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Information gathering system based on combination of random and selective accesses for ubiquitous environments

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ABSTRACT

In this paper, we focus on an information gathering system where a reader continuously collects information from mobile nodes in its access area, such as environmental information cameras and sensors. We assume that a mobile node is relatively tiny and does not have a high-precision antenna to sense carriers emitted by other nodes. Although a random access method like ALOHA can be easily used, it has disadvantages of transmission efficiency and energy consumption. To tackle these problems, we propose a novel method that is a combination of random and selective accesses. At first, a reader sends an ID request to all nodes. Then, each node replies its ID to the reader at a response probability involved in the request. Finally, the reader selectively gathers information from nodes according to the obtained ID lists. In our method, non-registered nodes and non-deleted nodes affect the system performance. The non-registered node is a node that is in the access area but its ID is not registered to the reader. The non-deleted node is a node that leaves the area but its ID is still registered to the reader. In this paper, we first derive their numbers by an analysis using the Inversion Formula of Palm Calculus. Then, we conduct simulation experiments to verify the analysis. Simulation results show that our method can achieve 70% of transmission efficiency while ALOHA and slotted ALOHA attain 18% and 36%, respectively when node mobility is relatively small.

1. INTRODUCTION

In an ubiquitous network, information and data exist anywhere and anytime. One of key issues is how to gather information effectively from numerous nodes in such a network. For example, in a physical distribution system, it is expected that an effective information gathering system can be attained by introducing Radio Frequency Identification (RFID) system.[1] In a current RFID system, a reader cannot effectively collect information from multiple nodes in its access area. This is because a collision occurs when multiple nodes simultaneously transmit their information to the reader. To tackle this problem, many researchers focus on anti-collision mechanisms that improves the probability that only one node transmits its information to the reader for a given length of time.[5–8]

However, they did not consider node mobility. In an ubiquitous network, it is possible that a node can freely move around. If each mobile node periodically captures the surrounding image by a camera equipped, the reader can monitor the access area by sequentially collecting the images from multiple nodes. Such a monitoring system can be used for detecting emergent events in the access area. In such a system, we need a novel information gathering method that considers the node mobility. Although ALOHA and CSMA-CA are the most popular media access control techniques for wireless networks,[?,?,3] it has been pointed out that their performances degrade as the node mobility becomes high. Furthermore, a mobile node does not necessarily enable to sense career emitted by others because its computing capacity and antenna performance for wireless communication are limited. On the other hand, a reader has a high computing capacity and a high-end antenna capable of career sense.

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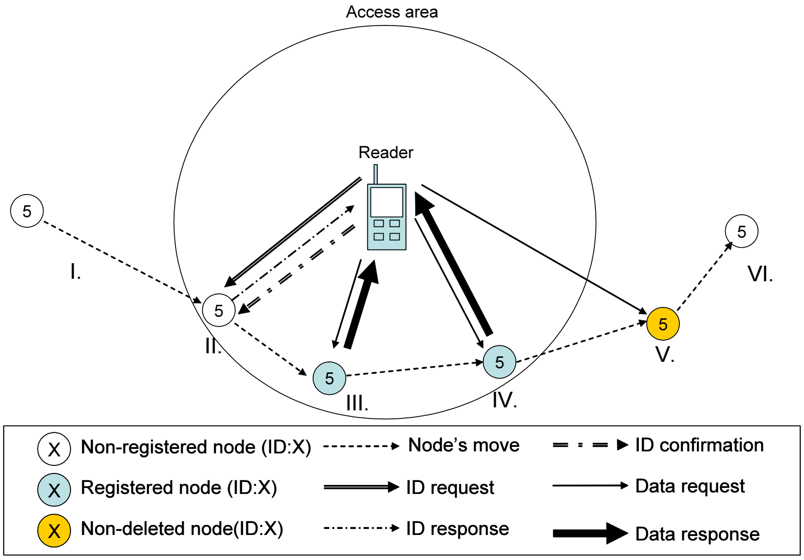


Figure 1. Overview of our system

In this paper, we propose a novel method to sequentially collect information from multiple mobile nodes. We assume that the information of a mobile node is composed of ID and its own data. The basic idea is dividing an information gathering phase into two phases: ID registration phase and data gathering phase. In the ID registration phase, a reader collects IDs from all mobile nodes by randomly accessing them one by one with a certain probability (i.e., response probability). To efficiently collect IDs from all nodes, the reader must appropriately control the response probability in accordance with the number of nodes in the access area. Once the reader knows an ID of a node, it can selectively access to the node without collisions among multiple nodes. We also introduce a method to switch the two kinds of phases to cope with the node joins and departures.

