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CONTINUOUS NEIGHBOUR DISCOVERY WITH EFFICIENT ASYNCHRONOUS WAKE-UP SCHEDULES IN WIRELESS SENSOR NETWORKS

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ABSTRACT

Due to low duty cycles requirement in many real world sensor applications, it is essential to design a protocol for continuous neighbour discovery with efficient asynchronous wake-up schedules. The existing BBID-based approaches have certain limitations. For instance, they lack blocks for certain duty cycles. To overcome this problem, in this paper we proposed a Neighbour Discovery Protocol (NDP) that leverages the efficiency in asynchronous wake-up schedules in Wireless Sensor Networks. A scheme named Flexible, Balanced and Energy Efficient Asynchronous Neighbour Discovery (FBE-ND) is proposed to improve performance of block based NDP. It ensures availability of blocks for all possible duty cycles and see that the sensor application works as desired. Towards this end, the BBDC generates discovery schedules for a wide range of duty cycles. First we introduce a simple version of the protocol that leads to better performance in terms of energy efficiency and latency. Then the protocol is revised further using adjustable occupancy rate of channel for further improvement. Our protocol is evaluated with a simulation study. The results revealed that the protocol outperforms existing NDPs such as Todis, Hedis, SearchLight, U-Connect and Disco. The protocol is useful for many sensor applications where low duty cycles are preferred in asynchronous WSN.

Keywords: *Continuous Neighbour Discovery, Wireless Sensor Network (WSN), Low Duty Cycles, Generation Of Discovery Schedules.*

1. INTRODUCTION

Wireless Sensor Networks (WSNs) have received tremendous attention as their usage became ubiquitous. They are widely used in diversified fields to have sensing, data aggregation and data communications. The devices in WSN relay on battery power sources that are limited in nature. Therefore, extensive studies are made on energy efficient approaches. Out of such studies, neighbour discovery is a fundamental problem in different kinds of wireless networks [2] since it is associated with access and communication. In such networks, discovery of neighbouring nodes is a prerequisite for connectivity and meaningful communication among nodes. A node can participate with other nodes in communication only after initial discovery. Discovering of nodes that are resource constrained without prior knowledge about position and power usage is what makes the process difficult. The aim of research related to neighbour discovery is to minimize discovery latency that is nothing but the time needed to contact neighbour nodes. As part of power saving approaches, nodes move to sleep mode as and when possible. In the sleep mode, a node cannot listen other nodes and also cannot transmit data to other nodes. When a node is active (not in sleep mode), it is capable of listening and transmitting data. The power consumption is negligible when node is in sleep mode when compared with that of active mode. There is relation between the active time of a node and its power consumption. Therefore, the usage of power by certain node is found by the fraction of time consumed in active stage over the total amount of time. Often it is specified as percentage of time spend by a node in active state and it is called as duty cycle. Therefore, there is coherent relation between efficient neighbour discovery, discovery latency and duty cycle.

In most of the research pertaining to ND, average discovery latency and worst-cast discovery latency are used to evaluate performance of discovery models. Therefore, it is desirable to have low

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average latency or minimum discovery latency besides low duty cycle. There is trade-off between discovery latency and duty cycle as low duty cycle causes high discovery latency and the opposite is true as well. As far as energy efficiency in WSN is concerned, energy aspect is taken care of by duty cycles while discovery latency is attributed to efficiency. There is need for balancing the two aspects to have improved energy efficiency. We believe that continuous neighbour discovery with efficient asynchronous wake-up schedules in wireless sensor networks with generation of discovery schedules plays key role in solving the problem. The existing literature has many related approaches. Discovery schedules are discussed in [2] while proactive wakeup approach is used in [5]. Asynchronous neighbour discovery is investigated in [2], [8], [16] and [23]. The neighbour discovery in the context of duty cycles is investigated in [2], [9], [16] and [22]. Particularly energy efficient neighbour discovery approaches are explored in [4], [5], [8], [12], [19], [23], [27] and [30]. From the literature, it is understood that the existing BBID-based approaches have certain limitations. For instance, they lack blocks for certain duty cycles. Therefore, it is essential to ensure generation of discovery schedules to overcome the problem. The purpose of the scheme proposed in this paper is to leverage the efficiency in asynchronous wake-up schedules in Wireless Sensor Networks. In this paper, first we introduce a simple version of the protocol that leads to better performance in terms of energy efficiency and latency. Then the protocol is revised further using adjustable occupancy rate of channel for further improvement.

