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Joint Resource Management and Storage-aware Routing with Heterogeneous Access for Wireless Ad-hoc Networks Routing

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Abstract: In this paper, the design and implementation details of wireless ad-hoc terminals are proposed to build a rapidly deployable, frequency-agile, heterogeneous wireless network. Several key protocol methods have been identified including name/address separation, robustness concerning link quality variation and disconnection, multi-homing, ad-hoc network formation, flexible inter-domain boundaries and resource coordination. This paper investigates the wireless ad-hoc terminals architecture that can be used to build rapidly deployable wireless network application, while the Heterogeneous Routing with Resource Management for Mobility (HRRM) mechanism is identified. The results show that the proposed approach has advantage over other scheduling schemes in optimizing incentives for both accuracy cross channel widths and signal attenuation, leading to highly successful time to discovery and resource management. *Copyright © 2013 IFSA.*

Keywords: Wireless ad-hoc networks, Configurability, Storage-aware, Mobility support.

1. Introduction

Wireless ad-hoc network is a decentralized type of wireless network. Each node participates in routing by forwarding data for other nodes, so the nodes forward data determination is made dynamically on the basis of network connectivity. In addition to the classic routing, ad-hoc networks can use flooding for forwarding the data. Consequently, two essential features, namely adaptability and configurability, characterize wireless ad-hoc networks. Adaptability is the ability to choose the appropriate communication mode in terms of wireless channel conditions in order to make predefined operation constraints such as bit error rates, power consumption, and interference levels [1-2]. Configurability is the competence to switch between different communications modes defined by the radio operating parameters, modulation type, carrier frequency and transmission power [3-4].

Achieving such aim in a portable, small form factor platform is to build a rapidly deployable heterogeneous wireless network, i.e. nodes made with limited priori RF, topologies and deployment-specific engineering planning. Particularly, it is useful in extreme constraints, including natural disasters, limited communication infrastructures and absence of cross-agency radio communication devices [5]. This technology may be used to interconnect an incompatible set of wireless consumer devices like home and mobile networks to enable the control of consumer electronic devices [6]. Complete interoperability is achieved, by making compatibility between all layers of communication stack. Higher

layer and protocol design studies have been addressed [6-8]. In [7-10], a specific gateway is used to bridge between IEEE 1394 devices [11-12] or to interconnect WiFi and ZigBee network [13-14].

Prior work has proposed the use of control channels to reserve bandwidth and resource [15-16]. While there are advantages to a control channel design, it is clear that control channels can be compromised, thus bringing down the network. Also, control channel based solutions are prone to the range-mismatch problem. These problems are overcome by not using a dedicated control channel. Since each wireless resource handoff strategies are best suited for different network, a new adaptive resource handoff algorithm with heterogeneous access is required.

In this paper, the use of wireless ad-hoc technology is adopted based on small form factor software radio platforms to establish a heterogeneous wireless network. Clearly, it can formulate a heterogeneous structure by inter-connecting a set of heterogeneous wireless terminals and functioning as base stations, working with wireless terminals in given geographic locations or cells.

The main contributions include:

1) The description of wireless ad-hoc network architecture for rapidly configurable network applications using accuracy cross channel widths and signal attenuation.

2) The case study of the proposed architecture, which indentifies adaptability and configurability, with dynamic name-address bindings for storage-aware on delay tolerant routing.

3) The mechanism design and implementation, i.e. Heterogeneous Routing with Resource Management for Mobility (HRRM), based on application performance requirements.

2. Proposed Configurable Architecture

The purpose of CR is to utilize the precious wireless network resources more intelligently. As shown in Fig. 1, the system consists of five sub-systems: configurable digital transceiver, channel monitoring, I/O devices, BER requirement and resource management module, heterogeneous routing with resource management. The communication management subsystem utilizes feedback from the channel monitoring and heterogeneous routing with resource management module to adjust the operation parameters in the RF front end. This configurability of ad hoc networks is uniquely maintained by the design of the configurable digital transceiver, and adaptability is implemented by the subsystems.

