Capacity Analysis for CDMA Based Cellular and Ad hoc Co-existence Networks

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Abstract*-The cellular and ad hoc co-existence network is expected as a complete solution for the wireless networks in the future. Traditionally, it is believed that under light traffic conditions, the low cost ad-hoc systems are preferred because of its dynamic feature and flexibility. The packets can be rapidly and directly transmitted to the intended nodes without the need of the centralized administration and infrastructure. On the contrary, if the traffic loading is heavy, frequent contention and collision on the MAC layer will seriously degrade the performance of the ad-hoc systems. Therefore, a centrally controlled architecture is necessary in large covered and densely populated districts. However, different from the conventional RTS/CTS mechanism, CDMA based ad-hoc systems are capable of the multipacket reception. The capacity tradeoffs between the CDMA based cellular and the ad-hoc networks not only monotonously depend on the traffic loading but also the cellular to ad hoc coverage ratio. In this paper, those tradeoffs are investigated. The throughput evaluation and an active defense against the multiple access interference in ad-hoc systems are also provided.*

Keywords: CDMA, Ad hoc, Cellular systems, MAI, Throughput

1. Introduction

In future B3G (beyond third generation) wireless networks, mobile communication services composed of heterogeneous, hierarchical, and multisized systems are expected. Cellular systems, centrally controlled by base stations often provide larger communication areas for high mobility customers, such as vehicles, while ad hoc systems are usually adopted to offer communication services between low-mobility mobile terminals.

In the literatures, for cellular and ad hoc co-existence networks, many works are undertaken to focus on efficiently balance traffic loads between cells by using ad-hoc stations to relay traffic from one cell to another cell dynamically [1-3]. In addition, some studies devote to use ad hoc to enable

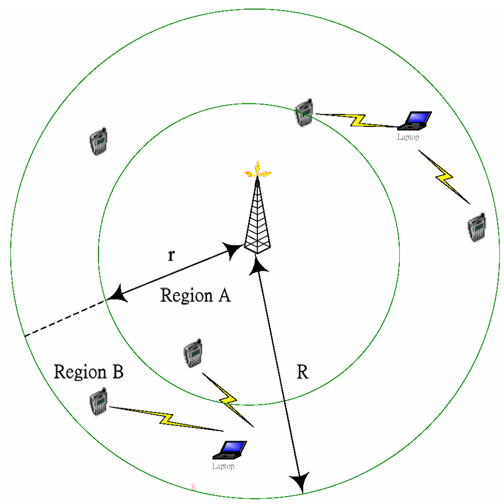

Figure 1. A cellular and ad hoc networks co-existence system

communications whenever nodes within the region without the cellular services. The ad hoc networks can also be used to adaptively adjust the coverage of a base station and improve the link quality during handover between cells [4] [5]. However, in [6], it is assumed that no traffic is removed from or injected into the same cell over the ad hoc air interface. Hence, the ad hoc traffic between mobile terminals is not calculated.

Besides, in IEEE 802.11 standard, the DCF (distributed coordination function) MAC (multiple access control) protocol addresses how the mobile terminals to share a single-common channel to avoid collisions. The RTS (request-to-send)/ CTS (clear-to-send) mechanism is used to resolve the hidden and exposed nodes problems. Because, in the CSMA/CA systems, one common-single channel is exclusively used by one terminal, thus it shall be that when the traffic is light, mobile terminals to transmit packets directly to each other is an attractive choice for minimum infrastructure requirements and better channel efficiency. On the other hand, if the network loading is heavy, lots of contentions and collisions on the MAC layer seriously degrade the system performance. Thus, a centrally controlled (cellular) network is preferred by using the coordinative scheduling.