Our contributions are as follows.

1. We proposed a Neighbour Discovery Protocol (NDP) that leverages the efficiency in asynchronous wake-up schedules in Wireless Sensor Networks.
2. We proposed a scheme named Flexible, Balanced and Energy Efficient Asynchronous Neighbour Discovery (FBE-ND) to improve performance of continuous neighbour discovery. It ensures availability of blocks for all possible duty cycles and see that the sensor application works as desired.
3. Simulation study is made with NS-2 for evaluating the proposed protocol and underlying scheme.

The remainder of the paper is structured as follows. Section 2 reviews literature on NDP protocols that focused on the asynchronous wake-up schedules in Wireless Sensor Networks. Section 3 presents the proposed protocol and the underlying scheme. Section 4 presents experimental results. Section 5 concludes the paper and gives directions for future work.

2. RELATED WORK

Neighbour discovery research has witnessed wide usage of duty cycles and the usage of wakeup radio for energy efficiency. Pegatoquet *et al.* [1] proposed a wakeup radio based protocol for wireless network to improve energy efficiency with neighbour discovery improvement. Chen *et al.* [2] explored different models and schedules for asynchronous ND on duty-cycled networks. Zhu *et al.* [3] proposed a rapid ND protocol known as Pharos for power constrained WSNs. Suarez and Nayak [4] studied on the concept of talking half and listening half for reducing power consumption in wireless networks. Chen *et al.* [5] on the other hand focused on proactive wakeup approach to ND in mobile sensor networks. Zhang *et al.* [6] investigated on slot-length control in order to reduce latency for ND. Mir and Ko [7] focused on self-adaptive ND approach by using the concept of sectored antennas. Chen *et al.* [8] proposed different protocol variants known as Q-Connect to have energy efficient ND in mobile sensor networks. Chen *et al.* [9] discussed about heterogeneous duty cycles in WSN for efficient ND. Carrillo and Mendez [10] studied different discovery models along with an enhanced multimodal switching mechanism. Similar kind of work is carried out in [14] and [24].

Jin *et al.* [11] explored on the quantum scale operation method for ND. Khan *et al.* [12] and Sareereh *et al.* [13] defined approaches for energy efficiency in WSN and the usage of novel ND methods. Wei *et al.* [15] introduced a Probabilistic Neighborship Model (PNM) for ND in IoT environment. Wakeup radio and its related works are discussed in [17]. Cai and Wolf [18] discussed about Self-Adapting Quorum-Based approach for ND. The notion of low power wakeup receiver is investigated in [19] while ND optimization for opportunistic networks is studied in [21]. The concept of cooperative ND is discussed in [25] while collision free ND is focused in [26]. Energy efficient communications in WSN is proposed in [27] with reinforcement learning. “Neighbour Discovery and Rendezvous Maintenance with Extended Quorum” is the main focus of the work of Zhang *et al.* [28] for betterment in ND. ND in presence of cross-technology communications is

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proposed in [29] while ND with energy efficiency for IoT use cases is made in [30].

