Energy-Efficient Adaptive Interface Activation for Delay/Disruption Tolerant Networks

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Abstract— **In sparse mobile networks, opportunistic access can be used to forward data in a so-called "store-carry-forward" manner using Delay/Disruption Tolerant Networking (DTN) techniques. In such environments, it is not always the case that a mobile terminal is within the communication range of other mobile terminals. Therefore, the terminal must first perform the energy-consuming process of "terminal discovery" before sending or receiving actual data. Since a mobile terminal is normally battery powered, it is a mandatory requirement to cut power consumption. Therefore, the discovery process must be executed efficiently. In other words, it is imperative to activate a network interface at the right time.**

In this paper, we analyze the performance issues with simple periodical interface activation and propose a new activation mechanism called DWARF (DTN-oriented wireless interface activation mechanism based on radio fluctuations) for efficiently discovering other terminals with less expenditure of energy. In the proposed mechanism, the interface activation interval is adjusted based on the surroundings. DWARF is a distributed mechanism and does not require prior knowledge such as patterns of human behavior. Computer simulation results show that DWARF discovers other terminals about 3.5 times more efficiently than a fixed-interval scheme without missing opportunities for connection.

Index Terms—Delay tolerant network, Energy efficiency, Communication interface activation

I. Introduction

In a challenged network environment in which, for example, there is no communication infrastructure and mobile terminals (MTs) are sparsely distributed, an MT sometimes faces the difficulty of finding a route to a destination when the MT generates data to be forwarded to the destination. An end-end path must be established in advance of forwarding data in traditional techniques such as ad-hoc networking. To tackle such a challenged environment, technologies such as Delay-Tolerant Networking (DTN) [1-2] as proposed by IRTF (Internet Research Task Force) exploit opportunistic access to forward data in a so-called "store-carry-forward" manner. In IRTF, the concept of "bundle" has been introduced. The bundle layer, which is a message-oriented overlay, is positioned between the transport and the application layers. A bundle, which is a block of data, is stored in an MT, physically carried by it and forwarded to the destination directly or through other MTs (multi-hop fashion) using a routing scheme in DTN [3].

In such a circumstance, the primary need is for an MT to search for other MTs that it can be connected to. To do that, the MT is required to continue transmitting a neighbor discovery request (NDREQ; e.g., an inquiry message in the Bluetooth or the UWB, or beacon in the wireless LAN) until the MT succeeds in discovering another MT (or MTs) by receiving a neighbor discovery response (NDRSP; e.g., an inquiry response message in the Bluetooth or the UWB) which is the reply message of the NDREQ. Since an MT is generally battery powered, it is a mandatory requirement to reduce the power consumption of the MT in order to provide practical DTN services. Therefore, it is required that a communication interface (I/F) is usually rendered inactive to reduce power consumption because activating an I/F consumes a similar amount of power to that in the communicating state [4-6]. One of the very challenging problems is when and how the MT should activate its I/F and start probing. While frequent activation would lead to wasting power, a longer activation interval could result in missing an opportunity to discover other MTs and a lot of time could consequently be taken to connect with them successfully; thus, there is a tradeoff between quicker discovery and lower power consumption.

Previous work exploits human behavior (contact patterns) which was investigated in an experiment involving nine volunteers using Bluetooth devices [5]. In this experiment, the algorithm was changed at 8 a.m. since behavior changed at around 8 a.m. according to the collected logs. While the work is very interesting and produced valuable results, it might not always work well since human behavior depends on culture, city structure, etc. An energy efficient interface activation scheme has been studied in [7]. This work focuses on the short range communication (SRC) interface (e.g., WLAN (Wireless LAN) or Bluetooth) activation of a "dual-mode terminal" which is also equipped with a WAN (Wide Area Network; such as cellular) interface, and leverages the transition of the signal quality measured in the WAN interface to activate the SRC interface efficiently. In this paper, we focus on the challenged environment in which there is no WAN.

Accordingly, we propose an energy efficient mechanism named DWARF (DTN-oriented wireless interface activation mechanism based on radio fluctuations) that simultaneously fulfills the following three requirements:

(1) Unnecessary power consumed in the search for other MTs is minimized
(2) No infrastructure is required
(3) No prior knowledge such as contact patterns is required

In order to adaptively control the I/F activation timing depending on the situation, DWARF activation is based on the hysteresis of the fluctuation of radio signals.

