WWAN/WLAN Two-Hop-Relay Architecture for Capacity Enhancement

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Abstract— **The integration of 3rd generation (3G) cellular networks and the IEEE 802.11 Wireless Local Area Networks has drawn considerable attention from the research and commercial communities. Emerging dual-mode mobile terminals could provide flexibility and system performance enhancement by providing seamless roaming between 3G WWANs and 802.11 WLANs. In this paper, we proposed a novel integrated WWAN/WLAN two-hop-relay architecture that both enhances the system capacity of 3G cellular systems and extends the system coverage area of 802.11 terminals. The proposed two-hop-relay architecture utilizes temporal channel quality variation to achieve increased system capacity. Typically, the system throughput is increased by 200-400% in a HDR system.**

I. INTRODUCTION

In modern cellular network design, the cellular systems utilize channel state information to enhance system performance. The WWAN cellular network operators are continually striving to provide better Quality of Service (QoS) for mobile terminals. These terminals can support higher speed connections. Other than connecting to the WLAN (Wireless Local Area Network) access point for alternative wireless access, mobile terminals with WLAN radio interfaces could also communicate with other WWAN/WLAN dual-mode terminals. Dual-mode WWAN/WLAN mobile terminals could act as gateways that relay data packets between cellular base stations and the other mobile terminals. To improve overall system capacity and QoS, especially in a CDMA cellular environment where multiple access interference (MAI) sharply limits performance, the WWAN network could encourage mobile terminals that have a good channel quality state to become intermediate relay gateways to assist those mobile terminals with a poor channel quality state to achieve better system performance. The two-hop-relay WWAN/WLAN architecture could reduce the dead spots in a cell and enhance the user throughput at places where radio signal reception is poor, as well as reduce multiple access interference in adjacent cells. The mobile terminal can directly connect to the cellular base station or connect through the WLAN interface to an intermediate gateway and use the WWAN cellular interface of the intermediate terminal to relay to the base station.

There has been a significant amount of research work on the integration of Third Generation Cellular Networks (3G) and IEEE 802.11 Wireless LAN. [1,2] Most of the work on integrating 3G and WLAN has been focused on scenarios where IEEE 802.11 technology is deployed as 802.11 access points. Previous integration research works mainly address the mobility management, Quality of Service, billing, network security, seamless handoff between 3G base stations and 802.11 access points. In this paper, we propose a novel way to integrate the WWAN and WLAN with a two-hop relay. Here, the 802.11 WLAN radio interface is considered as a tool to extend and to enhance the coverage and to improve the performance of 3G cellular systems. The IEEE 802.11 interfaces operate in *ad hoc* mode and connect to other neighboring dual-mode relay terminals. The WWAN/WLAN dual-mode mobile users can choose to use the direct cellular link to communicate with the cellular base station or to communicate with the 802.11 access point [if there is one within the WLAN transmission range]. In addition to direct connections to WWAN or WLAN access points, the mobile terminals can transmit packets through WLAN interfaces to the dual-mode intermediate relay gateway. After that, the relay gateway forwards the packets to the base station through the WWAN cellular link. The relay gateway can be dual-mode relay stations that are established by Wireless Internet Service Providers (WISP) or cooperating dual-mode mobile terminals.

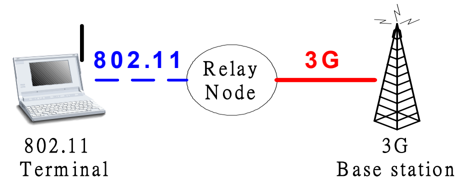


Figure 1: Two-hop-relay Architecture for 3G and 802.11 Integration

The WWAN/WLAN integration framework that we consider here could discover and utilize the better channel quality radio channels in cellular networks to achieve greater system throughput while not introducing protocol complexity in multihop routing. A mobile terminal periodically measures the channel quality of the WWAN cellular radio link and advertises its channel quality to neighboring terminals through WLAN interfaces. Dual-mode mobile terminals could become a relay gateway providing relay service for neighboring mobile terminals. The dead spots in cellular networks could be effectively eliminated through the WWAN/WLAN two-hop-relay scheme. In addition, mobile terminals equipped only with a WLAN radio interface could enlarge the roaming area by the two-hop integration with WWAN cellular networks.

