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# A Non-Uniform Node Deployment Approach for Event Detection Sensor Networks

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## Abstract

*Due to the traversal-multicast data transmission manner of the sensor network, the energy consumption of the network is unbalanced and the nodes close to the sink will consume more energy and die faster. This leads to the energy hole problem. In order to solve this problem, many non-uniform node deployment schemes have been proposed for event detection sensor networks. All these works did not consider the impacts of the spatial and temporal distribution on the node deployment strategy. However these factors are truly important, if the energy consumptions of nodes, in active mode, without transmitting or receiving data, are taken into concern. In this paper, the effects of spatial and temporal distribution on the node deployment are considered. Firstly the data transmission amount of the network is calculated, taking the spatial distribution of the events and coverage effects into concern. Exploiting this result the energy balance equation is proposed based on the temporal density of the events, for estimating the network lifetime. Accordingly the non-uniform distribution strategy is proposed, based on the estimation of the network lifetime, to fulfil the requirements of the applications. Numerical and experimental results are further provided to show the feasibility of the presented model.*

## 1 Introduction

Recent advances in processor, memory and radio technology have enabled the deployment of large scale sensor networks where thousands of small sensing nodes capable of sensing, communicating and computing are used for monitoring the physical world. A typical static sensor network consists of a large number of static sensing nodes and one or more static data collection nodes called sinks. Under this network structure the sensor nodes transmit sensed data

to sinks in a traversal-multicast manner through multi-hop paths. Consequently nodes near the sink node need to consume more energy to transmit their own data as well as the data belonging to the nodes further from the sink. This effect of unbalanced energy consumption leads to the energy hole problem for the sensor network[1].

There are mainly three types of systems for static sensor networks, which are query driven type, periodic type and event driven type, according to the type of data flow. For the systems with query driven workflow[2], the occurrence of sensing and data transmitting is dominated by the user's requirements, which cannot be controlled spatial-temporally. This implies that the balance of energy consumption cannot be obtained through network design. The applications with periodic workflow[3][4] normally require all the nodes to sense and transmit data at the same time periodically to the sink. In this occasion the energy hole caused by unbalanced energy consumption is unavoidable[5], even when more nodes are deployed in the area close to the sink. Event detection systems with event driven workflow of sensor network[6][7] are designed to detect and report the occurrences of certain events such as vehicle, enemy intrusion, animal and fire, etc. As it is enough for a relatively small number of nodes to cover a certain event in this kind of system, the redundancy of nodes in large scale high density networks can be exploited to conserve energy through coverage scheduling schemes[8][9][10][11][12][13]. Since statistically only a part of nodes need to transmit data to the sink, the non-uniform deployment of nodes can be leveraged to balance the energy consumption by deploying more nodes close to the sink[14].

To tackle the energy hole problem, many works have been proposed[15][1][5][14][16][17][18]. All of the works are based on the assumption that the sensor nodes consume energy only when transmitting. However in order to fulfil the coverage and connection requirements, there should always be certain number of nodes in active mode. Thus

the energy consumption for nodes in active mode without transmission should be considered. This implies that the temporal distribution of the events will impact the balance of energy consumption of the network, which will further affect the node deployment strategy. In addition the existing works did not consider the impacts of spatial distribution of events on the amount of data generated by each node. But the data amount to be transmitted by the nodes also has impacts on whether the energy consumption for transmission can dominate the network's power usage. Thus this factor also influences the deployment method of the network. In consequence, to design the proper node deployment strategy for achieving balanced energy consumption, which can prolong the lifetime of the network, the spatial and temporal distribution of the events should be considered.

In this paper, the level of unbalanced energy consumption in the network is investigated in terms of the spatial and temporal distributions of the events. The non-uniform deployment strategy is proposed based on the estimated network life time. The main contributions of this paper are as follows. 1) The data transmission amount of the network is analysed in consideration of the spatial distribution of the events. 2) The lifetime estimation model is provided, taking both energy consumptions for active mode and transmitting/receiving modes into concern, based on the results of the network data transmission amount. 3) The non-uniform node deployment strategy is presented, leveraging the derived network estimation model.

