A Simulation Framework for Performance Evaluation of Network Selection Algorithms in Heterogeneous Wireless Networks

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***Abstract*—Future wireless communication systems will be comprised by the integration of different radio access technologies (RATs), referred to as heterogeneous wireless network (HWN). In this paper, a realistic HWN simulator is proposed to evaluate different network selection algorithms, the main mechanism of joint radio resource management (JRRM). The simulator is designed for an HWN that comprises cellular and wireless local area network radio access technologies. Here, the simulator architecture and the assumed system model are illustrated. Using the simulator, the performance results of the network selection algorithms are generated and then compared against analytical results. The outputs from the simulator provide valuable insights for the design of HWNs.**

I. INTRODUCTION

An heterogeneous wireless network (HWN) is formed by the integration of multiple radio access networks that differ by capacity, coverage and cost. To get maximum benefits from an HWN, we need joint radio resource management (JRRM) [1] that manages the multiple radio access technologies' (RATs') resources in a combined manner. The two main techniques of JRRM are: 1) initial RAT selection for new calls, 2) vertical handoff (VHO) decision for roaming calls in multiple RAT coverage area. These two techniques are jointly referred to as *network selection algorithm*. Many authors, for example, [1] – [4], have proposed *network selection algorithms* in an HWN. In our previous works [1], [2], we have proposed a mobility based network selection algorithm and evaluated its performance using an analytical model. The major limitation of the analytical models in the literature is its inability to consider the effect of detailed system specifications and realistic data traffic characteristics, which would make the model mathematically intractable. Hence, to validate the existing analytical models and for realistic performance evaluation of network selection algorithm, we designed and implemented an HWN simulator.

The heterogeneous wireless network simulator is developed using the OPtimised Network Engineering Tool (OPNET) performance modeler [5], a commercially available network-level simulation software from OPNET technologies Inc. This paper presents a detailed framework for the HWN simulator comprising 1) CDMA2000 [6] radio access technology (RAT) that supports macro-cell coverage with low to medium data rate, and 2) IEEE 802.11 [7] RAT that has high data rate but is effective only in hotspot areas. The HWN simulator is built on the CDMA2000 Voice/Data Simulator [6] that is developed for the first phase CDMA2000 radio transmission technology (i.e., CDMA2000 1xRTT) and OPNET Wireless LAN (WLAN) model [7].

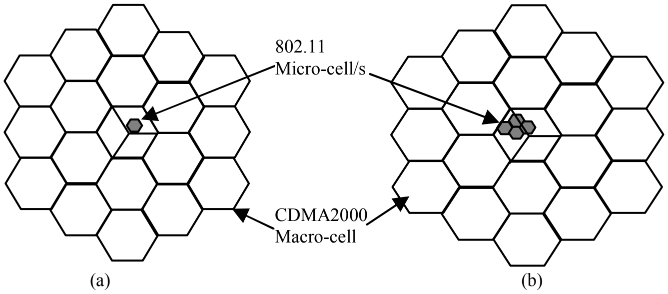

Fig. 1: Simulated service area (a) isolated micro-cells; (b) clustered micro-cells in hotspot (Central cell is surrounded by 2 rings of interferers)

The remainder of this paper is organized as follows. Section II describes the features of the HWN simulator. This section also describes the modeling of the simulator at three levels: the network level, the node level and the process level. For performance analysis of network selection algorithms using the HWN simulator, section III presents assumed traffic and mobility models. The performance results of two network selection algorithms are discussed in Section IV. Section V concludes the paper.

II. HETEROGENEOUS WIRELESS NETWORK SIMULATOR

The salient features of the HWN simulator are as follows:

1. Multiple-cell Network Configuration

Service area has multiple CDMA2000 macro-cell (each cell has 3 sectors) coverage in order to capture both intra and inter-cell interference, a major factor impacting CDMA system performance. IEEE802.11 micro-cell overlaps with CDMA2000 macro-cell in high user density hotspot area. Depending on the hotspot dimension, IEEE802.11 network can be configured in either of the following two structures: 1) isolated micro-cell when hotspot dimension is in the range of 100 meter radius, and ii) multiple micro-cells for hotspot area whose dimension is greater than 100 meters. Fig. 1 shows an illustrative simulated service area.

2. Multimode Mobile Terminal

Each mobile terminal (MT) has both CDMA2000 and 802.11 communication interfaces and is thus referred to as a multimode or reconfigurable terminal. Network selection algorithm in MT selects communication interface for a call.

