PARCelS: Pervasive Ad-hoc Relaying for Cellular Systems

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***Abstract*— Correlated usage of mobile devices intensifies traffic burstness and poses threat of congestion to current cellular-based wireless infrastructures. Inspired by the idea of integrating a cellular-based infrastructure with ad-hoc relaying, we propose a new architecture for the next-generation wireless networks, termed *PARCelS*, which utilizes roaming mobile hosts to perform route relaying. *PARCelS* is cost-effective as it saves the large investment in existent cellular-based infrastructures and does not need dedicated mobile devices. Our evaluations show that *PARCelS* can balance traffic load, avoid traffic congestion, and reduce latency.**

***Index Terms*— Mobile ad-hoc networks; hot-spot communications**

I. Introduction

In recent years, wireless networks have spread at an incredible speed as a result of the proliferation of mobile devices such as laptops and PDAs. Most of the current wireless networks operate in the cellular-based infrastructure mode [10], in which all traffic goes through a base station or access point. Even though more and more base stations have been deployed, the congestion problem still exists in these cellular-based networks due to an ever-increasing data traffic and a characterizing property of bursty traffic. Consider a campus library full of students using their laptops to access the Internet. While the aggregated capacity of the library network can be large, the simultaneous usage of mobile devices in one particular cell can cause the cell to be heavily congested. Such congested cells are called "hot spots." To avoid such hot spots, one possibility is to make a cell smaller so that a smaller number of users will be in a cell. However, this approach can be expensive because many more base stations are needed to provide the coverage and the utilization of these base stations can be low.

An alternative to the cellular-based infrastructure mode is the peer-to-peer mode. Recently, significant progress has been made in a class of peer-to-peer wireless networks, called ad-hoc or multi-hop wireless networks [13], [16]. Recent evaluations have shown that ad-hoc networks perform better in terms of throughput, delay and power than a single-cell network [7]. The drawback of ad-hoc networks, however, is that they cannot achieve wide-area communications such as those across the Internet. Since Internet access such as web browsing takes a large percentage of the total wireless traffic [15], it is unlikely that pure ad-hoc networks will overtake the dominant position of cellular networks in the near future. Considering the advantages and disadvantages of cellular and ad-hoc networks, we believe that a hybrid architecture of cellular and ad-hoc networks can be promising because such a hybrid architecture can solve the "hot spot" problem of the cellular networks by relaying traffic through an ad-hoc network from heavily congested cells to the cells that still have available channels. Furthermore, a hybrid architecture can also increase the capacity [9], [6] of a pure ad-hoc network by relaying traffic among mobile nodes through the base stations, which are connected through a wired network.

The feasibility of an integration of the cellular and ad-hoc networks is based on the fact that they use (and can be designed to use) different communication frequency bands. For example, some cellular networks are built upon existing voice network infrastructures, which are using licensed frequency bands. As an example, the PCS network operates at around 1900 MHz. On the other hand, most ad-hoc networks are using unlicensed bands such as 2.4 GHz.

The idea of "relay" was first introduced by Qiao et al. in *iCAR* [14]. In *iCAR*, a number of ARSes (Ad-hoc Relay Stations) are placed at strategic locations, and the ARSes can relay traffic between mobile hosts (MH) and base stations. Communications between a mobile host and a base station is done via the *C-interface* while those among mobile hosts are via the *R-interface*. When congestion happens in a cell, a mobile host that is initiating a new call[1] cannot use its C-interface to send its traffic to its base station. In this case, *iCAR* lets the mobile host use its R-interface to communicate with a nearby ARS, and the ARS can relay the signal through other base stations that still have available channels. With enough number of ARSes, *iCAR* can successfully balance data traffic. One potential issue of the *iCAR* architecture, however, is that placements of ARSes can incur considerable cost, and hence it may not be economically feasible for some applications.