Fu et al. [31] focused on the trend correlation concept in WSN in order to have better strategy for fault detection. Sun et al. [32] studied on underwater sensor networks where their aim was to observe delay aware and collision-free communications using MAC protocol. Nazib and Moh [33] investigated on WSN that is aided by Unmanned Aerial Vehicle (UAV) for fast data collection and energy efficiency. Cao et al. [34] focused on connectivity and reliability in a heterogeneous WSN towards making a coverage optimization strategy. Singh et al. [15] on the other hand studied on coverage probability prediction using Gaussian process regression method. From the literature, it is understood that the existing BBID-based approaches have certain limitations. For instance, they lack blocks for certain duty cycles. Therefore, it is essential to ensure generation of discovery schedules to overcome the problem.

3. PROTOCOL DESIGN

This section presents our protocol design for asynchronous ND. First we introduce a simple version of the protocol that leads to better performance in terms of energy efficiency and latency. Then the protocol is revised further using adjustable occupancy rate of channel for further improvement.

3.1 Simple Version

This section presents the design of the simple asynchronous NDP. In this version of the protocol, we use beacons in active slots as more as possible. This is to reduce probe slots in the process of ND. At the beginning of each slot, a beacon is sent and wakes up, in each schedule cycle, in the first slot. Its discovery schedule is expressed as in Eq. 1.

$$\varphi_L(m,t) = \begin{cases} 1, & if\ [t]_T = 0 \\ 0, & 1 \le [t]_T \le n \end{cases}$$
$$\varphi_B(m,t) = 1 \quad (1)$$

where the length of schedule cycle is denoted by T and the parameter n is equal to T while [t]T is used to denote t mod T reflecting slot index. As the interval of beacons is fixed, there is guaranteed discovery of nodes with bidirectional communication. Each wakeup slot is associated with a least one beacon. The duty cycle of the protocol is expressed as in Eq. 2.

$$DC = \frac{1+\alpha(n-1)}{n} \approx \frac{1+\alpha n}{n} \quad (2)$$

We ignore one beacon slot for each calculation (when it overlaps with wakeup sot) as large n is used in the process. The discovery latency is n and therefore L=n. The power-latency product is then computed as in Eq. 3.

$$\Lambda = DC \cdot L = \frac{1+\alpha n}{n} \cdot n = 1 + \alpha \quad (3)$$

When we compare our protocol with that of LL-Optimal discovery schedule, it can be expressed as in Eq. 4.

$$\lambda = \frac{\Lambda}{\Lambda_0} = \frac{1+\alpha n}{\sqrt{n}} \ge \frac{2}{\sqrt{n}} \quad (4)$$

when $\alpha = \frac{1}{n}$, the Eq. 4 gets $\frac{2}{\sqrt{n}}$ when $\Lambda = 2$ and DC = $\frac{2}{n}$. From the analysis, it is understood that the simple approach used in the protocol is better than that of LL-Optimal schedule as far as n value is sufficiently large. Notations used in this paper are shown in Table 1.

Table 1: *Notations used in this paper*

Notation	Description
M	Node
$\varphi_L(m,t), \varphi_B(m$	Binary functions
T	Beacons at time
T	Periodic discovery schedules with cycle
DC	Duty-cycle
L	Worst-case discovery latency
N_c	Number of common active slots
N	Parameter
H	S doubled due to the extra beacons
Γ	Balance factor
N_L and N_B	Number of wakeup and beacon slots
ψ_0	An LL-Optimal schedule
K	Number of active slots
Γ	Global balance factor
D	Number of different duty-cycles
γ_i	Balance factor
Rate	Rate of adjustable channel occupancy

With given duty-cycle, the proposed approach shows better performance with lower latency bound. For instance, with duty-cycle 5%, the proposed approach is bounded by 40 slots while LL-Optimal latency is bounded by 400 slots. Therefore, with larger n value our approach is better than LL-Optimal. The problem with this simple approach is that the value of α should be less than DC in Eq. 2 and it is not easy to satisfy this condition. Therefore, we improved it in such a way that it can operate on any duty-cycle.

