Resource Discovery Using Spatio-temporal Information in Mobile Ad-Hoc Networks[*]

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Abstract. In this paper we examine the benefit of reports about resources in mobile ad-hoc networks. Each disseminated report represents information about a spatio-temporal event, such as the availability of a parking slot or a cab request. Reports are disseminated by a peer-to-peer broadcast paradigm, in which an object periodically broadcasts the reports it carries to encountered objects. We evaluate the value of resource information in terms of how much time is saved when using the information to discover resources, compared to the case when the information is not used.

1 Introduction

A few recent papers augment routing protocols of mobile ad-hoc networks (MANET) in order to enable discovery of physical resources (see [9, 12]). However, the existing work does not distinguish between competitive and non-competitive resources. A competitive resource is used in an exclusive style, that is, it can be used by at most one consumer at any point in time. For example, a parking slot can be used by a single vehicle at a time, a taxi-cab request can be satisfied by a single cab, and a cab can satisfy a single request at a time. Thus parking slots, cab-customers, and cabs are competitive resources. In contrast, a non-competitive resource is used in a shareable style, that is, it can be used by more than one consumer at any point in time, for example, gas stations and traffic conditions.

In this paper, we consider discovery of competitive physical resources in a MANET, and conduct a comparative study of alternatives. One contribution is to quantify the benefit of using resource-discovery information. We define this benefit to be the (resource-discovery-time-without-information) minus (resource-discovery-time-with-information). As far as we know, this benefit has not been quantified previously. Our experiments show that by using resource-discovery information disseminated via a MANET the resource discovery time can be cut by as much as 70%.

Another difference between existing literature and the present paper is the following. Existing literature on MANET's has studied resource discovery in a *pull* fashion. Specifically, a mobile node disseminates queries in a MANET, in which routing

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protocols have been augmented and adapted for resource discovery. The nodes that have the queried resources will send the resource-information to the querying node.

However, in this paper we consider the *push* fashion, because the *pull* fashion can be inefficient, particularly in high mobility vehicular networks which are prone to frequent disconnection. In the *push* fashion, a resource periodically broadcasts resource-reports it produces to neighboring objects (i.e. objects that are within the wireless transmission range of the resource). These objects store the received reports in their local reports database. After that an object o periodically ranks the reports in its local reports database and broadcasts the top M reports to its neighboring objects. Thus resource-reports transitively spread out across objects. The reports are ranked by a relevance function that decreases the older the report gets, and the farther the reported resource is from o. We call this approach *peer-to-peer broadcast*, or *PPB*. PPB may seem like simple flooding, but the flooding is controlled by the relevance of reports which decays with distance and time. Consequently, the flooding is automatically limited to spatial and temporal proximity to the resource, similar to the behavior of an opportunistic peer-to-peer system (see [4]). Furthermore, our study shows that the performance of PPB, on disseminating useful resource information to consumers, is insensitive to the value of M. In other words, broadcasting only the top one report is as good as broadcasting the whole local reports database. This demonstrates that PPB is efficient in bandwidth consumption.

In Summary, This Paper Makes the Following Contributions. (1) It proposes a data model for representing physical resources, possibly having spatial and temporal characteristics. (2) It proposes the PPB method for disseminating resource-discovery information in MANET's. (3) It quantifies the value of resource-discovery information.

Before outlining the rest of the paper, let us observe that MANET resource discovery arises in many application domains including social networks, transportation, mobile electronic commerce, emergency response, and homeland security. For example, in a large professional, political, or social gathering, the technology is useful to automatically facilitate a face-to-face meeting based on matching profiles. In transportation, the PPB algorithm incorporated in navigational devices can be used to disseminate to other similarly-equipped vehicles information about relevant resources such as free parking slots, traffic jams and slowdowns, available taxicabs, and ride sharing opportunities. In mobile electronic commerce, the PBB algorithm is useful to match buyers and sellers in a mall, or to disseminate information about a marketed product. In emergency response, the PPB algorithm can be used by first responders to support rescue efforts even when the fixed infrastructure is inoperative; it will match specific needs with expertise (e.g. burn victim and dermatologist), and help locate victims. In homeland security, sensors mounted on neighboring containers can communicate and transitively relay alerts to remote check-points.

The rest of the paper is organized as follows. Section 2 develops the data model. Section 3 discusses resource discovery in PPB. Section 4 evaluates the benefit of using resource information in PPB. Section 5 discusses relevant work and section 6 concludes the paper.

