Distributed Multi-Head Clustering for People-Centric Sensor Networks

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***Abstract*—The emergence of powerful sensor-equipped smartphones led to a new form of people-centric sensing networks (PCSN), in which users collect sensor information via their mobile phone. This kind of mobile sensing allows for large-scale data collection on low costs but introduces new challenges: PCSNs need to cope with continuously contributed data and keep transmission and energy costs for users at a minimum in order to reach large-scale participation. In this paper, we propose a Distributed Multi-Head Clustering (DMHC) algorithm that aims at resolving these problems by forming sensing clusters with different roles for participating nodes. We conducted simulations to evaluate DMHC and our analysis shows that it significantly reduces mobile network traffic and user costs without introducing too much overhead.**

***Keywords*-*People-centric sensing*; *Mobile phone sensing*; *Clustering*.**

I. INTRODUCTION

Mobile phone technology has recently undergone a rapid change: Improvements in computation, storage, and wireless communication lead to a spread of powerful mobile devices such as smartphones and tablets. A recent trend is the integration of sensing capabilities into the latest generation of mobile devices. Currently available phones come with built-in accelerometers, gyros, location, audio, and image sensors. We expect that in the future even more sensing hardware will be integrated into mobile phones. For instance, Nokia proposed a future mobile phone[1] that is equipped with sensors for monitoring the environment, the user's health, and the current weather. With this development mobile phones evolve from standard phones, intended for personal communication only, to ubiquitous sensing devices that are globally distributed.

These devices could be applied to form a new kind of sensor network, so-called *people-centric sensing networks* [2] (also referred to as *mobile phone sensing* [3] or *mobile crowdsensing* [4]), where people serve as carriers for mobile phone-based sensors. People-centric sensing networks (PCSN) allow for large-scale global data collection and real-time information display. They could be used, for instance, to monitor environmental pollution, temperature, or noise intensity of urban areas. Even though PCSNs are related to wireless sensor networks (WSN), there are significant differences between those two types of sensor networks (cf. [5]). The main advantage of PCSNs is that data can be collected on a large-scale with automatically deployed, consumer-paid sensor nodes. This new kind of real-time data collection opens up new opportunities for services and applications. However, it also entails several new problems: One major challenge is to process enormous amounts of data contributed by users. Especially for network operators, millions of continuously transmitting mobile phones would lead to a serious challenge. People-centric sensing will not be accepted if data measurements congest the mobile network. At the same time, it is desirable to upload as much data as possible to improve the quality of information. Thus, methods are needed that reduce mobile network traffic without reducing data quality.

In this paper, we propose an algorithm that aims at resolving this problem. Our Distributed Multi-Head Clustering (DMHC) algorithm relieves the mobile network by forming sensing clusters. Within a cluster, collected sensor data is exchanged via ad hoc communication and uploaded in an aggregated form by the clusterhead. To compensate for the overhead introduced by forming the cluster and to minimize energy costs for users, DMHC selects only a subset of nodes as sensingheads, which are required to collect and transfer measurement data to the clusterhead. The election of clusterhead and sensingheads is based on remaining energy levels, communication costs, and capabilities of the nodes. Our analysis shows that DMHC significantly reduces mobile network traffic and user costs while generating only negligible overhead.

The remainder of this paper is organized as follows. In Section II, the problem is formulated and requirements are specified. Section III discusses related work. In Section IV, we present our DMHC algorithm, followed by our simulation results in Section V. Finally, we present our conclusions and future work in Section VI.

II. PROBLEM DESCRIPTION AND REQUIREMENTS

In this paper, we explore the problem of clustering PCSNs. Clustering, in this context, means partitioning its nodes into a set of *clusters* of geographically co-located nodes. Within each cluster, nodes assume one of the following roles (cf. Figure 1): *Clusterheads* are responsible for collecting measurement data within the cluster and transmitting these in aggregated form to a server responsible for storing the

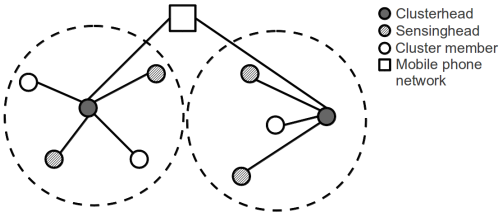

Figure 1. People-centric sensing network with multi-head clusters

collected data. *Sensingheads* are responsible for recording the measurement readings and transmitting them to the clusterhead. *Cluster members* have no specific function to fulfill, but might be requested to become a sensinghead if more measurements are needed. Each cluster consists of one clusterhead, one or more sensingheads, and possibly some cluster members. If there are too few nodes within a cluster, the clusterhead may additionally assume the sensinghead role; thereby minimal clusters consist of one node being clusterhead and sensinghead at the same time.