The overall cellular capacity could be also enhanced because mobile terminals with poor channel quality could utilize the two-hop-relay transmission scheme to transmit packet via mobile terminals with better channel quality.

II. DESIGN PHILOSOPHY: TWO-HOP-RELAY WWAN/WLAN

A. *Increase WWAN System Capacity*

The proposed WWAN/WLAN two-hop-relay scheme could be considered as a system level diversity technique to increase the WWAN capacity by utilizing temporal wireless channel variation. Mobile terminals utilize the good quality radio channels to increase the system capacity. All dual-mode terminals periodically estimate the cellular radio channel conditions cellular links by measuring the signal strength of the pilot signals from the base station. These terminals advertise their Channel State Information (CSI) of cellular connection quality through their WLAN radio interfaces to nearby mobile terminals. Mobile nodes retrieve the CSI of the neighboring nodes from the relay advertisement messages. They determine whether to use their own cellular link or opt for the advertised two-hop-relay service.

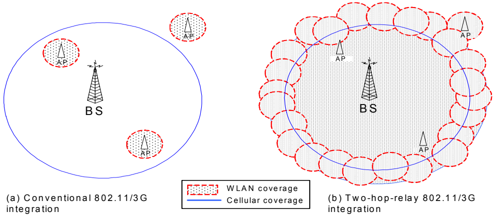
When data traffic of two terminals is sent in one cellular link, the base station should allocate more radio resources to this cellular link. In CDMA cellular systems, the adaptive radio resource allocation can be achieved by adopting the multicode CDMA (MC-CDMA) architecture [3] or the variable spreading gain CDMA (VSG-CDMA) architecture [4]. Radio resources can also be allocated in a time-division fashion such as TDMA or the CDMA2000 High Data Rate (HDR) system [5] and the UMTS HSDPA (High Speed Downlink Packet Access) system [6] in 3G cellular networks; in these systems, the base station could assign time slots asymmetrically to different radio links.

B. *Extend WLAN System Coverage*

Besides taking advantages of the variable nature of the QoS of wireless channels to increase system capacity, the WWAN/WLAN two-hop-relay scheme also extends the system coverage and facilitates the deployment of WLAN technology such as IEEE 802.11. In heterogeneous wireless access networks, WWAN cellular networks coexist with WLAN access point deployment. The integration of the fast-growing IEEE 802.11 technology and the next-generation 3G cellular networks has drawn significant interests from wireless carriers. IEEE 802.11, operating in the unlicensed ISM spectrum, provides high-speed Wireless Internet access at low cost. However, the transmission range of IEEE 802.11 radio interface limits the coverage area of an IEEE 802.11 access point.

Because of the short transmission range of 802.11 radios, 802.11 access points are mostly deployed in hot spots where high density of low-mobility mobile users gather. Figure 2(a) shows the 802.11 WLAN and 3G cellular coverage areas without applying two-hop-relay. The mobile terminals with 802.11 only have limited coverage area around 802.11 APs.

In a WWAN/WLAN two-hop-relay system, those mobile users with only 802.11 radio interface can achieve extended coverage area as shown in Figure 2(b). The 802.11 radio access covers not only the original 802.11 AP neighborhoods and extends the serving area that includes the 3G cellular cells, as well as an extended area outside the cell boundaries ---- provided that there are enough intermediate relay nodes. The dual-mode 3G/802.11 mobile terminals can choose the access methods between the 3G cellular base station, IEEE 802.11 Access Point, and the 3G/802.11 two-hop-relay scheme. Mobile terminals can get the best Quality of Service among any one of them. The single-mode 802.11 mobile terminals also benefit from the increased system coverage.