We first analyze the basic traits of the proposed method in a stationary state by using the Inversion Formula of Palm Calculus.[?] To verify the results of analysis and further evaluate the proposed method, we conduct several simulation experiments.

The remaining of the paper organizes as follows. We explain the proposed method in section 2. Section 3 describes the basic analysis of the proposed method. Then, we conduct simulation experiments to verify the analysis and evaluate the proposed method in section 4. Finally, we conclude the paper and discuss future works in section 5.

2. PROPOSED METHOD

2.1. Overview

Figure 1 illustrates an overview of our system. A reader collects data from nodes in its access area where it can contact nodes with a wireless communication. For simplification of explanation, Fig. 1 illustrates the case that only one node exists in the system. After a node comes into the access area (I), the reader communicates with the node to register the node's ID to reader's own ID list (II). The reader periodically collects data from the node. If there are multiple nodes in the ID list, the reader sequentially gathers data from them according to the ID list (III, IV). After the node leaves the access area (V), the reader knows that the node departure by detecting timeout (VI), it removes the corresponding ID from the ID list.

We explain a basic method using a combination of random and selective accesses in subsection 2.2. Then, we extend the basic method to cope with the node mobility in subsection 2.3.

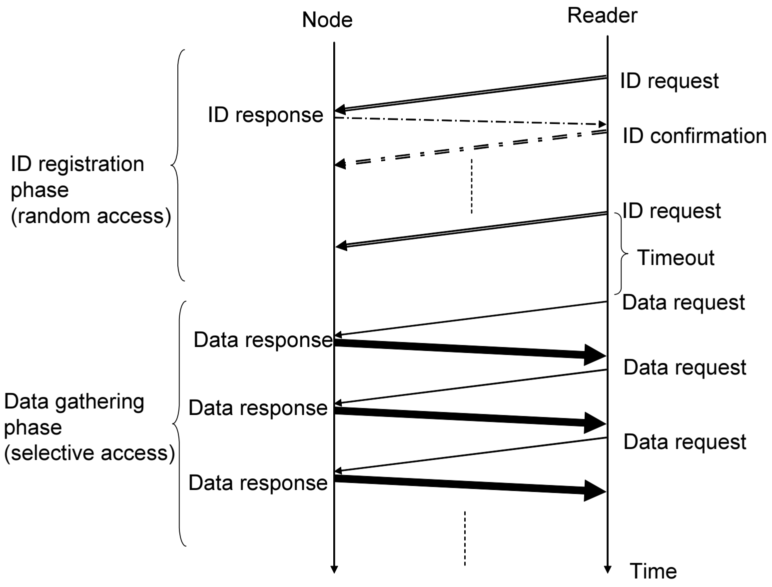


Figure 2. Overview of basic method

2.2. Basic method

Before explaining the whole of our method, we first discuss the case where nodes do not move around.

Figure 2 shows an overview of our basic method. The basic method consists of two kinds of phases: ID registration phase and data gathering phase. At first, an ID registration phase is initiated to collect each ID from all nodes in the access area. After the ID registration phase finishes, data gathering phase is infinitely carried out to gather data from them according to the ID list. In the following, we describe the details of each phase.

In the ID registration phase, the reader sends an ID request to all nodes in the access area. On receiving the ID request, a node that has not registered its ID (i.e., non-registered node) replies an ID response to the reader with the response probability defined in the ID request. The purpose of the probabilistic approach is to prevent that multiple nodes simultaneously respond to the same ID request, which results in a collision. On receiving an ID response, the reader registers the ID and sends an ID confirmation to the corresponding node. Note that the reader can communicate with a specific node using the ID. If a node receives an ID confirmation, it will not respond the succeeding ID requests. The reader detects timeout when any node does not reply the ID request for pre-determined time. The timeout can be also used for detecting the finish of the ID request phase. The ID request phase finishes when any node does not respond an ID request with the response probability of one.