Given the potential high cost of *iCAR*, in this paper, we propose Pervasive Ad-hoc Relaying for Cellular System (*PARCelS*), an architecture that is an integration of the cellular and ad-hoc networks. One of the novel and distinguishing features of *PARCelS* is that it does not need special mobile devices such as ARSes. On the contrary, it is the mobile hosts themselves who perform route relaying. As a result, we add the word "Pervasive" to the name of our system. Still consider the example of a campus library. During study hours, many students may be scattered around the library, using their laptops. For this example, instead of using dedicated ARSes, we can use the laptops of the students to relay traffic.

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[1] We use a call to refer to any wireless transaction.

By avoiding special devices, *PARCelS* is flexible and cost-effective, and therefore can be better suited to some application scenarios where dedicated mobile devices are expensive or hard to setup.

Another novel feature of *PARCelS* is its load-balancing algorithm. To relay the traffic from a cell through an ad-hoc network, *PARCelS* distributes traffic among neighboring cells upon congestion but before severe congestion happens. Thus, the load-balancing approach of *PARCelS* can be considered as a combination of proactive load-balancing and reactive load-balancing. Given such combination, *PARCelS* not only achieves load-balancing, but also reduces control traffic and setup latency. Furthermore, when choosing relay paths, *PARCelS* considers factors such as the current congestion state in a cell, traffic in the ad-hoc network, and mobility. Consequently, *PARCelS* finds high quality relay paths and avoids interference with the traffic in the underlying ad-hoc network. Moreover, in *PARCelS*, it is the base stations who monitor and distribute network status, thus reducing the workload on the mobile hosts and saving their power usage.

To evaluate the performance of *PARCelS*, we have conducted extensive simulations and we report in this paper some results for a typical network. The evaluations show that *PARCelS* is able to cope well with a sudden traffic burst. We also demonstrate that under continuous arrivals of new calls, *PARCelS* can spread traffic quickly and fairly among neighboring cells.

The rest of this paper is organized as follows. In Section II, we describe the details of *PARCelS*. In Section III, we evaluate its performance. Our conclusion and future work are in Section IV.

II. Description and Analysis of *PARCelS*

A. A simple relaying approach

To motivate the design of *PARCelS*, we first consider a simple relaying approach: when a mobile host needs to place a new call in a heavily congested cell, the mobile host searches on-the-fly for a relay route leading to a base station in a less congested cell.

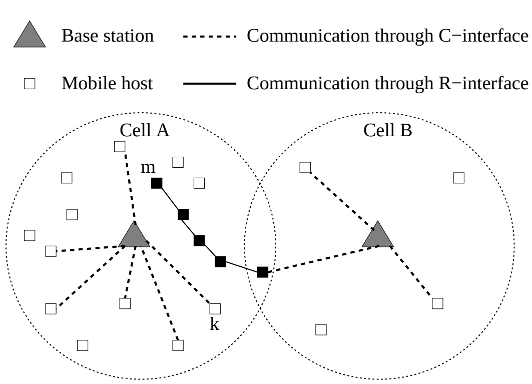

Fig. 1. A simple approach: the new call from mobile host m is relayed from cell A to cell B.

Figure 1 illustrates this approach. In this example, mobile host m is initiating a new call, but cell A is congested. Therefore m finds a route to relay its traffic through cell B.

We observe that this simple approach has three problems. First, the approach may generate a relay route with many hops. For example, if a mobile host happens to be near the center of a cell and therefore is far away from other cells, in order to relay its traffic through another cell, its traffic may need to travel many hops. As shown by Hsieh et al. in [7], due to mobility, the higher the number of relay hops, the higher the probability that the relay route breaks up, and therefore the lower the reliability of the relay. Second, the quality of a relay route may be low if the relay route goes through a hot spot in the ad-hoc network. Here by a hot spot in the ad-hoc network, we mean an area of the ad-hoc network with heavy data and relay traffic through the R-interface. Third, a mobile host in a busy cell may experience a large initiation delay, when searching for a relay route. This can be unacceptable for applications with tight delay requirement.