The remainder of this paper is organized as follows. In section II, we analyze the current problem more deeply, while section III presents the design concept of DWARF. In section

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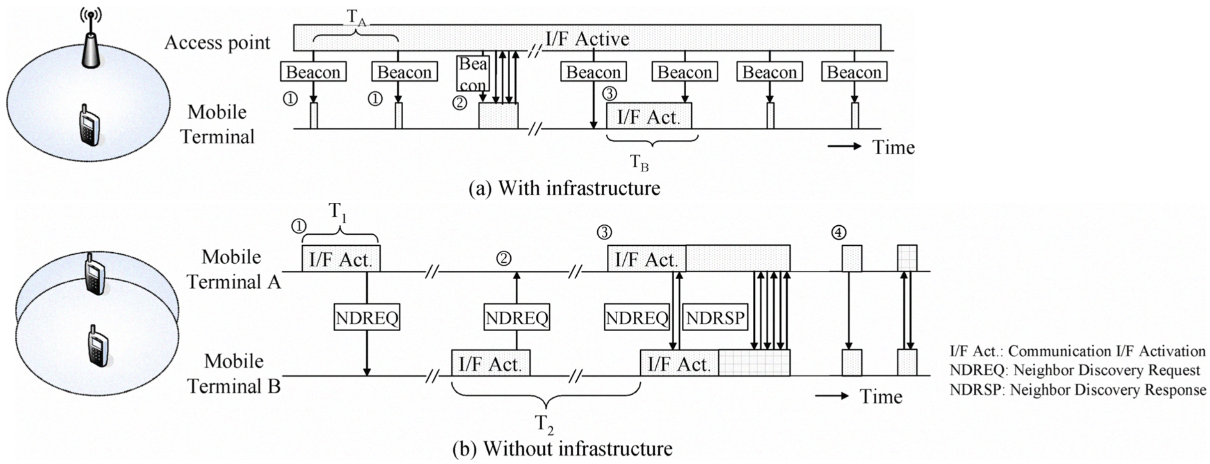


Fig. 1. Discovery process and communication interface activation

IV, we evaluate DWARF using a network simulator before concluding the paper in section V.

II. Problem Statement

It is known that the communication interface in the idle state (i.e., ready to amplify the power of the received signal or signal to be transmitted) consumes a similar amount of power to that in the active state (i.e., state in which data is transmitted or received) [4-6]. Because an MT is generally battery powered, several technologies have been applied to reduce the power consumption of an MT (i.e., to render the I/F of the MT inactive as much as possible).

For example, the WLAN Power Saving Mode (PSM) [8] can significantly reduce power consumption by allowing an MT to revert to 'sleep state' when there is no data to be transmitted to the MT. The MT only needs to wake up at in the pre-defined timing (i.e., ATIM (announcement traffic indication message) window that follows periodic beacon signal) to check if there is an ATIM addressed to the MT or not (Fig. 1 (a) ①). If an MT is notified of incoming traffic, the MT keeps the I/F active and receives the traffic (Fig. 1 (a) ②). Also in cellular systems, a BS (Base Station) periodically transmits a paging channel, which is the only thing an MT needs to monitor. The MT can doze at other periods, which increases standby time.

PSM (and the paging system in cellular systems) become(s) effective only when the MTs have already connected to an AP (Access Point). The MT, which is trying to connect to an AP, must keep the WLAN interface activated. Here, since an AP is normally connected to a power source and is therefore immune to the battery becoming exhausted, the AP always renders its I/F active and transmits a beacon signal within a relatively short interval (e.g., normally the interval T_A in Fig. 1 (a) is set to 100 ms in WLAN). Therefore, the duration T_B for which the MT must keep the interface active can be set to T_A (if the MT knows the radio channel used in this network in advance).

