QoS Provision for Remote Sensing and Control in Heterogeneous Environments

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Abstract— **In a heterogeneous wireless network environment, the network nodes are equipped with both wireless local area network (WLAN) and cellular interfaces. It is desirable to combine the higher bandwidth of a WLAN and the ubiquitous nature of cellular networks to provide the transport service for QoS demanding applications, such as remote sensing and control systems. Common solutions exploit the diversity of cellular channels by recruiting multiple WLAN peers to work as proxies for a MANET node that needs to communicate through the cellular network. One important problem when utilizing channel diversity in a heterogeneous wireless network environment is to balance the trade-off of channel diversity gains with MANET peer contentions. A greater number of proxies will inevitably increase the MANET contention and possibly QoS degrading of the cell, and fewer proxies may not be able to provide sufficient diversity. This paper aims to build a dynamic mechanism to determine the appropriate number of proxies to use. The mechanism uses the MAC layer retransmission rate as an indicator of the contention level in MANET. Simulation using cellular channel fading models and prevalent cell scheduling policies indicate the scheme can provide better QoS through channel diversity by using the appropriate number of proxies.**

I. Introduction

The development of cellular communication technologies makes it possible to deploy ubiquitous applications with higher QoS requirements. However, the data rate and QoS of cellular networks are not comparable to wired networks or wireless local area networks (WLAN). In a hybrid WLAN/cellular environment, the mobile hosts are equipped with both WLAN and cellular interfaces, referred as dual-mode nodes. WLAN technologies such as IEEE 802.11 suite of protocols have limited coverage. However the availability of relatively high bandwidth WLANs can be a good complement to the cellular link. By recruiting WLAN peers to form a mobile ad hoc network (MANET) and share their cellular channels, a mobile node can achieve the level of QoS that can never be met alone.

An instance of an application that could take advantage of dual mode connectivity is a remote sensing and control system [1]. Figure 1 shows an example of such a system. The wireless control terminal is equipped with both WLAN and cellular interfaces. The control terminal also has the capabilities of issuing control commands such as pan, tilt or zoom of visual sensors, or moving the base of mobile sensors. Sensory information, such as video and audio, will also be received and rendered by the control terminal. The control commands and sensory feedbacks, including possibly different types of media types, are referred to as supermedia [2]. In this paper, the control terminal may also be referred to as a control client or a client.

The communication between the control terminal and the sensors may traverse different types of communication channels. Usually the communication path will include cellular links with the base station (BS), wired networks (such as the Internet) and wired or wireless local area networks, to which the sensors attach. We focus on the communication issues of cellular link. Particularly, video, audio and other sensory feedbacks are transmitted from the BS to the control terminal, referred as the downlink. Control commands are sent from the control terminal to the BS, referred as the uplink. Prevalent cellular networks, such as CDMA2000, exhibit asymmetric bandwidth levels over the uplink and downlink. The downlink channel is usu-

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ally controllable by the BS, and may have greater bandwidth capabilities. This could be a blessing for remote sensing and applications since the sensory information usually has higher bandwidth demands. Nevertheless, the QoS provided by a single cellular link may still not be able to meet the needs of the application. Moreover, the requirement of high responsiveness and control loop stability of remote sensing and control applications often demands stable channel quality as well as higher bandwidth. This implies the end-to-end latency and latency variance (jitters) are important QoS metrics besides throughput. We aim to provide acceptable QoS for the application by exploiting the channel diversities of MANET peers in a hybrid MANET/Cellular environment. In the paper, we may use the terms proxies and peers interchangeably to refer to the nodes that are recruited by the control terminal node.

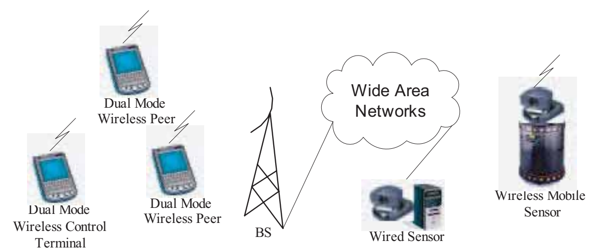

Fig. 1. An Remote Sensing and Control System in Heterogeneous Environments

The idea of using multiple communication channels to achieve diversity and resilience has been exploited in many layers of the protocol stack. Proposed solutions range from MIMO (multiple-input multiple-output [3]) antennas in chip level designs to multi-node antenna arrays [4]. Network layer solutions involve less hardware design complexity and therefore are more feasible in hybrid wireless environments. We therefore focus on the network level approach of utilizing multiple cellular channels to improve the performance of a latency sensitive application that resides on a mobile node. The node is equipped with both WLAN cellular interfaces and surrounded with mobile peers that have similar configurations. Through the WLAN interfaces, the control terminal and its peers can form a mobile ad-hoc network.