2 The Model

In our system, there is a single type of spatio-temporal resources, such as parking slots, car accidents (reports about such resources provide traffic-jam information), taxi-cab requests, ride-sharing invitations, or demands of expertise in disaster situations, and so on. These resources are spatial in the sense that they are tied to a location, and are temporal in the sense that they are valid or available only for a limited time-duration. We assume that resources are located at points in two-dimensional geospace. The state of each resource alternates between *valid* (i.e. available) and *invalid*. The period of time during which the resource is valid is called the *valid duration*. For example, the valid duration of the cab request resource is the time period since the request is issued, until the request is satisfied or canceled.

The validity of a resource R is indicated by its *validity report* (or *report* for short), denoted $a(R)$. The report may be produced by a sensor or a processor associated with the resource. Each report $a(R)$ contains three attributes, namely *resource-id*, *timestamp*, and *location*. Attribute resource-id is the identification of R that is unique among all the resources in the system. Timestamp indicates the time at which $a(R)$ is transmitted by R. Location indicates the location of R.

In addition to resources, the system consists of *moving objects*. At each point in time, a moving object o is either a *consumer* or a *broker*. o is a consumer if it is searching for a resource. o is a broker if it is not searching for a resource but is participating in PPB dissemination. Resources are used only by moving objects that are consumers. o has a *reports database* that stores the reports o has received. Moving objects and resources are collectively called *peers*.

Each report $a(R)$ has a relevance when it is received. The relevance of $a(R)$ to a moving object o is determined by the following spatio-temporal function.

Definition: The relevance of a report $a(R)$ to a consumer that receives it t time units after $a(R)$'s timestamp, and d distance units from the location of R is:

$$\mathrm{Rel}(a(R)) = e^{-\alpha \cdot t - \beta \cdot d} \quad (\alpha, \beta \geq 0) \tag{1}$$

α and β represent the decay factors of time and distance respectively. t represents the delay from the time when $a(R)$ is transmitted until $a(R)$ is received by the consumer, and is referred to as the *report delay*. We now show that for a competitive resource R, under some very reasonable conditions the relevance of a report $a(R)$ to a consumer o, as computed by Equation (1), equals to the probability that R is still valid when o reaches it.

Theorem 1: Assume that consumers arrive at a resource R according to a Poisson process with intensity λ. Let o be a consumer that moves at a constant speed v, and receives a report $a(R)$ t time units after $a(R)$'s timestamp, at distance d from the location of R. When $\alpha = \lambda$ and $\beta = \lambda / v$, Rel($a(R)$) as computed by (1) equals to the probability that R remains valid when o reaches it.

Proof Idea. Let t_0 be the timestamp of $a(R)$. According to the report transmission model, R is valid at t_0. Since consumers arrive at R according to a Poisson process with intensity λ, the probability that no other consumers reach R x time units after t_0 is $e^{-\lambda \cdot x}$. Observe that the consumer o will reach the resource $t+d/v$ time units after t_0, and thus the probability that R remains valid when o reaches it is $e^{-\lambda(t+d/v)}$, which equals to Rel(a(R)).

The theorem motivates our definition of the relevance function.

The relevance function we use in this paper is one example in which the relevance decays exponentially per time and distance. But there are other possible types of relevance functions in which other behaviors may be exhibited. Furthermore, other factors such as the travel direction with respect to the home of a resource, or the price of the resource, may be considered in the relevance function. However, in this paper we confine ourselves to time and distance alone.

3 Resource Discovery in PPB

In this section we first describe PPB in 3.1, and then, in 3.2 we discuss two resource-discovery strategies, one using resource-reports to discover resources, and another which does not do so.

3.1 PPB Dissemination

We assume that each peer participating in PPB is capable of communicating with the neighboring peers within a maximum of a few hundred meters, via for example, the 802.11 wireless technology. In addition, each peer is equipped with a GPS system so that (i) the peer knows its location at any point in time and (ii) the clock is synchronized among all the peers.

In the PPB dissemination, the resource-reports are periodically broadcast by resources to the moving objects that pass by, i.e. within transmission range. A report is broadcast only during the valid duration of the resource, and each report is timestamped with the broadcast time. Upon receiving new reports, a moving object o saves the new reports into its local reports database. Periodically, o sorts the reports in its local database according to their relevance, and broadcasts the top M reports. M is called the *broadcast size* and it is a parameter of the PPB algorithm.