After the ID registration phase, data gathering phase is sequentially carried out. In the data gathering phase, the reader selects a node from the ID list in an ascending order and sends a data gathering request to the selected node. On receiving the data gathering request, the node responds its own data to the reader. On the contrary to the ID request, the data gathering request is sent to only one node, thus any collisions do not occur. If the reader finishes gathering data from all nodes registered in the ID list, the next data gathering phase starts.

Since a collision may occur only in the ID registration phase, our basic method is effective as the number of data gathering phases becomes large.

2.3. Extended method

When a node can move around, it may freely enter and leave an access area. In such a case, the basic method cannot gather data from nodes that enter the access area after the ID registration phase finished. To tackle this problem, we extend the basic method by introducing a mechanism to switch the ID registration phase and the data gathering phase.

Whenever the ID list is empty and there is no data to be read, the ID registration phase is repeated. Otherwise, the following sequence is continued. First, the reader selects a node from the ID list in an ascending order and then gathers data from the selected node. Then, it changes to the ID registration phase with a pre-determined probability (P_{uir}) to detect a new node entering the access area. Regardless of the result of the ID registration, the reader resumes the data gathering phase again.

Furthermore, the reader must update its ID list whenever a node enters or leaves the access area. It can know a node departure by detecting timeout after sending a data gathering request. If the timeout occurs, the reader removes the corresponding ID from the ID list. A node that leaves the access area but its ID is still registered in the ID list is called as non-deleted node. On the other hand, when a new node enters the access area, the reader has to register its ID as soon as possible. However, there may be more than one non-registered nodes in the access area. To effectively read each ID from multiple non-registered nodes, the reader appropriately controls the response probability to avoid a collision. The optimal response probability is determined by the number of non-registered nodes but the details are described in section 3.

To gather data from a node before its departure from the access area, the reader has to restrict the time that each node can transmit its data to the reader at once. We introduce parameter D that is the ratio of the time for data response to the time for data request. The appropriate value of D depends on the application.

3. ANALYSIS

In this section, we focus on the most significant parameters that affect the system performance: the number of non-registered nodes (N_{rs}), the number of non-deleted nodes (N_{rd}), and the response probability (P_{idrsp}). If N_{rs} increases, the reader cannot effectively collect data from the registered nodes because it has to spend much time for registering the IDs of non-registered nodes. The large value of N_{rd} also degrades the efficiency of data gathering due to the increase of timeout at the data gathering phase. Furthermore, the reader has to control appropriately P_{idrsp} to read an ID from only one node at once.

We first derive N_{rs} and N_{rd}. These parameters are affected by other parameters of the proposed method and system environments. The related parameters of the proposed method are $P_{uir}$and P_{idrsp}. The system environments are the node mobility and the scale of the system, namely the number of nodes in the access area.

N_{rs} increases as time passes and decreases when the reader successes to register an ID of a node. On the contrary, N_{rd} also increases as time passes and decreases the reader detects a node disappearance. We define T^0 as the average interval between two successive ID requests.

$$T^0 = T_{id} + \frac{T_{data}}{P_{uir}} \tag{1}$$

Here, T_{id} is the average time of an ID registration sequence and T_{data} is that of data gathering sequence.

$$T_{id} = P_{idto}T_{idto} + P_{idreg}T_{idreg} + P_{idcol}T_{idcol} \tag{2}$$

$$T_{data} = P_{dtto}T_{dtto} + P_{dtreg}T_{dtreg} \tag{3}$$

Here, P_{idto}, P_{idreg}, and P_{idcol} are the probabilities of timeout, success of registration, and collision in the ID registration phase, respectively. T_{idto}, T_{idreg}, and T_{idcol} are time required for each event. On the other hand, P_{dtto} and P_{dtreg} are the probabilities of timeout and success of registration in the data gathering phase, respectively. T_{dtto} and T_{dtreg} are time required for each event.