3.2 Consideration of Adjustable Occupancy Rate of the Channel

It is important that an adjustable occupancy rate of channel improves performance of ND protocol. Keeping this fact in mind, the such rate metric is used in the protocol. The occupancy rate of channel is expressed as in Eq. 5.

$$\text{rate} = \frac{\alpha \cdot N_B}{T} \quad (5)$$

where the number of beacons used in a schedule cycle is denoted as $N_B = \sum_{t=0}^{T-1} \varphi_B$ (m, t). Each slot has at least one beacon, η is simplified as in Eq. 6 in order to represent rate.

$$\eta = \frac{\text{rate}}{\alpha} = \frac{N_B}{T} \quad (6)$$

We also introduce another metric to have holistic approach in evaluation of performance of ND protocol. It is known as the product of duty cycle, rate and worst-case latency and denoted as A. The metric is defined as in Eq. 7 for any given periodic discovery schedule.

$$A = DC \cdot L \cdot \eta \quad (7)$$

Therefore, A is adopted in finding performance of ND protocols with sufficiently large parameters. For reference protocols such as Quorum, U-Connect, SearchLight and LL-Optimal, this metric is computed as in Eq. 8, Eq. 9, Eq. 10 and Eq. 11 respectively.

$$A_Q = \frac{2}{N} \cdot n^2 \cdot \frac{2}{n} = 4 \quad (8)$$

$$A_U = \frac{3}{2p} \cdot p2 \cdot \frac{3}{2p} = \frac{9}{4} = 2.25 \quad (9)$$

$$A_S = \frac{2}{t} \cdot \frac{t^2}{2} = \frac{2}{t} = 2 \quad (10)$$

$$A_O = \frac{1}{n} \cdot n^2 . \frac{1}{n} = 1 \quad (11)$$

With our simple approach in ND with cycle n where one beacon is used in each active slot, the A metric is used as in Eq. 12.

$$A_{SN} = \frac{2}{n} \cdot n . 1 = 2 \quad (12)$$

As presented in Table 1, there is summary of ND protocols with symmetric case. It can be observed that the η for our simple approach is kept constant as it cannot be tuned as per user's needs. The rationale behind this is that it needs to send a beacon in each slot. Though simple approach is better than LL-Optimal, it is essential to adjust η for better performance.

3.3 Flexible Approach

This section provides the approach where η can be adjusted and it considers rate in ND in order to satisfy different requirements of user. Instead of using a beacon in each active slot, it can adjust it according to the need. Therefore, the schedules in the flexible approach can be expressed as in Eq. 13 and Eq. 14.

$$\psi_L(g,t) = \begin{cases} 1, & if\ [t]_L < m \\ 0, & otherwise \end{cases} \quad (13)$$

$$\psi_B(g,t) = \begin{cases} 1, & [t]_L = mi, i = 0,1,\ldots,n-1 \\ 0, & otherwise \end{cases} \quad (14)$$

The latency of this approach is expressed as L=mn while its duty cycle is expressed as in Eq. 15.

$$DC = \frac{m+\alpha(n-1)}{mn} \approx \frac{m+\alpha n}{mn} \quad (15)$$

As in Eq. 2, we ignore one beacon for ease of computation, the power-latency product in our flexible approach is computed as in Eq. 16.

$$A = \frac{m+\alpha n}{mn} . = mn = m + \alpha n \quad (16)$$

As the rate of our flexible ND model is kept as $\eta = \frac{n}{mn} = \frac{1}{m}$, the power-latency product is computed as in Eq. 17.

$$A = \frac{m+\alpha n}{mn} . mn . \frac{1}{m} = \frac{m+\alpha n}{m} = 1 + \alpha \frac{n}{m} \quad (17)$$

As m and n can be changed and $\alpha \frac{n}{m}$ is adjustable, this approach performs better than other reference ND protocols.