(a) Conventional 802.11/3G integration

(b) Two-hop-relay 802.11/3G integration

Figure 2: WLAN coverage area in 3G/802.11 integrated environments

C. *Why not multihop?*

In contrast to many other mobile multiple hop network architectures [7], we focus on a relay scheme that limits packet forwarding to one hop. There are several practical reasons to employ this two-hop relay approach. The rationale behind the two-hop-relay design is to reduce the system complexity, to avoid inefficient mobile *ad hoc* routing, to reduce the impact of inefficient random medium access protocols, and to alleviate the congestion bottleneck at the Internet gateway nodes.

The mobile *ad hoc* routing protocols are required to discover the multihop relay routes from the source nodes to the destination nodes in a mobile *ad hoc* network. Since routing in mobile *ad hoc* networks is distributed, mobile *ad hoc* routing protocols primarily rely on mechanisms that are based on flooding to discover a new route when there is no previous record in the route cache. Due to node mobility and radio signal strength fluctuation, the routing path from the source node to the destination node could easily become invalid. Frequent route changes and the resulting route discovery procedures could cause high signaling overheads. Multiple hop forwarding also results in greater time delay between mobile terminals and the gateway. The proposed WWAN/WLAN two-hop-relay scheme does not have the same delay latency issue since there are only one-time WLAN transmission and one time WWAN transmission. There are much less route changes and route discovery in the WWAN/WLAN two-hop-relay environment. The WWAN/WLAN two-hop-relay architecture provides an uncomplicated architecture to enhance the WWAN cellular system while avoiding the packet delay, signaling overhead, and system complexity in mobile *ad hoc* routing schemes.

Not only does a wireless multihop network face the formidable challenge of distributed mobile *ad hoc* routing, it also suffers from the inefficient link-layer medium access protocols. In a distributed environment, it is extremely difficult to compute a time-division scheduling without compromising the system performance with heavy handshaking control overhead. The node mobility and the dynamic nature of wireless communications also increase the difficulty of scheduling at the medium access layer. Wireless random access Medium Access Control (MAC) is required in mobile *ad hoc* networks. Random access wireless MAC utilizes control handshaking and backoff mechanisms to avoid packet collision. Contrary to TDMA or CDMA in a structured cellular network, the random access MAC that is used in distributed wireless network is inefficient in the spectral resource utilization. In multihop *ad hoc* network, sending data packets experiences several relay steps at intermediate nodes. In each of the relay step, transmitters need to make sure the shared medium is idle with the help of random access MAC protocols before transmission. This increases the end-to-end latency and impairs the radio resource utilization. In addition, IEEE 802.11 random access MAC has been reported to not perform well in mobile *ad hoc* environments[9]. On the other hand, the two-hop-relay system is composed of one direct cellular hop and the other WLAN random access hop. The cellular base station can efficiently allocate radio resource to the cellular terminals and intermediate relay stations. There is only one Wireless LAN hop that suffers from the inefficient random access medium access.

The Internet-connected multihop wireless networks along with the proposed two-hop-relay scheme face the same formidable task to alleviate the congestion bottleneck at the global Internet gateway. The gateway, which connects the global Internet and the local wireless multihop network, easily becomes the bottleneck when most of the traffic goes through a single node. As [8] demonstrates, the capacity of one wireless *ad hoc* network depends on the percentage of the global traffic of this network. The multihop network capacity is greater than the traditional single hop cellular network when the traffic flows are dominated by the local peer-to-peer applications. Nevertheless, the capacity of wireless *ad hoc* networks significantly decreases when the incoming or outgoing global traffic dominates. Multihop relay using the same wireless spectrum causes greater interference at the gateway. The proposed two-hop-relay scheme uses two separate spectrum reduces the interference at the gateway; hence, alleviates the gateway congestion.