As mentioned before, the reader successes to register an ID of a node if only one node sends ID response to it. Therefore, for each T^0, P_{idreg} becomes as follows.

$$P_{idreg} = {}_{N_{rs}}C_1 * P_{idrsp} * (1 - P_{idrsp})^{(N_{rs}-1)} \tag{4}$$

Next, we derive the rate R_{del} of removing a non-deleted node. The reader accesses $\frac{1}{P_{uir}}$ nodes for each T^0. If there are N_{ra} nodes registered to the ID list, the time that reader needs to access all of them becomes $N_{ra}T^0P_{uir}$. Suppose there are N_{rdc} non-deleted nodes in the access area, R_{del} is derived as follows.

$$R_{del} = \frac{N_{rdc}}{N_{ra} * T^0 * P_{uir}} \tag{5}$$

We assume that the number of nodes that enter the access area follows a poisson distribution whose average arrival rate is R_{in}. On the other hand, we assume that the average inter-arrival time between two successive node departures follows an exponential distribution whose average is $\frac{1}{P_{out}}$. We focus on the system performance in the stationary state not the transient state. In the stationary state, the number of nodes entering the access area is equal to that leaving the access area as follows.

$$R_{in} = N_{al}P_{out} \tag{6}$$

Furthermore, in the stationary state, the increasing amount of non-registered nodes, that is R_{in}, becomes the same as the decreasing amount of them as follows.

$$R_{in} = \frac{P_{reg}}{T^0} + P_{out} * N_{rs} \tag{7}$$

Note that we use the Inversion Formula of Palm Calculus (See Appendix A) with $\lambda = \frac{1}{T^0}$ and $E^0(\cdot) = P_{reg}$ because P_{reg} is an event-driven parameter and others are time-driven parameters. By introducing the Inversion Formula, the rate of registering non-registered nodes is also equal to the rate of removing non-deleted nodes R_{del} as follows.

$$\frac{P_{reg}}{T^0} = R_{del} \tag{8}$$

We can regard the process of removing non-deleted nodes as a queuing system in which the average arrival rate is the rate of removing non-deleted nodes R_{del} and the average service duration is the time that the reader accesses all nodes in the ID list, namely $N_{ra}T^0P_{uir}$. By using Little's law, we can derive the average number of non-deleted nodes removed, i.e., N_{rd}, as follows.

$$N_{rd} = \frac{N_{rdc}}{2} \tag{9}$$

The number of nodes in the ID list (N_{ra}) is sum of N_{rd} and the number of registered nodes (N_{rc}) as follows.

$$N_{ra} = N_{rd} + N_{rc} \tag{10}$$

The number of nodes in the access area (N_{al}) is sum of N_{rs} and N_{rc} as follows.

$$N_{al} = N_{rs} + N_{rc} \tag{11}$$

Based on the above mentioned equations, we derive N_{rs} and N_{rd}. By using Eq. (4) and Eq. (7), we obtain the following equation.

$$R_{in} = \frac{N_{rs} * P_{idrsp} * (1 - P_{idrsp})^{(N_{rs}-1)}}{T^0} + P_{out} * N_{rs} \tag{12}$$

We can indirectly obtain N_{rs} by using this equation.

On the other hand, N_{rd} is derived as follows.

$$N_{rd} = \frac{\frac{R_{in}^2 * T^0 * P_{uir}}{P_{out}}}{2 * \left(1 - \frac{R_{in} * T^0 * P_{uir}}{2}\right)} \tag{13}$$

The details of the derivation is described in Appendix B.

We also make an analysis on the optimal value of response probability P_{idrsp}, which maximizes P_{idreg}. We first differentiate Eq. (4) with respect to P_{idrsp} as follows.

$$\frac{dP_{idreg}}{dP_{idrsp}} = N_{rs}(1 - N_{rs}P_{idrsp})(1 - P_{idrsp})^{N_{rs}-2} \tag{14}$$

Since P_{idrsp} ranges $[0, 1]$, $(1 - P_{idrsp})$ is always positive. When $0 \leq P_{idrsp} < \frac{1}{N_{rs}}$, Eq. (14) becomes positive. When $\frac{1}{N_{rs}} < P_{idrsp} \leq 1$, Eq. (14) becomes negative. Thus, the optimal value of P_{idrsp} is following.

$$P^{opt}_{idrsp} = \frac{1}{N_{rs}} \tag{15}$$

Equation (15) indicates that the reader should control P_{idreg} in accordance with N_{rs}. However, the reader cannot directly obtain N_{rs}. To tackle this problem, we further introduce a method to autonomously control P_{idrsp} based on the results of the last ID request. If the reader successes to receive an ID response, it does nothing. Otherwise, it changes P_{idrsp} as follows.

$$P_{idrsp} = \begin{cases} P_{idrsp} * X & (0 < X < 1) \quad \text{(If collision occurs)} \\ P_{idrsp} * Y & (1 < Y) \quad \text{(If timeout occurs)} \end{cases} \tag{16}$$

X and Y are control parameters represents the trade-off between accuracy of the estimation and adaptability to changes of N_{rs}. Timeout/collision indicates that the reader underestimates/overestimates N_{rs} compared with the actual number of nodes.

