Dual-Beacon Mobile-Node Discovery in Sparse Wireless Sensor Networks

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***Abstract* – In sparse wireless sensor networks data collection is typically accomplished through specialized mobile nodes. One of the main challenges to be faced in this kind of networks is the energy-efficient and timely discovery of mobile nodes. In this paper we propose a simple yet effective discovery protocol based on two different Beacon messages emitted by the mobile node (i.e., Long-Range Beacons and Short-Range Beacons). Our simulation results show that, although very simple, the proposed scheme can provide a significant energy reduction with respect to the commonly used scheme based on a single Beacon, especially if the discovery phase is long.**

Keywords: Wireless Sensor Networks, Sparse Sensor Networks, Mobile Node Discovery, Energy Efficiency.

I. INTRODUCTION

A wireless sensor network (WSN) typically consists of a large number of sensor nodes densely deployed over a geographical area. Sensor nodes are small devices capable of sensing data from the surrounding environment, process them locally, and/or transfer them to a data collection point – usually referred to as *sink node* – through multi-hop communication. However, many real-life monitoring applications do not require a fine-grained sensing and, thus, a sparse network can be used. In a sparse WSN the distance between neighboring nodes is (much) larger than the transmission range of each sensor node and, thus, multi-hop communication is unfeasible. Data collection in sparse WSNs is accomplished through Mobile Elements (MEs), i.e., special mobile nodes that visit sensor nodes regularly, collect data and transport them to the sink node. Depending on the application scenario, MEs can be either part of the external environment (e.g., cars, buses, persons, animals), or part of the networking infrastructure (e.g., mobile robots). Also, MEs can have different mobility patterns, ranging from deterministic to completely random mobility [1,2].

A detailed description of opportunities provided by sparse WSNs with MEs and challenges to be faced is reported in [2]. One of the main challenges is the timely and energy-efficient ME discovery. Unless the ME's mobility pattern is deterministic, arrival times at sensor nodes are not known in advance. Hence, sensor nodes have to discover the presence of the ME in the area before starting exchanging data with it. Ideally, each sensor node should be able to discover the ME *all times* it visits the sensor node so as to reduce the delay in data delivery, and avoid possible packet losses at the local buffer. In addition, the ME discovery should be *timely*, so as to exploit as much as possible the short time available for data exchange. In practice, the discovery process is made difficult by sensor nodes' energy constraints. Due to their limited energy resources, sensor nodes cannot be always active and, usually, operate on a duty cycle.

Typically, *periodic listening* is used for ME discovery, i.e., the ME regularly sends Beacon messages to announce its presence in the area while sensor nodes wake up periodically, and for a short time, to check for possible advertisements from the ME. To ensure the timely discovery of (almost) all contacts the Beacon period and the sensor node's *duty cycle* (i.e. the fraction of time during which the sensor node is active with respect to the total time) have to be properly defined. Specifically, a low duty cycle (i.e., a long inactivity period) reduces the energy consumption at the sensor node – thus increasing its lifetime – but, at the same time, decreases the capability of detecting contacts. In general, using a fixed inactivity period usually results in a very inefficient scheme, especially when the total amount of time spent in the discovery state is large. Adaptive schemes that dynamically adjusts the inactivity period of the sensor node, depending on the estimated probability that the ME is nearby, have been thus proposed [3,4]. However, since the inactivity period is changed at the end of a predefined time slot, even using an adaptive scheme it may happen that the duty cycle is high but the ME is not nearby. Thus, a large amount of energy is wasted, especially if the time slot is large (for instance, it is 1 hour in [3] and 100s in [4]).

In this paper we propose a simple yet effective hierarchical approach that leverages two different Beacon messages, namely a *Long-Range Beacon* (*LR-Beacon*) and a *Short-Range Beacon* (*SR-Beacon*), that are transmitted by the ME with different transmission ranges. LR-Beacons announce the presence of the ME in the area, while SR-Beacons inform the sensor node that the data exchange can actually take place. Sensor nodes can thus use a very low duty cycle for most of the time and increase it only upon receiving an LR-Beacon. The proposed *Dual Beacon Discovery (2BD)* protocol can be used either as a stand-alone solution or in combination with an adaptive discovery scheme (e.g., [4]), to further improve its energy efficiency. Unlike other hierarchical discovery schemes proposed in the literature [5,6,7,8,9], our 2BD protocol does not require multiple radio technologies. Thus, it can be implemented on any sensor platform.