For the rest of the subsection we discuss how the broadcast period used in PPB is determined. For the sake of simplicity we assume that all the moving objects in the system use the same broadcast size. Denote by w the broadcast period. w is chosen based on the analytical model introduced in [1]. This model gives the throughput[1] of the wireless channel in an 802.11 ad hoc network as:

$$Th = \frac{L \cdot (p \cdot e^{-p \cdot \lambda \cdot \pi \cdot r^2 \cdot (1+9 \cdot (2 \cdot L/\tau+1))})}{\tau + p \cdot (L+\tau)} \tag{2}$$

where L is the transmission time of the average broadcast message (which is proportional to the length of the message), τ is the length of the media-access time slot (20µs for 802.11b), p is the probability with which a node starts a broadcast at an arbitrary media-access time slot, λ is the average number of nodes per unit size of area, and r is the transmission range in meters. Observe that the broadcast probability p can be

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[1] The throughput is defined to be the fraction of time in which the communication channel of a moving object is engaged in successful transmission of user data.

substituted by τ / w, because if every moving object broadcasts every w seconds, then for every moving object the broadcast probability at an arbitrary medium access time slot is τ / w. For example, if $w=5$ seconds and $\tau = 20\,\mu$s, then $p = \frac{20 \cdot 10^{-6}}{5} = 4 \cdot 10^{-6}$.

After substituting p by τ / w in Equation (2), if τ, L, λ, and r are fixed, then the throughput Th as a function of the broadcast period w is a bell curve. Thus there is a value of w that maximizes Th. Intuitively, when w is very big, then for a large fraction time the wireless channel is idle, and therefore the channel utilization is low. As the broadcast period decreases, the idle time decreases. But in the meantime the probability of collisions becomes higher, because the 802.11 broadcast does not use handshakes to avoid or detect collisions as unicast does. Thus there is a value of w that achieves the best tradeoff between the channel utilization and broadcast reliability. And this value is computed and used by the PPB algorithm.

Now we show that indeed, except for w, all the parameters of Equation (2) can be determined by a moving object. The object density λ can be determined by an object o in various ways. For example, each moving object periodically handshakes with each one of its neighbors and counts the number of neighbors, or o has a pre-loaded table in which each entry gives the object density at each geographic area at each time period (e.g. rush hour). The transmission time L can be computed as follows. Denote by S the size of a report in bytes, by b the transmission speed in bits per second (2Mbps for 802.11b), and by h the size of the MAC header of the broadcast message in bytes (47 for 802.11b). Then the transmission time L is $\frac{(S \cdot M + h) \cdot 8}{b}$. For example, if $S = 1000, M = 10, h = 47, b = 2 \times 10^6$, then $L \approx 40ms$.

Furthermore, the broadcast period w can be adjusted to parameterization of the bandwidth consumption. For example, a user may allocate only 10% of the available short-range bandwidth to resources-reports of the particular type (e.g. parking). The rest of the bandwidth may be dedicated to other resources, multimedia applications, etc. In this case, for determining the period w, the message transmission time L is computed with the broadcast size taken to be $10 \cdot M$ reports.

3.2 Resource-Discovery Strategies

In this subsection, we discuss two resource-discovery strategies for competitive resources; one does not use any reports, while the other one takes advantage of the reports of competitive resources.

Blind Search. The first competitive resource-discovery strategy is a naive one, called *blind search*, or BS. With this strategy, a consumer moves around the area where a resource of interest could possibly be located, and it takes possession of the first resource that is valid at the time when the consumer reaches it. For example, a driver who is looking for a parking slot simply drives around on the streets that are within walking distance from the destination, and parks at the first parking slot that is available when passed by. The area within which the consumer looks for a resource is referred to as the *search space*.

Information Guided Search. The second strategy is *information guided search*, or IGS. With this strategy, a consumer starts with a blind search. The search continues until either a valid resource is encountered (i.e. passed by in the road network), or some resource-report $a(R)$ is received. In the latter case, the consumer attempts to capture R (i.e. moves along the shortest path to R). If R is invalid when the consumer reaches it, then the consumer discards $a(R)$, returns to the closest point in the search space, and continues the blind search. Clearly, if a valid resource is passed by on the way to R, then the consumer captures it and the search ends. If another report $a(R')$ is received during the trip to R, and the relevance of $a(R')$ is higher than $\mathrm{Rel}(a(R))$, then the consumer goes to R'. Thus, the relevance function plays an important role in the use of resource-discovery information.