The paper is organized as follows. In section 2 the network model will be presented. Based on the network model the mathematical model for data transmission amount will be proposed in section 3. Exploiting the result of the data transmission amount, the lifetime estimation method will be further provided in the next section. The non-uniform node deployment strategy will also be addressed in this section, leveraging the lifetime estimation. The evaluation of the proposed non-uniform deployment strategy will be presented in section 5. In section 6 the related works of this paper are discussed. The last section will conclude this paper.

## 2 Network Model

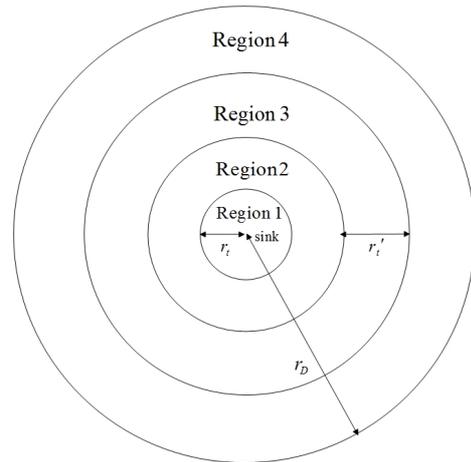
The desired sensing field is assumed to be a circle region with radius  $r_D$ , i.e. the area of the network is  $\pi r_D^2$ . The sink node is located at the centre of the network. Sensing nodes of the network are assumed to be homogenous with sensing range  $r_s$  and communication range  $r_t$ . That is to say each sensor can sense each event occurs within its sensing field, which is a circular region with the area of  $\pi r_s^2$ . A node can communicate with all the nodes in the circular region of  $\pi r_t^2$ . Within the distance of  $r_t$  from the sink node, nodes can communicate directly with the sink node. Out of this region

nodes transmit data to the sink node through multi-hop path. All sensing nodes originate and forward a unit of information of  $m$  bits, about any event they sense to the sink. Since this paper mainly focuses on the large scale sensor network, the radius of the network is assumed to be far larger than the transmission range ( $r_D \gg r_t$ ). The sink node is assumed to be a super node without energy constraints. In addition the transmission speed of a node is assumed to be a constant value  $\gamma$  bits/s.

Nodes in the network are assumed to be scheduled by a proper scheduling scheme, so that the density of active nodes can be maintained to be a constant value  $\lambda_n$  for a proper coverage degree (full coverage at least)[13], which can fulfil the application's coverage requirement. In this way, all nodes can work alternatively to conserve energy, which leads to the prolongation of the network lifetime.

The occurrences of events are regarded as two independent Poisson processes on spatial dimension and temporal dimension. Densities of these two processes are  $\lambda_s$  and  $\lambda_t$  respectively.

The network is divided into several circular regions with the same centre of the sink node. Except for the first region, the widths of all the other regions are the same with the value of  $r'_t$  ( $r'_t \leq r_t$ ), which can ensure the communication between two nodes in adjacent regions. The first region is composed of the nodes that can communicate with the sink directly. Hence it has the width of  $r_t$ . The network division model used in this paper is shown in Figure1. Since nodes in the inner-most region can communicate directly with the sink node, the width for this region is the transmission range  $r_t$ . The nodes in other regions need to transmit their information to the sink node through relay nodes in the next inner-circular region.



**Figure 1. The division of the network**

Each node has the same initial energy of  $e_{ini}$ . The energy

consumption model for radio transmission is assumed to be the first-order radio model as follows[15]

$$e_{tx} = e_{elec} + e_{amp}d^\beta \quad (1)$$

This model shows the energy consumption for transmitting one bit. The parameter  $e_{elec}$  is the energy consumed for activating the circuit of radio transceiver and the  $e_{amp}$  is for the transceiver amplifier to communicate.  $d$  is the distance for transmission. The energy for receiving one bit is just the energy consumed by the transceiver circuit. Thus we have

$$e_{recv} = e_{elec} \quad (2)$$

Energy consumed per unit time for a node in the active state is assumed to be a constant value  $e_{act}$ . The cost for a node in sleeping mode is neglected.

### 3 Data Transmission Amount

Nodes of the network need to transmit data through multiple-hop paths. In this scenario, nodes in the inner-region of the network need to relay packets, coming from all the nodes from the outer-regions. Thus in order to obtain the relationship between lifetime and node deployment density, the data amount transmitted by each region needs to be calculated at first. In this section the data transmission amount will be derived considering the coverage effects, the density of the active nodes and the density of events on spatial dimension.