Investigating the three problems above, we notice that the problems of the simple approach are mainly due to two reasons. First, mobile hosts do not coordinate their actions. With coordination, the performance of the system can be greatly improved. Still consider the example where the mobile host m is trying to set up a new call and cell A is congested. In Figure 2, with coordination, mobile host k releases its current data channel to mobile host m, and then relays its traffic through cell B via a much shorter relay route. Second, the search for a relay route is totally reactive. Thus, not only the located path quality may be low, but also the setup delay can be high.

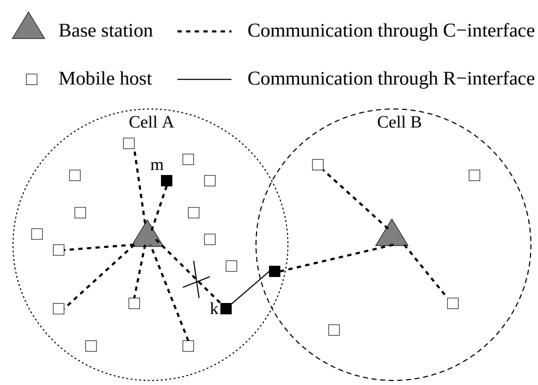

Fig. 2. A better solution: mobile host k releases its channel to m, and switches to a short relay route through cell B.

B. Description of PARCelS

To address the weaknesses of the simple approach, *PARCelS* exploits the states of the cells in order to coordinate the actions of the mobile hosts and therefore improves the quality of the relay routes. Moreover, such coordination can also prevent severe congestion and reduce setup latency.

1) Congestion states: In order to exploit the states of the cells, the mobile hosts in a cell need to learn the state of the cell from the base station. To inform the mobile hosts about its state, a base station can periodically announce its congestion state to all mobile hosts in its cell. To avoid introducing extra traffic, such an announcement of congestion state can be just a field of a beacon message from a base station. In the following, we refer to such an announcement as a *congestion indication*.

A congestion indication indicates one of the two congestion states: moderate congestion and severe congestion. In *PARCelS*, the congestion state reflects the fraction of occupied Data Channels (DCH). In our system, specifically, a fraction of 90% - 95% corresponds to moderate congestion, and a fraction of 95% or above means severe congestion.

2) Overview of the protocol steps of PARCelS*:* When a base station starts to indicate congestion, a mobile host in the cell with reserved data channels should start to search for relay routes. The search is performed by broadcasting route discovery messages (RDM). When a RDM reaches a mobile host in a cell with more free channels, a route trace-back message (RTM) is generated and sent back to the searching mobile host.

After finding several relay routes, the searching mobile host selects the best relay route by computing relay desirability values, which are a weighted function of the length of the relay routes, power status of the nodes, and the mobile hosts' motion. One simple implementation is a linear function: $-k_1 * L + k_2 * P + k_3 * M$, where k_1, k_2 and k_3 are positive constant, L is the relay route length, P the lowest battery lifetime of the nodes along the route, and M the moving direction of the mobile host (leaving is 1 and entering is -1). As the function implies, we favor routes with short length and strong power, and we choose the mobile hosts that may leave and need hands-off soon.

The desirable routes are then sent to its base station, who selects the best w mobile hosts, where w is adapted by the congestion window algorithm as explained in Section II-B.3. When selecting the w hosts, the base station achieves load balancing by considering the locations and the status of the destination base stations, as well as the relay status of the relaying hosts (the base station keeps track of the relaying status of each host).

The base station then transfers the communication states of those selected mobile hosts to the destination base stations as what happens during a hand-off process. Note that, unlike the hand-off process, such state transfers will not cause service interrupt.

3) Protocol details: In the previous subsection, we presented an overview of *PARCelS*. To make *PARCelS* efficient and practical, we apply the following techniques to improve its performance. The first three techniques are used to improve the process of relay route discovery, and the last two are to make *PARCelS* adaptive to bursty traffic and different congestion states.

First, we use time-to-live (TTL) to limit the scope of the relay route discovery traffic. A route discovery message (RDM) with TTL decremented to zero will be dropped.