4 Value of Resource Information

In this section, we evaluate how much time is saved when a consumer uses resource-reports to capture a competitive resource (resource-reports are disseminated by the PPB dissemination mechanism). First we describe the simulation method. Then we present the simulation results.

4.1 Simulation Method

Evaluation Metrics. We use the discovery time as the metrics for evaluating the benefit of the resource-discovery strategies. For a competitive resource, discovery means that the consumer captures the resource, i.e. it arrives at the resource while the resource is still valid. For example, discovering a parking slot means that the driver reaches the parking slot before it is occupied. The *discovery time* is the length of the time period starting when the consumer starts to search the resource type and ending when a resource of that type is captured. Traditionally, the effectiveness of a data dissemination algorithm is measured in terms of its throughput (how many resources are found) and the response time (i.e. the time it takes on average to find a resource). The resources addressed in this paper, whose state alternates between valid and invalid, enable us to combine the two measures into a higher level one, namely the discovery time.

Simulation Environment. We implemented our own simulation system in Java. First we describe the simulation of mobility and resources, and then we describe the simulation of wireless communication.

Simulation of Mobility and Resources. We synthetically generated and moved objects within a 1.2mile×1.2mile grid network. The distance between two neighboring grid points is 0.1 mile (approximately the length of one street block) (see Figure 1). Resources are generated at all non-border four-way intersections.

Each consumer o is introduced at a random location on the grid network. o is assigned a square as its search space, such that (i) the side length of the square is 0.6 mile; (ii) o is initially located on one of the four edges (i.e. north edge, east edge, south edge and west edge) of the square with equal probability; (iii) the square is aligned with the grid network such that o is as close to the middle of the edge as possible. The square is referred to as the *search square of o*. o moves along its search square to search resources either clockwise or counter-clockwise with equal probability. With IGS, consumers may leave the search square to capture resources that are inside or outside the square. o moves at a constant speed. The motion speed of o is randomly picked up from the interval [v-5, v+5] where v is a parameter. Initially, c consumers are introduced. Out of these consumers, fraction k use the IGS strategy (referred to as *IGS consumers*), and the others use the BS strategy (referred to as *BS consumers*). k is referred to as the *IGS consumer ratio*. Whenever an IGS (or BS) consumer captures a resource, and is thus eliminated from the system, a new IGS (or BS) consumer is introduced. Consequently, at any point in time there is a fixed number, c, of consumers in the system, fraction k using resource information.

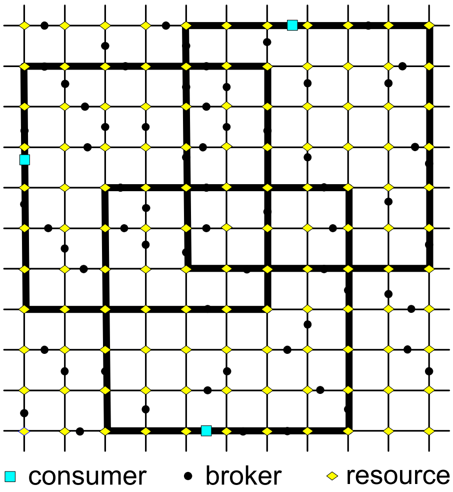

Fig. 1. The grid network, resources, search square, brokers and consumers

There are g brokers per square mile. The mobility of each broker B is simulated as follows. We randomly choose two points on the grid network, and assign them as the start point and the first stop of B respectively. The path of B is the shortest path between the start point and the first stop. B moves along its path from the start point to the first stop at a constant speed. When the first stop is reached, another random point is chosen as the second stop of B, and B moves from the first stop to the second stop at the same constant speed. And so on. The motion speed of a broker is randomly chosen from the interval [v-5, v+5].

After a resource R is captured and thus becomes invalid, there is a time period until another resource is generated at the same intersection as R. This time period is referred as an *invalid duration*. The length of invalid duration follows an exponential distribution with mean q.