We want to limit the geographic extent of clusters in order to obtain measurements of nearby sensors at comparable locations. Thus, we aim for 1-hop clusters and so each node should have a link to the clusterhead. This implies that measurements of nodes that are within communication range are “comparable”. As the geographical variance of measurements strongly depends on the sensor type (e.g., temperature or CO_2), we assume that the communication range is automatically adapted (by varying the transmission power) in order to meet the sensor type spatial specifics. In case of parallel measurements with different sensor types, the range needs to be adapted according to the sensor type with the highest spatial variance.

Furthermore, the clustering algorithm should fulfill the following requirements:

- *Mobility-Adaptive*: The clustering algorithm needs to cope with continuous node mobility.
- *Distributed*: To allow for scalable sensing networks, the clustering algorithm should be distributed.
- *Energy-Efficient*: Due to limited energy resources, clustering should use as little power as possible.

III. RELATED WORK

There is a lot of research work related to people-centric sensing. Most work focuses on approaches and techniques that enable data collection with mobiles phones ([6]–[8]), but the potential communicational overload caused by these continuous sensing approaches is often neglected.

However, in the field of wireless sensor networks (WSN) and mobile ad hoc networks (MANET), efficient communication is an important research question. To achieve scalability, nodes are often grouped into clusters. For this process, various clustering algorithms have been proposed ([9], [10]). Our DMHC is based on Distributed Mobility-Adaptive Clustering (DMAC) proposed by Basagni [11], which enables clustering for scenarios with mobile nodes. Several surveys provide a detailed overview of clustering algorithms ([12], [13]). In contrast to our work, most existing clustering algorithms only distinguish between clusterheads and cluster members.

An orthogonal approach to the cluster-based concept is to reduce communication costs by eliminating redundant sensing data transmissions with the help of a prediction-based algorithm [14]. Data is only transmitted when it deviates from the predictions and if it changes the statistic with a high probability. The problem of this approach is that applied prediction models have to be adapted and optimized for each type of sensor data, if significant reduction is to be achieved. This is a complementary concept to ours and could be applied in addition to our clustering algorithm.

Another aspect of our approach is the reduction of energy costs, which we achieve with different roles per cluster. Several other approaches for energy efficient mobile sensing have been proposed. Wang et al. [15] presented a framework that only powers a minimum set of sensors and uses appropriate sensor duty cycles to achieve energy efficiency. Priyantha et al. [16] proposed a sensing architecture where sampling and processing of sensor data is offloaded to a dedicated low-power processor. As these approaches typically focus on energy-efficiency per node, they could also be integrated into our proposed clustering algorithm.

To the best of our knowledge, our approach is the first that allows for multi-head cluster partitioning for people-centric sensing networks.

IV. DISTRIBUTED MULTI-HEAD CLUSTERING

In this section, we describe a distributed multi-head algorithm that sets up sensing clusters in PCSNs. The algorithm consists of two phases: (A) the set-up and maintenance of clusters (including the election of clusterheads) and (B) the election and initiation of sensingheads.

A. Cluster set-up and maintenance

The set-up and maintenance is mainly based on DMAC. DMAC partitions nodes of a mobile network into clusters in a distributed manner by applying a weight-based criterion. Our DMHC is an extension and adaption of DMAC for people-centric sensing networks. Messages, node weights, and procedures used in our proposed DMHC are explained in the following.

1) Clustering messages: In order to form a cluster, nodes need to be aware of neighboring nodes. This is achieved by using periodic broadcasts, so called *PeriodicClusteringMessages* (PCM). A PCM contains a node’s ID, its remaining energy (i.e., its battery charge level), and its current communication costs. The latter are a combination of its *costs per transmission* (*cpt*) and its accumulated *total* *costs* for previous transmissions (*tc*). Due to the reception (or the absence) of PCMs, the status of links to neighboring nodes can be detected.