III. RELAY SERVICE DISCOVERY

In the WWAN/WLAN two-hop-relay system, mobile terminals are required to exchange channel quality information with neighboring mobile terminals. The two-hop-relay service discovery control signaling flows are shown in Figure 3. In the figure, the Cellular Networks (CN) denotes a generic Wireless Wide Area Networks. It can be a second generation GSM network or one of the 3G cellular networks such as UMTS or CDMA2000. The actual signaling message flows may be slightly different from one cellular network standard to another. In addition, some operations performed in the CN shown in the figure may actually be performed in several nodes within a cellular network rather than performing at only one single point. These operations may be performed in the network edge like base station and MSC, or in a distant location such as HLR and AuC. For the sake of simplicity, we use a single icon to represent the whole cellular network and concentrate on the two-hop relay scheme. The intermediate node, Relay Gateway (RG) is the dual-mode terminal that has both the WWAN cellular radio interface and the WLAN radio interface. The RG can be a fixed gateway or a mobile node.

The cellular network carriers can provide some incentive pricing to encourage mobile terminals to perform the relay functionality (recognizing that such mobiles will have bigger battery drain and less throughput). The other way is for the wireless service providers to build some dual-mode RGs. The RG may play not only the role of intermediate relay terminal but also the role of end-user. Besides forwarding data packets for other nodes, the RG can transmit packet for its own application. Nevertheless, we only present the message flows that are related to the intermediate relay functionality in Figure 3. The Mobile Node (MN) can be a dual-mode terminal or a WLAN-only terminal. However, we do require that the MN subscribes to the integrated service through the cellular service provider, or has a roaming agreement with the cellular service provider so that the MN can be authenticated and authorized by the CN.

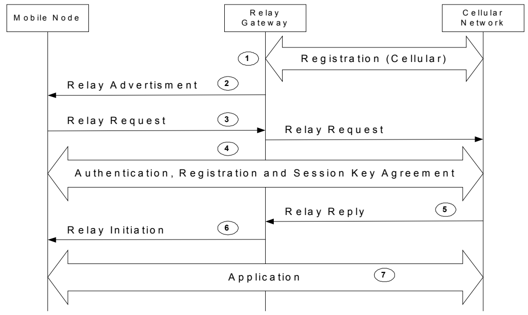


Figure 3: Message flows of two-hop-relay access discovery

The RG must be authenticated and registered with the WWAN cellular networks before the RG establishes any two-hop relay connection for other mobile terminals. The registration process follows the general cellular registration procedures and it depends on the types of cellular systems. The registration of being an intermediate RG is necessary to obtain the corresponding access authorization. It may also result in different pricing and resource allocation policies for a RG and a non-gateway MN. The mobile networks could provide incentive pricing to encourage mobile terminals to serve as gateways.

After the registration process, the RG is attached to the cellular network, and can utilize the global Internet connectivity for its own applications through the WWAN cellular link. The RG periodically broadcasts the *Relay Advertisement* message, which is shown as the message 2, through its Wireless LAN radio interface. The *Relay Advertisement* message includes the current Base Station identification number, Gateway identification number, Bandwidth Indicator Type, Bandwidth Indicator Value, and Registration Method fields. The Base Station identification number identifies the serving base station in the cellular networks. The Gateway identification number is used to identify RG nodes in the same serving base station. The Bandwidth Indicator Value, in general, indicates the data rate per mobile terminal that the gateway and the base station can support. However, Bandwidth Indicator Value field could be filled with QoS or any other system performance metrics. Bandwidth Indicator Type determines the format of the Bandwidth Indicator Value in this signaling message. The Registration Method field shows whether the mobile terminal is required to register directly through cellular link or can be registered through the Wireless LAN radio interface, when these two methods are both available.

A dual-mode MN can compare the Channel State Information (CSI) of its direct cellular connection and the Bandwidth Indicator value in the received *Relay Advertisement* message to decide whether establishing a direct cellular connection or a two-hop-relay connection. The power consumption of direct communication and two-hop-relay, mobility pattern of the terminal, and time constraints of applications are also possible factors that involved in the decision process. When the MN is a dual-mode terminal, the MN sends the *Relay Request* to the RG after comparing the pros and cons of the two-hop-relay. When the MN only has a WLAN radio interface, the MN has no other choice but sends the *Relay Request* to the RG right after receiving *Relay Advertisement* message. The RG stores the identification, which can be the IP address in the All-IP Wireless networks or the IMSI in GSM or UMTS system, of the MN. Then RG forwards the *Relay Request* message to the CN and waits the authentication result and authorization from the cellular networks. For example, in the integrated IEEE 802.11/3G integrated environment, the AAA (Authentication Authorization Accounting) server can get the subscription information from the HLR/AuC to see if the mobile user are eligible for the two-hop-relay service.