We have evaluated the 2BD protocol, by simulation, in a sparse WSN scenario. The obtained results show that 2BD can provide significant energy savings, with respect to the traditional approach based on a single Beacon, even when the discovery phase is short (e.g., 15s).

The rest of the paper is organized as follows. Section II discusses the related work. Section III introduces the system model we refer to. Section IV describes the 2BD protocol. Section V outlines the simulation setup, while Section VI presents the simulation results. Finally, Section VII concludes the paper.

II. RELATED WORK

A classification and detailed description of possible approaches to ME discovery is reported in [2]. The most common approach is based on *periodic listening*, i.e., the ME regularly sends Beacon messages to announce its presence while sensor nodes wake up periodically to check for possible advertisements from ME. One of the first algorithms for ME discovery is presented in [10]. It is based on a fixed duty cycle, i.e., the inactivity period of static nodes is constant over time. A fixed duty cycle is also used in [1,11,12,13]. This approach is quite simple but inefficient, especially when sensor nodes spend a long time in the discovery state.

Adaptive solutions that dynamically adjust the sensor node's duty cycle, depending on the estimated probability that the ME is nearby, have been also proposed [3,4]. In [3] time is divided in hours and, for each hour, the probability to come in contact with a mobile node is estimated, based on the past history, using a reinforcement learning approach. The duty cycle is then adjusted from hour to hour, depending on the estimated contact probability. A similar approach is exploited in [4] where, however, time is divided into time slots of shorter duration (i.e., 100s) and a more complex approach, based on Q-learning, is used to estimate the contact probability. In both the previous solutions, when the estimated contact probability is high, the duty cycle remains at a high value for the whole duration of a time slot, even if the ME is not nearby, thus consuming more energy than necessary. The 2BD scheme proposed here can be combined with the adaptive scheme in [4] to further increase its energy efficiency.

Hierarchical discovery schemes have been previously proposed in [7] and [9]. Both papers address the problem of device discovery in mobile opportunistic networks and consider handheld devices equipped with two or more radios having different transmission range, bit rate, and energy consumption (e.g., a Mote radio and a WiFi interface). In [7] the lower-level radio channel is used to discover, appropriately configure, and activate the higher-level radio subsystem when a connection with a nearby device is desired. Data exchange only occurs through the higher-level radio. For instance, a mobile device can receive the WiFi configuration parameters from a nearby WiFi Access Point through the Mote radio. This information is then used to activate and configure the WiFi interface on the mobile device. In [9] mobile nodes use the low-power radio for peer discovery and the high-power radio for data exchange. While these proposals have some similarities with our 2BD scheme, nevertheless there some important differences. First, we address a different scenario (sensor networks instead of opportunistic networks of handheld devices). In addition, our proposal does not require multiple radio technologies, which are typically not available in current sensor platforms. Finally, 2BD uses long-range communication for discovery and short-range communication for data exchange, while the previous proposals take the opposite approach.

Hierarchical discovery in sensor networks (possibly with mobile nodes) is addressed in [8], where the *network interrupt* approach is proposed. The latter relies on two different radios, i.e., a primary high-power radio – usually in sleep mode – and a control low-power radio which is always powered on. A node can activate the primary radio of a another nearby node at any time, just sending a beacon over the low-power radio. *Sparse Topology and Energy Management* (STEM) [5] and *Pipelined Tone Wakeup* (PTW) [6] also use two different radio channels for wakeup signals and data packet transmissions, respectively. Unlike the previous solutions, our proposal uses a single radio for both discovery and data exchange and can, thus, be implemented on all currently available sensor platforms.

III. SYSTEM MODEL

We consider a single ME and assume that the network is sparse so that, at any time, the ME can communicate with, at most, one sensor node. The communication can take place only during a *contact*, i.e., when the sensor node and the ME are in the transmission range of each other. Obviously, the contact time depends on the path followed by the ME and its speed. We assume that ME's arrival times cannot be predicted by the sensor node. Therefore, the sensor node must perform a discovery phase for the timely detection of the ME. Upon detecting the ME, the sensor node can switch from the discovery state to the communication state and start exchanging data with it. Since the discovery phase takes some time, the actual time available for data communication is (significantly) shorter than the nominal contact time. Throughout this time interval will referred as the *residual contact time.* After the end of the data transfer phase the sensor node can switch to the discovery state again in order to detect the next contact. However, if some (even partial) information about ME mobility are available, the sensor node can exploit these information and go to sleep for some time, thus saving energy.