Utilizing multiple cellular channels can potentially improve the system performance, and of course comes with costs. In spite of the processing overhead of decomposing and combining traffic of multiple channels, there are two questions that need to be answered. First, the peer nodes of the MANET are highly likely to be located in the same cell. Recruiting more nodes to have active data transactions will inevitably increase the cell load, therefore it is not apparent that the collective performance of the application will be improved. Second, in order to deal with momentarily bad conditions in certain channels, it is desirable to have more peer nodes to exploit the spatial diversity. However, communication among the peers will cause contentions and collisions, the effect of which will become worse as the number of active peers increase. In this paper, we answer the first question by demonstrating that under prevalent scheduling policies it is possible to achieve better collective performance even if the peers are within the same cell. To answer the second question, we design an adaptive peer management scheme to optimally control the number of peers based on the performance gains and contention effects. A novel contention indicator is introduced based on the MAC layer retransmission rates and backoff timers.

The rest of this paper is organized as follows. Section II covers related work. In section III, we examine the scheduling policies of prevalent cellular data networks and simulate the possible bandwidth gains when using more than one simultaneous connecting proxies. An adaptive peer management scheme is presented in section IV. We simulated the performance of the proxy group control scheme under the NS2 simulator, and the results are presented in section V. Section VI provides the conclusions.

II. Related Work

The integration of cellular networks and wireless LANs has drawn much attention from research communities. Some efforts have focused on developing multi-hop cellular networks by adding multi-hop relays into the cellular networks. The methods range from using a single wireless interface for both the relay and infrastructure mode [5], and using two interfaces to connect to the cellular data network and the mobile ad hoc network simultaneously. Some research [6], [7], [8], [9], [10] and our work fall into the second category. In the Unified Cellular and Ad-hoc Network Architecture (UCAN [6]), a relay proxy forwards packets from the base station to the clients with poor channel quality via high-bandwidth IEEE 802.11-based ad hoc links to improve throughput of the cellular network. A greedy and on-demand proxy discovery mechanism is introduced but the adversary effects of traffic contention caused by more proxies are not addressed. iCar [7] uses network operator managed relay proxies to divert bursty traffic from one congested cell to another idle cell. The scheme is not applicable to ad-hoc users that reside in one cell. CHUM (Cooperating ad Hoc network to sUpport Messaging [9]) is proposed as an approach to integrate 3G networks and ad hoc networks in a manner that significantly reduces 3G network costs to provide energy efficient solution for instant messaging and better QoS support by aggregation idle cellular links [11], [12].

Compared with those schemes, our work goes one step further by asking the question of under what condition the benefits of relay proxies outweigh their costs. We answer the question by measuring the contention caused by MANET peers through the MAC layer packet retransmission rate, and design a dynamic mechanism to control the number of relay proxies.

The value of spatial channel diversity in homogeneous environments has been studied from the physical layer to the network layer of different wireless communication systems [4], [13], [14], [15], [3]. A comprehensive overview of the studies can be found in [16]. Even in wired networks, the value of traffic diversity in the Internet has been studied and exploited to provide better QoS under multi-homing [17] or application layer overlay networks [18], [19], [20]. A key difference of that research and this paper is that we target our design under the settings of MANET/cellular heterogeneous environments and emphasize the tradeoff of diversity gains and contention avoidance. Our work is motivated by supporting remote sensing and control applications in pervasive environments, and special attention is given to reducing end-to-end latency and latency jitters. This is important to ensure system responsiveness and stability of the control loop.

III. Model of Bandwidth Sharing in Cellular Networks

Recruiting peer proxies to share their cellular bandwidth involves introducing more active cellular network users. In most cases, all the users will reside in the same cell. As a result, the workload of the cell will increase. Since most cellular data networks are packet switch networks, heavier workload will inevitably influence the amount of bandwidth that each user can get. Therefore it is not straightforward that bandwidth sharing will increase the throughput of the control terminal. However, due to small scale fading of the radio signal, different cellular users receive different data rates even if they share the same large scale physical environments. Cellular bandwidth sharing can take advantage of this fact to ensure the control terminal receives stable QoS even if the radio signal of its single channel experiences the fading effects.