The fourth step involves in several signaling messages for the MN to register with the CN. During the registration process, the MN and the CN mutually authenticate each other and the CN check the subscription profile of the MN. After authentication, the MN and the network should generate the cipher key and integrity key that are going to be used.Afterwards, the CN sends the *Relay Reply* message. The RG notifies MN whether the relay service is authorized or declined. In this figure, it shows the scenario that authorization is successful. The RG sends out the *Relay Initiation* message to notify the MN to start the actual applications. When the MN receives the *Relay Initiation*, it can start the applications, which are secured by the session keys that are previously obtained.

IV. SYSTEM PERFORMANCE EVALUATION

A. *Performance Evaluation Method*

The performance evaluation settings emulate the CDMA2000 HDR system [5]. In the HDR system, mobile terminals are served with different data rates dynamically. The cellular base station allocates the radio resources in a time-division fashion. The resource management unit at the base station schedules the data packets toward mobile terminals according to their SINR and the corresponding data rates. To increase the system capacity, the base station adaptively assigns time slots to mobile terminals that are currently located in high data regions. As a result, the HDR channel adaptive scheme achieves better overall system performance than traditional TDMA and CDMA systems, but cannot achieve the fairness among the users due to the fact that users with better channel quality will get more radio resources than the users with poor channel quality. In the HDR system, the ratio of the maximum delay for bad channel condition terminals to the minimum delay for good channel terminals characterizes the unfairness and the capacity that the system can achieve.

The simulation setup represents the scenarios of the integration of 3G cellular system and IEEE 802.11 WLAN. Dual-mode mobile terminals are uniformly distributed over 1000-meter 3G cells. The WLAN system uses a random access MAC protocol and supports a much higher data rate compared to the WWAN system. We assume that the wireless spectrum of the WWAN systems do not overlap with the spectrum of the WLAN systems so that the radio signals of the WLAN system and the WWAN system will not interfere with each other. One dual-mode gateway will serve only κ end users. The value of κ differs from one WLAN/WWAN integration scenario to another. It depends on the mobile terminals' computing capability and the relative radio transmission rates of the WLAN radio link and the WWAN radio link. In the simulation, we set $\kappa=7$.

The radio propagation model in simulation is shown in Equation (1). We consider both the path-loss and the shadowing effect in our radio propagation model. The received signal power $S_{RX} = k\ S_{TX}\ \xi\ (d)^{-n}$. The constant k models the combination of the antenna gains and the line losses of both transmitters and receivers. The radio model is composed of a path-loss component $(d)^{-n}$ and a shadowing component ξ. The distance between the transmitter and the receiver is denoted as d. The path loss exponent n is assumed in the range $2 \leq n \leq 4$. The shadowing component ξ follows the lognormal distribution. As the lognormal random distribution suggest, $\log_{10}(\xi)$ follows the normal distribution with zero-mean and standard deviation $\sigma\, dB$.

The system data rates is the performance metric to evaluate the two-hop-relay scheme. All of the base stations transmit in the same power level. The mobile terminals will receive radio signals with different SINR γ values, which are determined by the distance from mobile terminals to the base station and the degree of shadowing effect. The downlink traffic throughputs and required SINR values of the HDR system are given in [5].

B. Downlink High-Data-Rate System Performance

We will study the dynamic data rate HDR system capacity in various scenarios with a different number of mobile terminals per cell, transmission ranges of WLAN radio interfaces, and radio operational environments. In addition, we also compare the two-hop-relay HDR/WLAN system with the generic HDR system with different delay latency ratios L_{max}/L_{min} [5]. The HDR delay latency ratio is defined as the maximum user delay among all HDR users divided by the minimum user delay among all HDR users. Since wireless radio resources can be allocated unevenly in HDR systems, L_{max}/L_{min} represents the unfairness in HDR system. The HDR system should allocate the radio resources not to violate the delay latency ratio constraint while maximizing overall system throughput. In general, the overall system throughput increases with the delay latency ratio L_{max}/L_{min}.