3. Support of Non-uniform User and Mobility Distributions

The simulator supports the non-uniform user and mobility distributions due to the existence of hotspot in the macro-cell area. Hotspot area has several times higher user density compared to out-of-hotspot area. Three types of user mobility models namely – quasi static (mean speed is zero for t time

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units), pedestrians (mean speed of 5 km/hr) and urban vehicular (mean speed of 50 km/hr) users are considered in the system area.

4. Support of Voice and Packet Data Traffic

The HWN simulator supports both voice and packet data calls. Users can set the call arrival rate, call duration, packet size, packet arrival patterns etc. to model different applications. Constant-bit-rate (CBR) traffic and bursty data traffic are modeled for voice and data applications, respectively.

5. Support of Physical and Data Link Layer Functionality

CDMA2000 air-interface process model [6] and OPNET's IEEE802.11 radio transmission pipeline [7] are used to capture individual RAT wireless link characteristics. To communicate over the CDMA2000 network, the Radio Link Protocol (RLP) [6] and simplified Point-to-Point Protocol (PPP) [6] have been implemented. Radio Link Protocol (RLP) ensures correct packet data transmission between the BSC and the MT, employing error detection (no correction mechanism), proper frame sequencing, and frame retransmission. Each MT and BTS has its own individual identifier. The PPP protocol maps the IP address to MT identifier to deliver IP packets to the correct MT. To communicate reliably over a shared wireless link in WLAN, DCF MAC [8] protocol is used.

In the following subsections, the detailed modeling of the simulator is described.

A. *Network Model*

In the network model, the network topology is described in terms of sub-networks, nodes, links and geographical context. The following assumptions are made for the service area to be considered for simulation:

1. The entire service area is divided into 19 hexagonal macro-cells: a central macro-cell surrounded by two rings of cells, as shown in Fig.1. Each cell is tri-sectored so the service area in the simulation environment has 57 sectors. The assumed 19 cells are sufficient for realistic wireless network performance simulations [9].
2. Single hotspot area (grey shaded area of Fig. 1) is located in the central macro-cell. Depending on the hotspot dimension, one or more micro-cells can be deployed in the hotspot.
3. For inter-connecting the two RATs, the loosely coupled [10] integration architecture is assumed.
4. For simplicity, we assume each MT can generate either voice or data call but not both types simultaneously. Each MT communicates with remote terminals such as fixed telephone, an HWN application server.
5. The HWN application server supports different application types including web browsing, e-mail, file transfer, etc.
6. For the CDMA2000 channel, a propagation model consisting of average path loss and log-normal shadowing is considered [1]. For 802.11 air-interface, free space propagation model is assumed [7].

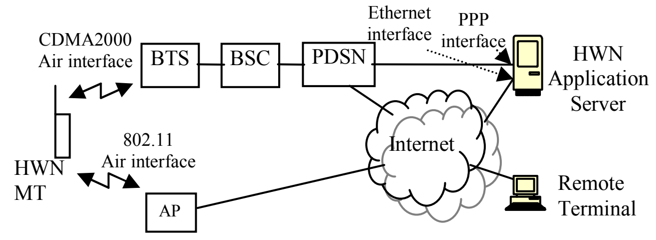

Fig. 2 HWN network architecture for the developed simulator

The detailed and realistic CDMA2000 network and radio channel parameter values are listed in [6]. IEEE 802.11 network configurations are listed in Table 1. To avoid hidden terminal problem [8], the 802.11 micro-cell radius is assumed to be 100 meters in the simulation results presented in this paper. Hence, the maximum distance between two MTs in the micro-cell remains less than 300 meters and no collusion occurs due to hidden terminal.

The HWN network model (shown in Fig. 2.) includes the HWN (multi-mode) mobile terminals, CDMA2000 base transceiver station (BTS), CDMA2000 base station controller (BSC), CDMA2000 packet data serving node (PDSN), IEEE802.11 access point (AP), HWN (multimode) data application server and remote (fixed) terminal. The CDMA2000 network elements such as BTS, BSC and PDSN are reused from an existing CDMA2000 simulator [6]. The CDMA2000 nodes supporting voice traffic such as Mobile Switching Center (MSC) and Public Switched Telephone Network (PSTN) are not modeled because the origins and destinations of the voice calls are not of interest. The HWN simulator also uses standard built-in OPNET node models for IEEE 802.11 access point (AP) and remote terminal. One of the main contributions of HWN simulator design work is the design of HWN (multi-RAT) mobile voice terminal node, HWN (multi-RAT) mobile data terminal node and HWN server node.