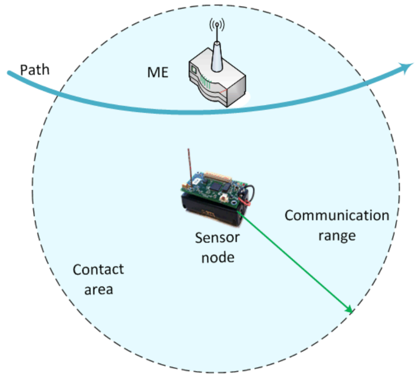

Figure 1. Reference scenario

IV. 2-BEACON DISCOVERY PROTOCOL

Before introducing the 2BD protocol, it may be worthwhile describing briefly the discovery protocol based on a single Beacon that is commonly used in WSN with MEs. As shown in Figure 2, to announce its presence in the area the ME emits Beacon messages of fixed duration T_{BD} at regular time intervals T_{BI}. On the other side, the sensor node operates on a duty cycle and wakes up periodically to listen for possible Beacons. Upon receiving a Beacon it realizes that the ME is within the contact area and the data transfer phase can thus take place. To allow a correct behavior, the sensor node's active period T_{ON} must be sufficiently long to ensure the complete reception of a Beacon message, i..e, the following relationship must hold: $T_{ON} \geq T_{BI} + T_{BD}$.

In this discovery protocol both the active and inactive periods are fixed and, consequently, the duty cycle used in the discovery phase – defined as $\delta = T_{ON} / (T_{ON} + T_{OFF})$ – is fixed as well. To allow a better energy efficiency, however, the inactivity period (and, hence, the duty cycle) should be adjusted dynamically during the discovery phase, depending on the probability that the ME is close to the contact area. To implement this strategy in a real environment, the 2BD protocol takes a simple hierarchical approach based on two different duty-cycle values[1]. The sensor node typically operates with a *low duty cycle* δ_L to save energy, and switches to a *high duty cycle* δ_H only when the ME is supposed to be close to the contact area. Information about the ME's location are made available to sensor nodes by the ME itself through two different Beacon messages, namely *Short-Range Beacons* (SR-Beacons) and *Long-Range Beacons* (LR-Beacons).

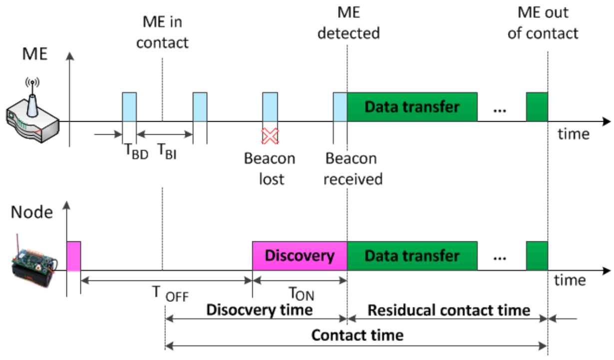

Figure 2. Traditional discovery protocol.

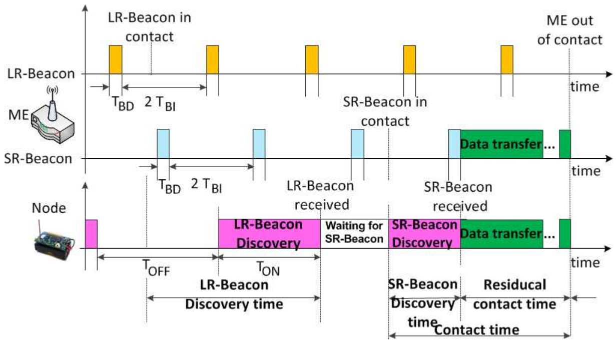

Figure 3. 2BD discovery protocol.