However, the consideration in a CDMA system is much more different from a CSMA/CA one. For example, in the former case, multiple packets can be transmitted at the same time, while in the latter one, only one packet is allowed to be relayed in a time slot; otherwise, a collision happens and a re-transmission is required. Besides, in [7], following the CSMA/CA based IEEE 802.11 DCF protocol; the authors concluded that a larger transmission range achieves better network performance in an ad hoc network. But in CDMA systems, a larger transmission range implies much power consumption is needed for an energy-constrained ad hoc node. Furthermore, much mutual interference power is thus involved in the CDMA system if every node increases its transmission power.

In this paper, we investigated in the influence on the system throughput by adjusting the cellular to ad hoc coverage ratio in a CDMA based cellular and ad hoc co-existence network. Moreover, a defensive scheme to reduce the multiple access interference in the wireless ad hoc networks is proposed. The rest of the paper is organized as follows: Section 2 describes the system model and the proposed strategy where a mathematical method to analyze the system performance is also provided. In Section 3, numerical results are presented, and finally, concluding remarks are summarized in Section 4.

2. System Model

2.1. Co-existence Architecture

The concept layout for a CDMA based cellular and out-of-band ad hoc co-existence network is depicted as shown in Figure 1. For a practical scenario, in the proposed system model, the service region that a base station offers is assumed a circular area with radius R and normally partitioned into six 60° sectors by using directional antennas. This technique is so-called sectorization which many modern base stations support. Here, the coverage of a sector is divided into two regions as displayed in Figure 1. The inner region, Region A, is a smaller sector with radius r, while the outer region, Region B, is a one-sixth concentric circle represented by a ring chip. User terminals (nodes) in the inner region access the wireless network over the cellular links while the users near the cell's boundary in Region B construct an ad hoc network for communications because they usually require too much power to maintain the quality of the connection to the far away base stations.

Here, a user terminal is also simply called a node for convenience. Each node is in the dual-band mode. That is, it shares the same baseband structure but switches between two different RF bands using the soft radio technology. Besides, in an energy-constrained ad hoc network [8], one node who has rich power or a better quality of connection (less fading or path loss) to the base station of the cellular system is usually selected as a gateway node It acts as a wireless bridge to relay packets to other systems and a master to deal with the nodes' association or de-association to the local area network which it is in charge of.

Moreover, since the cellular and the ad hoc networks considered here are both CDMA based, any node in each system has the multiple packets reception (MPR) capability [9]. That is, all collided packets in a time slot can be successfully received by an intended node except the condition that there are errors in a packet due to the multiple access interference (MAI). In the proposed model, a node having a packet to send is referred to as in the backlogged state; otherwise it is in the unbacklogged state. It is assumed that each node can at most hold one packet in a time and has equal probability to transmit. But this model can be easy to expand to the special case where every node intending to transmit a real time packet, such as voice message, has high priority. Moreover, all nodes in an ad hoc network are assumed fully connected. That is, a system where nodes can transmit directly to each other and a packet received by a node can also be detected by other nodes not intended for it.

In this paper, we proposed a simple scheme which is an efficient defense against the multiple access interference (MAI) in a CDMA based ad hoc network. At first, we assume that the spreading code of every node is known to every other node after initialization. Any node can be a potential transmitter or receiver but it cannot transmit and receive packets at the same time due to half-duplex operation. Each node in the same ad hoc network has to broadcast a beacon as a busy tone before its transmission, thus to inhibits other nodes who intend to relay packets to it in this instant to stop transmitting. In other words, if one packet intended for a node which is not idle or in the reception mode, it will be backlogged and not be transmitted to reduce multiple access interference in an ad hoc network.

2.2. Markovian Analysis

The mathematical analysis is an extension work referred to [10]. As the configuration of the co-existence system in Figure 1, we assume there are Mc nodes in Region A while Ma nodes are in Region B. In the following derivation, let M be the number of nodes in the same network, i.e., $M=Mc$ for a pure cellular case; while $M=Ma$ for the ad hoc one, respectively. Let n, the number of backlogged nodes in a network (either cellular or ad hoc), be the state in a Markov chain. $q_a(k,n)$ ($q_r(k,n)$) denotes the probability that k unbacklogged (k backlogged) nodes transmit packets in a given time slot. It is thus obtained that

$$q_a(k,n) = \binom{M-n}{k}(1-P_a)^{M-n-k}(P_a)^k$$

and

$$q_r(k,n) = \binom{M-n}{k}(1-P_r)^{M-n-k}(P_r)^k$$

where P_a is the probability that there is at least one packet arriving at an unbacklogged node for transmission, and P_r is the transmission probability for a backlogged node.