Besides PCMs, nodes use two types of messages for the cluster set-up: *CH* messages indicate that the sender has assumed the clusterhead role and are broadcasted in order to reach all neighboring nodes. Nodes in the vicinity overhearing the *CH* can join this cluster. If a node receives multiple *CH* messages, it joins the cluster with the bigger weight (cf. Section IV-A2). This can be indicated by sending a *Join* message to the clusterhead. *Join* messages are broadcasted as well, but have to be directed, i.e., they have to contain the clusterhead's ID in order to indicate the cluster they want to join. As *Join* messages may indicate a change from of cluster, they have an impact on the previous cluster as well and thus are also processed by the former clusterhead. In addition, *Join* messages include a set of sensing capabilities S (e.g., $S = \{Temp, CO_2\}$) that indicates, which sensors are provided by the joining node.

2) Node weights: In our approach, we adapted DMAC's concept of applying a weight-based criterion to allow for distributed clustering. However, DMAC does not specify the determination of the nodes' weight. In DMHC, the weight is calculated based on factors that are highly relevant for the deployment in people-centric sensing networks, namely communication costs and remaining energy levels.

In order to avoid excessive costs for users caused by continuous data transmissions, DMHC selects the node with the lowest communication costs (i.e., *min(cpt+tc)*) as clusterhead. In case communication costs are equal for two nodes, the one with the higher remaining energy (*re*) level receives the bigger weight. If the previous factors do not yield a distinct clusterhead, the node with the lower ID is chosen.

3) Clustering procedures: In order to respond to the previously specified messages, DMAC specifies several procedures. Those procedures are run by each node locally.

- *Init()*: The init() procedure is called whenever the node has no associated clusterhead. This may happen in two situations: (1) If the node has just joined the network (e.g., when it has just been switched on) and thus obviously cannot be member of a cluster yet. (2) If a node has lost its clusterhead. *Init()* determines whether there is a neighboring node with a bigger weight than itself. If this is the case, it joins that cluster, otherwise, it will become a clusterhead.
- *LinkFailure(u)*: If a node's connection to another node *u* gets lost (recognized through the lack of PCMs), it checks whether itself or *u* have had the clusterhead role. If itself is the clusterhead, it removes node *u* from the cluster members. If node *u* has been the clusterhead, the node restarts the *Init()* procedure to find a new clusterhead. Otherwise, the link failure has no direct impact on the node and is ignored.
- *NewLink(u)*: If a node receives a *PCM* of a new neighbor *u* and *u* is a clusterhead with bigger weight, the node affiliates with *u*.
- *OnReceivingCH(u)*: If a node receives a *CH* message, which indicates that *u* is a clusterhead, the node affiliates with this cluster if *u* has a bigger weight.
- *OnReceivingJoin(u,z)*: If a nodes receives a *Join* message, which indicates that *u* wants to affiliate with the cluster of *z*, the node has to check if *u* has just left its own cluster or wants to join it (i.e., $node = z$). If z is no clusterhead, it ignores the incoming *Join*. Node *u* learns about the failed association with the next PCM received from z.

B. Sensinghead election

If possible, there should be multiple sensingheads in a cluster in order to improve the robustness and compensate for faulty measurements of individual nodes. In order to keep the energy consumption as low as possible for the users, too many redundant measurements should be avoided. Thus, a trade-off between redundancy and energy saving is needed.

1) Election process: DMHC solves this by selecting only a specified fraction (*sensinghead ratio* ρ) of participating nodes as sensingheads. To ensure robust measurement results for small clusters, a minimum number of sensingheads υ can be specified. If a new node joins a cluster with n nodes, the sensinghead election is triggered if

$$(|Sensingheads| < \upsilon) \vee (\frac{|Sensingheads|}{n+1} < \rho). \qquad (1)$$

Next, a priority class P_j is calculated that takes account of the capabilities of the new node j:

$$P_j = \max_{s \in (S_j \bigcap S_{Req})} (n - \sum_{k=1}^{n} |\{s\} \bigcap S_k|) \qquad (2)$$

where S_j is the set of sensing capabilities of the joining node j, and S_{Req} denotes the set of capabilities required for the sensing tasks in the network. If $S_j \bigcap S_{Req} = \emptyset$, P_j is set to 0; nodes in this priority class are ignored in the following steps. The other priority classes (P_1,...,P_{n-1}) sort the nodes in such a way that nodes with scarce capabilities within the cluster (i.e., a sensor type that only a small subset of cluster members possesses) get into a lower priority classes. The idea behind this is to chose those nodes only for sensing tasks that require these scarce capabilities and that only those nodes can fulfill.