SR-Beacons and LR-Beacons are periodically emitted by the ME in an interleaved way as shown in Figure 3. For both, the emission period is equal to $2 \cdot T_{BI}$ so that the overall Beacon period is still T_{BI}, like in the traditional approach. However, the two Beacon types are associated with different transmission ranges and, thus, convey different information. SR-Beacons are transmitted with the same transmission-power level used during the communication phase and, thus, they experience a transmission range *r*, throughout referred to as *communication range*. Therefore, they are aimed at informing the sensor node that the ME is within the contact area and communication can, thus, take place. Instead, LR-Beacons are sent with more transmission power and, hence, they have a transmission range *R* larger than the communication range *r*. Throughout *R* will be referred to as the *discovery range*.

During the discovery phase a sensor node operates with a duty cycle δ_L and wakes up periodically for possible Beacons from the ME. Upon receiving an LR-Beacon the sensor nodes increases the duty cycle to δ_H and waits for an SR-Beacon. As soon as an SR-Beacon is received – irrespective of the current duty cycle – the sensor node

[1] In principle, the protocol could be extended easily to the case of multiple duty-cycle values.

switches to 100% duty cycle and starts the communication phase. To avoid energy wastes, after receiving an LR-Beacon the duty cycle is reset to the low value δ_L if a subsequent SR-Beacon is not received within a pre-defined timeout.

V. SIMULATION SETUP

To evaluate the performance of the 2BD protocol, and compare it with the traditional discovery protocol based on fixed duty cycle, we implemented an *ad hoc* event-driven simulator. We considered the sparse scenario depicted in Figure 1 with one sensor node and a single ME. For the sake of simplicity, and without losing in generality, we assumed that the ME moves with a constant speed along a straight line at a fixed distance *D* from the sensor node. Under these hypothesis, the duration of the (nominal) contact time only depends on the ME's speed.

To evaluate the performance of the two considered discovery protocols we measured the following indexes.

- *Contact Miss Ratio*, defined as the fraction of potential contacts that are *not* detected by the sensor node.
- *Residual Contact Ratio*, defined as the ratio between the average residual contact time and the nominal contact time.
- *Energy per Contact*, defined as the average energy consumed by the sensor node per detected contact.

The Energy per contact is derived as the ratio between the total energy consumed by the sensor node in the discovery state and the number of detected contacts. With the single-Beacon protocol, the total energy consumption is given by $E_1 = T_{disc} \cdot \delta \cdot P_{rx}$, where T_{disc} is the total time spent by the sensor node in the discovery state, δ is the duty cycle used for discovery, and P_{rx} the power consumption in receive mode. Similarly, when using the 2BD protocol the energy consumption can be expressed as $E_2 = (T_{LR} \cdot \delta_L + T_{SR} \cdot \delta_H) \cdot P_{rx}$, where T_{LR} (T_{SR}) is the total time spent waiting for an LR-Beacon (SR-Beacon) and, thus, using the low (high) duty cycle δ_L (δ_H). Finally, to measure energy savings provided by 2BD, with respect to the single-Beacon approach, we also considered the following index

$$S = \frac{E_1 - E_2}{E_1}$$

The Contact Miss Ratio and Residual Contact Ratio measure the performance of the discovery protocol, while the Energy per Contact indicates its energy efficiency. Ideally, we would like to detects all contact (i.e., the Contact Miss Ratio should be zero) – with an acceptable Residual Contact Ratio to transfer all data available at the sensor node to the ME – with the minimum energy expenditure. In practice, depending on the specific application, we can tolerate missing a limited number of contacts. The acceptable Residual Contact Ratio depends on several factors, e.g., data acquisition rate, average inter-contact time, quality of communication channel, etc. In the following we will assume that our case-study application requires the discovery of at least 90% of contacts (i.e., Contact Miss Ratio < 10%) with a Residual Contact Ratio larger than 40%.

TABLE 1. SIMULATION PARAMETERS.

Parameter	Value
Beacon period (T_{BI})	100 ms
Beacon duration (T_{BD})	10 ms
ME Speed	40 Km/h
Distance from the sensor node	15 m
Discovery range (*R*)	{100m, 200m}
Communication range (*r*)	50 m
Nominal contact time	8.6 s
High duty cycle δ_H	3%
Transmission power (P_{tx}) at 0 dBm	52.2 mW
Reception power (P_{rx})	56.4 mW