Here, let us assume an infrastructure-less network in which an MT has to probe environments to check if there are other MTs to be connected or not. In this case, even if there is an MT (MT-B in Fig. 1 (b)) nearby another MT (MT-A), MT-B cannot sense a NDREQ transmitted by MT-A when MT-B is in sleep mode (i.e., the I/F is rendered inactive) (Fig. 1 (b) ①). In the same manner, the trial results in failure and MT-B transitions into the sleep state again (Fig. 1 (b) ②) if MT-A is dozing when MT-B probes environments. MT-A is only detected by MT-B if MT-B stays awake when MT-A sends the NDREQ (Fig. 1 (b) ③). When the MT detects other MTs, it might move into power- saving mode after negotiating with the other MTs (Fig. 1 (b) ④) [6]. From the above description, it is clear that the discovery process without infrastructure requires much more energy compared to that with infrastructure. The I/F activation duration T_1 and the interval T_2 shown in Fig. 1 (b) represent a tradeoff between power consumption and rapid detection; namely, overly frequent I/F activation (probing) decreases the battery life, while infrequent I/F activation eliminates the possibility of finding other MTs and establishing connections.

Note that the optimal interval varies based on the situation. Fig. 2 shows some examples of situations where MTs would be in a challenged environment. In Fig. 2 (a), there are no other MTs around an MT (MT-1), and MT-1 is in a static condition. This is the case in which, for example, a user of MT-1 sleeps in her room and MT-1 is on a desk. In this case, there would be few opportunities for MT-1 to encounter other MTs, which means a long interval (i.e., infrequent I/F activation) is preferable. In Fig. 2 (b) where MT-1 exists but moves around, infrequent I/F activation is also preferable since it is unlikely that MT-1 comes into contact with other MTs with which to be connected. This is like the case where the user is walking about her room with MT-1. In Figs. 2 (c) (d) (e) where there is another MT (MT-2) in the vicinity of MT-1 and either of the MTs or

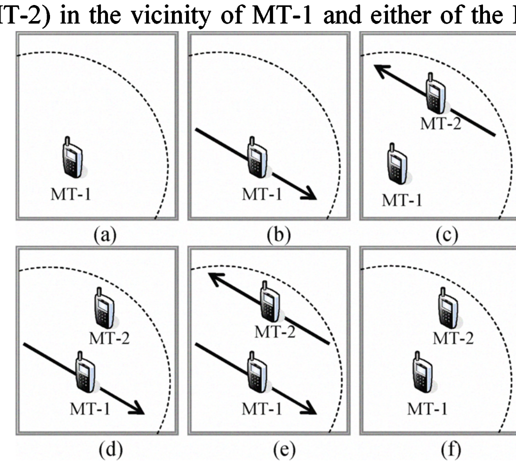


Fig. 2. Situations in which MTs would be in a challenged environment

both of them is/are moving around, e.g., in a shopping center, frequent I/F activation would be desirable because there are many opportunities to discover other MTs and forward the storing/carrying data. However, in Fig. 2 (f) where there is also MT-2 in the vicinity of MT-1 but both are in a static condition, there are fewer opportunities for data to be spread to more MTs, which means a long interval may be acceptable in this case.

From the above considerations, we propose a novel energy-efficient adaptive I/F activation mechanism in the following section.

III. DWARF: Energy Efficient Adaptive Interface Activation for DTN

DWARF (DTN-oriented wireless interface activation mechanism based on radio fluctuations) takes an entirely different approach than has been suggested in earlier studies. As stated in the previous section, the optimal interval in I/F activation varies depending on the situation. It is necessary to activate the I/F when the possibility of data dissemination is high in order to achieve efficient activation. Then, in DWARF, an MT autonomously deduces the possibility based on the measurement of environmental fluctuation and adaptively changes the interval based on the deduction.

The MT transmits NDREQ and monitors the reflected signals to probe the surrounding environment (Fig. 3). What the MT obtains is simply signal strength or an amplitude of the signal and delay of the echo, etc., and those measured data are stored in the MT as time series data. Figures 4 (a) (b) show the examples in which signal strength and amplitude (with echo delay) are stored as time series data, respectively. Note that Fig. 4 does not represent any real measurements but are just models for illustration purposes.