Furthermore, we assume the arrival process of the newly generated packets at each node is identical independently Poisson distributed with mean rate l / M in one time slot. Hence, $P_a = 1 - e^{-(2l/M)}$ and $P_a = 1 - e^{-(l/M)}$ for the TDD (Time Division Duplex) cellular system and the ad hoc system, respectively. The transition probability, P_{nk}, means the possibility that k out of n packets fail to transmit in a given time slot. In other works, the system state transfers from the current state where n backlogged nodes are in the network to a permissible next state where k nodes are backlogged. Hence, we can get

$$P_{nk} = \begin{cases} \sum_{y=n-k}^{n} \sum_{0}^{M-n} r_{(x+y)[x+(n-k)]} q_r(y,n) q_a(x,n), \\ \qquad 0 \le k < n \\ \sum_{x=k-n}^{M-n} \sum_{0}^{n} r_{(x+y)[x-(k-n)]} q_a(x,n) q_r(y,n) \\ \qquad n \le k \le M \end{cases}$$

where r_{nk} is the probability that k out of n packets are successfully received by their intended receivers. Solving the Markov chain by the flow equilibrium equations and $\sum_{n=0}^{M} p_n = 1$, the steady-state probabilities p_n are obtained.

2.3. Derivation of r_{nk}

Now, we commence to put our hand to derive the packet success reception probability, r_{nk}. Before that, we need to compute the packet correction probability, P_c, at first. It is the probability that a packet can be relayed over the air without errors or those errors can be successfully corrected. Let N be the total number of packets transmitted in a time slot and G be the spreading gain. Moreover, we apply the Gaussian assumption about the multiple access interference (MAI) and assume bit errors occur independently. Thus, the bit error rate, x, is equal to $\frac{1}{2}\cdot\left[1-erf(\sqrt{\frac{3G}{2(N-1)}})\right]$ and $erf(z)$ is defined as an error function, $\frac{2}{\sqrt{p}}\int_0^z e^{-t^2}dt$. Then,

$$P_c = \sum_{i=0}^{t} \binom{L}{i} x^i (1-x)^{L-i} ,$$

where t denotes the number of bit errors that can be corrected by a linear block code and L is the packet length in bits. If the correlation between each matched filter at the receiver is zero, thus the probability that all packets are correctly received by their intended node is

$$s_{nk} = \binom{n}{k} P_c^{\,k} (1-P_c)^{n-k} .$$

Note that r_{nk} is the probability that k out of n packets in a time slot are successfully received by the base station or their intended node. In CDMA systems, the condition that all collided packets transmitted at a time slot can be detected correctly by their intended receivers means that there is no bit error in the packets or the bit errors can be corrected by coding. That is, the mutual interference power caused by the transmitters colliding among each other can be overcome by the spreading gain or the error control coding techniques. Therefore, we have $r_{nk} = s_{nk}$ for the cellular systems.

However, in this paper, for the ad hoc network, we propose a novel scheme to reduce the interference power during the transmission period. As mentioned before in Section 2.1, every node having one packet to send needs to broadcast a beacon to inform other nodes before transmission. If one node receives the informed message from the intended node which has packets to transmit, too, it will stop transmitting procedure at that moment. This scheme is similar to the well-known RTS (request-to-send) mechanism in IEEE 802.11 standard. In case, each node hears the beacon from the node which it intends to transmit (i.e., the node is also in the transmission mode and not idle for reception). It will back off and wait the next chance to send. Remember that the probability that it will just re-transmit in the next time slot is P_r. Thus, the multiple access interference in the ad hoc CDMA network is significantly decreased.