4. EXPERIMENTAL RESULTS

Experiments are made with NS-2 simulations. The performance of the proposed asynchronous NDP is evaluated against the state of the art in terms of fraction of discoveries versus discovery latency (slots). Simulation is made with 40 nodes. Nodes are positioned closely so as to avoid interference. Between each pair of nodes there is bidirectional link thorough which they can communicate with each other. Similar to Disco, in our simulation, time slot is fixed to 10ms. Therefore, the value for alpha is set at 0.54/10 that is equal to 0.054. Every node has unique ID and that is used as seed for generating random numbers. Prior to a node starting ND, random delay is added to ensure that synchronization of wakeup schedules is avoided.

4.1 Results

In our approach, we found that there is need for one beacon in order to have bidirectional communication between two nodes. In other words, we believe that using two beacons is redundant. This fact is established in our empirical study as shown in Figure 1. Disco and SearchLight protocols are simulated with one beacon and two beacons. The results of experiments revealed that a single beacon is sufficient to have bidirectional communication.

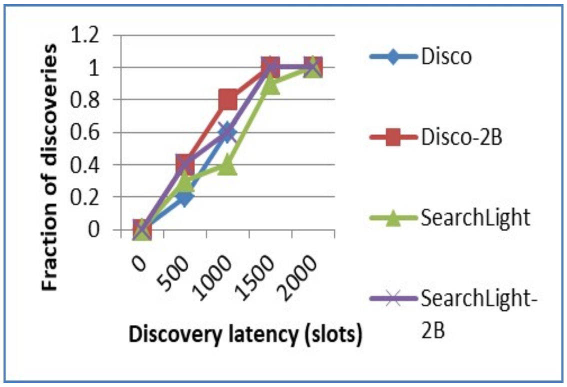

Figure 1: Shows drawback of two beacons approach due to its redundancy with 5% duty cycle

When the two protocols are evaluated using 5% duty-cycle, it is found that in both the cases, the protocols witnessed 100% with respect to fraction of discoveries before worst case latency. As this is consistent, we conclude that single beacon is sufficient for bidirectional communication. However, when two beacons are used, we found higher discovery rate. This has influenced us to use more beacons in order to have reduced latency in ND.

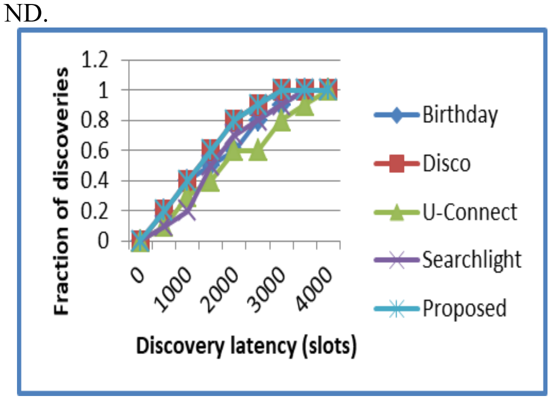

Figure 2: Cumulative distribution function of discovery latency with 5% duty cycle

As presented in Figure 2, different slots are provided in horizontal axis and vertical axis shows the fraction of discoveries. The results are obtained with simulations where 5% duty-cycle is used for all reference protocols and the proposed protocol. All reference protocols used one beacon in active slots. The balance factor is set at 1 for all protocols used in empirical study. It is observed from the results that the proposed protocol is relatively faster than reference protocols with lowest latency bound. Except the proposed protocol, other protocols could not reach 100% as there were beacon collisions.

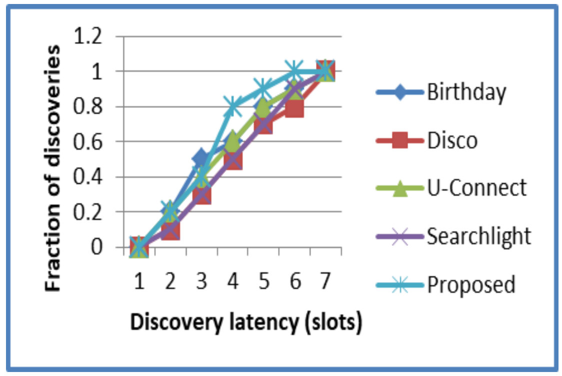

Figure 3: Cumulative distribution function of discovery latency with 1% duty cycle