Let us assume that an MT (whose owner is sleeping) is on a desk at night. In this case, successive measured signals

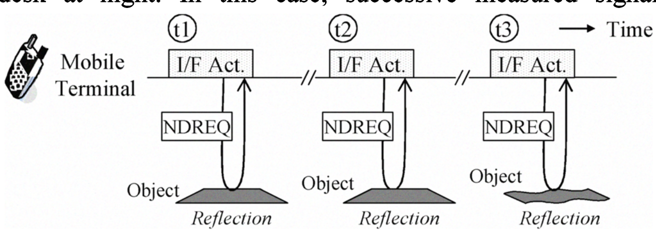
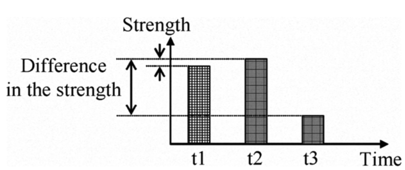
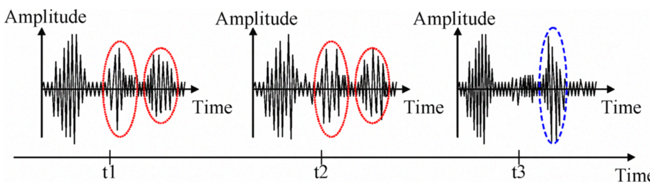


Fig. 3. An MT transmits NDREQ and monitors the reflected signals



(a) Signal strength



(b) Amplitude of the signal and delay of the echo

Fig. 4 Examples of measured data models (not representing any real measurements)

reflected by objects could have something in common and little fluctuations/differences can be observed between them, e.g., as shown in *t1* and *t2* in Figs. 3 and 4. In DWARF, when a similar trend is observed, the next interval to activate the I/F and probe environments is set to be longer. On the other hand, let us assume the owner is walking around in a shopping center. Since the surroundings of the owner are changing every moment due to her own movement or that of other users, different tendencies in reflected signal would be found (e.g., between *t2* and *t3* in Figs. 3 and 4). In this case, a shorter interval is set.

Note that the MT may have to be equipped with more than one antenna (one for normal use such as transmitting and receiving data, and the other for receiving the echo) to realize this mechanism. Furthermore, what an MT observes depends on the radio technology used; e.g., UWB (Ultra Wide Band) can provide high time resolution [9] which enables an MT to monitor the amplitude and delay of a reflected wave as in Fig 4 (b). For example, in [9], a reconfigured module which is initially designed for communication in the UWB works as a UWB radar which has two antennae, for signal transmission and receiving, respectively, and detects different wave patterns of echoes between open and closed door environments as well as the presence and absence of human body environments. Although impulses are used in such a radar function, some information such as a device ID might be superimposed on them by adding pulse position modulation (PPM) [13]. In DWARF, it is sufficient to detect the rough changes in an environment, which means it does not require higher resolution. Although these feasibility studies are important, they are outside the scope of this paper and a detailed discussion is part of our future work.

IV. Performance Evaluation

We have evaluated the proposed DWARF approach as well as the fixed-interval I/F activation scheme using the *ns-3* (ns-3.5) network simulator [10]. We also used the ONE simulator [11] to use the real-world moving pattern in which MTs moved around on a map of the central area of Helsinki. The moving pattern was exported to the ns-3 in which MTs moved according to it.

A. Preliminary Evaluation

First of all, we evaluated how the frequency in the I/F activation affected energy consumption and missed opportunities to discover other MTs. Note that, in this evaluation, we assume that the power consumed in the NDREQ process is equivalent to the number of I/F activations. In other words, if the number of activations is halved, the energy consumed in the process can be also reduced by half.

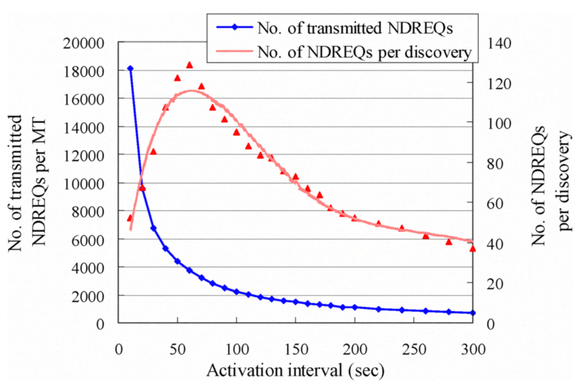
In this evaluation, we had 54 MTs on the map covering an area of 4.5 x 3.4 [km^2]; 50 MTs simulated ordinary people (referred to as wdMTs in this paper) who go to work in the morning, spend their day moving inside their offices or having meetings, go shopping or walk around the streets after work, and finally commute back to their homes in the evening; 2 MTs simulated buses (referred to as Buses) which run along pre-defined routes and can carry more than one wdMT; the last

