENT

This work was partially carried out in the framework of the research contract ”Reti di comunicazione e localizzazione con tecnologia Ultra Wide Band” between the INFO-COM Department of the University of Rome La Sapienza and Thales Italia SpA - Land & Joint Systems Division.

REFERENCES

[1] “IEEE 802.15.TG4a official web page,” http://www.ieee802.org/15/pub/TG4a.html.
[2] IEEE 802.15.4 SG4a, “802.15.4IGa Informal Call for Application Response,” July 2003. [Online]. Available: http://grouper.ieee.org/groups/802/15/pub/2003/15-03-0436-00-004a-echelon-sg4a-call-application-response.ppt
[3] C. R. Lin and M. Gerla, “Adaptive clustering for mobile wireless networks,” *IEEE Journal on Selected Areas in Communications*, vol. 15, no. 7, pp. 1265–1275, September 1997.
[4] M. Gerla and J. T. Tsai, “Multicluster, mobile, multimedia radio network,” *Wireless Networks*, vol. 1, no. 3, pp. 255–265, August 1995.
[5] S. Basagni, “Distributed and mobility-adaptive clustering for multimedia support in multi-hop wireless networks,” in *IEEE 50th Vehicular Technology Conference, (VTC 1999-Fall),*, vol. 2, September 1999, pp. 889–893.
[6] A. McDonald and T. Znati, “A mobility-based framework for adaptive clustering in wireless ad hoc networks,” *IEEE Journal on Selected Areas in Communications*, vol. 17, no. 8, pp. 1466–1487, August 1999.

[7] C. Li, M. Ye, G. Chen, and J. Wu, "An energy-efficient unequal clustering mechanism for wireless sensor networks," in *IEEE International Conference on Mobile Ad hoc and Sensor Systems*, November 2005.

[8] M. Chatterjee, S. K. Sas, and D. Turgut, "An on-demand weighted clustering algorithm (WCA) for ad hoc networks," in *IEEE Global Telecommunications Conference*, vol. 3, November/December 2000, pp. 1697–1701.

[9] S. Theodoridis and K. Koutroumbas, *Pattern Recognition*, 4th ed. Academic Press, 2009.

[10] A. Varga, "OMNeT++," *IEEE Network Interactive*, vol. 16, no. 4, July 2002.

[11] L. De Nardis, M. G. Di Benedetto, and S. Falco, "Higher layer issues, Ad-Hoc and Sensor Networks," in *UWB Communications Systems - A Comprehensive Overview*. Hindawi Publishing Corporation, 2006, ch. 4, pp. 205–252.

[12] "IEEE 802.15.4a channel model final report, rev.1 (november 2004)," Available at: ftp://ieee:wireless@ftp.802wirelessworld.com/15/04/15-04-0662-00-004a-channel-model-final-report-r1.pdf, November 2004.

[13] G. Giancola and M.-G. Di Benedetto, "A Novel Approach for estimating Multi User Interference in Impulse Radio UWB Networks: the Pulse Collision model," *Signal Processing, Special Issue on Signal Processing in UWB Communications*, vol. 86, no. 9, pp. 2185–2197, September 2006.