We use equation (1) with $\alpha = \lambda$ and $\beta = \lambda / v'$ as the relevance function, where v' is the motion speed of the consumer, and $\lambda = 2 \cdot c \cdot v / l$; l = 31.2 miles is the total length of all the edges in the grid network, c is the number of consumers, and v is the average speed of consumers. Observe that in computing β we use the actual speed of the consumer (namely v'), which is randomly distributed around the mean v, whereas in computing λ we use the mean v. When computing the relevance, we use the *route-distance* as the distance metric. The *route-distance* between two locations on the grid network is the length in miles of the shortest path between them on the grid network.

We argue in the appendix that with our simulation setup the arrival of consumers at a resource approximates a Poisson process with intensity λ. Furthermore, we traced in simulations the arrival of consumers at each resource and found that the arrival process indeed approximates a Poisson process with intensity λ. Thus, according to Theorem 1 the relevance function gives the probability that the resource is valid when the consumer reaches it.

Simulation of Communication. We assume that each moving object allocates only fraction *a* of the available short-range bandwidth to the simulated resource type. *a* is a parameter and is referred to as the *bandwidth allocation*. When computing the broadcast period as described in section 3.1, we use the data of 802.11b, and therefore the length of a time slot is 20μs. The data transmission speed is chosen to be 5.5Mbps. The transmission range is 150 meters. The size of each resource report is 32 bytes. The node density varies from 150 to 450 objects/mile^2, depending on the broker density *g* and the number of consumers *c*. The broadcast size varies from 1 to 121. All the parameters for the simulation system are illustrated in Table 1.

Our simulation system omits detailed representation of protocol layers and radio propagation. It models the reliability of communication by each neighbor correctly receiving a broadcast with certain probability. We consider two factors, i.e. (i) signal collisions due to hidden nodes; (ii) deteriorative channel conditions due to relative motion. To model the communication failures caused by signal collisions, we adopt the analytical model proposed in [1]. The analytical model computes the probability that a broadcast message is received by all of the sender's neighbors without suffering any collisions. Such a broadcast is referred to as a *successful broadcast*. In our simulation system, if a broadcast is not successful, then none of the sender's neighbors receives the broadcast message.

A successful broadcast is correctly received by each neighbor with certain probability depending on the relative speed of the sender and the receiver. The probability is referred to as the *reception probability*. We adopt the empirical results of [5] to determine the reception probability. Specifically, given the relative speed *s*, the ratio between the 802.11b throughput under *s* and that under relative speed 0 is obtained from [5]. This ratio is taken to be the reception probability.

Table 1. All parameters and their values

Parameter	Symbol	Unit	Value
Mean of invalid duration	q	minute	10, 15, 20, 25, 30
Broadcast size	M	report	1, 5, 10, 30, 50, 70, 90, 110, 121
Transmission range	r	meter	150
Motion speed	v	miles/hour	10, 20, 30, 40, 50
Number of consumers	c	objects /mile^2	50, 100, 150, 200, 250
IGS consumer ratio	k		0 to 1 with increment 0.1
Broker density	g	objects /mile^2	0, 50, 100, 150, 200
Data transmission speed	b	bits/second	2×10^6
Medium access time slot	τ	second	20×10^{-6}
Medium access control header	h	byte	47
Report size	S	byte	32
Bandwidth allocation	a		0.001, 0.002, 0.01, 0.1, 1

In summary, Each Simulation Run is Executed as Follows. At the beginning of the simulation run, 121 resources are generated, each at one four-way intersection. c consumers and g×1.2×1.2 brokers are introduced at time 0 (remember that the total area simulated is 1.44 square miles) at random locations. Fraction k of the consumers are IGS consumers and the others are BS consumers. Resources and brokers periodically broadcast reports according to the PPB dissemination mechanism described in section 3.1. Each broadcast is correctly received by a neighbor with certain probability as described above. The sending and receiving of each broadcast is completed instantaneously (i.e. they take 0 time). The simulation run terminates after twenty simulated hours, out of which the first 500 seconds is the warm-up time period for the system to stabilize.

During each simulation run, the discovery time of each consumer is collected. The resource-discovery times of all the IGS consumers and the discovery times of all the BS consumers are averaged respectively. In the conducted simulation runs, the ratio between the 95% confidence interval and the simulation result (i.e. the average discovery time) ranges from 4% to 19%, with the average ratio being 6.6%.