Since the radio signal received by the terminal is the sum of many signals received from different directions, the instantaneous received signal strength may fluctuate even if the terminal moves over very small distances. When the receiver moves only a fraction of a wavelength, the received signal power may vary by up to three or four orders of magnitude (30 or 40 dB) [21]. For cellular frequencies in the range of 1 GHz to 2GHz, the effective movements can be less than a meter. Such movements are very common for cellular users and as a result the data rate received by the users will have dramatic change due to small scale fading effects. In the following parts, we simulate the effects of bandwidth sharing in a typical cellular network. We consider a CDMA based cellular data network.

In a cellular network, the forward channel (or downlink channel as referred in some literature), which is from the base station to the user, is often controlled by a scheduler in the base station. The reverse channel, is an asynchronous channel where all users contend for the usage. The relation between the forward rate and power of a mobile node in a CDMA network can be given as [22], [23]:

$$\phi = (\frac{E_b}{P_I})(\frac{R}{SINR}), 0 \leq \phi \leq 1 \qquad (1)$$

where ϕ is the fraction of the base station power required to support a data rate R, E_b is the received energy per data bit, P_I is the total interference power, and $SINR$ denotes signal to interference plus noise ratio. The quantity E_b/P_I depends on the physical layer frame error rate (FER) and is often maintained below a threshold. Base station power control refers to changing ϕ to maintain a rate R given a certain $SINR$, and rate control refers to changing R given a certain $SINR$ to maintain a fixed ϕ value. It has been proved that in continuous bandwidth conditions, time multiplexing is superior to code multiplexing in CDMA networks [22]. This policy is also adopted in CDMA2000 HDR (High Data Rates, also known as 1xEvolution Data Only or 1xEV-DO) [24]. In CDMA2000 HDR, the scheduler at the base station allocates the whole capacity of the channel to one user at a time at the maximum power, which corresponds to $\phi = 1$. In order to decide which user to allocate the bandwidth to at each time step, proportional fairness scheduling policy is often used [25].

Assume that the channel of a given cell is shared among N users through fixed time slots. The length of one time slot is denoted by τ_l. The time slot length is 1.66 ms in EV-DO and 1.25 ms in EV-DV (Evolution Data and Voice). The input to the scheduler includes a rate vector $R^\tau = (r_1^\tau, \cdots, r_N^\tau)$, which is the achievable data rate r_i^τ for user i during the next time slot τ. R^τ is determined by the channel conditions of each user. For users residing in the same cell, R^τ will be mainly determined by the small scale fading effects of each user channel.

The proportional fairness policy always allocates the channel to the user that has the largest ratio of the next time slot achievable rate over its previously achieved rate. Let k denote the user that is picked for the next time slot, and then it holds

$$\frac{r_k}{A_k} = \max_{j \in \{1, \cdots, N\}} \left(\frac{r_j}{A_j}\right) \tag{2}$$

where

$$A_j(\tau) = (1 - \alpha) A_j(\tau - 1) + \alpha r_j. \tag{3}$$

Equation (3) calculates the previously achieved rate $A_j(\tau)$ at time step τ for user j. $\alpha (0 < \alpha < 1)$ is a coefficient to control the influence of history rates on the calculation of the achieved rate.

We can see that the proportional fairness policy favors two types of users:

1) The nodes that have good achievable rates (or channel qualities).
2) The nodes that have smaller previous achieved rates.

Through bandwidth sharing among cellular users, more than one nodes are recruited to serve the current application. Thus the chance of the node (or nodes) that contribute to the current application being scheduled in the next time slot is increased. This takes advantage of the first type of users favored by the scheduling policy. Also compared with being served by a single node, the application is served by a collection of nodes. As a result, the previous achieved rate of each of the collected node will be smaller compared with the case when only one node serves the application. This exploits the second type of users.

We simulated the effects of using multiple proxies in a cellular network under a Gaussian fading channel with 1.2% variance. The simulation consists of a proportional fairness scheduling module and an wireless channel fading simulation model. Following previous literature [24], we used Gaussian fading to model the channel characteristics. Similar results can be obtained by using Rayleigh fading or Rician fading models. For some simulation scenarios, cross traffic generators (CTGs) are introduced. CTGs cannot be recruited as proxies but they will remain as cellular users in the scheduling algorithm. It is assumed that all cellular users require a class of 1 MBPS rate, and the actual achievable rate of each user is determined through the fading channel simulation.