TABLE I: SIMULATION PARAMETERS (PRELIMINARY EVALUATION)

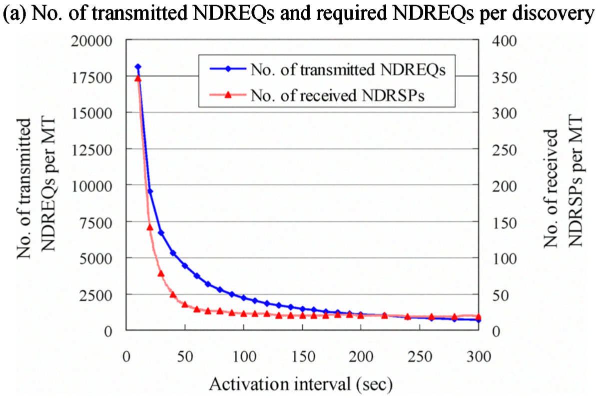
Parameters	Value	Remarks
Area size [km²]	4.5 x 3.4	
The number of MTs	54	50 wdMTs, 2 Buses, 2 Msgrs
I/F activation duration T_1 [s]	3	
I/F activation Interval T_2 [s]	10 – 300	
Radio coverage [m]	~ 41	
Movement model	Working day movement (wdMTs)	
	Bus movement (Buses)	
	SPMBM (Msgrs)	
Moving speed [m/s]	0.8 – 1.4	wdMTs
	7.0 – 10.0	Buses, Msgers
Pause duration [s]	10 – 30	Buses
	100 – 300	Msgers
The number of offices	10	
Simulation time [sec]	260000	About 3 days

2 MTs simulated messengers (referred to as Msgrs) who move in accordance with the shortest path map-based movement (SPMBM) model [12] which is a derivative of the Random Waypoint (RW) model. In the SPMBM, MTs calculate shortest paths to randomly selected destinations on the map using Dijkstra's algorithm and move to the destinations following the roads as defined by the map data. Table I provides details of the parameters used in this evaluation.

In this simulation, each MT periodically activates the I/F and waits for a NDREQ from other MTs for 3 [s] (i.e., $T_1 = 3$), and after that the MT broadcasts a NDREQ followed by the deactivation of the I/F. When an MT receives a NDREQ only while activating the I/F, the MT sends out a NDRSP to the sender. Once an MT becomes associated with another MT, counting messages about the MT stops until the association breaks (which is deduced from the idle time (about $3 * T_2$ [s])). The interval of an I/F activation T_2 varied from 10 [s] to 300 [s].



(a) No. of transmitted NDREQs and required NDREQs per discovery



(b) No. of transmitted NDREQs and received NDRSPs

Fig. 5. Preliminary experimental results

TABLE II: SIMULATION PARAMETERS (DWARF EVALUATION 1)

Parameters	Value	Remarks
The number of MTs	54 – 204	50–200 wdMTs, 2 Buses, 2 Msgrs
I/F activation Interval	10	Fixed Interval scheme
T_2 [s]	10	Large radio fluctuation in DWARF
	40	Small radio fluctuation in DWARF
The number of offices	10 – 30	5 person / office on average.

In fact, the interval followed normal distribution with a standard deviation of 1.