Since in the ad hoc network, the transceiver at each node is half-duplex. Only those nodes which are idle or in the reception modes have a chance to correctly detect the packets intended for it. Moreover, it is assumed that each node has equal probability to transmit to every other node and whenever one node inhibited transmission is in the reception mode regardless of that instant at which he is idle or just in the back-off time waiting for the next transmission. Therefore, the probability that j of i packets are allowed to be transmitted (i.e., j nodes are just during the back-off period waiting for transmission or idle for reception) is

$$z_{ij} = \binom{i}{j}\left(\frac{M-i}{M-1}\right)^{j}\left(\frac{i-1}{M-1}\right)^{i-j} .$$

Hence, in the ad hoc network,

$$r_{nk} = \sum_{j=k}^{n} z_{nj} \cdot s_{jk} .$$

2.4. Performance Measurement

The performance we need to consider herein is throughput. The network throughput is defined as the average number of packets successfully received by their intended receivers in a time slot. Given state n of the Markov chain, we have

$$T(n) = \sum_{m=1}^{M} Pt(m) \cdot \sum_{i=0}^{k} i \cdot s_{mi}$$

where $P_t(m) = \sum_{m=0}^{n} q_a(m,n) \cdot q_r(n-m,n)$ is the probability that m packets are transmitted in a given time slot. Note that the cellular system considered here is Time Division Duplex (TDD). Hence, the average throughput of the cellular system is

$$\overline{T_c} = \frac{1}{2}\left[\sum_{n=0}^{M} T(n) \cdot p_n^c\right]$$

Similarly, we can obtain the average throughput in the ad hoc network by the equation,

$$\overline{T_a} = \sum_{n=0}^{M} T(n) \cdot p_n^a$$

Furthermore, the throughput with different coding rate, r_c, and spreading gain, G, has a different occupation of bandwidth resource. Thus, normalization is required for the capacity comparisons with different coding rate or spreading factor. Following [11], the Gilber-Varsharmov lower bound for block codes, we have the normalized throughput

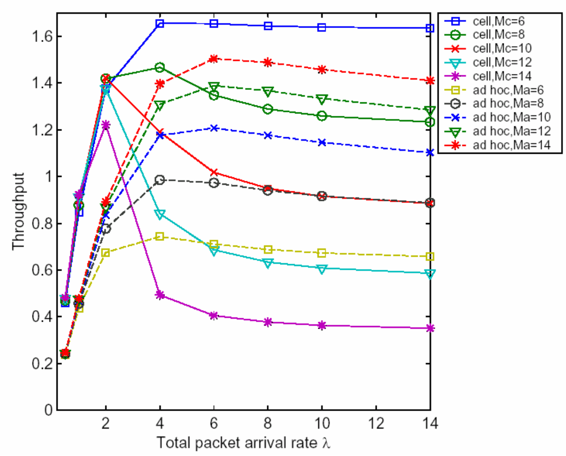

Figure 2. Throughput vs. λ for G=5, t=3, and Pr=0.6.

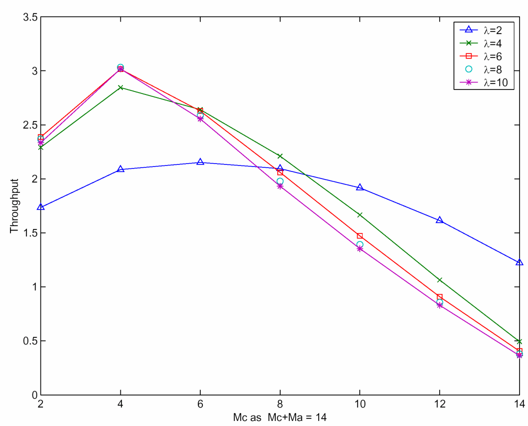

Figure 3. Total throughput of cellular and ad hoc co-existence networks vs. *Mc* with *Mc* + *Ma* =14.

$$h_c = \frac{r_c \cdot \overline{T_c}}{G} ,$$

and

$$h_a = \frac{r_c \cdot \overline{T_a}}{G} ,$$

for the cellular and the ad hoc systems, respectively, where a is equal to $\frac{2t+1}{L}$ and $r_c = 1 + a\log_2(a) + (1-a)\log_2(1-a)$.