When multiple cellular proxies are available in the simulation, the achieved rate is calculated by averaging the collective rate of those proxies through the simulation time span. For a single client (taken as the case where there is one proxy, which is the client itself) case, the achieved rate is calculated by average the rate of the particular client over the simulation time span.

The changing trend of the achieved cellular rate versus the number of recruited proxies is shown in Figure 2. The curves starting with P denote the achieved rate with proxies, and the curves starting with S denote the achieved rate without proxies. S curves are not influenced by the number of recruited proxies and their fluctuation comes from the channel fading effect of different simulation runs. S curves are plotted for comparison purposes. The numbers following each curve legend denote different simulation scenarios. In scenario 1, there are no CTGs. And there are 5, 10, and 15 CTGs in scenarios 2, 3, and 4, respectively. We can see that even a few number of proxies are even quite effective in improving the achieved rates. CTGs impact the performance of both single client case and the case with proxies. An increase in the number of proxies can reduce the impact of CTGs. This can be further illustrated in another set of simulations as shown in Figure 3.

As the number of CTGs increases, the achieved rate of the cases with more proxies tend to decrease slower, compared with the cases where there are no or fewer proxies. When no CTG is present, the achieved rates of single client case, the cases with 5 proxies and 20 proxies are 0.917, 0.993, and 0.994 MBPS, respectively. The cases with proxies have an improvement of 8.2% and 8.4% over the single client case, respectively. When 10 CTGs are present, the achieved rates of single client case, the cases with 5 proxies and 20 proxies are 0.119, 0.354, and 0.676 MBPS, respectively. The cases with proxies have an improvement of 198% and 469% over the single client case respectively. In practice when the number of CTG is large, it tends to be difficult to recruit more proxies.

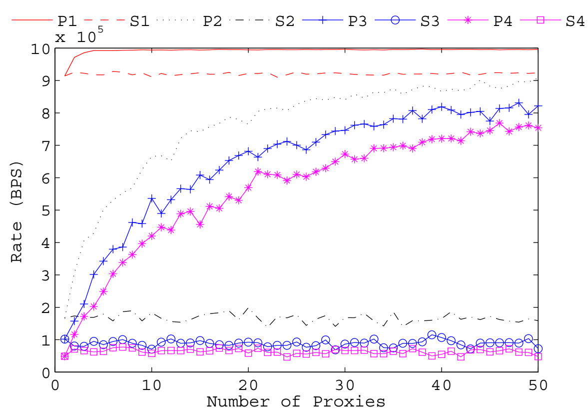

Fig. 2. Cellular Rate vs. the Number of Proxies

IV. A Dynamic Multi-proxy Selection Algorithm

The use of multiple cellular network relay proxies in the MANET can help improve the network QoS of the sender. However, it is also possible that multiple transmission flows increase the traffic load of the network and cause further congestion for the wireless network. For the cellular network, we can assume generally the BS will enforce an admission control policy to prevent the system load from exceeding its capacity. For the MANET, however, it is difficult to impose such a policy. Moreover, since

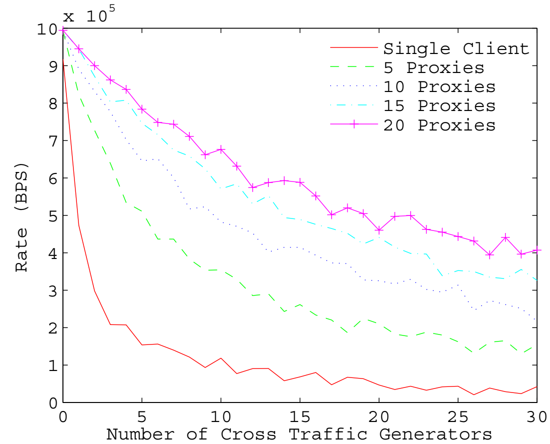

Fig. 3. Cellular Rate vs. the Number of Cross Traffic Generators

all cellular proxies need to communicate with the control client through its WLAN interface, media contention and congestion in the MANET will have serious performance impact on the client.