4.2 Simulation Results

Impact of the Broadcast Size on IGS (Figure 2). Figure 2 shows that increasing the broadcast size does not improve the performance of IGS. In other words, with the PPB algorithm, broadcasting only the top one report is as good as broadcasting the whole database (121 reports). This is because PPB chooses the broadcasted reports based on their spatio-temporal relevance which reflects the benefit of the reports. The fact that broadcasting the top one report is enough is a nice property. It indicates that PPB is efficient in bandwidth consumption, and that it is drastically different than flooding that would broadcast all the reports in the database.

Overall Comparison Between IGS and BS. Figures 3 to 8 show the performance of IGS and BS under different parameter setups. There are three curves in each figure. Two of them represent the discovery times of IGS and BS collected in the same simulation run. The third curve, referred to as *benchmark BS*, represents the discovery time of BS under the same parameter setup, except that the consumer ratio $k = 0$. Thus benchmark BS represents the performance of BS when there are no IGS consumers in the system. From Figures 3 to 8 we can see the following. (i) IGS consistently outperforms both BS and benchmark BS. Sometimes IGS reduces discovery time by 70% compared to BS. (ii) Benchmark BS is always better than BS. This is because the IGS consumers capture resources faster than the BS consumers in the same system, which makes the BS consumers spend more time on searching than if there are no IGS consumers.

IGS Consumer Ratio (Figure 3). The discovery time of IGS increases as the IGS consumer ratio increases. This is because as the IGS consumer ratio increases, more consumers use reports. Thus for each individual IGS consumer, the chance to capture a reported resource decreases. In other words, in competitive situations the value of resource information decreases as more consumers have access to this information. Further observe that the discovery time of BS also increases as the IGS consumer ratio increase. This is because the more IGS consumers, the more likely it is that a resource is captured by an IGS consumer, and thus the less chance for a BS consumer to capture a resource.

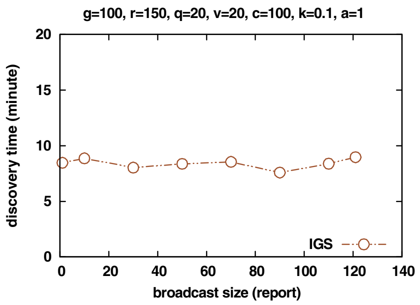

Fig. 2.

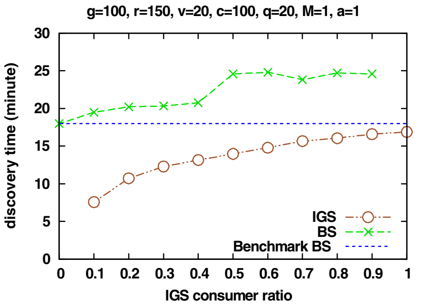

Fig. 3.

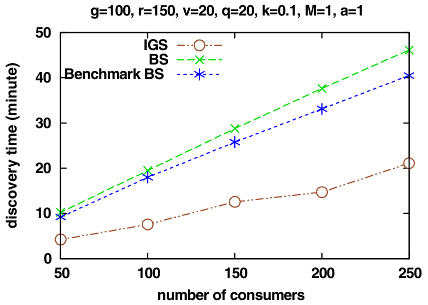

Fig. 4.

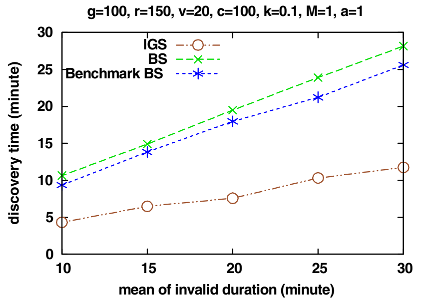

Fig. 5.

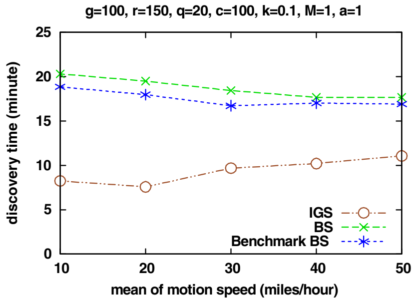

Fig. 6.

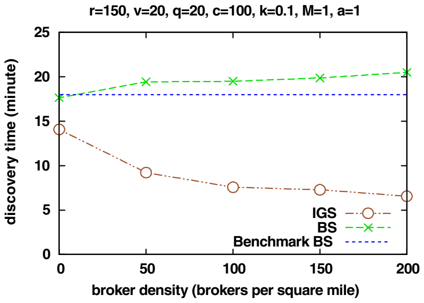

Fig. 7.