B. *Node Model and Process Model Design*

In this section, each HWN node's internal architecture is specified in terms of process (functional) modules and data flow between them, referred to in OPNET as the *node model*. In the *process model*, behaviors of the processes (e.g., algorithms, protocols, applications) are described using a finite state machine (FSM) and a high level programming language such as C or C++.

Table 1 IEEE802.11 Network Configurations [7]

Physical layer	Direct Sequence Spread Spectrum
Data Rate	11 Mbps (maximum data rate for IEEE802.11b standard)
Transmission power	1 mW (for 300 meter transmission)
Retransmission limit	7 (default value from the standard)
Contention Window (min/max)	31/1023 (default value for DSSS)
Buffer Size	1024 kbits (large enough to avoid buffer overflow in most cases)
DCF	Enabled
RTS/CTS	Disabled (lower overall throughput)

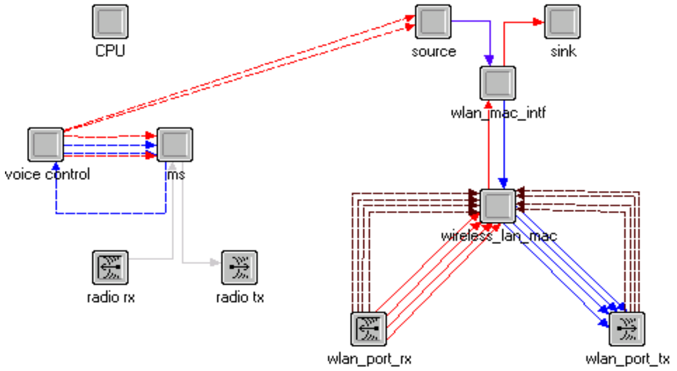

Fig.3 HWN mobile voice terminal node model

a) HWN Mobile Voice Terminal

Fig. 3 shows the node model for the HWN mobile voice terminal as implemented in OPNET. Based on the selected RAT, circuit-switched or packet-switched communication is established through CDMA2000 or 802.11 air interfaces, respectively. Our contributions, to model a multi-RAT voice terminal, are mainly focused on the *voice control* and *MS* process models, and are described as follows:

Voice Control process: The FSM of the *voice control* process model is shown in Fig. 4. This process initiates (at START state triggered by *START* event) and terminates (at END state triggered by *END* event) voice calls using voice call inter-arrival-time (IAT) and voice call duration as input parameters. Based on *suitable RAT* information on the network selection scheme, the START state forwards the initiated call to CDMA2000 or WLAN and the MT moves to the IN_CALL state. From the IN_CALL state, *VHO_CHECK* event is periodically (at constant time interval Δt) generated to make a transition to the VHO state. At the VHO state, the process checks whether VHO is required (based on *suitable RAT* information of the network selection scheme) for the existing call. If the VHO criterion is satisfied, the process hands off the call to the new RAT. After VHO check, the MT returns to the IN_CALL state. The upper bound of periodicity (Δt_u) of the *VHO_CHECK* event is determined based on the travel time of a WLAN user who is moving out of the micro-cell in a radial direction with the maximum speed v_{max} (in the system). Let the WLAN user be on the boundary of the micro-cell (d_1=100 meters) at time t_1 and at time t_2 (where $t_2>t_1$), the same user is crossing 802.11 AP transmission range (i.e., d_2=300 meters). Then the upper bound of periodicity, $\Delta t_u = t_2 - t_1 = \dfrac{d_2 - d_1}{v_{\max}}$. The Δt_u ensures that none of the WLAN users loses packets because of going out of the AP transmission range. For the assumed mobility model in Section III (the maximum user speed is 80 km/hr), the periodicity of VHO decision should be less than Δt_u = 9 seconds.

All the other states and events of this process module are described in [6]. Note that two types of transition arrows are shown in Fig. 4 where solid arrows represent unconditional transition and dotted arrows represent conditional transition.