In this section, we devise a dynamic contention detection and multi-proxy selection scheme to solve this problem. The basic idea is to have the control client monitor the contention level of the WLAN (indicated by the link layer retransmission rate) and the cellular bandwidth gains. Using those parameters, the control client estimates the transmission latency for a given traffic block. By calculating the derivative of the estimated latency over the number of proxies, the control client knows whether to increase, decrease, or maintain the number of proxies.

In a WLAN with multiple paths that originate from the sender, the control client is the most possible victim when the increased traffic load causes media layer contentions and interferences. Also, it is shown that a few more hops in the MANET will decrease the QoS dramatically [15]. Thus we only consider the impact of additional proxies on the first node of the multi-path, which is the control client. It is also safe for us to assume that the majority of the proxies are only one hop away.

When the number of paths is so large that excessive contention occurs, the QoS of the whole application degrades. This problem is closely related with the capacity of MANETs. It has been shown [26] that in a MANET with n nodes, the throughput $\lambda(n)$ obtainable by each node for a random destination is $\Theta(\frac{W}{\sqrt{n \log n}})$, given the rate of each node is W bits per second. Numerical simulations also show that the throughput of an IEEE 802.11 infrastructureless network will decrease once the number of node-pairs that are exchanging traffic is over 15 [27]. In our case of a MANET/cellular network, the impact of node density could be even worse since the control client is the bottleneck of the MANET communication.

Of all the costs associated with using multiple cellular proxies, the potential MANET contention caused by the proxies is a major constraint of the system performance. It is important to find a measure to describe the QoS degrading when excessive contention occurs. Unlike wired networks, where increased RTT is a good sign of built up queues because of congestion in routers, RTT is not a good measure because the major reason for QoS degrading in wireless networks is not due to built-up queues in the relayers, but packet loss or link layer retransmissions caused by increased media contention. Instead of using RTT as a metric of overloaded traffic, we develop a metric based on the link layer retransmission rate detected by the MANET senders to monitor the condition of the media channels. Both media collision and channel noise can cause link layer retransmissions. Unlike media collisions, channel noise can be regarded as independent of the number of MANET users. Thus the retransmission rate can be taken as a measure of the degree of media contention in a MANET. By modeling the 802.11 media channel as an $M/G/1/PS$ system, it is shown that the collision probability increases logarithmically with the number of users [28]. In reality, the rate of retransmissions caused by collisions should be constantly monitored to facilitate the proxy selection process.

By taking the link layer retransmission rate as a collision indicator and using the retransmission rate and the cellular network bandwidth model proposed in section III, we propose a scheme to dynamically adjust the number of proxies to achieve optimal system latency for a given traffic block. The multi-proxy selection algorithm can be illustrated in Figure 4.

Considering the asymmetric nature of the cellular link and the targeted application, the multi-proxy selection algorithm is designed to optimize the performance of downlink traffic. The major traffic flow will be from the BS to proxies, and then from proxies to the client. The system will bootstrap by recruiting a constant number of proxies. After that, the multi-proxy selection algorithm illustrated in Figure 4 is invoked periodically to maintain the optimal number of proxies in the active proxy group. The proxy group control algorithms determine whether to increase, decrease, or maintain the number of nodes in the proxy group. We assume the number of members in the proxy group is denoted by k. To support the proxy group control algorithm, each node i in the proxy group maintains two metrics, the measured link layer retransmission rate β_i and the cellular rate c_i. More details about retransmission rate measurement are discussed later. The achievable cellular rate can usually be obtained from the BS [22]. Periodically the retransmission rate β_i and the cellular rate c_i are sent to the client by being piggybacked to data packets.

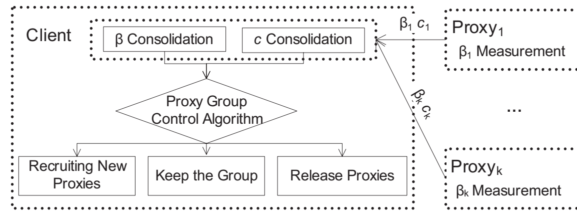

Fig. 4. The Multi-proxy Selection Process

The β consolidation module processes the individual retransmission rate of each proxy to arrive at a collective retransmission rate of the proxy group and the client. As discussed at the beginning of this section and proved in [28], the collective retransmission rate is a monotonically increasing function of k. We denote it as $\beta(k)$ or β when there is no confusion. A simple consolidation process is to set $\beta(k)$ to be the arithmetic mean of all β_i. A more sophisticated method can take into account the amount of traffic carried by each proxy and use a weighted average. The c consolidation module calculates the collective cellular rate c by adding together the cellular rate c_i of each proxy i. Assuming the number of recruited proxies does not exceed the capacity of the given cell, as shown in the cellular bandwidth sharing model of section III, c is a monotonically increasing function of k. Thus the collective cellular rate c can also be noted as $c(k)$ to reflect the dependence.