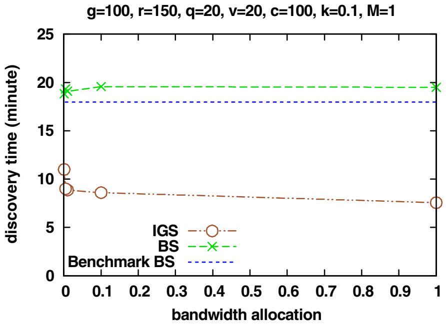

Fig. 8.

Number of Consumers (Figure 4). The discovery time of IGS and that of BS both increase as the number of consumers increases. However, the curve of IGS is flatter than that of BS. In other words, IGS is less sensitive to the increase of competition introduced by the increase of the number of consumers. This suggests that resource information is especially valuable in the areas where consumers are dense (such as downtown), i.e. competition for resources is fierce.

Mean of Invalid Duration (Figure 5). The discovery time of IGS increases as the mean of invalid duration increases. So does the discovery time of BS. However, the discovery time of BS increases faster than that of IGS. In other words, IGS is less sensitive to the increase of competition introduced by scarcity of resources. Thus, again, the value of information increases as competition for resources increases.

Mean of Motion Speed (Figure 6). Observe that an increased mean motion speed has a negative impact on IGS. This is somehow surprising because a higher speed is supposed to enable a consumer to capture a resource faster. However, higher mobility also leads to more deteriorative channel conditions and thus lower broadcast reception probability. Thus IGS consumers are less advantageous against BS consumers.

Broker Density (Figure 7). The discovery time of IGS decreases as the broker density increases. Intuitively, the increase of the broker density generates two contrary effects on performance. On the one hand, the reliability of broadcast decreases due to higher contention and more deteriorative channel conditions. On the other hand, each successful broadcast is likely to reach more objects. Figure 7 shows that the positive effect outweighs the negative one. Thus as the broker density increase, the newly generated reports are propagated more quickly and reach the consumer sooner, giving the consumer a higher probability of capturing a resource. In other words, the faster information spreads, the higher its value.

Bandwidth Allocation (Figure 8). Figure 8 plots the performance of IGS as a function of the bandwidth allocation for a particular parameter configuration. The discovery time of IGS is higher with partial capacity than that with the full capacity, but still lower than that of BS. Particularly, the discovery time of IGS increases from 7.5 minutes to 9 minutes as the bandwidth allocation (fraction) decreases from 1 (corresponding to 5.5Mbps baseline bandwidth) to 0.002 (corresponding to 11Kbps baseline bandwidth), and to 11 minutes as the fraction decreases to 0.001 (corresponding to 5.5Kbps baseline bandwidth. The reason for the increased IGS discovery time is that with the reduced bandwidth the broadcast period increases (to 5 seconds with 11Kbps and 10 seconds with 5.5Kbps). Further observe that the performance of IGS degrades very slowly as the bandwidth allocation decreases. This suggests that the bandwidth consumption of the PPB algorithm for one resource type is far below the full network capacity and therefore it is able to support many resource types and other network applications.

5 Relevant Work

A lot of works have been done in peer-to-peer data dissemination in MANET's (see e.g. [8, 10, 11, 13]). Most of these works are concentrated on how to disseminate resource information, whereas we study *how much* benefit the resource information may generate. In technical report [3], Goel et al. propose an architecture for dissemination of traffic information in mobile P2P environments and evaluate the benefit of traffic information in terms of the reduction of travel time. Their approach is geared to traffic information. For example, vehicles generate traffic reports only when the expected travel time on the road segment differs significantly from the travel time actually experienced by the vehicle, whereas we consider general spatio-temporal resources. Furthermore, they do not study how to use the resource information, whereas we do so in this paper.

This paper differs from our prior work [2] on the same topic mainly in three aspects. First, we make more realistic assumptions. For example, in [2] we assume that there is a single consumer. Second, we use peer-to-peer broadcast for reports dissemination whereas [2] uses pair-wise interactions. Finally, in this paper we use the relevance function to prioritize the communicated resource reports.

This paper differs from our prior work [14] in that in [14] we compare PPB with the client/server model whereas in this paper we compare PPB with other algorithms.