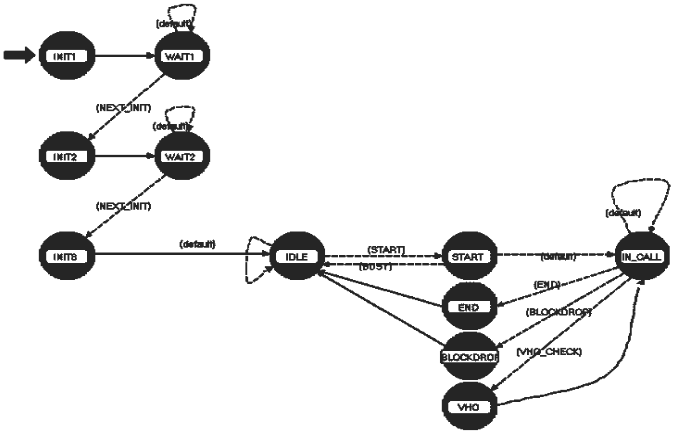

Fig. 4 Voice control process model

MS process: The finite state machine (FSM) of the *MS* process model is shown in Fig. 5. After initialization, state IDLE is responsible for processing each incoming event. Every 2 seconds (less than or equal to VHO_CHECK event interval), state 2S selects the *suitable RAT* for the HWN mobile terminal (for both voice and data calls) based on the network selection scheme. The process sets up circuit-switched voice channel (i.e., fundamental voice channel (VFCH) [6]) for new call and handoff calls in CDMA2000 (at the START_VOICE state), and transmits the voice frame at every 20 ms (at the 20MS state). It also releases the VFCH channel at the end of a voice call in CDMA2000 or when a voice call is headed off from CDMA2000 to 802.11 (at the END_VOICE state). The process collects the statistics (e.g., VHO dropping) related to new calls, VHO calls and HHO calls in CDMA2000 RAT. The states related to the data call processing in described in the next subsection.

OPNET built-in process models *wlan_mac_intf* and *wireless_lan_mac* are used to capture WLAN data link layer functionality. WLAN receiver and transmitter process modules *wlan_port_rx* and *wlan_port_tx* are also used from OPNET standard model library [7]. The CPU, CDMA2000 *radio rx/tx* processes are obtained from CDMA2000 simulator [6].

b) HWN Mobile Data Terminal

Fig. 6 shows the node model for the HWN mobile data terminal in OPNET. In this node model, the TCP/IP reference

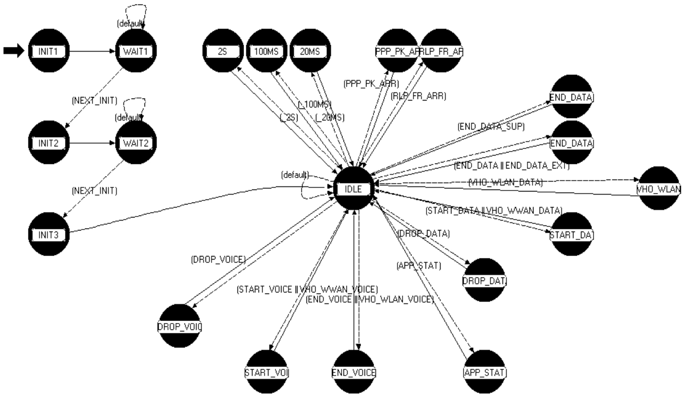

Fig. 5 MS process model

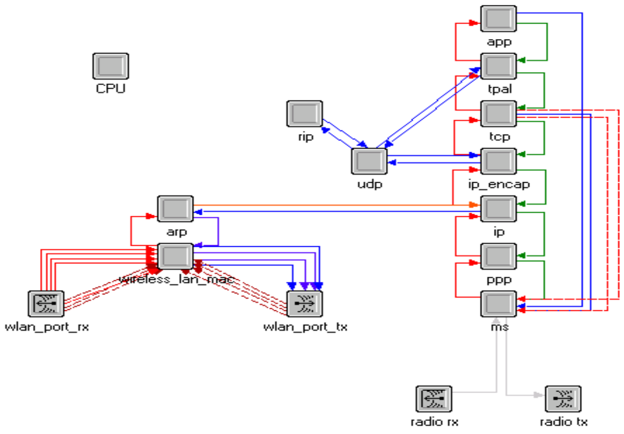

Fig. 6 HWN mobile data terminal node model

model [8] with CDMA2000 and 802.11 air interfaces is used to communicate with remote servers. CDMA2000 and 802.11 air interfaces have two separate IP addresses of separate subnets. Here, the contributions (with respect to data handling functionality) are made in the *MS* and *ip_encap* process models, described as follows:

MS process: This process (Fig. 5) sets up circuit-switched fundamental data channel (DFCH) [6] and packet-switched supplementary data channels (DSCH) [6] for the bursty traffic (at the START_DATA state) when CDMA2000 RAT is selected for a session (at the 2S state). At the VHO_WLAN state, when a data session is headed off from CDMA2000 to 802.11, the process releases the DFCH and DSCH channels. The RLP is also implemented in this process. All other states of this process module related to data handling functionality in CDMA2000 RAT are described in [6].