Second, after receiving a congestion indication, a mobile host broadcasts its RDM after a randomized waiting time t, where $0 < t < T$, and T is a configuration parameter. When multiple mobile hosts broadcast simultaneously, RDMs are likely to collide, resulting in poor performance. Consequently, introducing a random waiting time can significantly reduce the chance of collision among adjacent mobile hosts.

Third, we allow a RDM to be dropped at hot spots of the ad-hoc network, where traffic is heavy on the R-interface. In particular, we drop RDMs randomly at a mobile host based on a probability function that varies according to the extent of traffic in the ad-hoc network. As we have discussed in the previous section, hot spots will affect the stability of a relay path. By dropping RDMs at hot spots, we automatically remove low quality relay routes, and avoid interference with the traffic in the ad-hoc network.

Fourth, *PARCelS* responds adaptively to different congestion states. When the congestion state is severe, *i.e.*, a large fraction of the data channels has been occupied, a mobile host uses a higher initial TTL value for its RDM. By using a higher TTL, the mobile host is more likely to find a relay route, and therefore can help to spread the traffic. On the other hand, when the congestion state is moderate, a mobile host uses a lower initial TTL value for its RDM. Specifically, in our experimental evaluation below, we set the initial TTL as 2 in a severe congestion state, and 0 in a moderate congestion state. By setting TTL to 0, a mobile host essentially only checks whether or not it is located at the overlapping region of two cells. If a mobile host is located at the overlapping region of two cells, it can simply switch to a less congested cell without appealing to relaying through an ad-hoc network.

Fifth, we introduce a congestion window to address different congestion states and traffic bursts. Using a variant of the AIMD algorithm [5], which is widely used in protocols such as TCP [8] and GAIMD [18], due to its efficiency and simplicity, a base station dynamically adjusts its congestion window size w, which specifies an upper bound on the number of mobile hosts that the base station will transfer to other cells. Specifically, if the congestion state of a base station is not relieved after one round, the window is incremented by one. Otherwise, the window is reset to 1.

C. Performance analyses of PARCelS

Given the design of *PARCelS*, we observe that it has the following desirable features:

- High probability to find short relay paths. Mobile hosts with short relay paths are normally located in the brim of a cell, where they are closer to other cells. Suppose the area of a cell is 1, and the area of the brim is g (g $<$ 1). In the simple approach, the probability of a mobile host being in the brim is g. In *PARCelS*, the probability, p, is given by: p = 1 $-$ (1$-$g)^M, where M is the number of channels. When M is sufficient large, p is approaching 1. Therefore, *PARCelS* can almost certainly find a short relay path.
- High quality relay paths. Because *PARCelS* drops RDMs at hot spots of an ad-hoc network, it avoids interference with the traffic in the ad-hoc network. Furthermore, the desirability value of a relay route is a function of not only the length and power of the relay path, but also the speed and direction of the involved mobile hosts. As a result, mobile hosts leaving a cell are more likely to be chosen for relaying. Because their state information is transferred to the destination base station before relaying, *PARCelS* avoids paying the price of hand-off.

- Adaptive load-balancing. By using multiple congestion states, *PARCelS* is able to balance traffic at the early stage of congestion. Note that such adaptation is essentially a combination of proactive load-balancing and reactive load-balancing. If the system always proactively maintains the optimal balance, the balancing overhead may be high, but the network may not have that much traffic, and therefore some control traffic is wasted. On the other hand, if the network waits until there is a new call and then reacts to find a new path, the cost to find a new path can be very high since the network can be severely congested. By starting to balance load when the network starts to be congested but not severely congested, our system achieves a good balance: since the network just starts to become congested, it is likely that more new calls will arrive. As a result, starting to proactively balance traffic as a reaction to congestion is unlikely to be wasteful.[2]
- Low initiation delay. Since *PARCelS* distributes traffic before severe congestion, when a mobile host initiates a new call, the probability of it finding a free data channel in its cell is high. Therefore, the probability that a node needs to search for a relay path before its communication is low.