6 Conclusion and Future Work

In this paper we studied resource information for the discovery of competitive physical resources in mobile environments. First, we introduced a model of resource discovery information. Then we considered an information dissemination mode, namely *Peer-to-Peer Broadcast* (PPB). We determined that PPB results in reduced discovery time compared to the case where no information is used. Sometimes the discovery time is cut by 70%. We studied the impact of various parameters on the value of resource information (i.e. the amount of discovery time saved by using the information). The results show that in PPB mode, the value of resource information increases as the contention on resources increases. In addition, in PPB mode the resource information is more valuable when the broker density and the transmission range are large. However, resource information is less useful as more consumers use it. We also determined that the motion speed has little impact on the value of resource information.

A lot remains to be done in the future. For example, when-to-broadcast and what-to-broadcast in PPB need further study. Ranking of reports across different resource types including non-competitive resources needs to be addressed. Incentive mechanisms that stimulate brokers to participate in report dissemination are worth studying. How to integrate vehicular networks with cellular network is also worth studying.

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Appendix

In this appendix we justify the fact that in our experiments the IGS strategy uses the relevance definition given in Equation (1). To do so, we show that the conditions of Theorem 1 are satisfied by our experimental setup. More specifically, we argue that in our simulations the arrival of consumers at a resource R approximates a Poisson process with intensity $\frac{2 \cdot c \cdot v}{l}$.

A Poisson process having intensity λ is a sequence of events such that[2]:

1. The numbers of events that occur at time 0 is 0.
2. The process has stationary[3] and independent[4] increments.
3. The probability that exactly one event occurs in a sufficiently small time interval of length δ, is $\lambda \cdot \delta$.
4. The probability that two or more events occur in a sufficiently small time interval is 0.

Now we show that in our simulations the arrivals of consumers at a resource *R* (each such arrival is an event) roughly satisfy the above properties. First, since each consumer *o* is introduced at a random location, the probability that *o* is introduced at the home of *R* is zero. Thus the number of consumers that arrive at *R* at time 0 is 0.

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[2] Probability and Mathematical Statistics, Z. Sheng et al. (eds), Third Edition, Higher Education Press, China, 2001.

[3] An event sequence has *stationary increments* if the number of events during a time period depends only on the length of the time period and not on its starting point.

[4] An event sequence has *independent increments* if the numbers of events which occur in disjoint time intervals are independent.

Second, since the number of consumers in the system is fixed, the number of consumers that arrive at R during a time period depends only on the length of the time period, and not on its starting point. Thus the arrival process can be considered to have stationary increments. Furthermore, since the consumers move independently, the number of consumers that arrive at R during a time interval is independent of the number of consumers that arrive at R during any other disjoint time interval. Thus the arrival process can be considered to have independent increments.

Third, consider a sufficiently small time interval $[t, t+\delta]$. The probability that exactly one consumer arrives at R is the probability that at time t there is exactly one consumer within distance $v \cdot \delta$ from R, and moving towards R.

Now let us estimate the latter probability. Since consumers are introduced at random locations and they move at random directions, at time t the c consumers can be considered uniformly distributed in the grid network. Let the total length of all the edges in the grid network be l. Since R is located at a four-way intersection, the probability that at time t there is exactly one consumer within distance $v \cdot \delta$ from R is $c \cdot \frac{4 \cdot v \cdot \delta}{l} \cdot (\frac{l - 4 \cdot v \cdot \delta}{l})^{c-1}$. (The second factor is the probability that a specific consumer is at the required distance, and the third one is the probability that all the others are not there). Because δ is sufficiently small, this is close to $\frac{c \cdot 4 \cdot v \cdot \delta}{l}$. The consumer within distance $v \cdot \delta$ may either move toward or away from R at time t, with equal probability. Thus the probability that at time t there is exactly one consumer within distance $v \cdot \delta$ from R, and moving towards R, is $\frac{c \cdot 4 \cdot v \cdot \delta}{l} \cdot \frac{1}{2} = \frac{2 \cdot c \cdot v}{l} \cdot \delta$. In other words, according to condition 3 $\lambda = \frac{2 \cdot c \cdot v}{l}$.

Finally, since consumers are introduced at random locations and they move at random directions, the probability that two or more consumers arrive at R within a sufficiently small time interval is negligible.

In summary, in our simulation setup the arrival of consumers at a resource approximates a Poisson process with intensity $\lambda = \frac{2 \cdot c \cdot v}{l}$.

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