The RF front-end has input parameters, including amplifier gains, operation frequency, and channel filters bandwidth. As in Fig. 1, the input parameters of the digital transceivers present the operational units in the signal processing chain. The digital wireless transceiver typically contains a chain of function blocks described by physical layer specifications of their wireless situation, *i.e.*, sampling rate, modulation, and coding scheme. Every one is broken into a combination of digital signal processing blocks, such as filters, signal transforms, and logical and arithmetic operations. The output parameters of the configurable transceiver are the performance metrics maintained by wireless ad-hoc networks, *e.g.* BER and the power level. The communication management and control subsystem performs several key tasks in the wireless ad-hoc networks design:

- Wireless resource management controls;
- Management of the mode switching mechanism;
- Mode switching decision based on the values given by the end-to-end performance metrics.

The design is partitioned between DSP and FPGA. The DSP is dedicated for communication, control and packet handling tasks. And the digital signal processing intensive operations, such as filtering and up/down conversion, are performed in FPGA.

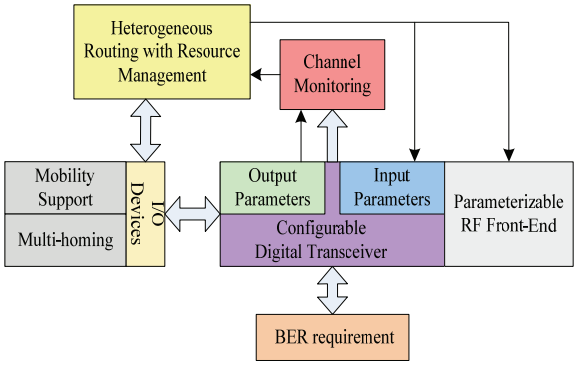

Fig. 1. Configurable Architecture with Channel Monitoring.

3. Wireless Access Challenges and Requirements

3.1. Mobility Support for Dynamic Binding

Mobility in Data Plane (DP) has been extensively investigated, in conjunction with protocols such as mobile IP and 3GPP. Seamless mobility can be supported by having a unique name for any DP attached objects, and then providing a mechanism for dynamic binding of the name to the current points of attachment. As shown in Fig. 2, three functional requirements can be translated to the following protocol design:

- Dynamic binding of names to wireless network addresses;
- Redirection of in-transit data packets, with regard to the routing layer with disconnection delay tolerance;
- The named DP-attached objects.

Also, complete disconnection because of mobility and insufficient signal strength is a common

occurrence in wireless DPs including both 3G/4G and WiFi. Given the increasing dominance of wireless medium as the last hop for network access, such link quality variations could be natively supported at different layers of the DP architecture. This results in the following requirements:

- Link quality awareness at both the intra-domain/inter-domain routing layer, to allow for robust packet delivery strategy.
- Increased visibility of edge link quality to distinguish between wireless network errors from other DP anomalies.
- Disconnection tolerant routing and transport protocols, which are capable of temporarily storing packets during disconnections and rerouting to the new point of attachment.

In the sense of traffic engineering, when the traffic pattern is easy to learn, this method can help wireless node to adapt each other's traffic pattern and efficiently utilize the available degree of freedom in time.

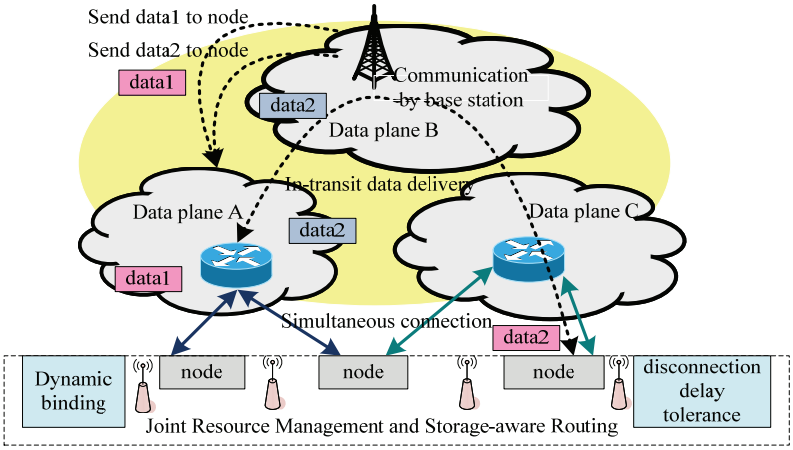

Fig. 2. Host mobility support for sending data.