IP_Encap process: The finite state machine (FSM) of the ip*_encap* process model is shown in Fig. 7. This OPNET built-in process (operating at the network layer) obtains packets arriving from higher protocol layers and creates IP packets in ENCAP state before forwarding them to the IP layer. The modification of this process is done to forward an IP packet through the *selected* air interface (RAT). To perform this functionality, the destination IP address of the transmitted packet is set to one of server IP addresses that can be reached through the selected RAT. For arriving IP packets, the process strips IP headers from the packet in DECAP state before passing on the packet to higher layers.

The details about other process modules are given in References [6] and [7].

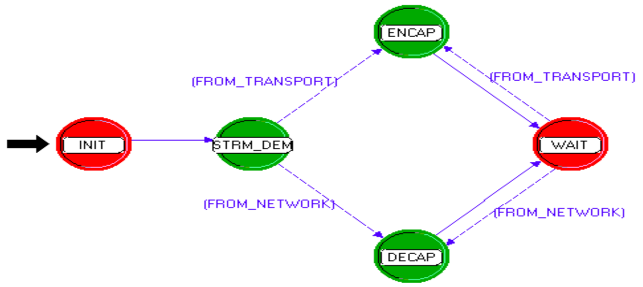

Fig.7 IP_Encap process model

c) HWN Server

The OPNET node model for the HWN server is built on TCP/IP protocol stack with point-to-point [6] and Ethernet [5] wired interfaces. The server uses the source IP address of the arriving (uplink) packet, as the destination IP address of the packet it transmits (downlink). Hence, the server does not need network selection procedure to select the output interface. To avoid any delays due to queuing, it is assumed that the server has unlimited system resources so no packet or job scheduling algorithms are used.

III. TRAFFIC AND MOBILITY MODEL

We assume that voice calls arrive according to a Poisson process with rate λ calls per second. Voice call duration is exponentially distributed with mean $1/\mu$ seconds, where μ is the average call completion rate. Due to higher available bandwidth in the WLAN, it is assumed that the source rate of the voice call in WLAN (i.e., 16 kbps) is higher than that of CDMA2000 (i.e., 9.6 kbps).

During the simulation, a mix of www, e-mail and FTP data packets are generated following a predefined ratio. Packet data is modeled by ON/ OFF process at three time scales: session, call and packet. For data applications, the associated assumptions are presented in Table 2:

Table 2 Traffic Model for WWW, FTP and e-mail data applications [6]

Model Parameter	WWW	File Transfer (FTP)	E-mail
Data session IAT	Exponential (mean = 533 seconds)		
Proportion of time in www/ ftp/ email session (%)	20	2	78
Distribution for # of packet data calls per session	Geometric (mean = 5)	1	Geometric (mean = 2)
Reading time b/w packet calls	Exponential (mean = 120 secs)	not applicable	Pareto (mean = 90, β = 30, α = 1.5)
Distribution for # of packets per packet call	Truncated Pareto (mean = 25, β = 22.4, α = 1.1, m = 100)	Pareto (mean = 62, β = 5.64, α = 1.1)	Calculated by the formula: (Email size / packet size), where Email size ~ Weibull(mean = 15, β = e^9, α = 2.04)
Distribution for packet size (bytes)	fixed at 480 bytes	fixed at 480 bytes	fixed at 480 bytes
Distribution for Inter-arrival time b/w packets (secs.)	Exponential (mean = 67 msecs)	Exponential (mean = 67 msecs)	Exponential (mean = 67 msecs)

Three types of user mobility are considered- urban vehicular, quasi-static and pedestrian. The parameter values of the mobility model are given in Table 3.