PARCelS does require mobile hosts to relay route searching traffic, and this may cause extra data traffic and use the battery of the mobile hosts. However, we argue that the search overhead is small due to the following two reasons. First, TTL limits the scope of RDM. As we discussed before, a short relay path can be almost certainly found in *PARCelS*. Therefore, we can use a small initial TTL to limit the scope and amount of the search traffic. Second, since mobile hosts at hot spots block RDMs, the search and relay traffic in the ad-hoc network is confined within areas with light ad-hoc traffic. Furthermore, much of the workload on route selection and handoff are moved to base stations, who in general have abundant resources.

III. EVALUATIONS OF *PARCelS*

In this section, we evaluate the performance of *PARCelS*. We present the results for a typical network. The results for other networks are similar.

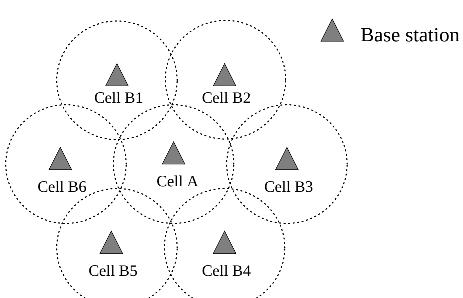

Fig. 3. The topology of the evaluated network. Each cell has a radius of 1 and each base station has 100 data channels.

[2]We can further reduce the control overhead of proactive load balancing by observing traffic patterns.

Our evaluated network is shown in Figure 3. The network consists of seven cells: A and B_i (i = 1, ..., 6). Each cell has a radius of 1 and each base station has 100 available data channels. In this section, we let d denote the cell distance between cell A and cell B_i; m denote the density of relay mobile hosts, which is defined as the ratio between the total number of mobile hosts and the number of mobile hosts with data traffic; and r denote the coverage range of a mobile host using the R-interface.

A. Effects of cell distance d, mobile host density m, and coverage range r

We first evaluate the effects of cell distance d, relay mobile host density m, and coverage range r. As the initial condition, we assume cell A is totally congested; that is, it already has 100 calls. For this evaluation, we plot two performance metrics: 1) the number of mobile hosts with 0 relay hop, i.e. the number of mobile hosts which do not need any relay to carry their calls; and 2) the number of mobile hosts with 1 or 2 relay hops.

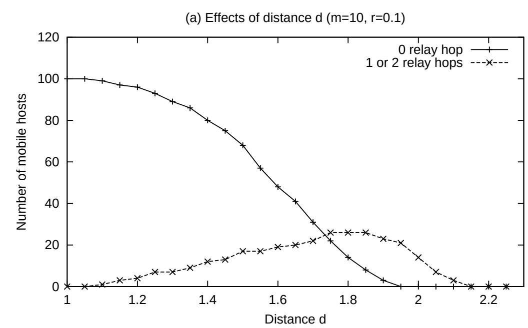

Fig. 4. Effects of cell distance d (relay mobile host density $m = 10$ and coverage range $r = 0.1$).

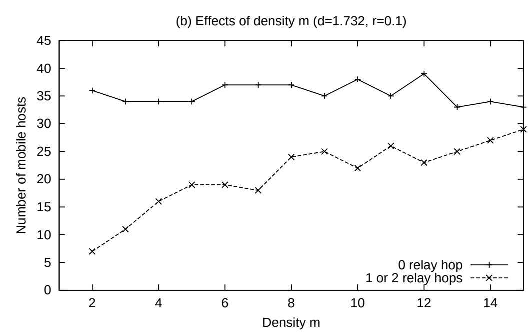

Fig. 5. Effects of mobile host density m (cell distance $d = 1.732$ and coverage range $r = 0.1$).