3.2. Multi-homing Support

More details about multi-homing based cooperative way and how we implement and parallelize the method on host mobility in this section. Currently, a single device can have only one IP address at a time, restricting multi-homing to scenarios where both interfaces belong to the same data plane operator, namely autonomous system. As shown in Fig. 3, efficient support for host multi-homing asks for the following key requirements:

1) Independence of names for data plane attached objects and network addresses, allowing a single name to have multiple NAs.

2) Routing protocols with some visibility of link quality along the available alternate paths.

3) Service semantics to support policies for choosing between multiple paths.

Wireless ad-hoc and peer-to-peer networks are important for infrastructure less scenarios such as vehicle-to-vehicle (V2V) communications. However, support for such wireless P2P scenarios is currently limited to reuse overlay services or relegated to lower layer solutions such as WiFi Direct. Such networks integration within the framework presents a unique set of challenges. These include:

1) Name resolution, authentication, routing and security services capable of disconnected operation.

2) Fast service discovery and ad-hoc network formation.

3) Inter-domain routing support for large-scale migration of networks.

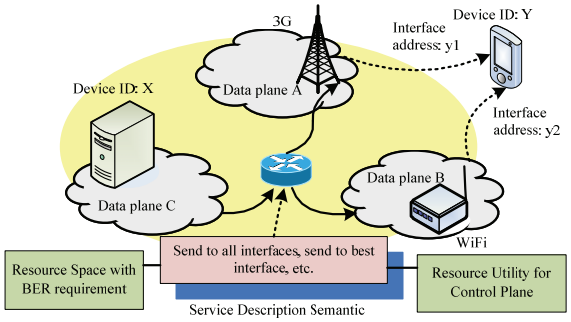

Fig. 3. Qualitative illustration of multi-homing support.

4. The Multi-hop Mobility with Routing

4.1. Multihop System Model

The wireless ad-hoc networks consist of M primary users (PUs) and N secondary users (SUs). PUs hold licenses for specific frequency bands and could only occupy the assigned portion of the wireless resource. SUs do not have any licensed resource and opportunistically send the data by using idle portions of the PUs resource. Let the wireless ad

hoc network stands for a directed connectivity graph $G(V,E)$, where $V=\{v_1,\ldots,V_{N+M}\}$ be a finite set of nodes, with $|V|=N+M$, and $(i,j)\in E$ is a unidirectional wireless link from node V_i to V_j.

Wireless nodes from the subset $PU=\{v1,\ldots,v_M\}$ are designated as primary users, and nodes from subset $SU=\{v_{M+1},\ldots,v_{M+N}\}$ are designated as SUs. The configurable digital transceiver can tune to a set of contiguous frequency band $[f,f+\Delta B]$, where ΔB demonstrates the maximum bandwidth of the nodes.

The available (SP) Service Plane is assumed to be organized in two separate frequency bands. A CP (Control Plane) is utilized by all SUs for resource access negotiation and is assumed to be time slotted. A DP (Data Plane) is used for data communication with multi-homing support. The DP consists of a set of discrete frequency bands $\{f_{\min},f_{\min+1},\ldots,f_{\max-1},f_{\max}\}$, each of bandwidth *w* and identified by a discrete index. The interval $[f_i,f_{i+\Delta f_i}]$ be the discrete set of frequency bands selected by SUs *i* from f_i and $f_{i+\Delta f_i}$, with bandwidth $w\Delta f_i$. Each backlogged SUs contends for resource access on the control frequency band f_{CC}, where $f_{CC}\notin[f_{\min},f_{\max}]$. If let $w\Delta f_B$ stand for the maximum bandwidth of the wireless ad-hoc networks, where Δf_B be the maximum number of mini-bands, $\Delta f_i\le\Delta f_B$ denotes the constraint of the maximum bandwidth of the wireless ad-hoc networks.