1) Wireless LAN Transmission Range

First, we demonstrate the performance of the original HDR system and the HDR-based two-hop-relay system with different L_{max}/L_{min} ratios. In Figure 4, the original HDR without WLAN relay is denoted as HDR while other two-hop-relay systems are labeled with different WLAN relay ranges. For example, the two-hop-relay system with 100 meter WLAN transmission range is labeled as R100 in Figure 4. By utilizing the channel state information to achieve better system performance, the HDR system allocates different quantities of radio resources to users. As the ratio L_{max}/L_{min} increases, the HDR system can allocate more time slots to mobile terminals in better channel condition and thus enhance the overall system capacity at the cost of user fairness. Both the original HDR system and the HDR-based two-hop-relay systems achieve greater throughput as the delay latency ratio L_{max}/L_{min} increases.

We also observe that the system capacity gain of the two-hop-relay system increases as the WLAN radio transmission range increases. Provided that the mobile terminal density remains the same, the greater the WLAN transmission range, the higher the possibility to find a better intermediate relay node. As a result, the system throughput increases with the WLAN transmission range. In the figure, we find that the two-hop-relay with 50-meter WLAN-range outperform the original HDR system about only 5%~6% because it is difficult to find other relay candidates within the short 50-meter range. Even if a mobile terminal can possibly find another mobile terminal within the 50-meter radius, the distances from both terminals toward the base station are about the same and the radio signal attenuations due to path loss are around the same level. As a consequence, the radio channel conditions of these two terminals are merely determined by the shadowing effect and have a greater chance to fall in the same state. As the WLAN transmission range increase to 100 meters, the capacity gain reaches the 28%~35% region. For wide-range WLAN scenarios, the two-hop-relay system capacity increases significantly. Using a 150-meter radius WLAN to relay for HDR system can achieve a 55%~75% capacity gain. While in the 200-meter case, the throughput in the two-hop-relay system is more than doubled from the original HDR system. The two-hop-relay system capacities range from 200% to 300% of the original HDR system capacities.

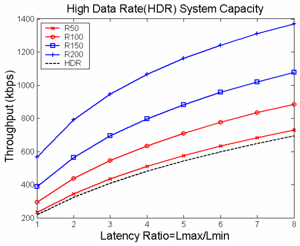


Figure 4: HDR downlink capacity V.S. Latency Ratio

2) Radio Channel Conditions

We will demonstrate the shadowing effect on the HDR-based WWAN/WLAN two-hop-relay system with different WLAN transmission ranges in the following figures. The shadowing effect, which is characterized by the lognormal random distribution, reduces the HDR-based system performance in most of the cases. When the standard deviation of the lognormal random variable increases, which implies the volatility of the radio channel quality increases, the throughput of the original HDR decreases. Nonetheless, the relative system capacity percentage gains increase steadily when the radio signal quality varies more severely.

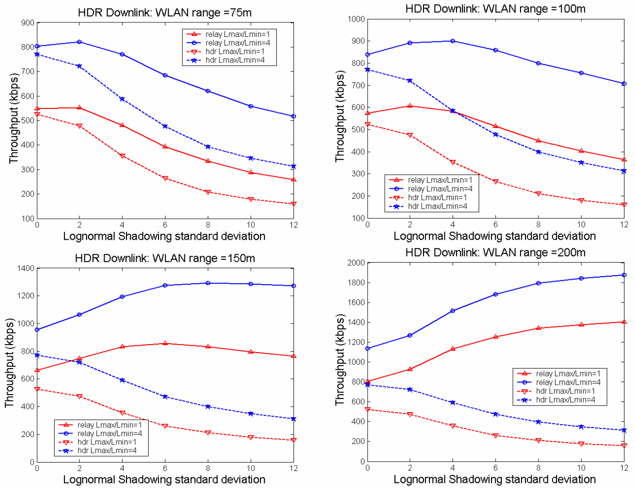


Figure 5: Shadowing Effect on HDR system capacity

The shadowing effect may increase or decrease the absolute values of the system throughput in the two-hop-relay system, as shown in Figure 5. However, in general, the relative capacity gain increase as σ increases. One interesting observation is that the maximum system capacity appears at different lognormal standard deviation values when the WLAN transmission range differs.