Assume the amount of a traffic block to be sent is n and the data rate of the ad hoc network is r. We can take r as the achievable bandwidth of the shared MANET media. For example, for IEEE 802.11b, the achievable bandwidth could be 2 MBPS or 11 MBPS depending on the networking conditions. The latency to transmit the traffic block is composed of two parts, the latency from the BS to the proxies and the latency from the proxies to the control client in the MANET. Before reaching the BS, the traffic has to traverse other communication channels, for example, the Internet. The latency of those communication channels can be optimized too but is beyond the scope of this paper. The time used by the proxies to obtain the traffic from the base station can be approximated as $t_1(k) = \frac{n}{c(k)}$. For the latency in the WLAN, we model the impact of the retransmission rate over the latency. Given n as the net traffic to be sent and the link layer retransmission rate β, the actual traffic to be sent is $\frac{n}{1-\beta(k)}$. And the latency for transmitting the traffic in the WLAN is $t_2(k) = \frac{n}{(1-\beta(k))r}$.

The total latency is a performance indicator of the system given k proxies:

$$t(k) = t_1(k) + t_2(k) = \frac{n}{c(k)} + \frac{n}{(1-\beta(k))r}. \quad (4)$$

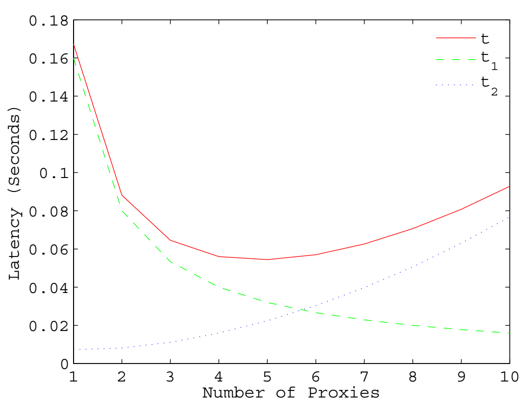

Fig. 5. Simulated Latency vs. the Number of Proxies

The relationship of t, t_1 and t_2 versus k can be simulated as shown in Figure 5. β is simulated through a monotonically increasing function from $[1, +\inf)$ to $(0, 1)$. The parameter c is simulated through a monotonically increasing function from $[1, +\inf)$ to $(1.0e6, +\inf)$, which denotes 1 MBPS channel for each cellular connection. The parameter n is $8e4$ bits, which denote 10 1000-byte packets. The parameter r is $11e6$ to denote an IEEE 802.11b channel. The result shows when k is around 5, the latency is minimized. We can also observe that $t(k)$ is a convex function, so its extremum can be located through the derivative of k.

We obtain the derivative of k for equation (4):

$$t'(k) = \frac{n\beta'(k)}{r(1-\beta(k))^2} - \frac{nc'(k)}{c^2(k)}. \quad (5)$$

β' and c' can be calculated using numerical methods. Depending on the sign of t', we can decide whether to increase or decrease the number of proxies. In practice, t' is compared with a small positive threshold value δ. If $|t'| \leq \delta$, k is near optimal and we keep the number. If $t' < -\delta$, it means k value is on the left of the optimal value and we need to increase it. If $t' > \delta$, it means k value is on the right of the optimal value and we need to increase the number of proxies.

In reality, $\beta(k)$ or $c(k)$ may not be strictly monotonically increasing functions. Changes of physical environments may cause $\beta(k)$ or $c(k)$ to fluctuate. In that situation, the local extremum indicated by $t'(k)$ may not be the global extremum. We reduce the possibility of the local extremum by randomizing the amount of increment or decrement imposed on k. For example, if k needs to be increased, a random number is drawn from $[1, K]$ to be the increment value, where K is an upper bound of the increment. When t' indicates a near optimal k, a small amount of randomized increment or decrement can also be applied to avoid local extremum. As noted before, the maximum of k is limited by the capacity of the current cell. We assume that the proxies being recruited are facilitated with mechanisms to be notified of a capacity overflow. Otherwise, a upper bound of k is set for the algorithm.