4. SIMULATION EXPERIMENTS

In this section, we conduct several simulation experiments to evaluate the system performance and the validity of the analysis in section 3. We evaluate the system performance in terms of the efficiency of ID registration and data gathering. N_{rs} can be used to evaluate the efficiency of ID registration. Smaller value of N_{rs} means that the reader effectively collects IDs from nodes in the access area. On the other hand, we evaluate the efficiency of data gathering with two kinds of criteria: N_{rd} and N_{read}. If N_{rd} is small, the reader can gather data from nodes with less number of timeout. N_{read} is average number of data gathering per node, which is defined as the ratio of the total number of data gathering to the total number of nodes entering the access area during the simulation. The larger N_{read} is, the more often the reader can gather data from each node in the area.

In the next subsection, we explain the simulation settings. Then, we evaluate the basic characteristics of the proposed method and verify the validity of the analysis in subsection 4.2. Subsection 4.3 presents the effectiveness of autonomous control of P_{idrsp} described in section 3. 最後に P_{uir} を調整することで ID 登録とデータ収集のどちらを優先すべきかを評価する？

4.1. Simulation settings

本シミュレータではノードのモビリティ条件, リーダ, ノードの処理遅延, 通信時間など様々な設定を行うことができる. アクセスエリアに滞留するノード数は式 6 より, ノードのモビリティ条件である R_{in},P_{out} を調節することで設定可能である. 今回のシミュレーションでは $N_{al} = 120$ 前後になるように設定している. すると R_{in}, P_{out} は $(R_{in}, P_{out}) = (1, 0.00833), (2, 0.0166), \cdots$ と R_{in}, P_{out} は一対一で決定される.R_{in},R_{out} が環境設定のパラメータであるのに対し, システムそのものに関するパラメータ, つまりリーダ, ノードの処理遅延, 通信時間を調節することも可能である. id 登録フェーズ, データ読み出しフェーズにおける各イベントにかかる時間が設定される. これにより 2.3 節において触れた D を決定することができる. リーダとノードの 1 回の通信でやり取りするデータ量が大きいアプリケーションでは D の値は大きくなり, 逆の場合は D の値は小さくなると考えられる.

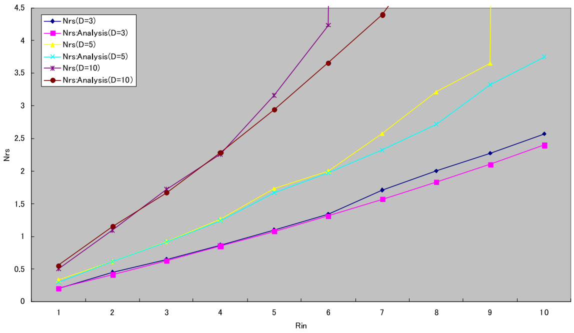
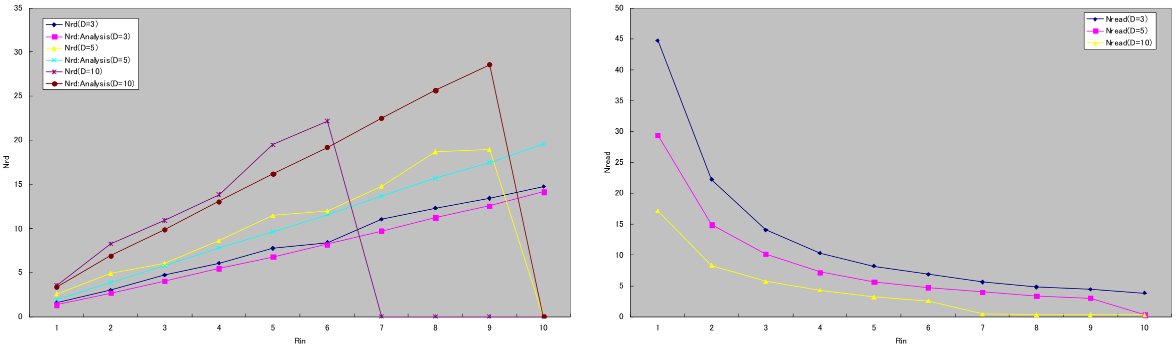


Figure 3. Efficiency of ID registration ($P_{idrsp} = 0.1$, $P_{uir} = 1$)



(a) N_{rd}

(b) N_{read}

Figure 4. Efficiency of data gathering ($P_{idrsp} = 0.1$, $P_{uir} = 1$)

4.2. Basic characteristics

In this subsection, we set P_{idrsp} and P_{uir} to 0.1 and 1, respectively to evaluate the basic characteristics of the proposed method.