Figures 4 to 6 show the results. We make the following three observations. First, from Figure 4, we observe that as we increase the cell distance d, the number of mobile hosts with longer relay paths increases. When d is very large, no short relay path exists. Second, from Figure 5, we observe that as we increase m, more mobile hosts are available for providing relay service, and therefore short relay paths are easier to find. Third, from Figure 6, we observe that increasing the coverage

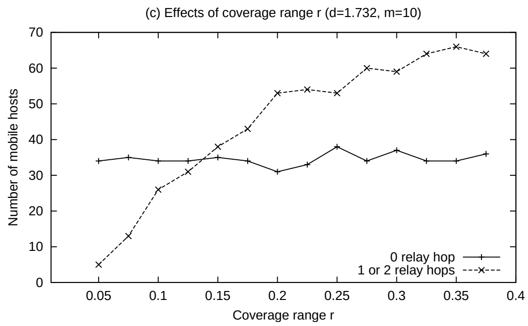

Fig. 6. Effects of coverage range r (cell distance $d = 1.732$ and mobile host density $m = 10$).

range r enables a mobile host to communicate with distant mobile hosts, resulting in shorter relay paths since fewer relay hops are needed.

B. Effects of background traffic in the ad-hoc network

We next evaluate the effects of background traffic in the relaying ad-hoc network. In the previous evaluation, we assume that the underlying ad-hoc network is exclusively reserved for relaying. When mobile hosts communicate via the R-interface, their signals will interfere with other signals. In this evaluation, we assume that besides relaying traffic, the mobile hosts communicate with each other through the ad-hoc network with a probability of 0.05.

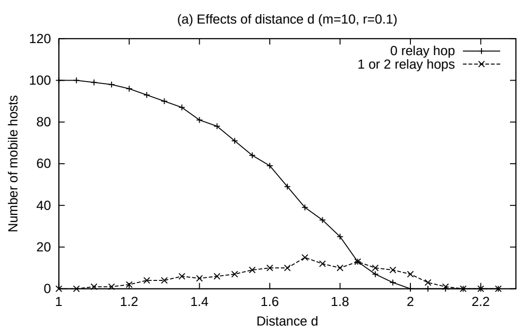

Fig. 7. Effects of background traffic in the ad-hoc network, fixed mobile host density m and coverage range r.

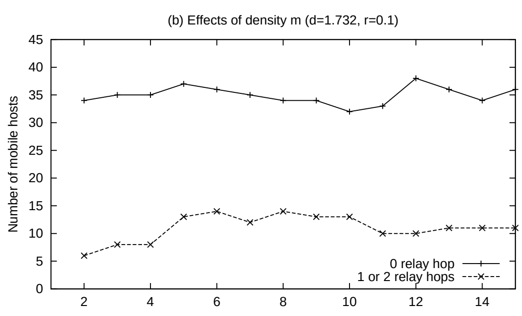

Fig. 8. Effects of background traffic in the ad-hoc network, fixed cell distance d and coverage range r.

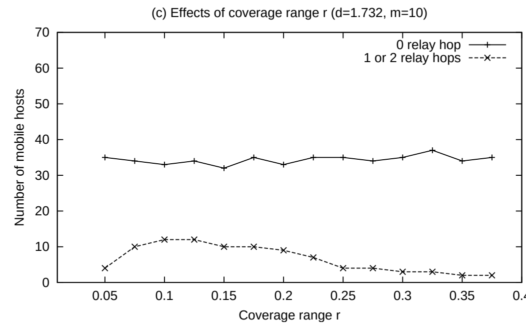

Fig. 9. Effects of background traffic in the ad-hoc network, fixed cell distance d and mobile host density m.

Comparing Figures 4 to 6 with Figures 7 to 9, we observe that the number of relay paths with length 1 or 2 is reduced. This is because *PARCelS* automatically drops RMD messages at hot spot areas. The number of relay paths with length 0, however, is basically unchanged since they require no resource in the ad-hoc network.

C. Dealing with bursty traffic

We next evaluate the performance of *PARCelS* to deal with bursty traffic. To generate a scenario with bursty traffic, we assume that the initial numbers of mobile hosts that are requesting data channels at base stations A, B_1, B_2, B_3, B_4, B_5, and B_6 are 130, 100, 95, 70, 70, 80, 85, respectively. Note that in this scenario, cell A initially has a large number of active mobile hosts.