The proxy hunting process can be based on any broadcasting based mechanisms as proposed by previous work [6], [12]. Failure recovery processes will also be invoked when one or more of the active proxies fail. In order to reduce the overhead of hunting for new proxies, when k needs to be decreased the node IDs of the released proxies can be cached as candidate proxies in a local pool of the client. Later when more proxies are needed, the proxies in the local pool are first probed and used. The candidate proxies are also preferably required to maintain connection information for the relay traffic if connection oriented transport protocols such as TCP are used to support reliable traffic. This further reduces the connection setup overhead. Alternatively, connectionless reliable transport services can also be used. Examples include forward error correction based connectionless reliable transport services, such as [20].

V. Simulation Results

We simulated the performance of the multi-proxy selection algorithm using the cellular network bandwidth model discussed in section III and the MANET/802.11 modules of NS2 ([29], version 2.29).

In the simulation, the MAC layer of NS2 802.11 is modified to support retransmission rate measurement. The measurements consider both retransmissions and the backoff timer of retransmissions. Successive retransmissions after the first retransmission are assigned more weight.

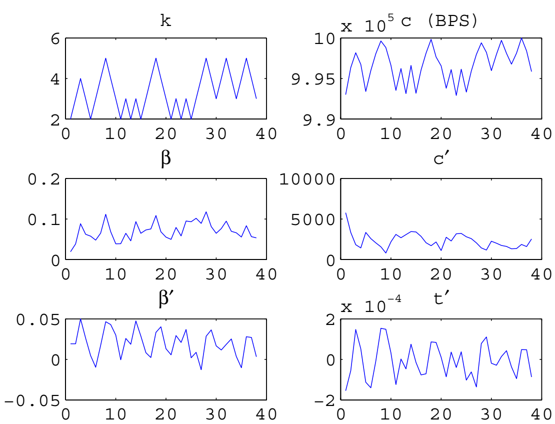

Fig. 6. Parameters of Proxy Group Control with no CTGs

In the MANET scenario, the simulation area is a $400m \times 400m$ rectangle. The client node is placed in the center of the area and the potential proxy nodes scatter around it within the power range. Each mobile node was simulated to work with the Orinoco 802.11b network card, which has a data rate of 11 $Mbit/sec$ and a transmission range of 60 m. For the cellular network, each cellular interface requests an average of 1 MBPS rate. We used the on/off traffic pattern to measure the performance of the proxy selection algorithm. At each simulation step, the client requests a traffic block of 5K bytes. As in section III, we simulated the effects of using multiple proxies in a cellular network under a Gaussian fading channel with 1.2% variance. In the proxy group control algorithm, we use a simple linear k adjustment algorithm, that is, increasing or decreasing k by one upon each t' indicator is calculated. More sophisticated algorithms can be used in real implementations to reduce the effect of local extremum as discussed in section III.