#### 3.1 In-Region Data Origination Amount

Denote  $r'_d$  as the radius of the inner-boundary for certain region. The occurrences of events influencing only the nodes inside the region are in the area started from the circle having the radius  $r'_d + r_s$  with the width  $r'_t - r_s$ . The total number of packets that generated by the occurrences of events in this inner region,  $M_{in}$ , can be calculated as

$$M_{in} = \int_0^{r'_t - 2r_s} N_{in} \lambda_s 2\pi(r'_d + r_s + r'_s) dr'_s \quad (3)$$

where  $N_{in}$  is the number of nodes influenced, by the whole coverage area of the occurrence of a single event  $r'_s$  away from the circle with the radius  $r'_d + r_s$ . It can be derived as

$$N_{in} = \pi r_s^2 \lambda_n \quad (4)$$

For the convenience of the derivations in section 3.4, we define the function

$$M_{in}(r'_d, r, \alpha) = \int_0^\alpha N_{in} \lambda_s 2\pi(r'_d + r + r'_s) dr'_s \quad (5)$$

#### 3.2 Outer-influence

Considering the coverage effects, the occurrences of events out-side the outer-boundary of a region might cause the origination of information in this region. Clearly only the events in the region with the distance in the range  $(0, r_s)$  can influence the inner region. Thus the total number of packets that generated by this outer-influence effect can be calculated as

$$M_{oinf} = \int_0^{r'_s} N_{oinf} \lambda_s 2\pi(r_d + r'_s) dr'_s \quad (6)$$

where  $r_d$  is the radius of the outer-boundary of certain region. In the formula above the number of nodes that are influenced by a single event,  $N_{oinf}$  can be obtained as

$$N_{oinf} = \lambda_n A_{oinf} \quad (7)$$

where  $A_{oinf}$  is the area of the region influenced by the event. For the convenience of the derivations in section 3.4, the following function is defined

$$\Delta M_{oinf}(r_d, \alpha) = \int_0^\alpha (N_i - N_{oinf}) \lambda_s 2\pi(r_d + r'_s) dr'_s \quad (8)$$

#### 3.3 Inner-influence

Similar to the outer-influence effects, the occurrences of events in the inner-region of one region can also influence the data origination of the region. Suppose the radius of the outer-boundary of the inner-region of certain region is  $r_d$ . Events occurring in the area bounded by the two boundaries with radius  $r_d - r_s$  and  $r_d$  will have this effect. The total number of packets that generated by this effect can be calculated as

$$M_{iinf} = \int_0^{r_s} N_{iinf} \lambda_s 2\pi(r'_i + r'_s) dr'_s \quad (9)$$

where  $r'_i = r_d - r_s$  and  $N_{iinf}$  is the number of nodes that affected by one event, occurring  $r'_s$  away from the circle with the radius of  $r'_i$ .  $N_{iinf}$  can be derived as

$$N_{iinf} = \lambda_n A_{iinf} \quad (10)$$

where  $A_{iinf}$  is the area that the event covers the outside outer-region. For the convenience of the derivations in section 3.4, we define the two functions

$$M_{iinf}(r_d, r'_i, \alpha) = \int_0^\alpha N_{iinf} \lambda_s 2\pi(r'_i + r'_s) dr'_s \quad (11)$$

$$\Delta M_{iinf}(r_d, r'_i, \alpha) = \int_0^\alpha \Delta N \lambda_s 2\pi(r'_i + r'_s) dr'_s \quad (12)$$

where  $\Delta N = N_i - N_{iinf}$ .