3. Numerical Results

In Figure 2, we consider a cellular and ad hoc co-existence system with L=100, G=5, and t=3. At first, we can see that for the cellular network, if the number of nodes is fixed, the throughput increases in the

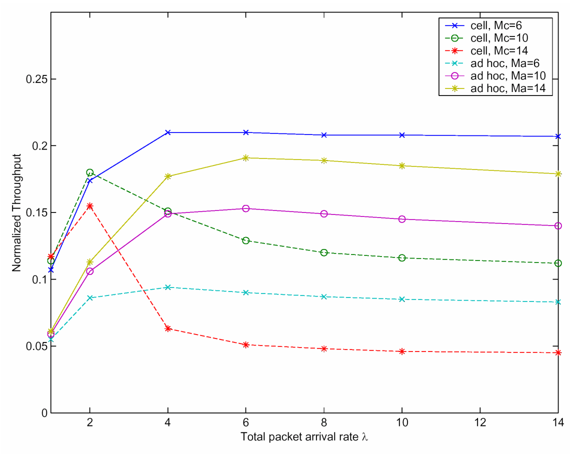

Figure 4. Normalized throughput for G=5, t=3, and Pr=0.6.

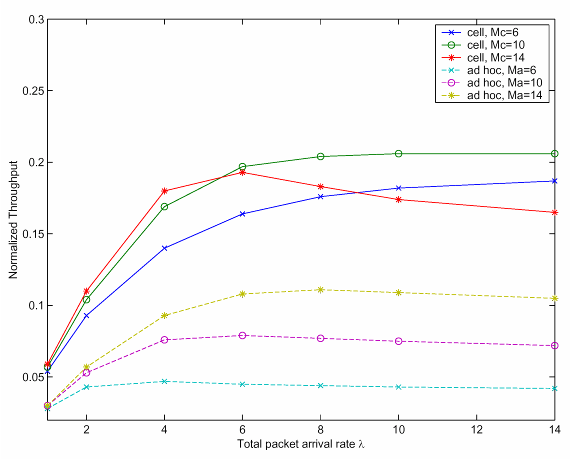

Figure 5. Normalized throughput for G=10, t=3, and Pr=0.6.

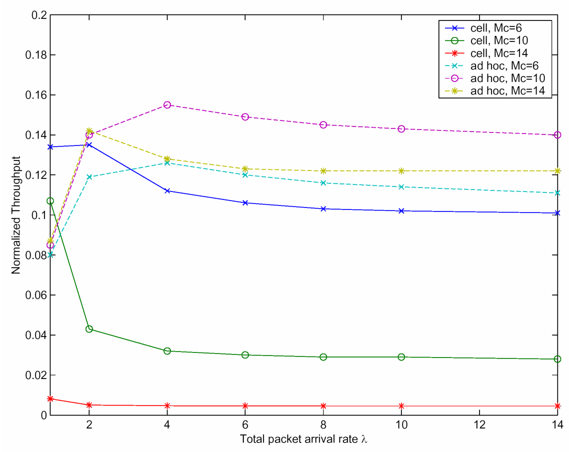

Figure 6. Normalized throughput for G=5, t=0, and Pr=0.6.