For the sensinghead election, we used two possible approaches in DMHC: The first one is called *sequential sensinghead election* (SSE) and is based on the sequence of arriving and leaving nodes. The first nodes joining a cluster are selected as sensingheads until the sensinghead ratio ρ is reached. From then on, the clusterhead checks for each new node whether ρ is still met. If the sensinghead ratio drops below ρ due to the newly arrived node, this node becomes a sensinghead. If a sensinghead leaves the cluster, for instance due to an association with another cluster, the cluster member that joined first is selected as a new sensinghead. The second approach, called *highest remaining energy* (HRE), considers the remaining energy level as the decisive factor. Every time a new node joins a cluster, the clusterhead compares the energy level of the newly joined node with that of the current sensingheads. If the new node has a higher energy level, it becomes a sensinghead and the former sensinghead with the lowest remaining energy level becomes an ordinary cluster member.

2) Sensinghead messages: Since nodes need to know whether they are supposed to conduct measurements or not, the clusterhead has to inform them about their role within the cluster. For this reason we introduce two new types of messages: *RevokeMeasurement (RM)* and *MeasurementRequest (MR)* messages. When joining a cluster, a new node assumes to be a sensinghead by default. *RevokeMeasurement* messages are sent by the clusterhead to inform the receiver that he is not a sensinghead anymore. *MeasurementRequest* messages are used to indicate that nodes should start measuring. MR messages are only sent after link failures or *HRE* sensinghead elections.

V. EVALUATION

We conducted simulations to evaluate the performance of DMHC. In this section, we will first describe the simulation setup, followed by the presentation of the simulation results.

A. Simulation setup

For our simulations we used the JiST/SWANS simulation environment [17], which allows the simulation of large-scale wireless networks. The size of the simulation area was set to 5×5km. In this area the mobile phone nodes, varying from 1-100 nodes, were moving around. Nodes were randomly distributed, and mobility was modeled by using the Random Waypoint Model with speeds between 1 and 6 m/s and a pause time of 10 seconds. Each run simulated a period of 6 hours and was repeated 50 times. For the wireless communication, we facilitated the built-in wireless LAN (WLAN) simulation components and employed the free-space model using a standard configuration for the WLAN communication (transmission strength: 15 dBm, antenna gain: 1dB). For the sake of simplicity, we assumed $(S_n)_{n \in N} = S_{Req}$ for sensing capabilities of all nodes N.

B. Mobile network transmissions

We first evaluated the amount of mobile network transmissions by comparing the naive approach without clustering, in which all nodes conduct measurements and transmit the collected data themselves, to our cluster-based approach. It is obvious that our algorithm reduces the network traffic, as only clusterheads communicate via the mobile network, instead of all mobile nodes without clustering. However, we analyzed, which node densities result in clusters that are large enough to significantly reduce mobile network traffic.

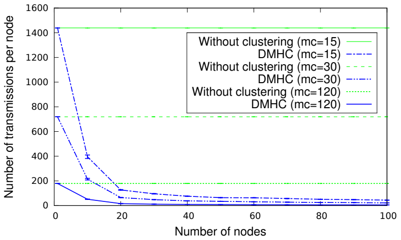

Figure 2. Normalized average number of mobile network transmissions

We ran simulations with different measurement cycles (*mc*={15s, 30s, 120s}). Figure 2 illustrates the normalized average number of transmissions, i.e., the total number of average transmissions in relation to the number of nodes. DMHC significantly reduces the network transmissions compared to the naive approach, even for low node densities. With 10 nodes only, we achieve a network traffic reduction of approximately 70%, and from 40 nodes on even more than 95% reduction. These results lead to the conclusion that DMHC makes sense even in less densely populated areas and can help to significantly reduce the network traffic imposed by people-centric sensing.