In general, traffic flows are carried over multi-hop routes with interface addresses. Let the traffic demands consist of a set $\mathbf{S}=1,2,\ldots,S$, where $S=|\mathbf{S}|$, of unicast sessions. With host-mobility support, each session $s\in\mathbf{S}$ is maintained by a fixed source–destination node pair.

Each node characterizes a separate queue for each session *s*, for which it is either a source or an intermediate relay. At time slot *t*, let $Q_i^s(t)$ be the number of queued packets of session *s* waiting for transmission at SUs *i*. Let $r_{ij}^S(t)$ be the transmission rate on link (i,j) for session *s* during time slot *t*, and le $\mathbf{R}$ be the vector of rates. For $\forall i\in SU$, the queue is updated as follows:

$$Q_i^S(t+1)=\Big(Q_i^S(t)+\sum_{k\in SU,k\ne i}r_{ki}^S(t)-\sum_{l\in SU,l\ne i}r_{il}^S(t)+\lambda_i^S(t)\Big) \quad (1)$$

4.2. Dynamic Name-Address Bindings with Storage-aware Routing

With different interface addresses, Heterogeneous Routing with Resource Management for Mobility (HRRM) is based on the idea of separating names of end-users or other network-connected objects, and their routable addresses or locators. Independence of names and addresses makes it possible for mobile nodes to have a permanent, location independent name or globally unique identifier which can then be mapped to a set of routable NA concerning the current points of attachment. The method focuses on integrating a global name resolution service as a basic network-layer service, which could be efficiently accessed both by end-user devices and in-network routers, base stations and access points.

The protocol stack handles host and network mobility support through fast dynamic binding of identifiers to locators. When a user sends packets directed to a specific identifier, the network subsystem must quickly get the set of NAs and route the packets correspondingly. The problem of providing a fast global name resolution service at Internet scale through a router DHT (Distributed Hash Table) based Direct Mapping scheme for achieving a good balance between scalability, injected traffic, consistency, availability and total airtime deployment.

As performing the name resolution, this distributes the mappings among wireless routers using an in-network single-hop hashing technique which derives the network address of the storage router directly.

HRRM uses a generalized storage-aware routing approach in order to support delay and disconnection tolerance in the routing layer. This basic idea in storage-aware routing is for each router to have some storage capability and make forward vs. store decisions according to both short-term and long-term path quality metrics.

Additionally, data packets along paths which become disconnected are handled of the protocol with delayed delivery and replication features. Particularly, each router maintain two types of topology information: (a) The intra-partition graph is formed by collecting flooded link state advertisements, which carry fine-grained, time-sensitive information about the links in the network; (b) Secondly, the DTN graph is implemented via epidemically disseminated link-state advertisements, which carry connection probabilities between all wireless nodes. Concerning intelligently utilizing in-network storage, storage-aware routing outperforms traditional and storage-augmented link-state protocols in both fast service discovery and ad-hoc network formation environments.

5. Joint Routing and Resource Management with Mobility Support

5.1. Resource Space with BER Requirement

As for frequency *f*, SUs *i* needs to satisfy the BER requirement, when it transmits to SUs *j* and avoid interfering with ongoing receivers. Respectively, let $SINR_{PU}^{th}$ and $SINR_{SU}^{th}$ be the SINR thresholds to achieve a target BER_{PU}^{*}, and BER_{SU}^{*} be SUs. The condition could be

$$\frac{P_i(f)\cdot L_{ij}(f)\cdot G}{N_i(f)+\sum_{k\in V,k\neq i}P_k(f)L_{ij}(f)} \geq SINR_{SU}^{th}(BER_{SU}^{*}), \quad (2)$$

where $P_i(f)$ is the transmit power of *i* on frequency *f*. *G* is the processing gain, with the length of the spreading code. $L_{ij}(f)$ is the transmission loss from nodes *i* to *j*. And $N_j(f)$ is the receiver noise on frequency *f*. The expression $\sum_{k\in V,k\neq i}P_k(f)L_{ij}(f)$ is the interference at node *j*.