### 3.4 Region Data Transmission Amount

The data amount that needs to be transmitted by each region can be calculated through the results presented in previous sections. Suppose there are totally  $G$  regions in the sensing field. Sensor nodes in region  $i$  need to transmit all the data generated by them and the data originated in its outer-regions. Thus the packets of the data include those generated solely inside the region formed by the inner-boundary of region  $i$  and the outer-boundary of region  $G$ . Besides except for the first region, the inner-influence of events in region  $i - 1$  also needs to be considered. Due to the inner-influence effect near the outer-boundary of region  $G$  and outer-influence effect close to inner-boundary of region  $i$ , the packets generated by the two effects need be excluded. Denote  $r'_{di}$  as the radius of the inner-boundary of region  $i$  and  $r_{di}$  as the radius of the outer-boundary of region  $i$ . The total number of packets that need to be transmitted by region  $i$  ( $1 < i \leq G$ ),  $M_i$ , is

$$M_i = m_{in} + m_{inif} + \Delta m_{inif} + \Delta m_{oinf} \quad (13)$$

where

$$m_{in} = M_{in}(r'_{di}, r_s, r_D - r_s) \quad (14)$$

and

$$m_{inif} = M_{inif}(r_{di-1}, r_{di-1} - r_s, r_s) \quad (15)$$

and

$$\Delta m_{inif} = \Delta M_{inif}(r_{dG}, r_{dG} - r_s, r_s) \quad (16)$$

and

$$\Delta m_{oinf} = \Delta M_{oinf}(r_{di-1}, r_s) \quad (17)$$

As region 1 does not have inner-region, the packets number for this region to transmit is

$$M_1 = m_{in1} + \Delta m_{inif} \quad (18)$$

where

$$m_{in1} = M_{in1}(0, 0, r_D - r_s) \quad (19)$$

The data amount for region  $i$  to transmit,  $D_i$ , is

$$D_i = M_i \cdot m \quad (20)$$

## 4 Deployment Strategy

Through the results of the data transmission amount for each region, obtained in the previous section, the network lifetime for each region can be estimated, based on the density of events on the temporal-dimension. In addition, through the estimation a measure can be defined to analyse the energy waste for uniform node distribution strategy. There are different definitions for the lifetime of sensor

network[13][14]. The network lifetime used in this paper is defined as the period of time, during which the network can keep certain density of sensor nodes required by the application. Exploiting the lifetime analysis the non-uniform node deployment strategy can be achieved.

### 4.1 Network Lifetime Estimation

If the density of the occurrences of events on the temporal dimension is  $\lambda_t$ , the average waiting time for the occurrences of events is  $1/\lambda_t$ . Except for the first waiting period, the duration  $1/\lambda_t$  can be divided into two durations, which are transmission duration and active duration, as shown in Figure2. Denote  $e_{w1}$  as the average energy consumption in

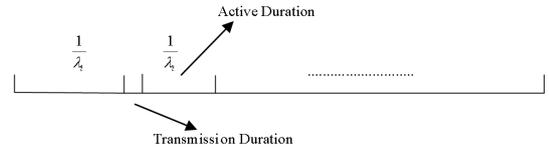


Figure 2. The Working Serious for Certain Region

the waiting period for the first occurrence of events. Also let  $e_{trans}$  and  $e_{active}$  be the energy consumptions for the transmitting duration and active duration respectively. The energy balancing equation for region  $j$  can be derived as follows

$$e_{all} = e_{w1} + k_j (e_{trans} + e_{active}) \quad (21)$$

$e_{w1}$  can be obtained as

$$e_{w1} = \frac{1}{\lambda_t} e_{act} A_j \lambda_n \quad (22)$$

where  $A_j$  is the area of region  $j$ . The derivation of  $e_{trans}$  is

$$e_{trans} = D_j \cdot e_{tx} + D_{j+1} e_{recv} \quad (23)$$

Also  $e_{active}$  can be calculated as

$$e_{active} = e_{act} A_j \lambda_n \left( \frac{1}{\lambda_t} - \frac{D_j + D_{j+1}}{\gamma A_j \lambda_n} \right) \quad (24)$$

Let  $\nu_j$  stand for the deployment node density for region  $j$ . The  $e_{all}$  can be obtained as

$$e_{all} = \nu_j A_j e_{ini} \quad (25)$$

Through (21) the parameter  $k_j$  can be resolved as

$$k_j = \frac{e_{all} - e_{w1}}{e_{trans} + e_{active}} \quad (26)$$

The estimated lifetime for the  $j_{th}$  region,  $T_j$ , can be derived as

$$T_j = (k_j + 1) \frac{1}{\lambda_t} \quad (27)$$

## 4.2 Lifetime Waste Ratio

In this section, lifetime waste ratio is defined to estimate the energy waste for the uniform node deployment strategy. For the uniform node deployment strategy, it is assumed that the node density is a constant value  $\nu$  for the whole network. In this situation the network lifetime is dominated by the first region. Also the region with the longest lifetime is the  $G_{th}$  region. Hence the lifetime waste ratio can be defined as follows

