

DFMAC: DTN-Friendly Medium Access Control for Wireless Local Area Networks Supporting Voice/Data Services

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Published online: 9 May 2010
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Abstract In this paper, we consider a wireless communication network for both local nodes residing in densely populated hot spots and nomadic nodes roaming in a large area. Wireless local area networks (WLANs) are deployed in the hot spots, while a delay/disruption tolerant network (DTN) provides services to nomadic nodes in the large area with low node density. We investigate the radio resource allocation for a DTN/WLAN integrated network, and propose a DTN-friendly medium access control (DFMAC) scheme for the hot spots supporting voice/data services. Analytical models are established to characterize the interactions between a DTN and WLANs under the proposed DFMAC. Numerical and simulation results demonstrate that our proposed MAC scheme can provide a deterministic delay guarantee for the voice services of local nodes, while achieving an efficient performance tradeoff for the data services between nomadic nodes and local nodes.

Keywords delay/disruption tolerant network (DTN) · wireless local area network (WLAN) · integrated network · medium access control (MAC)

1 Introduction

Nowadays, wireless local area networks (WLANs) are widely deployed at communication hot spots such as libraries, cafeterias, classrooms, and other public areas, because of their inherent low implementation cost [1]. Both delay sensitive voice service and delay tolerant data service can be supported by WLANs to facilitate service demands within the hot spots [2]. In order to further enlarge wireless service coverage, the notion of wireless metropolitan area sharing networks (WMSNs) can be employed [3], where publicly and/or privately owned wireless Internet access points (APs) are shared. Similar concepts have been widely implemented in commercialized applications such as FON [4] and vehicular ad hoc networks (VANETs) (e.g., MobTorrent [5]). However, the main problem in WMSNs is that the deployment of the existing APs limits the service coverage area and hence caps system performance. Without sufficient APs, network connections for a mobile node become intermittent when the node roams outside the hot spots. In fact, this problem exists in other network environments such as wireless campus area networks (WCANs) [6] where WLANs are constrained in separate buildings, and rural area networks (RANETs) [7] where hot spots are separated by large physical distances.

As a widely accepted solution for intermittent network connections, a delay/disruption tolerant network (DTN) can provide robustness for data transmissions [8]. The key idea behind DTNs is the store-carry-forward routing [9], where data messages are stored and carried by wireless nodes for a considerably long period of time. Whenever a communication opportunity arises, the stored and carried data messages can be delivered.

This paper was presented in part at IEEE International Conference on Communications and Networking in China (CHINACOM) 2009.

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In the literature, most of the existing work on DTN routing assumes a sparse node distribution and a low traffic load, whereby the issue of link-layer packet collisions is not taken into account. However, a recent study indicates that the link-layer contention problem cannot be ignored, especially in densely populated areas (e.g., hot spots) [10]. How to deal with link-layer contention within the DTN framework is a challenging yet open issue. On the other hand, there exist extensive research results for medium access control (MAC) in WLANs supporting voice/data services. In IEEE 802.11e, the enhanced distributed channel access (EDCA) can provide service differentiation by classifying access categories for services with different quality of service (QoS) requirements [2]. However, the contention-based MAC of EDCA can only provide stochastic delay guarantee for voice services and thus limits the voice capacity. In order to provide a deterministic delay guarantee, IEEE 802.11e hybrid coordination function (HCF) incorporates a superframe structure and provides a polling-based contention-free period for voice services. By utilizing voice multiplexing, deterministic access prioritization, and voice packet aggregation, the voice/data capacity of IEEE 802.11e HCF can be further improved [11]. In addition, a probabilistic token-based scheme is proposed, which not only achieves high channel utilization but also provides service differentiation for delay sensitive voice service and best-effort data service [12]. However, the existing work focuses on nodes in hot spots only. How to ensure effective and efficient MAC in the presence of nomadic nodes needs further investigation.