Figure 5 (a) shows the results for an average number of total transmitted NDREQs per node and the average number of NDREQs taken to discover an adjacent MT (which is calculated by: *the number of received NDRSPs / the number of transmitted NDREQs*). It follows that the longer the interval, the fewer NDREQs each MT transmitted. However, regarding the number of NDREQs per discovery, a peak can be observed around 60 [s] in terms of the interval, which means such intervals are least efficient with regard to energy consumption. This could be because MTs do not always move, but instead remain in one place such as in a house or office in the applied mobility model and therefore there is no obvious difference in the number of received NDRSPs between, for example, the interval of 60 [s] and that of 120 [s] as shown in Fig.5 (b). While longer intervals than around 200 [s] resulted in better energy efficiency, absolute numbers of successful discoveries tended to be too few; for example, each MT could contact other MTs 19 times through the whole simulation (every 3.8 [hr] on average) at an interval of 240 [s]. Although the interval of 10 [s] is less effective in terms of energy consumption compared to longer (longer than 200 [s]) intervals, we use this as the default interval in the following evaluations because each MT was able to successfully detect other MTs every 12.5 [min] on average, which could make DTN services feasible.

B. *First Evaluation of DWARF*

Next, we evaluated the basic performance of the DWARF approach. In this evaluation, just for simplicity, an MT considers the signal environment to be fluctuating largely if:

1) the MT itself is moving (Fig. 6 (a)), *or*
2) there is at lease one other MT moving within a 20 [m] radius (which is equivalent to about half the radio coverage) of the MT (Fig. 6 (b))

only when the MT transmits a NDREQ.

When the MT considers the signal environment to be fluctuating significantly, the MT sets 10 [s] as the next interval for I/F activation. On the other hand, when smaller fluctuation is observed (i.e., the MT itself is stopped and there is no moving MT in the vicinity), the MT sets the interval at 40 [s].

As shown in Fig. 6, DWARF has an inherent problem in that it can sometimes wrongly deduce environments; MT-1 in Fig. 6 (a) in fact does not need to set a shorter interval since there is a slight chance that MT-1 may encounter other MTs with which to be connected. In addition, MT-1 cannot sense other MTs moving outside the 20 [m] radius even if they exist inside the communication coverage according to the second condition described above and as shown in Fig. 6 (c). In the evaluation here, these adverse effects are taken into consideration. However, there could be more or less false-positive and

TABLE III: SIMULATION PARAMETERS (RANDOM WAYPOINT)

Parameters	Value	Remarks
The number of MTs	54	
Moving speed [m/s]	1.11 – 2.78	4 [km/h] – 10 [km/h]
Pause duration [s]	60 – 1800	

TABLE IV: SIMULATION RESULT (RANDOM WAYPOINT)

	Fixed Int.	DWARF
No. of transmitted NDREQs per MT	22603	17478
No. of NDREQs per discovery	119.3	82.5

false-negative deductions in reality, which is ignored for simplicity in this evaluation.

In this simulation, the number of wdMTs varied from 50 to 200. Table II shows the parameters which are different from or not seen in the preliminary evaluation.

Figures 7 (a) - (c) show results. From Fig. 7 (a), which shows the average number of total transmitted NDREQs per MT throughout the simulation, DWARF enabled MTs to cut the number of NDREQs, which is directly related to the power consumed in the NDREQ process, by around two-thirds. On the other hand, concerning the average number of received NDRSPs, which is equivalent to the number of successful discoveries, DWARF achieved almost the same number as the fixed-interval scheme (instead, DWARF could achieve a slightly higher number of received NDRSPs because of fewer collisions). As a result, the average number of NDREQs required to discover other MTs was also reduced by around two-thirds. Figure 7 also shows that the number of NDREQs required to discover other MTs decreased with increasing density of MTs, which is fairly self evident.

C. *Evaluation of DWARF using other movement models*

Here, we evaluated DWARF using other movement models; RW and SPMBM [12] models to examine whether DWARF works independent of the movement model or not.

1) *Random Waypoint Model*

TABLE V: SIMULATION PARAMETERS (SPMBM)

Parameters	Value	Remarks
The number of MTs	54 – 162	54, 81, 108, 162
Moving speed [m/s]	1.11 – 2.78	4 [km/h] – 10 [km/h]
Minimum pause duration [s]	0	
Maximum pause duration [x]	120 – 1800	120, 600, 1800

TABLE VI: SIMULATION RESULT (EVALUATION. E)

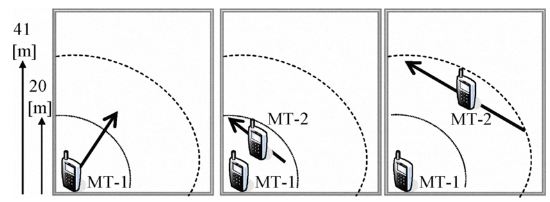
	Simple DWARF	Modified DWARF
No. of transmitted NDREQs per MT	6193	5474
No. of received NDRSPs per MT	342	368
No. of NDREQs per discovery	18.1	15.0

Table III shows the parameters used in this evaluation. Unlisted parameters are the same as those in Table II (and I). The results are shown in Table IV, from which we can see that DWARF could reduce the number of transmitted NDREQs by 23% as well as reducing the number of NDREQs required on average to discover other MTs by 30%.