$$\Psi = \frac{T_G - T_1}{T_G} \quad (28)$$

Exploiting (27) it can be further derived as

$$\Psi = \frac{k_G - k_1}{k_G + 1} \quad (29)$$

## 4.3 Node Deployment Density

Through the analysis in previous sections, the non-uniform node deployment strategy can be designed, according to the lifetime requirement for the application. Each region can then be deployed according to the estimated node density. Given certain lifetime requirement  $T_{req}$ , the network density for each region can be calculated through the lifetime estimation. For fulfilling the lifetime requirement of  $T_{req}$ , the node deployment density for region  $j$  can be derived as

$$\nu_j = \frac{(T_{req}\lambda_t - 1)\xi + e_{w1}}{A_j e_{ini}} \quad (30)$$

where  $\xi$  is

$$\xi = e_{trans} + e_{active} \quad (31)$$

## 5 Performance Evaluation

In this section the non-uniform node deployment strategy, provided in this paper, will be evaluated through network simulations. The simulations are performed by the java based network simulator J-SIM[20][21][22]. For issuing the experiments, it is extended to support node deployment and simulation time evaluation. In the experiments each node selects the neighbouring node with the largest residual energy in the next inner-region as the data relay node[5].

### 5.1 Parameter Settings

The parameter settings for the experiments are listed in Table1. The sensor hardware parameters, such as energy consumption parameters, transmission speed parameters and transmission range parameters are selected similar

to the Motes[23][24]. Region width is set to be 30 meters to ensure that each node can find rely nodes in the next inner-region.

**Table 1. Parameter Settings**

Parameter Name	Value
$e_{ini}$	$2J$
$e_{act}$	$1.25 \times 10^{-5} J/s$
$e_{elec}$	$5.0 \times 10^{-11} J/s$
$e_{amp}$	$1.0 \times 10^{-11} J/s$
$\beta$	2
$\gamma$	250k
$r_D$	300m
$r_t$	40m
$r'_t$	30m
$m$	640bits

### 5.2 Performance

For the evaluation of the performance of the non-uniform deployment strategy, proposed in this paper, two ratios are used. The first ratio is the lifetime waste ratio, defined in section 4.2, which indicates the degree of unbalancing for energy usage in the network. Although this measure is previously presented for the circumstance of uniform deployment, it can also be used for evaluating the simulation results for non-uniform deployment strategy.

The second measurement, lifetime expectation ratio, is defined as

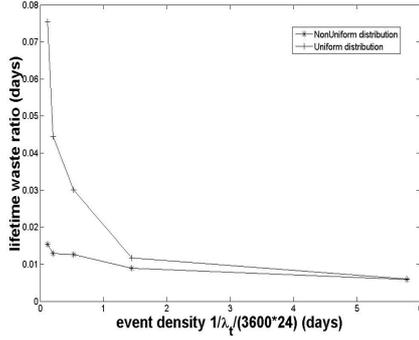
$$\omega = \frac{T_{sim}}{T_{req}} \quad (32)$$

where  $T_{sim}$  is the simulation result for the network lifetime.

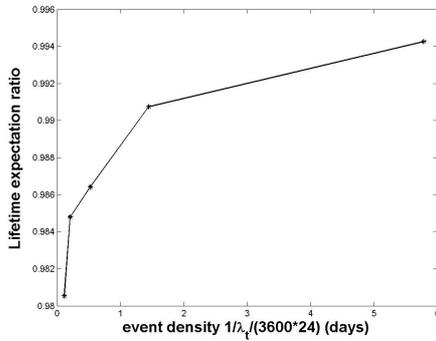
In Figure3 the simulation results for lifetime waste ratio of the network with non-uniform deployment and uniform deployment, in terms of temporal density of events are shown. Through the results, it is clear that using non-uniform deployment strategy presented in this paper, the energy consumption of the network is greatly balanced. Figure4 shows the lifetime expectation ratio for the same simulation. The results also prove that the non-uniform deployment strategy in this paper can achieve good performance. In Figure5 the results for lifetime waste ratio according to spatial density of the events are shown. Figure6 gives the results of lifetime expectation ratio for the same simulation. These results further prove the feasibility of the non-uniform deployment strategy provided in this paper.