In this work, we consider a DTN/WLAN interworking environment [13]. Different from other interworking paradigms such as cellular/WLAN integrated networks [1, 14], in the DTN/WLAN interworking environment under consideration, ubiquitous wireless coverage is not provided or not even available to nomadic nodes. Nomadic nodes can only get real-time Internet access within the hot spots serviced by WLANs. We focus on resource allocation within hot spots and propose a DTN-friendly MAC (DFMAC) scheme based on a superframe structure and token passing strategies. Under the DFMAC scheme, a deterministic delay guarantee can be provided to the voice services of local nodes, while a performance tradeoff for data services between nomadic nodes and local nodes can be achieved by tuning phase duration parameters. Analytical results are provided to demonstrate the performance of DFMAC. We further validate our performance analysis with extensive computer simulations. Performance comparisons with the existing schemes are also provided to show the effectiveness and

Table 1 Summary of important symbols used

Symbol	Definition
B_U	Buffer size for the uplink delay tolerant data service at the tagged nomadic node
H_k	k th hot spot in the network coverage area
K	Number of packets in each message
M_H	Number of hot spots
$M_{LD,k}$ ($M_{LV,k}$)	Number of local data (voice) nodes within hot spot H_k
N_V	The maximum number of voice packets that can be generated by a voice source during each superframe
$P_{OFF,i}$ ($P_{ON,i}$)	The probability that there are i voice packet arrivals during a superframe, while at the beginning of this superframe the voice source is at the OFF (ON) state
R_{TR}	Radio transmission range
T	Duration of superframe
T_B	Duration of beacon
$T_D(k)$	The maximum duration of dedicated phase within each superframe in hot spot H_k
$T_{DL}(k)$ ($T_{UL}(k)$)	The maximum duration of DL (UL) subphase within each superframe in hot spot H_k
T_O	Duration for transmitting the overhead of a voice packet
T_P	Duration for data packet transmission
$T_{PL,D}$ ($T_{PL,V}$)	Duration for the payload transmission of a data (voice) packet
$T_{R,i,k}$	Token rotation time of local data node i within hot spot H_k
T_{SJ}	Sojourn duration
T_T	Duration for token passing
$\bar{T}_V(k)$	Average channel time occupied by local voice services in a superframe
$1/\alpha$ ($1/\beta$)	Average duration of the ON (OFF) period of local voice traffic flows
$\beta_{DL}(k)$ ($\beta_{UL}(k)$)	The maximum fraction of DL (UL) subphase within each superframe in hot spot H_k
γ_V	Inter-visiting rate
$\lambda_{i,k}$	Average packet arrival rate of local data node i within hot spot H_k
λ_U	Average message arrival rate of the tagged nomadic node
ϕ	Diameter of hot spot
ψ	Network coverage area
τ_I	Waiting time for the wireless channel to be idle before voice/data packet transmission
τ_{IV}	Waiting time for the wireless channel to be idle before the transmission of a local voice node switching from the OFF state to the ON state
τ_{AD}	Waiting time for the wireless channel to be idle before sending the ARRIVAL or DEPARTURE message
τ_V	Inter-arrival time of voice packets

efficiency of the newly proposed DFMAC. To the best of our knowledge, this is the first work in the literature to capture the interworking of DTN/WLAN and devise a strategy to balance radio resource allocation between these two network components.

The remainder of the paper is organized as follows. In Section 2, we present the system model under consideration. In Section 3, the proposed DFMAC scheme is discussed in details. The performance analysis of DFMAC is presented in Section 4, followed by numerical results in Section 5. We conclude this research in Section 6. As many symbols are used in this paper, Table 1 summarizes the important ones.