図 3, 図 4(a), 図 4(b) は,D=3,5,10 毎に R_{in} の変化に伴う N_{rs},N_{rd},N_{read} の変化を表したものである. 図 3, 図 4(a) においては解析結果から得られる解析値もプロットした. 図 3, 図 4(a), 図 4(b) を見ると,D の値に関係なく R_{in} が大きくなるにつれ N_{rs},N_{rd} の値は大きく, N_{read} の値は小さくなる. つまりモビリティが高くなるにつれ ID 登録, データ読み出しのパフォーマンスが低下していくことがわかる. また,$R_{in} \leq 6$ の範囲では,R_{in} の値に関係なく,D が大きくなるにつれ N_{rs},N_{rd} の値は大きく, N_{read} の値は小さくなる. すなわち, ノードから収集すべきデータ容量が大きく,1 回のデータ通信時間が長い場合, 本方式のパフォーマンスが低下することがわかる.

本方式は N_{rs} が発散するとシステムとして成り立たなくなる. なぜなら ID 登録フェーズにおいて, ID 応答が衝突し続け,ID 登録が全く成功しない状態となりデータ読み出しを行えない状態へ陥ってしまうからである. 図 3 を見ると D=10 の場合,$R_{in} \geq 7$ で,D=5 の場合では $R_{in} \geq 10$ で, グラフには掲載していないが D=3 の場合では $R_{in} \geq 12$ にまでモビリティが高くなると,N_{rs} が発散状態に陥る. このような状態では N_{rd} は 0 へと収束するが, パ

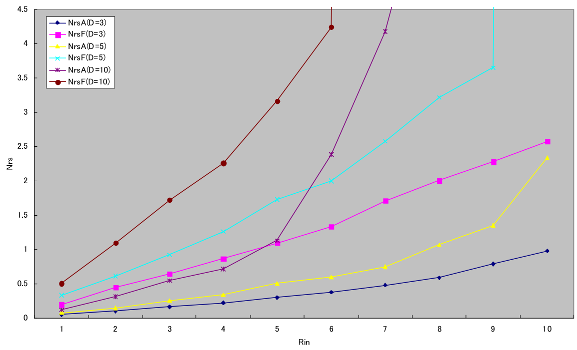


Figure 5. Efficiency of ID registration ($P_{idrsp} = auto$, $P_{uir} = 1$)

フォーマンスが向上しているわけではなく, むしろ低下しているということに注意したい. また N_{read} も 0 に収束しパフォーマンスが低下する. N_{rs} が発散状態陥る理由は P_{idrsp} を固定値にしているためであり, この問題を解決すべく式 (17) を用いた P_{idrsp} の最適制御を行うことが必要となる. この結果については次節 4.3 で扱う.

N_{rs},N_{rd} の解析の妥当性について述べる. シミュレーションにおいて N_{rs} の発散が起こらない範囲で,D=3,D=5,D=10 のとき,N_{rs} の平均誤差はそれぞれ 0.078,0.13,0.16 となった. また, N_{rd} についてもその平均誤差はそれぞれ 0.69,1.17,1.59 となった.D の値が大きくなるにつれその誤差は大きくなるが, これは解析式を求める際の近似が影響を及ぼしているものである.

4.3. Effectiveness of autonomous control of P_{idrsp}

前節のシミュレーションは $P_{idrsp} = 0.1$ と固定した値で行われた. しかしこのように P_{idrsp} を固定すると N_{rs} が大きい場合衝突を招く原因となる. また N_{rs} が小さい場合は id 要求のタイムアウトの原因ともなる. このような問題を解決する 1 つの方法に, P_{idrsp} の値を固定値ではなく, 状況に応じて変動させることが挙げられる. そこで以下の式に基づき P_{idrsp} を変動させた.