## 6 Related Works

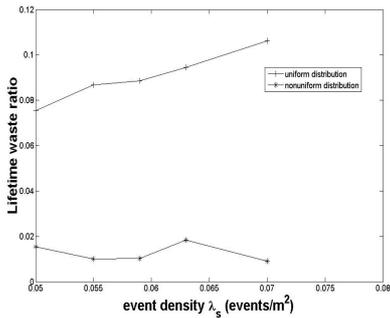
The energy hole problem was considered in [15], [1], [5], [14], [16], [17], [18] and [19]. In [1] energy hole prob-



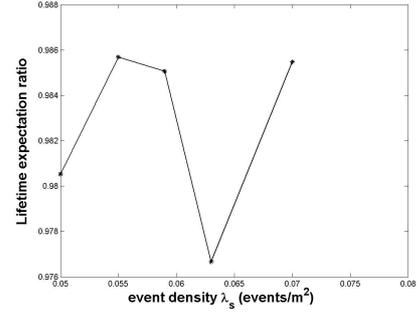
**Figure 3.** Simulation result for the lifetime waste ratio for uniform and non-uniform deployment strategy, in terms of  $\lambda_t$ , under the conditions of  $\lambda_n = 0.02$ ,  $\lambda_s = 0.05$  and  $T_{req} = 19days$



**Figure 4.** Simulation result for lifetime expectation ratio of non-uniform deployment strategy, in terms of  $\lambda_t$ , under the conditions of  $\lambda_n = 0.02$ ,  $\lambda_s = 0.05$  and  $T_{req} = 19days$



**Figure 5.** Simulation result for the lifetime waste ratio for uniform and non-uniform deployment strategy, in terms of  $\lambda_s$ , under the conditions of  $\lambda_n = 0.02$ ,  $\lambda_t = 0.0001$  and  $T_{req} = 19days$



**Figure 6.** Simulation result for lifetime expectation ratio of non-uniform deployment strategy, in terms of  $\lambda_s$ , under the conditions of  $\lambda_n = 0.02$ ,  $\lambda_t = 0.0001$  and  $T_{req} = 19days$

lem was analysed through a mathematical model and the effectiveness of different schemes for mitigating this problem was investigated. A non-uniform deployment strategy by associating the number of nodes with the distance from the sink node was proposed in [17]. The result of [5] proved that if all nodes need to transmit data periodically, the ideally balanced energy consumption cannot be obtained. The authors of [18] turned to the solution of non-uniform energy distribution strategy first. Then in [14] the non-uniform node deployment strategy is presented with the consideration of scheduling scheme. In their papers the effects of different positions for sink node was considered. The non-uniform node deployment strategy for motion object detection system was investigated in [15]. And a Gaussian distribution scheme for deploying the nodes was considered in [16]. The authors of [16] analysed the system coverage and lifetime in terms of different parameters for Gaussian distribution. In [19] an autonomous deployment algorithm was proposed for networks composed of mobile sensors.

As far as we know, no work has considered the energy consumption for nodes in active mode, without transmitting and receiving. Still no work has investigated the effects of spatial density of events on the node deployment strategy. Although [15] considered the impact of temporal density of the motion object events, it is based on the scenario different from this paper. In this paper the impact of spatial and temporal density for events on the node deployment strategy have been rigorously analysed.

## 7 Conclusion

In this article, the energy hole problem of sensor networks is investigated in consideration of energy consumptions for nodes without transmitting and receiving, in terms of spatial and temporal density of the events. The analytical

models for estimating the lifetime and the degree of the unbalanced energy consumption level are given. Based on the estimation of the network lifetime, the non-uniform node deployment strategy is proposed. Simulation results prove that the presented non-uniform node deployment strategy is feasible.

The results indicate that the spatial and temporal distributions of events greatly influence the strategy of the node deployment, for balancing the energy consumption of the network. The paper also shows that the energy consumption for nodes in active mode without transmitting or receiving should be considered when designing the network node deployment.

As the balance of energy usage for region-to-region routing is also crucial for the prolongation of the network, this issue will be investigated rigorously in our future work.

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