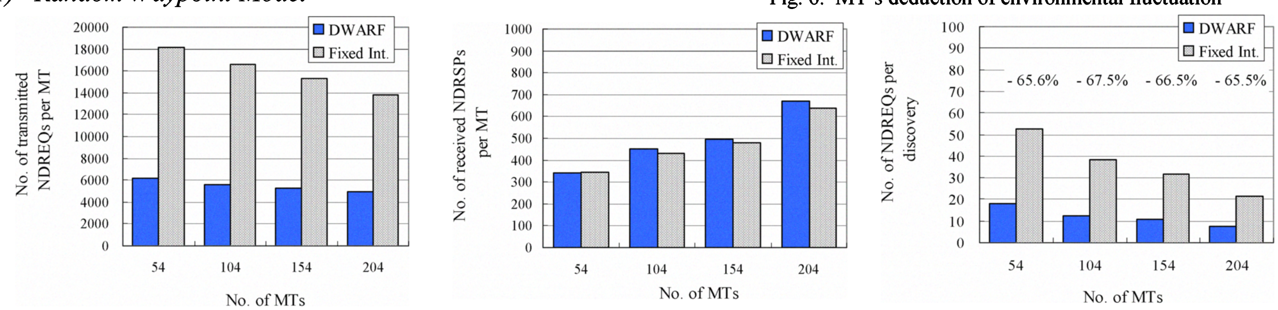
2) *Shortest Path Map-Based Movement Model*

Specific parameters in this evaluation are shown in Table V. In this evaluation, both the number of MTs and pause duration varied. According to the results shown in Fig. 8, the longer the MTs pause, the more efficiently DWARF works. This can be understood from the fact that DWARF is equivalent to the fixed-interval scheme if the pause duration is set to zero. It was also found that the efficiency of DWARF is independent of the number of MTs.

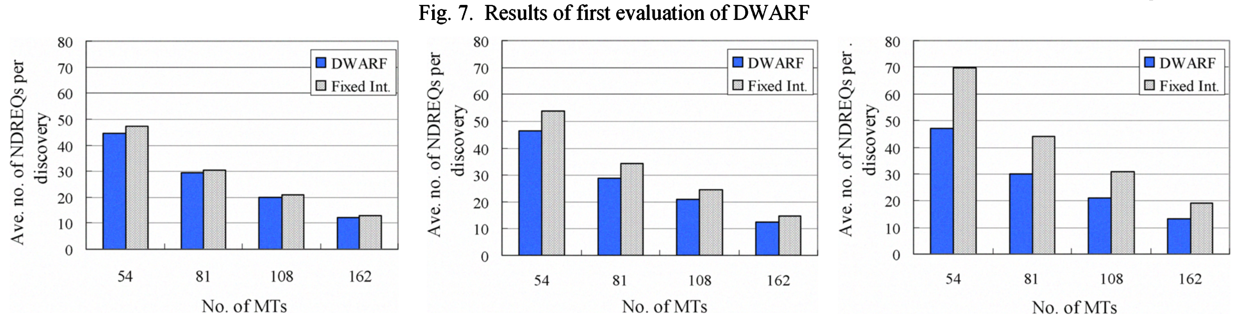
From the results presented in this subsection, we can confirm



(a) Large fluctuation (b) Large fluctuation (c) Small fluctuation
Fig. 6. MT's deduction of environmental fluctuation



(a) The number of transmitted NDREQs (b) The number of received NDRSPs (c) The number of NDREQs per discovery
Fig. 7. Results of first evaluation of DWARF



(a) Pause duration: 0 – 120 [s] (b) Pause duration: 0 – 600 [s] (c) Pause duration: 0 – 1800 [s]
Fig. 8 The number of NDREQs per discovery (Shortest Path Map-Based Movement Model)

that DWARF works well even in the other movement models.