C. Communication costs

DMHC considers the communication costs during the clusterhead election. Ideally, in case of a high amount of data flatrate users, each cluster consists of at least one node with zero communication costs.

In our analysis, we evaluated the impact of the penetration rate of flatrate users on the average communication costs per node. Therefore, we ran simulation trials where 5%, 15%, and 25% of nodes had a data flatrate and were not charged for transmitting data. For the remaining nodes, each transmission via the mobile phone network was counted as a “charged transmission”. The communication costs can then derived by including the actual costs per data transmissions ($charged\_transmissions * cpt$). For these trials, sensingheads conducted measurements with *mc*=15s, and PCM messages were broadcasted with a PCM cycle (*pc*) of 3-4 seconds.

The results are illustrated in Figure 3. In trials without clustering, the average communication costs drop according to the percentage of flatrate users, as only those nodes do not contribute to the overall communication costs. In trials with DMHC, the flatrate penetration has a relatively low impact compared to the cost reduction introduced by simply clustering participating nodes. The average communication costs for high-density settings become very low, as the probability of having a user with a data flatrate within each cluster obviously increases with larger cluster sizes. The

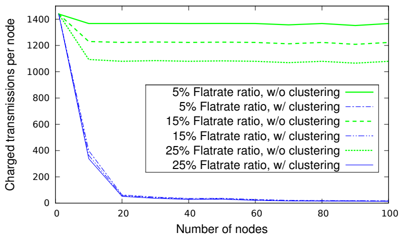

Figure 3. Number of charged transmissions per node

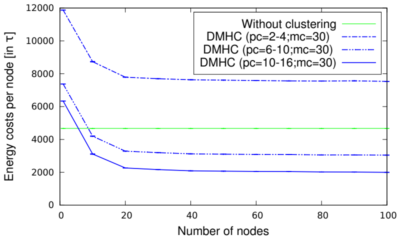

Figure 4. Energy costs for Scenario 1

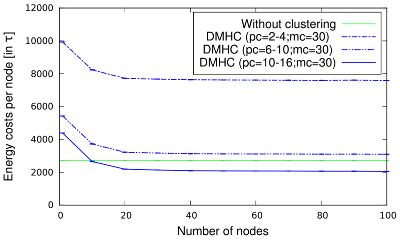

Figure 5. Energy costs for Scenario 2

results show that DMHC significantly lowers the costs and hereby provides a basis for a large-scale user participation.

D. *Energy costs*

We consider energy costs as the sum of energy used for mobile network transmissions, ad hoc transmissions, and sensor measurements. For those energy consuming tasks, the amount of task occurrences were analyzed in three different simulation trials for varying ratios of PCM and measurement cycles. We specified a high, medium, and low PCM-to-measurements ratio. In the high PCM-to-measurements ratio, PCMs were sent every 2-4 seconds (i.e., with a *pc* of 2-4s) and measurements were collected every 30 seconds. In this setting, a lot of ad hoc messages were exchanged in comparison to the amount of conducted measurements. In the medium and low PCM-to-measurements settings, PCMs were broadcasted every 6-10 and 10-16 seconds respectively, while measurements were conducted with the same rate (*mc*=30s). We made assumptions for relative energy costs for the above mentioned energy consuming tasks and considered two scenarios. In *Scenario 1*, mobile network transmissions consume six times more energy than ad hoc transmissions, based on the findings in [18]. Further, we assumed that the energy consumption of sensor measurements is low in comparison to energy used for transmissions (e.g., for temperature sensors). In *Scenario 2*, we assumed lower relative energy costs for mobile network transmissions (factor 3 compared to those of ad hoc transmissions), but also assumed slightly higher energy costs for sensor measurements. In Table I, the energy costs for the mentioned scenarios are listed, specified in relation to an energy cost unit τ.

Table I
ENERGY COST RATIOS FOR SCENARIOS

	Scenario 1	Scenario 2
Mobile network transmissions	6τ	3τ
Ad hoc transmissions	1τ	1τ
Sensor measurements	0.5τ	0.8τ

The results of Scenario 1 show that for trials with medium and low PCM frequency, energy costs are lower than without DMHC from 10 nodes onwards (see Figure 4). Only the setting with a very high frequency of periodic broadcasts exceeds the energy costs of the naive approach. Figure 5 shows the results for Scenario 2. The energy costs of DMHC exceed those of the naive approach in the setting with a medium PCM frequency. However, the additional energy overhead is relatively small and might be acceptable, if communications costs are lowered significantly instead.