As presented in Figure 3, different slots are provided in horizontal axis and vertical axis shows the fraction of discoveries. The results are obtained with simulations where 1% duty-cycle is used for all reference protocols and the proposed protocol. All reference protocols used one beacon in active slots. The balance factor is set at 1 for all protocols used in empirical study. It is observed from the results that the proposed protocol is relatively faster than reference protocols with lowest latency bound. Except the proposed protocol, other protocols could not reach 100% as there were beacon collisions.

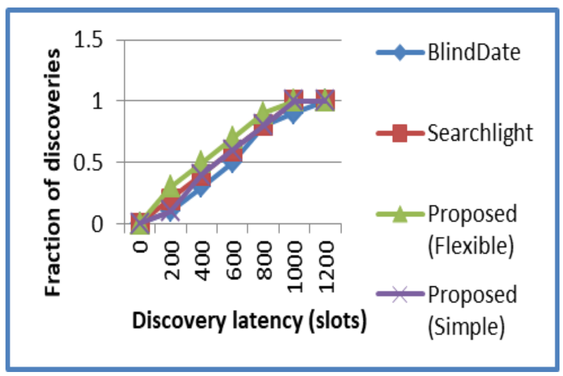

Figure 4: Cumulative distribution function of discovery latency with 5% duty cycle compared with BlindDate and SearchLight

As presented in Figure 4, different slots are provided in horizontal axis and vertical axis shows the fraction of discoveries. The results are obtained with simulations where 5% duty-cycle is used for all reference protocols and the proposed protocol. The proposed protocol versions are compared with BlindDate and SearchLight. SearchLight is used with 2 beacons in active slots and its balance factor is set to 2. In the same fashion, for BlindDate alpha is set to 4 and 2 beacons are used in active slots. In order to have fair comparison with the reference protocols, in the proposed (flexible) version alpha is set at 2. From the results, it is understood that the proposed (flexible) version is faster than other existing protocols used in comparison. It is also understood that the reference protocols with alpha>1, within worst case latency, could not reach 100% discovery due to beacon collisions. Proposed (simple) version also reached 100% discovery and showed fastness in discovery when compared with BlindDate

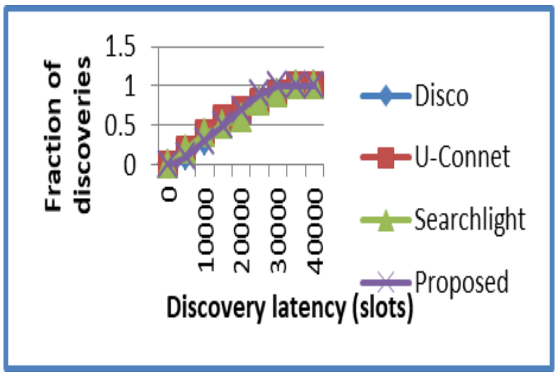

Figure 5: Cumulative distribution function of discovery latency with 1% and 5% duty cycles respectively used by two groups of nodes in the sensor network

As presented in Figure 5, different slots are provided in horizontal axis and vertical axis shows the fraction of discoveries. The results are obtained with simulations where both 1% and 5% duty-cycles are used for all reference protocols and the proposed protocol. The 40 nodes are divided into two groups and they operate at 1% and 5% duty cycles respectively. When the fraction of discoveries exceeds 50%, the protocols showed that their discovery rate slowed down as the group of nodes with 5% duty-cycle could discover each other with bounded latency. An important observation nevertheless is that the proposed protocol showed significantly better performance over other reference protocols as it has least bad case bound.