Table 3 Mobility Model

Mobility Parameter	Value
Percentage of user in hotspot	50% [3]
Quasi-static user speed (km/hr)	0
Pedestrian user speed (km/hr)	*Normal*(5 km/hr, 2 km/hr)
Vehicular user speed (km/hr)	*Normal*(50 km/hr, 10 km/hr)

IV. SIMULATION RESULTS AND DISCUSSION

In this paper, we present the performance results of two network selection algorithms:

1) *WLAN if coverage* scheme [3]: It suggests that sessions within the hotspot should always use only WLAN for communication due to higher bandwidth and cheaper cost.

2) Mobility based scheme [1]: Quasi-static users in the hotspot (HS) occupy WLAN and higher mobility users in the HS occupy WWAN (i.e., CDMA2000).

To validate the outputs of the simulator, each simulation is run for a sufficient amount of time to reach steady state condition. Ten simulations were run for each scenario with different independent random seeds to establish confidence intervals (CIs) in the results. The results presented are average values with 95% CIs. Further validation is achieved by comparing simulation results with the results derived from analytical model in [1].

We present results of two important performance metrics of HWNs: 1) VHO rate for voice (real-time) call, and 2) data throughput. In Fig. 8, the variation of VHO rate for voice calls under different HS mobility condition (θ_s) and HS radius are presented. In the experiment, a user density of 20 users (10 voice users and 10 data users) per sector in a macro-cell is assumed. It is seen that the analysis results are within the CIs of the simulation results, hence they are statistically equivalent. For the WLAN if coverage scheme, VHO rate increases with θ_s because the scheme selects 802.11 under all mobility conditions. For HS of 100 meter radius, VHO rates of voice calls are significantly low for the mobility based scheme because it uses user speed information to avoid unnecessary VHOs. It is also shown that, with an increase of HS radius (from 100 meters to 400 meters), the gradient of VHO rate versus θ_s curve for the WLAN if coverage scheme decreases. The reason is that, with the increase of HS radius, the HS residence time for high mobility (i.e., pedestrian to vehicular) users increases and hence the probability of moving out of HS decreases. For quasi-static users, the HS residence time (minimum 300 secs) is not proportional to the HS radius. Hence, for the proposed mobility based scheme, VHO rate does not vary with HS radius and thus not plotted in the figures, for clarity. Fig. 9 shows the data throughput in the HWN plotted against the total number of voice and data users per sector in a macro-cell. The results show that, with the increase of total number of users, data throughput increases for both network selection schemes due to increased loading. The analysis results are within CIs of the simulation results in most cases, thus validating the analytical model in [1]. However, in few cases two types of result are not statistically equivalent because different traffic models are assumed in the analysis and simulation (though equal mean values are used). The simulation results show that both network selection schemes have almost equal (means differ by <2%) throughput for all user density because source data rate is equal for both RATs.

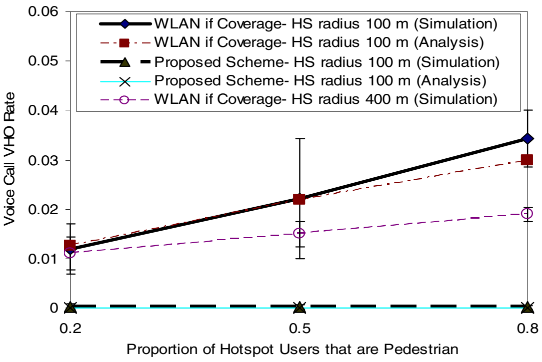

Fig. 8 Voice call VHO rate

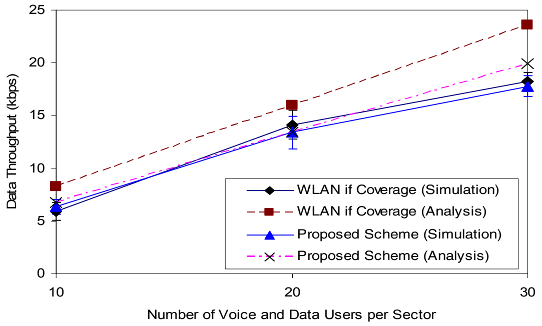

Fig. 9 Data throughput

V. CONCLUSIONS

This paper addresses the issue of modeling heterogeneous wireless networks (HWN) using an OPNET simulation framework. The HWN simulator includes realistic traffic model, non-uniform user and mobility distributions, physical and data link layer functionalities of CDMA2000 and IEEE802.11 RATs. It can be configured for different loading conditions, hotspot mobility environments, hotspot topology, and user distributions. Simulations are done to evaluate the performance of two network selection algorithms, i.e., WLAN if coverage and the mobility based scheme.

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