Unless differently specified, in our experiments we used the parameter values shown in Table 1. Transmission and reception power consumptions are those of the ChipCon CC2420 transceiver [14], assuming a supply voltage of 3 Volts. We assumed that the communication range of both the sensor node and the ME is constant and equal to 50m. However, to evaluate the impact of the communication range on the perfomance of the 2BD protocol we considered additional values for *r* (i.e., 25m and 75m) [2]. We also assumed that the ME can vary dynamically its transmission-power level so as to transmit SR-Beacons and LR-Beacons with transmisison ranges *r* and *R*, respectively. Finally, the channel quality is modelled through the well known disk model, i.e., packet loss is assumed to be 0% when the sensor-ME distance is lower than the transmission range, and 100% otherwise. To derive confidence intervals we used the replication method with 90% confidence level. In all experiments we performed 10 replicas, each consisting of at least 10,000 ME passages (i.e., potential contacts).

VI. SIMULATION RESULTS

To compare the perfomance of 2BD with that of the single-Beacon protocol we performed experiments under different operating conditions. For each experiment we first determined the minimum duty cycle that must be used with the single-Beacon approach to meet the application requirements (i.e., Contact Miss Ratio <10% and Residual Contact Ratio > 40%). Then, we investigated how much

[2] All these value are consistent with the transmission and reception power consumptions indicated in Table 1. Please consider that, for a given transmission power, the communication range can be different depending on environmental conditions.

gain can be achieved, in terms of energy efficiency and/or performance, using 2BD instead of the single-Beacon protocol.

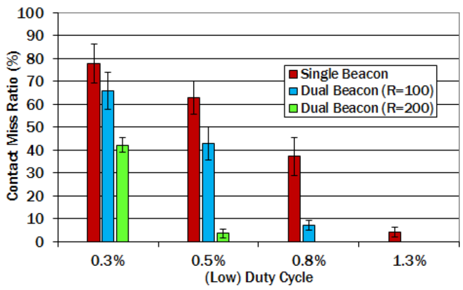

Figure 4. Contact Miss Ratio (r=50m).

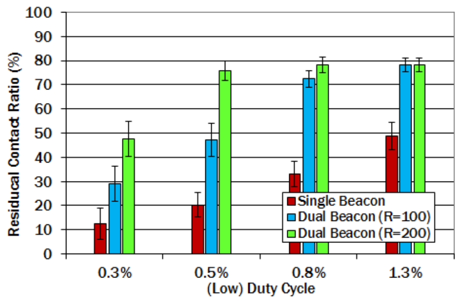

Figure 5. Residual Contact Ratio (r=50m).

A. Impact of the Discovery Range

Figure 4 and Figure 5 show the Contact Miss Ratio and Residual Contact Ratio as functions of the duty cycle used by the sensor node. For the 2BD protocol the duty cycle shown on the x-axis is the low duty cycle δ_L (the high duty cycle is always set to 3%). In this specific scenario, where the communication range r is equal to 50m, a duty cycle of, at least, 1.3% is needed to meet the application requirements when using the single-Beacon protocol. Instead, with 2BD the same requirements can be satisfied with a low duty cycle δ_L equal to 0.8% if R=100m, and 0.5% if R=200m.

From the results in Figure 4 it is not yet clear whether or not this also results in a better energy efficiency as, with 2BD the low-duty-cycle phase is followed by a high-duty-cycle phase. To make the comparison fair we need to compare the total energy consumed by the two protocols in the overall discovery phase. Such a comparison is shown in Figure 6 which shows the average total energy consumed, per detected contact, as a function of the *waiting time*, i.e., the time interval from when the sensor node enters the discovery state to when the ME enters the communication range of the sensor node. It may be worthwhile recalling here that the communication range r is assumed equal for both protocols and, thus, the waiting time is equal for both protocols.

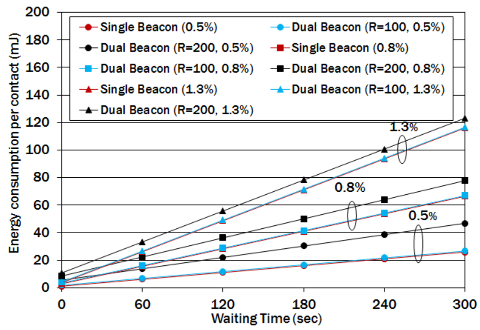

Figure 6. Average energy consumption per contact.