The other constraint models the condition that receiver *l* is not maintained by *i*'s transmission. It is concluded that interference at node $l\in V$, $l\neq j$ is $NI_B(f)+\Delta I_{il}(f)$, where $\Delta I_{il}(f)$ be the additional interference at *l* caused by *i*'s transmission, $P_i(f)L_{il}(f)$, and $NI_B(f)$ be noise plus interference at *l* before *i*'s transmission. We have

$$\frac{P_l^R(f)}{NI_l(f)+\Delta I_{il}(f)} \geq SINR^{th}(BER^{*}), \quad l\in V, l\neq j \quad (3)$$

where $P_B^R(f)$ is the signal power being received at receiver *l*. Given the fact that it has to be true for all ongoing transmissions, thus

$$P_i(f)\leq \min_{l\in V}\frac{\Delta I_l^{\max}}{L_{il}(f)} \triangleq P_i^{\max}(f), \quad (4)$$

where

$$\Delta I_l^{\max}(f)=\begin{cases}\dfrac{P_l^R(f)}{SINR_{PU}^{th}(BER_{PU}^{*})}-NI_l(f), l\in PU\\ \dfrac{P_l^R(f)}{SINR_{SU}^{th}(BER_{SU}^{*})}-NI_l(f), l\in SU\end{cases}, \quad (5)$$

The above constraint characterizes that the SINR at receiver *j* needs to be above a predefined number, which demonstrates that the power received at receiver *j* on frequency *f* has to be very high to allow configurable transceiver *j* to decode the signal given its current noise and interferences successfully.

5.2. Resource Utility for Control Plane

For wireless environment, the CP (Control Plane) is assumed to be time slotted. At each time slot when node *i* is backlogged and not already transmitting, node *i* can measure the resource utility for link (i,j). Thus

$$U_{ij}(t)=c_{ij}(t)\cdot[Q_i^{S^*}-Q_j^{S^*}], \quad (6)$$

where s^* is the session with a maximal differential backlog on link (i,j). Remind that the notion of wireless resource utility is demonstrated for specific link (i,j). The resource utility function is based on the principle of dynamic configurable devices, where it is concluded that a policy that jointly assigns resources at the physical/link layers and route. Let $c_{ij}(t)$ be the achievable capacity for link (i,j), with the current resource condition

$$c_{ij}(\mathbf{F}_i,\mathbf{P}_i)\triangleq\sum_{f\in\mathbf{F}_i=[f_i,f_{i+\Delta f_i}]} w\cdot\log_2\left(1+\frac{P_i(f)L_{ij}(f)G}{N_i(f)+I_j(f)}\right) \quad (7)$$

where $I_j(f)$ stands for the interference at *j* on *f*. The achievable values of c_{ij} depend on the dynamic resource management policy, *i.e.*, resource-selection vector $\mathbf{F}_i=[f_i,f_{i+\Delta f_i}]$ and power allocation vector $\mathbf{P}_i=[P_i(f)],\forall i\in SU,\forall f\in\mathbf{F}_i$. Routing with consideration of a differential backlog can decrease the probability of relaying data through a congested relay node. As a result, in the proposed HRRM mechanism, wireless nodes with a smaller queue size have a higher probability of being selected as the next hop.