4.2 Evaluation

Different NDPs are analysed and their performance is summarized in Table 2. As presented in Table 2, the performance of different protocols in ND is compared in terms of different parameters in synchronous and asynchronous settings. From the summary of results, it is understood that the proposed protocol showed better performance over the state of the art in ND. . As per the details provided in Table 2, different parameters are presented in summary. According to the details, the proposed approach has adjustable η that leverages performance as per the requirements. Some parameters reflected about proposed approach show that it does better than the state of the art. There are some threats to validity of the proposed approach. First, there might be tradeoffs among different variables such as occupancy rate of channel, latency and duty cycle. Second, the simulations made using NS-2 have limitations in choosing number of nodes while in the real world WSN may have very large number of nodes. Therefore, it is essential to have further evaluations with more advanced testbeds.

5. CONCLUSION AND FUTURE WORK

In this paper, we have designed and implemented an asynchronous neighbour discovery protocol that is energy efficient, balanced and flexible in nature supporting both symmetric and asymmetric approaches. First a simplified approach is followed in designing the protocol that is flexible. Then it is enhanced further to reduce number of tunable parameters from two to one. There is consideration of trade-off between different parameters such as occupancy rate of the channel, latency and duty cycle. We proposed a scheme named Flexible, Balanced and Energy Efficient Asynchronous Neighbour Discovery (FBE-ND) to realize the desired functionalities in the asynchronous NDP. First we introduce a simple version of the protocol that leads to better performance in terms of energy efficiency and latency. Then the protocol is revised further using adjustable occupancy rate of channel for further improvement. NS-2 simulation study revealed that the proposed protocol shows better performance over the existing ones. In future we believe that, our protocol leads to further improvements in continuous neighbour discovery research.

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Table 2: Performance evaluation of different NDPs

Protocol	**Parameter**	**DC**	**L**	**Λ**	**Λ**	N_B	**H**	**γ**	**A**	**Asymm?**
Quorum	N	$\frac{2}{n}$	n^2	$2\sqrt{L}-1$	2	2n	$\frac{2}{n}$	1	4	No
Disco	p1, p2	$\frac{1}{p1}+\frac{1}{p2}$	p1p2	$2\sqrt{L}$	2	p1+p2	$\frac{1}{p1}+\frac{1}{p2}$	1	4	Yes
U-Connect	P	$\frac{3}{2p}$	p^2	$\frac{3\sqrt{L}+1}{2}$	1.5	$\frac{3p}{2}$	$\frac{3}{2p}$	1	2.25	Yes
SearchLight	T	$\frac{2}{t}$	$\frac{t^2}{2}$	$\sqrt{2L}$	$\sqrt{2}$	t	$\frac{2}{t}$	1	2	Yes
SearchLight (2B+stripe)	T	$\frac{2}{t}$	$\frac{t^2}{4}$	$\sqrt{L}$	1	t	$\frac{4}{t}$	2	2	Yes
BlindDate (4B+stripe)	S	$\frac{3}{5s}$	$\frac{5s^2}{2}$	$\sqrt{\frac{9}{10}L}$	$\sqrt{\frac{9}{10}}$	6s	$\frac{12}{5s}$	4	3.6	Yes
LL-Optimal (Combinatoric)	N	$\frac{1}{n}$	n^2	$\sqrt{L}$	1	n	$\frac{1}{n}$	1	1	No
Proposed Simplified Approach	N	$\frac{2}{n}$	N	2	$\frac{2}{\sqrt{n}}$	n	1	n	2	Yes
Proposed Generic Approach	m, n	$\frac{m+\alpha n}{mn}$	mn	$m+\alpha n$	$\frac{m+\alpha n}{\sqrt{mn}}$	n	$\frac{1}{m}$	$\frac{n}{m}$	$1+\alpha\frac{n}{m}$	Yes
Proposed Balanced Approach	N	$\frac{1+\alpha}{n}$	n^2	$n(1+\alpha)$	$1+\alpha$	n	$\frac{1}{n}$	1	$1+\alpha$	No