As expected, the energy per contact increases with the waiting time. In addition, for a given waiting time, the energy per contact consumed by 2BD is slightly larger than that consumed by the single-Beacon protocol using a duty cyle $\delta = \delta_L$. This is due to the additional energy consumed during the high-duty-cycle phase, i.e., while waiting for an SR-Beacon. However, since this phase is typically much shorter than the overall discovery phase, and 2BD is able to satisfy the application requirements with a low duty cycle δ_L significantly smaller than δ, the results in Figure 6 clearly show that 2BD can provide relevant energy savings with respect to the single-Beacon approach. For reader's convenience, we summarized in Table 2 the relative energy savings S provided by 2BD for different waiting times. As expected, energy savings become more and more relevant as the waiting time increases. However, even for short waiting times (e.g., 15s) the energy reduction provided by 2BD is more than 20%. Finally, it may be worthwhile emphasizing that 2BD not only reduces the energy consumption but also provides a better performance in terms of Residual Contact Ratio, as highlighted in Figure 5.

TABLE 2. ENERGY SAVINGS WITH DUAL BEACON (R=50M).

Waiting Time (s)	**R=100m δ_L=0.8%**	**R=200m δ_L=0.5%**
15	22.2%	22.2%
30	33.3%	33.3%
60	38.5%	46.2%
120	40.8%	55.1%
180	42.2%	57.7%
240	42.6%	58.5%
300	43.1%	59.5%

B. Impact of the Communication Range

In the previous section we have assumed that the communication range is 50m and, correspondingly, the nominal contact time is 8.6s. In this section we investigate if, and how much. the communication range (i.e., contact time) can impact on the performance of 2BD. To this end, we considered two additional values for r, i.e., r=25m and r=75m (the corresponding contact times are 3.6s and 13.2s, respectively).

When the communication range is small, i.e., r=25m, the contact time is short (3.6s) and, thus, the probability to miss contacts is high, especially if the sensor node's duty cycle is low. We found that, with the single-Beacon approach, the minimum duty cycle that allows detecting at least 90% of contacts (with a Residual Contact Ratio > 40%) is 3%. Instead, with 2BD the same requirements can be satisfied with δ_L =2% if R=100m, or δ_L =1% if R=200m (the high duty cycle is always set to 3%). Energy savings provided by 2BD, with respect to the single-Beacon approach, for different waiting time are shown in Table 3**.** The trend is very similar to the one observed in the previous scenario (i.e., when r=50m).

TABLE 3. ENERGY SAVINGS WITH DUAL BEACON (R=25M).

Waiting Time (s)	**R=100m δ_L=2%**	**R=200m δ_L=1%**
15	21.0%	26.3%
30	26.7%	40.0%
60	29.6%	51.9%
120	31.7%	58.4%
180	32.4%	60.8%
240	32.8%	62.6 %
300	33.1%	63.2%

When the communication range is 75m the nominal contact time is long enough (13.2 s) to allow the detection of almost all contacts even with a low duty cycle. We found that, with the single-Beacon approach the application requirements can be satisfied with a 0.9% duty cycle. However, even in this less-critical scenario 2BD is able to provide a significant improvement in terms of energy efficiency as the same application requirements can be met with δ_L =0.7% if R=100m, and δ_L =0.5% if R=200m. The resulting energy savings, for different waiting times, are shown in Table 4. Since the scenario is now less critical, energy savings achieved by 2BD are, generally, smaller than in previous scenarios.

VII. CONCLUSIONS

In this paper we have addressed the problem of mobile node discovery in sparse sensor networks with Mobile Elements (MEs). We have shown that the energy efficiency of ME discovery can be significantly improved using an hierarchical approach based on two different Beacons emitted by the ME with different transmission ranges. We have analyzed the performance of the 2BD protocol, by simulation, in a sparse network. The obtained results show that the proposed approach can provide a significant energy reduction with respect to the traditional single-Beacon approach. Even when the time spent in discovery state is short (e.g., 30s), 2BD can provide an energy saving up to 40%.

TABLE 4. ENERGY SAVINGS WITH DUAL BEACON (R=75M).

Waiting Time (s)	**R=100m δ_L=0.7%**	**R=200m δ_L=0.5%**
15	14.3%	0.1%
30	20.0%	10.0%
60	26.3%	26.3%
120	26.5%	35.3%
180	28.0%	38.0%
240	30.3%	39.4%
300	30.9 %	40.7%

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