D. Evaluation of DWARF with various intervals in the case of small radio fluctuation

Then, we varied the interval in the I/F activation from 60 [s] to 300 [s] in the case of small radio fluctuation. Other parameters are the same in Table II. The results of this evaluation are shown in Fig. 9. The results of the fixed-interval scheme are incorporated for reference purposes. According to Figs. 9 (a) (b), the number of NDREQs required to discover other MTs is almost constant (i.e., independent from the interval), which means, for example, this value can be adjusted based on the remaining battery level, etc.

E. Evaluation of DWARF with aggressive and restrained probing in the case of large radio fluctuation

So far, we have used only two parameters in relation to I/F activation, for large and small environmental fluctuations, in each evaluation. However, since DWARF preferably adopts a shorter interval even when an MT moves around and there are no other MTs in the vicinity of the MT, which is actually the case in infrequent I/F activation (as shown in Fig. 2 (b)), we change the interval in the case of large fluctuation depending on the probing result to address this issue in this evaluation.

When an MT detects that an environmental fluctuation is large, the MT sets a smaller value, e.g., 10 [s], as the interval. However, after the MT fails to discover other MTs after a certain number of times, e.g., after five times in a row, the interval the MT sets increases exponentially up to the pre-defined interval in a small fluctuation, e.g., 40 [s]. After some intervals pass, the MT sets a smaller value again, and this pattern is repeated. An example of the algorithm of this pattern is shown in Fig. 10.

We compared the performance of this algorithm shown in Fig. 10 with DWARF described in subsection B. According to the result shown in Table VI, this modification results in less NDREQs being required as well as more NDRSPs received.

V. Conclusion

In this paper, we propose a novel wireless interface activation mechanism in challenging network environments. DWARF enables an MT to vary the interval of activating the interface based on the degree of environmental fluctuation.

This paper presents the first results of DWARF, which showed that this approach has huge potential for enhancing efficiency as well as reducing power consumption.

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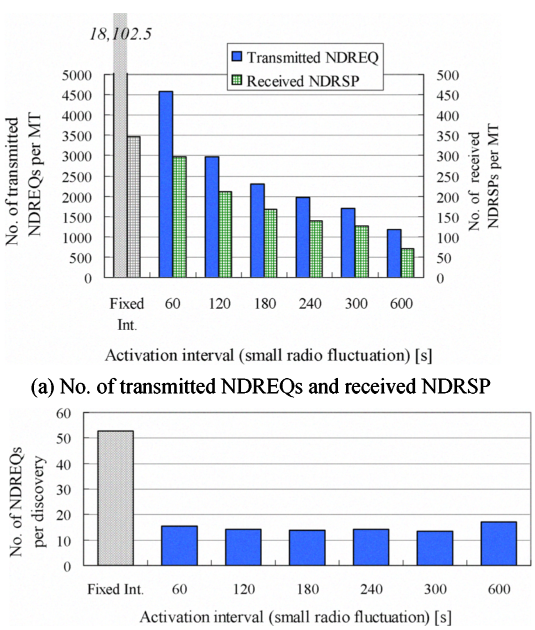

(a) No. of transmitted NDREQs and received NDRSP

(b) No. of NDREQs per discovery

Fig. 9 Result of DWARF at various intervals (in small radio fluctuation)

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Activate I/F
If receives NDREQ
Association start.
Reset no_reply_counter
else
Broadcasts NDREQ
if receives NDRSP
  Association start.
  Reset no_reply_counter
else
  if small environmental fluctuation
    set the interval to N(40, 1)
    Reset no_reply_counter
  else
    no_reply_counter += 1
    if no_reply_counter < 6
      set the interval to N(8, 1)
    else
      set the interval to (N(8, 1) + min(2^(no_reply_counter-5), N(40, 1))
    endif
    if no_reply_counter > 20
      Reset no_reply_counter
    endif
  endif
  Deactivate I/F
  endif
endif
```

Fig. 10 Example of DWARF algorithm (T_2 in small radio fluctuation = 40[s])