6. Simulation Results

6.1. Accuracy Cross Channel Widths and Signal Attenuation

HRRM mechanism is implemented in OMNET++, it is showed that HRRM's performance is close to optimal under various conditions. The packet detection accuracy is evaluated. The methodology is firstly described, and then the accuracy is showed when varying two parameters: frequency band width and signal attenuation. A session is started from one HRRM device, and the number of packets received at a second device is

measured using a packet storage-aware sniffer. Simultaneously, the scanner of the second device is used to count the number of packets detected by HRRM. The experiment is repeated for 5, 10 and 20 MHz frequency bands widths, and for each width, the subsystems traffic intensity is varied. All the numbers are over 10 runs. In every run, 110 packets of size 1000 bytes each are sent for dynamic resource management policy.

To support policies for choosing between multiple paths, HRRM is also used to measure the airtime utilization for HRRM resource assignment. It is showed that HRRM performs as expected in Fig. 4.

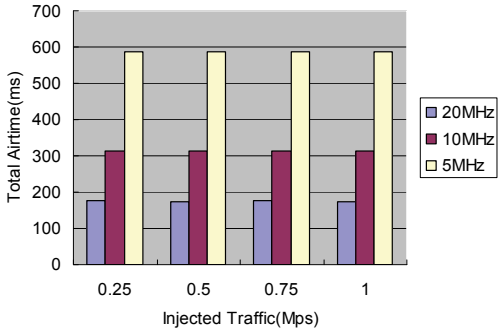

Fig. 4. Accuracy of air time utilization.

The total time occupied by the packets doubles on halving the frequency bands width. This stems from the observation that halving the frequency bands width also halves the effective transmission rate. Since the same number of packets is sent at a given width, the total airtime is constant, even when the rate of injected packets is changed for BER requirement. Consequently, the accuracy at low signal strengths is measured by connecting two HRRM wireless devices through a tunable parameterized RF front-end attenuator, and performing the same experiment with configurable digital transceiver. Fig. 5 presents the percentage of data packets that were detected by HRRM and the packet storage-aware sniffer upon varying the attenuation.

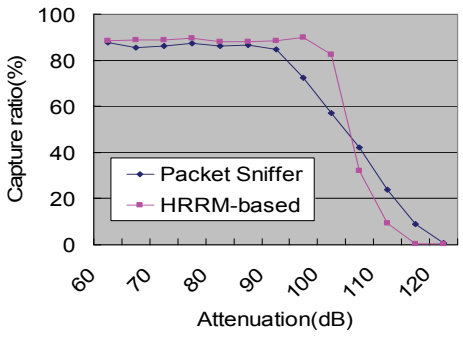

Fig. 5. Discovery of wireless nodes with distance.

At low attenuation, both HRRM and the packet sniffer implement very well. Nevertheless, HRRM outperforms the packet storage-aware sniffer, as it is even able to detect corrupted data plane packets. At higher attenuation, HRRM continues to detect more packets than the storage-aware sniffer until 96 dB attenuation.

6.2. Resource Management on Throughput

Fig. 6 presents which frequency band could achieve the highest throughput, considering any given background intensity with service description semantics. For dynamic binding of names to network addresses, selecting a 20 MHz frequency band has best throughput until a background traffic intensity of roughly 18 ms inter-packet delay. Given different interface addresses, the metric shows that roughly at this level of background traffic, 10 MHz and 20 MHz become equally good, and the narrower 10 MHz frequency band surpasses the wider frequency band thereafter. At about 24 ms inter-packet delay, 5 MHz starts achieving the highest throughput, which is accurately predicted by the metric. It is clear that the metric yields a reasonably accurate prediction of which frequency band width will result in the highest throughput given a certain level of background traffic. Fig. 7 shows how HRRM reacts to varying degrees of background traffic.

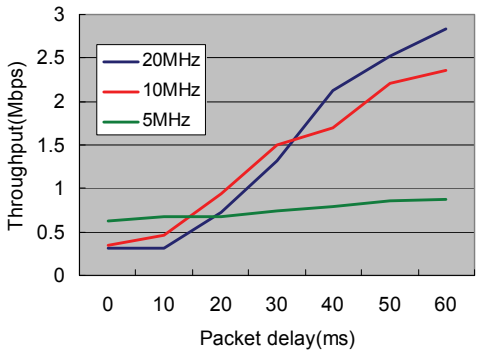

Fig. 6. Packet delay with throughput.