E. *Number of measurements*

We evaluated the impact of the sensinghead ratio ρ and the minimum sensinghead number υ on the actual amount of measurements. In a first step (*S1*), we simulated three settings with different sensinghead ratios $\rho = \{10\%, 25\%, 50\%\}$ and a constant sensinghead minimum of $\upsilon = 2$. In a second step (*S2)*, we varied the sensinghead minimum $\upsilon = \{2, 3, 5\}$ for a constant $\rho = 10\%$. For these trials, *mc* was set to 15 seconds, and *pc* to 3-4 seconds.

The results from *S1* show that the number of measurements rapidly converges (see Figure 6). From about 30 nodes on, the amount of measurements per node remains stable, which shows that the effect from introducing sensingheads can also be useful in low-density settings. As the sensinghead ratio ρ specifies the minimal ratio, the number of measurements per node converges to an amount slightly higher than indicated, i.e., 58%, 17%, and 8% above ρ. The results from *S2* lead to similar conclusions (see Figure 7). Although υ has a significant impact for low-density settings, the number of measurements drops very fast in all trials. A stable average is reached from 30-40 nodes onwards.

F. *Ad hoc overhead for sensinghead election*

In the last analysis, we compared the ad hoc overhead of *SSE* and *HRE*. The main part of the overhead arises from PCMs sent out by each node. The number of those messages is the same for both approaches. The difference lies in the amount of non-periodical messages, thus we focused solely on ad hoc messages required for the pure cluster formation and maintenance (i.e., *CH*, *Join*, *RM*, and *MR*). The results (Figure 8) show that SSE performs slightly better. This is due to the fact that HRE re-determines all sensingheads every time a node joins or leaves the cluster. However, the difference of both approaches is relatively small compared to the overall ad hoc overhead.

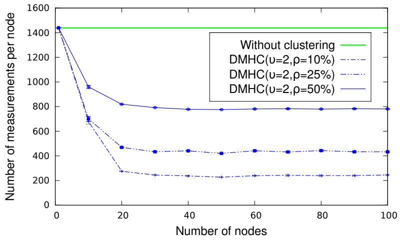

Figure 6. Varying sensinghead ratios (*S1*)

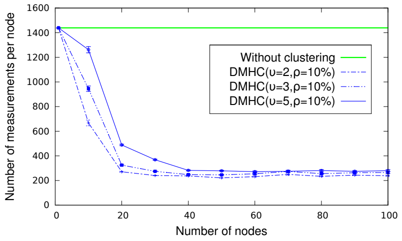

Figure 7. Varying min. sensingheads (*S2*)

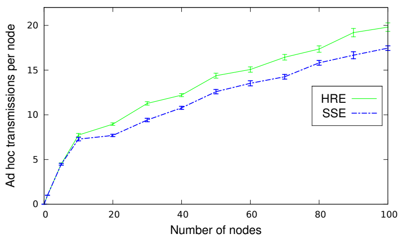

Figure 8. Ad hoc overhead

VI. Conclusion and Future Work

We presented our DMHC algorithm, which forms sensing clusters in order to reduce network traffic and user costs. Each cluster consists of a clusterhead, responsible for the communication of the data, and multiple sensingheads, responsible for the data collection. Clusterheads are selected based on the communication costs in order to keep user costs as low as possible. For the sensinghead election, we proposed two approaches: *SSE* and *HRE*. We analyzed our DMHC algorithm based on simulations using the JiST/SWANS framework. The results show that already for low node densities, DMHC significantly reduces network transmissions, transmission costs, and number of measurements. Energy costs are also within reasonable boundaries, and the ad hoc overhead comparison shows that the performance of both sensinghead election algorithms is adequate.

In our future work, we will elaborate our concept on two main aspects: First, we will implement an adaptive sensinghead election, which automatically adapts ρ to optimize the coverage. Second, we plan to integrate prediction-based approaches to further minimize traffic. In addition, a more comprehensive evaluation is planned, in which the proposed approach is compared to other clustering schemes and more realistic urban mobility and energy models are applied. Further, we will investigate in privacy and incentive schemes that can be utilized to complement our concept.

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