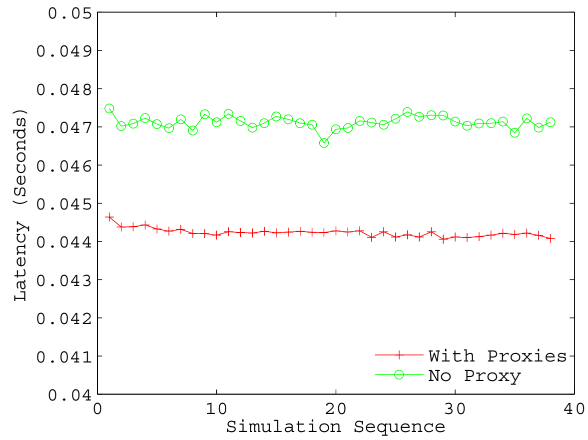

Fig. 7. Latency Comparison When There Is no CTGs

The simulations are carried out under the situation when there are no Cross Traffic Generators (CTGs) in the cellular network and when there are CTGs in the cellular network. Figure 6 shows the parameters of proxy group control with no CTGs. In the figure, the X axis denotes the simulation event sequence. For each simulation event interval, QoS indicator t' is calculated and k is updated. The Y axis of each subgraph denotes the parameters as indicated by the title of each subgraph. In the given simulation conditions, k is stabilized around 4, although the upper bound of k is set to be 10. The collective cellular rate c is able to benefit from channel diversities and maintain an average rate of 9.96 MBPS. It is also clear that as k increases or decreases, β and c also increases or decreases. The derivative of latency, t', which is calculated according to Equation (5), serves as a good cue to control the number of proxies k. The latency comparison of the cases with and without proxies is shown in Figure 7. All the simulation parameters are the same except that in the case where there is no proxies k is always set to 1. The average latency for 5 K bytes on/off traffic in the two cases are 44.2 and 47.1 microseconds. The standard deviations are 0.108 and 0.166 microseconds. The improvements when proxies are used for latency and its standard deviation are 6.1% and 35%. The use of proxies are particularly effective in reducing end-to-end latency variance.

Figure 8 shows the parameters of proxy group control with no CTGs. In the simulation, 5 CTGs in the cellular network are introduced. We observe that in the simulation with CTGs, the proxy group control process takes more simulation steps to converge (about 10 steps in the simulation, while in the case without CTGs, the converging time is almost negligible). The reason is that when CTGs are present, more proxies are needed to meet the requirement of QoS indicator. We can also see that the average number of proxies required is also increased from around 4 with no CTGs to around 12 with CTGs. The converging trend is also shown in the latency comparison (Figure 9). Once k stabilizes, the average latency for 5 K bytes on/off traffic in the two cases are 47.4 and 83.3 microseconds. The standard deviations are 0.971 and 1.73 microseconds. The improvements when proxies are used for latency and its standard deviation are 43% and 44%. When CTGs are present, using proxies are even more effective in reducing end-to-end latency and its variance.

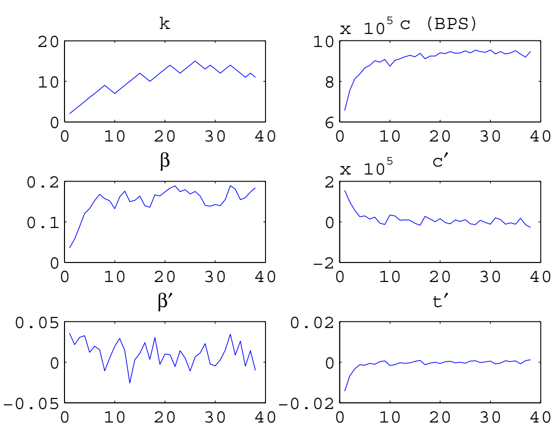

Fig. 8. Parameters of Proxy Group Control with CTGs

VI. Conclusions

We aim to provide acceptable QoS for remote sensing and control applications by exploiting the channel diversities of MANET peers in a hybrid MANET/Cellular environment. Utilizing multiple cellular channels can potentially improve the system performance, and of course comes with costs. Compared with previous schemes, our work goes one step further by asking the question of under what condition the benefits of relay proxies outweigh their costs. We answer the question by measuring the contention caused by MANET peers through the MAC layer packet retransmission rate, and design a dynamic mechanism to control the number of relay proxies.

The model evaluation under common fading channels using prevalent scheduling algorithms indicate that utilizing channel diversity has great potential of improving the system performance. Built upon the cellular bandwidth sharing model we designed a dynamic proxy group control algorithm that will automatically adjust the number of proxies based on the cellular network bandwidth gain and MANET contentions. Simulations under NS2 indicates the proposed scheme is effective in reducing end-to-end latency and latency variance. When cross traffic generators are present, the gains obtained by multiple proxies are even more impressive.

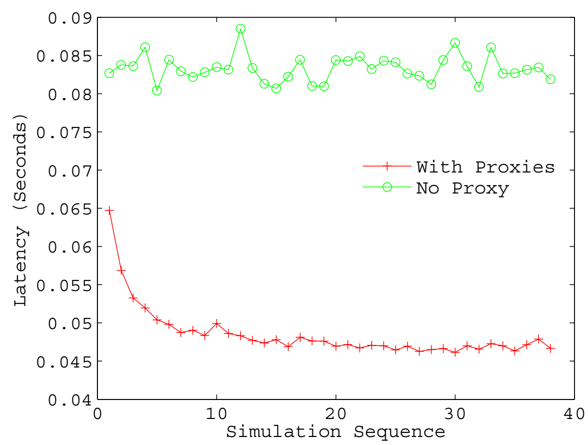

Fig. 9. Latency Comparison When There Are CTGs

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