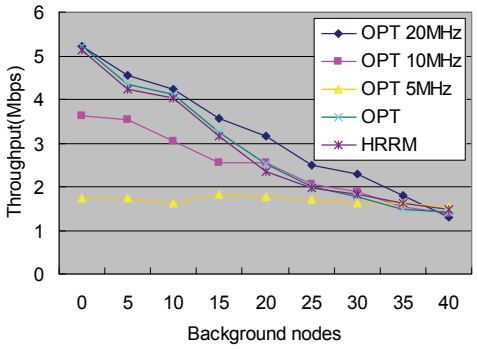

Fig. 7. Influence of background traffic on throughput.

In practical, there are some background client-pairs in the system, each being randomly allocated to one of the free UHF frequency bands, and each sending at a packet interval delay of 30 ms. It presents that HRRM achieves close to optimal end-to-end performance for varying degree of background traffic. With little or no background traffic, HRRM runs as well as picking the widest available optimal frequency band with channel monitoring.

Fig. 8 presents the impact of spatial variation on per-client throughput for mobility support. In this scenario, there are 10 users connected the wireless ad hoc node, and one background client per UHF frequency band, transmitting with 25 ms inter-packet delay. Spatial variation is maintained, each client and the wireless node start with a common resource map. To demonstrate the adaptability of resource assignment, an experiment is set up with a wireless node and a user in our building. The resource map has the following free UHF frequency bands: 25 to 30, 32 to 35, 39 and 48. Therefore, it has fragments of size 20 MHz, 10 MHz and two frequency bands of 5 MHz to form a wireless ad hoc network. Every frequency band and wireless node using HRRM spends 1 second on every UHF frequency band to determine the airtime utilization using HRRM. All wireless nodes feed their airtime to the wireless node, which computes the metric and decides on the frequency band to use for the network. For multi-homing support, the throughput of joint routing and resource management is showed with time, and the corresponding value on the different resource chunks in Fig. 9.

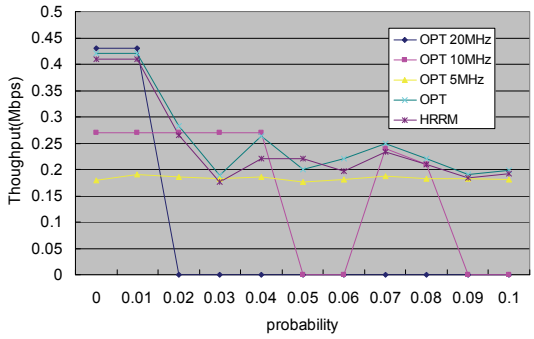

Fig. 8. Impact of spatial variation on throughput.

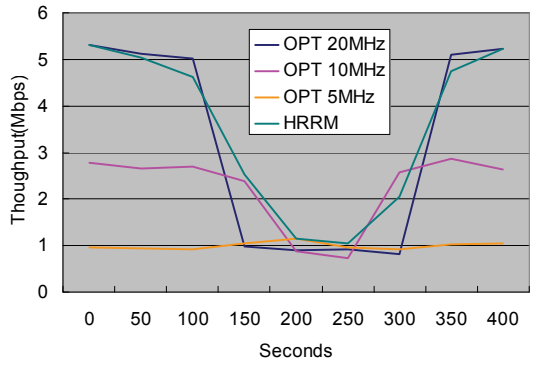

Fig. 9. Experimental validation of resource assignment.

7. Conclusion

In sum, to analyze emerging wireless access and mobility scenarios, this paper proposes a brief overview of the multi-hop mobility with routing for future Internet design considerations. Specifically, the key design features of dynamic name-address bindings and storage-aware routing have been outlined and shown to address some of these requirements. Also, the model of joint routing and resource management with mobility support was derived. Finally, through the simulation, the result shows that the resource allocation mechanism HRRM performed better than traditional schemes in the aspects of resource consumed and fairness.

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