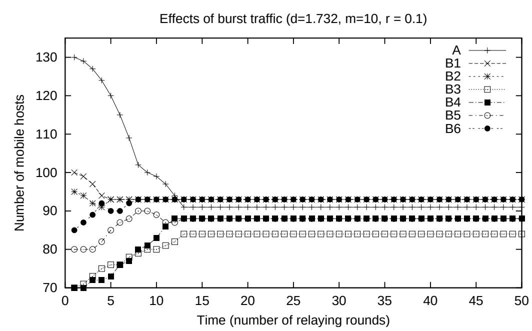

Fig. 10. Responses to an initial imbalance, where cell A has a large number of requests.

Figure 10 shows the evolution of the number of mobile hosts that are requesting data channels at each cell. We observe that when *PARCelS* starts to react, it can spread a burst of traffic to other cells fairly and quickly.

D. Dealing with continuous arrivals

We next evaluate the performance of *PARCelS* when requests arrive continuously to cell A. For this scenario, we assume that the initial number of mobile hosts that are requesting data channels at each base station is 70. However, during the first 10 units of time, 5 new calls arrive at cell A during each unit of time. From Figure 11, we observe that *PARCelS* is able to react and spread the new calls from cell A to other cells, therefore avoiding overloading cell A.

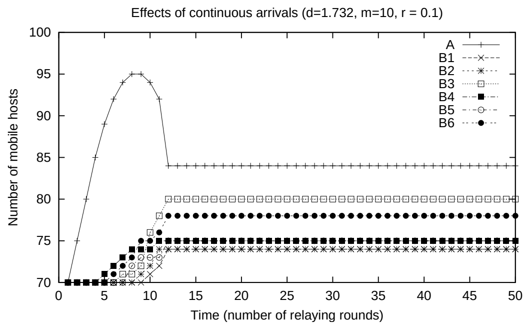

Fig. 11. Dealing with continuous arrivals, where new calls arrive at cell A continuously.

IV. Conclusion and Future Work

We proposed *PARCelS*, an architecture for the integration of cellular and ad-hoc networks. *PARCelS* utilizes roaming mobile hosts to perform route relaying. We showed that *PARCelS* is scalable and cost-effective as it saves the large investment in existent cellular-based infrastructures and does not need dedicated mobile devices.

One of our main future work is on the security and incentive issues. For security, the main concern is that a general mobile host may not be trustworthy. Even though this problem is true for the general ad-hoc networks (see [1] for an overview), whether or not we can use simple security mechanisms for our particular design is an interesting problem. Also, one potential issue on depending mobile hosts to relay traffic is that they may not have incentive to relay others' traffic. There are two approaches to solve this problem in the context of general ad-hoc networks: one is to use a reputation system (*e.g.*, [11], [2], [12], [17]), and the other is to use a credit system (*e.g.*, [3], [4], [19]). In particular, we proposed Sprite, a simple, cheat-proof, credit-based system for mobile ad-hoc networks [19]. Evaluations of a system combining both *PARCelS* and Sprite are currently underway.

Another potential issue is on power efficiency. We can image many scenarios where power efficiency is not the major issue. For example, in the campus library example we discussed previously or in a campus network with many classrooms, we can assume that the users general can have access to power outlets and therefore power is not the major issue. Furthermore, our system intentionally puts many functionalities on the base stations to reduce the load on the mobile hosts. However, power efficiency can be an issue for battery-powered mobile nodes. We are currently measuring the extra power consumed by relaying others' traffic as well as algorithms to further improve power efficiency.

Yet another issue is on mobility. Again, although we can image many scenarios where mobility is not an issue and our initial evaluations showed that *PARCelS* actually can deal with mobility well, further evaluations and optimizations may be necessary.

Furthermore, the focus of this paper in on using mobile nodes to relay traffic for the cellular networks. As we mentioned in introduction, the base stations, which are connected by wired networks, can also help to relay traffic among the wireless mobile nodes, and therefore improve the capacity of the mobile wireless ad-hoc network.

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