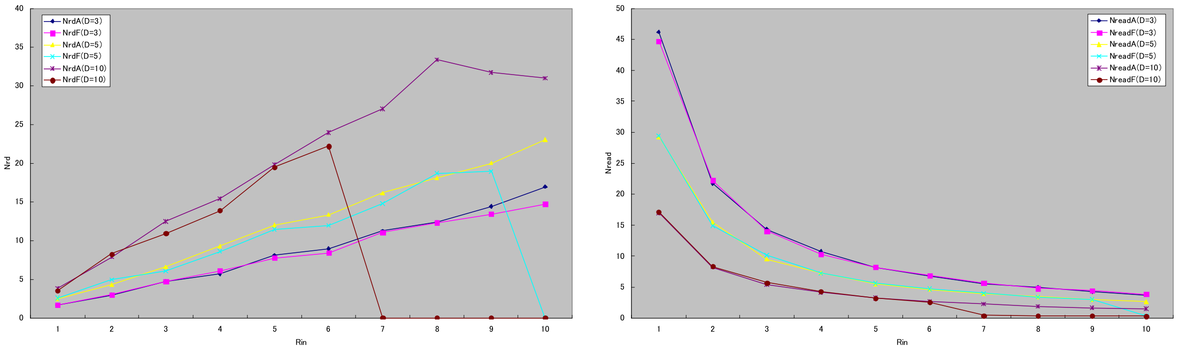
$$P_{idrsp} = \begin{cases} P_{idrsp} * X \quad (0 < X < 1) \quad (If \quad collision \quad occurs.) \\ P_{idrsp} * Y \quad (1 < Y) \qquad\quad (If \quad time \quad out \quad occurs.) \end{cases} \tag{17}$$

リーダが衝突を検知すると N_{rs} が大だと判断し,P_{idrsp} を小さくする. またリーダがタイムアウトを検知すると N_{rs} が小だと判断し,P_{idrsp} を大きくする. この X,Y の決定はシミュレーション試行による経験値で X=0.9462,Y=1.08 とした.

図 5, 図 6(a), 図 6(b) は P_{idrsp} を式 17 に従い変動させた場合と, 固定させた場合を比較したグラフである. 図 5 を見ると, 最適な P_{idrsp} を推測しながら変動させるほうが N_{rs} 数を抑えられることが確認できる. しかしながら,D=10 のとき,$R_{in} \geq 7$ 以上になると急激に N_{rs} の数が増大することがわかる. 最適な P_{idrsp} が推測できているので,P_{idrsp} を固定している場合と異なり登録が全く成功しなくなることはないが, システム的な限界点に達したと考えるのが妥当である. このことは図 6(a) を見ると,D=10 の場合,$R_{in} = 8$ を境に N_{rs} が減少に転じていることからもわかる. これは id の削除が効率よく行われているのではなく,N_{rs} が増大したため, それに伴い削除すべき未削除ノードも減少した結果であると考えられる. これらを考慮すると D が大きい場合,R_{in} が大きくなりすぎるとシステムが成り立たない可能性がある. しかしながら P_{idrsp} を固定した場合と比べるとモビリティへの対応は十分高くなった. また, 図 6(b) を見ると P_{idrsp} を固定した場合, 変動させた場合に大きな変化は見られない. よって P_{idrsp} は固定するより変動させたほうが R_{in} が大きくても読み出しを続行させることができ, N_{rs} も抑えることができる. すなわち P_{idrsp} をモビリティに合わせて最適制御することでより高いモビリティに対応できるということを確認することができた.

4.4. Puir について

解析では $P_{uir} = 1$ として扱ったが, シミュレータでその値を変化させ, システムに及ぼす影響を見た.



(a) N_{rd}

(b) N_{read}

Figure 6. Efficiency of data gathering ($P_{idrsp} = auto$, $P_{uir} = 1$)

5. CONCLUSION AND SUMMARY

本論文ではユビキタス環境に適応する無線通信方式の提案を行った．ランダムアクセスとセレクティブアクセスの組み合わせにより従来方式に比べ高い転送効率を得ることができた. 本方式においてイベントドリブンとタイムドリブンな事象の混在する状態を Palm Calculus を用いることにより解析した．通信効率と未登録ノード数, 未削除ノード数にはトレードオフの関係があることを確認した．これらのバランスを保つようなパラメータチューニングが必要となる．また, ノード数, ノードのモビリティなどが動的に変化すると予想できるユビキタス環境において, それらの条件にフレキシブルに対応できるようリーダの id 要求に対するノードの id 応答確率を動的に変化させることで未登録ノード数の発散を防げることを確認した．今後の課題は Puir をはじめてとする各パラメータの最適制御法の研究, ノードの消費電力の考慮, シミュレータの改良, 複数リーダにおけるリーダコリジョン問題,[10,11]も考慮していく必要がある．