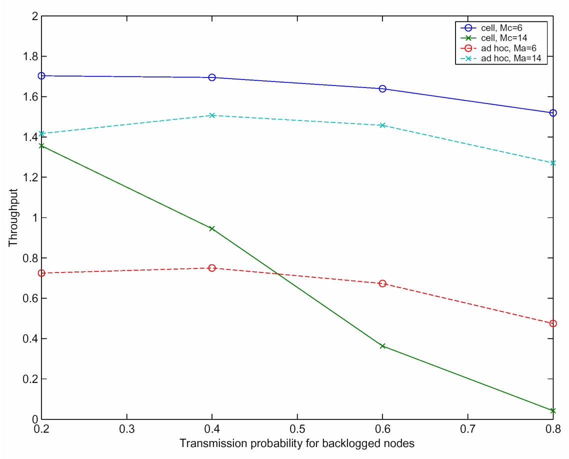

Figure 7. Throughput vs. Pr for G=5 and t=3.

beginning but is reduced with the increase of the value of l . This is because in a single-cell CDMA network, under the assumption of ideal power control, the signal to noise ratio (SNR) can be simply represented by SNR=1/(K-1) [12], where K is the number of packets transmitted in a time slot. Hence, if SNR with the increase of K (l) is too small to meet the QoS, throughput in a CDMA network will be declined due to the multiple access interference.

Secondly, if the total packet arrival rate, l , is fixed, the more nodes there are, the less throughput is carried in a cellular network. Note that all nodes generate packets with equal arrival rate l / M_c . Hence, large M_c means higher probability that lots of packets may be transmitted at the same time in a slot leading to a poor SNR condition. On the other hand, for an ad hoc network, larger M_a with a fixed l means that the possibility of the colliding condition where most nodes having packets to send are also intended to be transmitted will be lower. Note that each node in an ad hoc network is assumed to be half-duplex.

Finally, if l / M_a is fixed, the performance (throughput) of achieves better with the increase of l in the interested range.

In Figure 3, in the numerical calculations, we assume the total number of the nodes is finite, e.g., $M_c + M_a = 14$. Note that in case *Mc*=14 or *Ma*=14, it is a pure cellular or ad hoc network, respectively. It is observed that the total system throughput is relative to the number of nodes in cellular to that in ad hoc coverage ratio. The larger value of l is given, the smaller coverage of the centrally controlled cell shall be to achieve the maximum system throughput.

Figures 4-6 show the effects of the spreading gain, *G*, and the error correction capability, *t*, on the throughput with a normalized bandwidth resource. In these figures, different numbers of nodes in the cellular and ad hoc networks are given, respectively. It is clear that, with powerful receivers, i.e., higher spreading gain and larger number of correctable bit errors, the cellular network has a better improvement in most conditions. But, meanwhile, throughput will be seriously degraded if the link quality of the cellular connection is destroyed. It is concluded that the multiple access interference and the stability of the communication environment have more significantly influence on the cellular network than the ad hoc one.

As shown in Figure 7, it is demonstrated a potential problem which may occur in our proposed scheme. In case of the condition that the re-transmission probability is large, the time for a node taking for re-transmission shall be increased. Because with a large *Pr*, the nodes who would like to transmit to each other always hear the beacon (busy tone) broadcasted from the other side, thus they are always waiting for transmission and the normalized throughput will be slightly decreased. Figure 7 also reveals that for the cellular network whatever the value of *Pr* is. the normalized throughput will be seriously decreased as the M_c is large.

4. Conclusions

In CDMA based wireless ad hoc network, in case of a packet transmitted by one node to another, which is not in the reception mode, throughput of the CDMA system will suffer degradation from the multiple access interference increased by the frequent re-transmissions. Therefore, in order to overcome this problem, in this paper, we proposed a scheme that each node needs to broadcast a beacon (busy tone) before transmission to inform other nodes stop transmitting to it.

Furthermore, we found that in a heterogeneous CDMA system, in order to achieve better throughput, the deployment of the coverage of the centrally controlled area to the ad hoc region ratio not just depends on the traffic load but also the number of the communicating nodes. The numerical results reveal that it has better to impose traffic just on a few nodes in a slotted cellular network, while it prefers more nodes for spatial reuse in an ad hoc CDMA network.

Acknowledgment

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