Given the same mobile terminal density, the expected number of mobile terminals can be greater in those two-hop-relay systems using wider range WLAN radio interfaces. Similarly, as σ increases, the chance that a low data rate user can find a high data rate user increases. Therefore, the lognormal random shadowing causes better opportunities to find an intermediate relay gateway with better WWAN connection quality. This is analogous to the multipath-fading scenario in wireless communications but in different system protocol layers with different scopes of dynamic wireless channel quality variation. This two-hop-relay scheme can be considered as a macro-diversity technique, which utilizes the channel state variation in different WWAN connections to achieve better system performance.

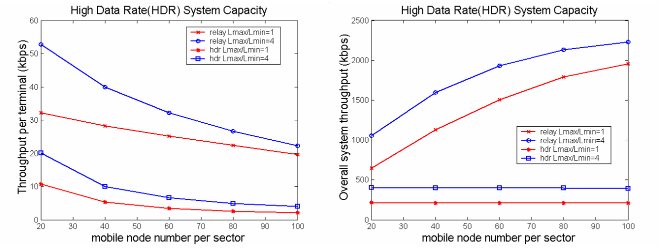


Figure 6: HDR system capacity with different mobile node density

3) *Mobile Terminal Density*

The increase in the mobile node density in a given WWAN cell reduces per mobile terminal throughput as illustrated in Figure 6. This result is quite intuitive because more mobile terminals sharing the same limited wireless radio bandwidth will make per user throughput decline. If we evaluate the system performance in terms of the total system throughput, the overall system throughput will increase with the number of mobile terminals in the two-hop WWAN/WLAN relay system. In the original HDR system, given the same delay latency ratio, the mobile terminal density shows no effect on the overall throughput. While the per user data rate distribution is independent of the number of mobile terminal in the system, the ratio of the time slots assigned to high data rate users to the amount over the time slots assigned to low data rate users should be kept the same regardless of the mobile terminal density. On the other hand, the greater mobile terminal density causes the greater possibility that a low data rate mobile terminal can find a high data rate mobile terminal to relay. Hence, the overall system capacity of the two-hop-relay system benefits from the increasing number of mobile terminals.

V. CONCLUSION

In this paper, we proposed a two-hop-relay architecture to integrate WWAN and WLAN. Dual-mode WWAN/WLAN terminals periodically estimate the channel state information and advertise the WWAN channel conditions to neighboring mobile terminals through WLAN radio interfaces. Mobile terminals compare their own WWAN channel conditions to the channel conditions of nearby terminals. The good channel quality terminals will serve as the intermediate Relay Gateways. Mobile terminals transmit data packets to Relay Gateways through the WLAN interfaces and Relay Gateways forward packets through the good quality WWAN channels.

The two-hop-relay technique can be considered as a macro-diversity technique that takes advantages of the wireless channel variation. The two-hop-relay architecture could achieve better capacity gain in scenarios with high mobile terminal density, wide WLAN radio transmission range, and variable radio channel conditions. A downlink HDR-based system benefits significantly from the two-hop-relay scheme due to the great data rate differences in different SINR reception scenarios. The overall throughput increases 2~4 times in a two-hop-relay HDR system.

In conclusion, the WWAN/WLAN two-hop-relay scheme substantially boosts the capacity of the cellular networks under a broad range of conditions. It also brings additional service coverage to WLAN-only terminals in the integrated deployment scenario of Third Generation cellular base stations and IEEE 802.11 access points. Without handling the difficulties that generic multihop routing cause, the two-hop-relay scheme retains low system complexity while significantly improving the system performance.

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