In this paper, we proposed a radio communication method to fit ubiquitous environment. The method could achieve high transfer efficiency by using combination of random access and selective access. This result is higher than legacy methods. In analysis of the method, Palm calculus makes it easy to analyze a state that is consisted of combination of event driven phenomenon and time driven phenomenon. In our simulations, we confirm trade-off among transfer efficiency, non-registered nodes, and non-deleted nodes. It's very important to balance this relation by tuning appropriate parameters. In ubiquitous environment, it's natural to think that the number and mobility of the nodes is not constant. So our method can deal such case by changing probability of id response. A future problem is a study of the most suitable control probability of id reply, consideration of consumption electricity of a node, and improvement of a simulator.

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APPENDIX A. PALM CALCULUS

Palm calculus[9] is a set of formulas that relate time averages versus event averages. Time averages are obtained by sampling the system at arbitrary time instants. The event averages are obtained by sampling the system when selected state transitions occur. In general, the behavior of a system can be expressed as a Markov chain. If the chain is irreducible, which means that any state can be reached from any state in a infinite number of steps, then the stationary regime is independent of the initial conditions. If the system is both irreducible and converges to some stationary behavior, then it has an unique stationary regime and is said to be “ergodic.” In such a system, the following inversion formula makes sense in the steady state.

$$E(X_t) = E(X_0) = \lambda E^0 \left(\sum_{s=1}^{T_1} X_s \right) \tag{18}$$

Here, $E(X_t)$ and $E(X_0)$ are time averages at t and 0 in stationary regime, respectively. $E^0(\cdot)$ is palm expectation. Xs is some observation of the system that is jointly stationary with the simulation. T_1 is the number of transitions. λ is intensity that is the number of transitions per time unit.

APPENDIX B. DERIVATION OF N_{RD}

From Eq. (6) and Eq. (11), we obtain

$$N_{rc} = \frac{R_{in}}{P_{out}} - N_{rs}. \tag{19}$$

Next, we derive the following equation from Eq. (10) and Eq. (9).

$$N_{ra} = N_{rc} + \frac{N_{rdc}}{2} \tag{20}$$

From Eq. (19) and Eq. (20), N_{ra} becomes

$$N_{ra} = \frac{R_{in}}{P_{out}} - N_{rs} + \frac{N_{rdc}}{2}. \tag{21}$$

From Eq. (8), Eq. (5), and Eq. (4),

$$\frac{N_{rdc}}{T^0 * N_{ra} * P_{uir}} = \frac{N_{rs} * P_{idrsp} * (1 - P_{idrsp})^{(N_{rs}-1)}}{T^0} \tag{22}$$

From Eq. (4) and Eq. (7),

$$N_{rs} * P_{idrsp} * (1 - P_{idrsp})^{(N_{rs}-1)} = P_{out} * \left(\frac{R_{in}}{P_{out}} - N_{rs} \right) * T^0 \tag{23}$$

By substituting Eq. (22) to Eq. (23), we get

$$\frac{N_{rdc}}{T^0 * N_{ra} * P_{uir}} = P_{out} * \left(\frac{R_{in}}{P_{out}} - N_{rs} \right). \tag{24}$$

We obtain the following approximate expression by omitting N_{rs} in Eq. (21) and Eq. (24).

$$N_{rdc} = \frac{\frac{R_{in}^2 * T^0 * P_{uir}}{P_{out}}}{1 - \frac{R_{in} * T^0 * P_{uir}}{2}} \tag{25}$$

Finally, N_{rd} is derived from Eq. (9) and Eq. (25).

$$N_{rd} = \frac{\frac{R_{in}^2 * T^0 * P_{uir}}{P_{out}}}{2 * \left(1 - \frac{R_{in} * T^0 * P_{uir}}{2}\right)} \tag{26}$$

We should note here that Eq. (26) is an approximate expression that makes sense when N_{rs} is relatively small. The validity of this analysis is evaluated in our simulation experiments (section 4).