2 System model

Consider a DTN/WLAN integrated network as shown in Fig. 1, where a number of isolated small hot spots (H_k , $k = 1, 2$) are scattered around a large network region. Wireless Internet APs attached to the Internet backbone provide wireless access to the nodes in their hot spots. Under this network architecture, we consider two kinds of wireless nodes, namely (1) the local nodes residing in hot spots and (2) the nomadic nodes which can roam within the entire network region. All mobile nodes and APs are equipped with a short range radio transceiver. Nomadic nodes comprise a DTN, whereas local nodes in a hot spot comprise a WLAN. A nomadic node can access a WLAN when it comes into a hot spot. The WLAN within a hot spot is fully connected and the connections are reliable, but the network connections become intermittent for nodes outside hot spots. The nomadic nodes can stay disconnected for hours and travel through a hot spot within several minutes. The DTN and WLANs operate in different frequency channels to prevent the transmission interference between these two network components. With unique features of a DTN and a WLAN, a DTN/WLAN integrated network is imperative in order to better serve nomadic nodes when they travel within hot spots.

In the DTN/WLAN integrated network, two categories of services should be differentiated in resource allocation of a WLAN, i.e., local services and delay tolerant data services. The local services are generated by local nodes and destined for a server in the Internet (uplink) or vice versa (downlink), while delay tolerant data services are generated by nomadic nodes and destined for a server in the Internet (uplink) or vice versa (downlink). The local services are further categorized into local voice services and local data services. Each local voice service can be described by a two-way (uplink and downlink) ON/OFF model. At the ON state, voice

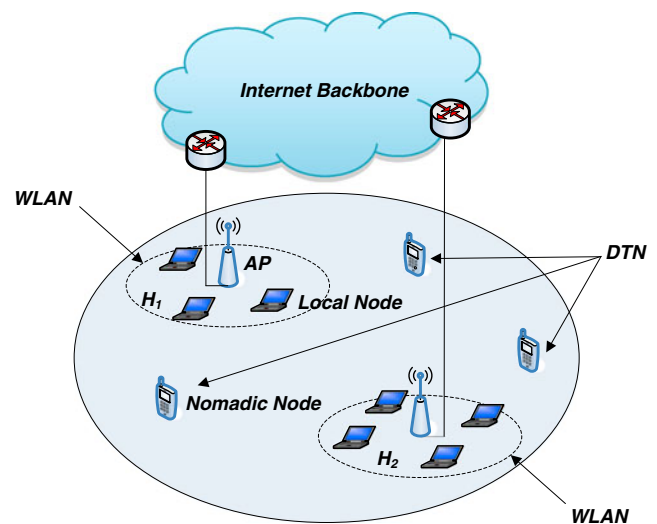


Fig. 1 An illustration of the DTN/WLAN integrated network

packets are generated by a voice source with a constant inter-arrival time, while at the OFF state, no voice packet is generated. In the DTN framework, delay tolerant data services are represented in self-contained messages (referred to as bundles [8]). Segmentation of a message into packets is necessary for link-layer transmissions in a WLAN. Here, we focus on the case where messages are delivered by direct transmissions between nomadic nodes and the APs, while the impact of message relaying among nomadic nodes is left for further work.

The two categories of services have different QoS requirements. For local nodes, the packet delay of voice services and the throughput of data services are the major QoS measures. On the other hand, for delay tolerant data services to nomadic nodes, low throughput and large delay are acceptable. As storage capability is usually limited for nomadic nodes, delivery probability under a limited buffer space becomes the most important performance metric. In this work, we consider the local voice services have the highest priority. In other words, the delay requirement of local voice services should be consistently satisfied regardless of the arrivals and departures of nomadic nodes in a WLAN. On the other hand, for data services, as the time that a nomadic node remains in a hot spot is expected to be very brief, its messages should be transmitted with high priority when the node is connected via the WLAN. In order to provide service differentiation between delay tolerant data services and local data services, an efficient resource reservation for higher-priority nomadic nodes is indispensable [15], to be discussed in Section 3.

3 DTN-friendly medium access control (DFMAC)

The DFMAC is a token-based scheme designed for WLANs where local nodes and nomadic nodes coexist. A superframe structure is implemented to provide a deterministic delay guarantee for local voice services while achieving service differentiation between delay tolerant data services and local data services. Intra-phase and inter-phase token passing mechanisms are provided to achieve efficient resource allocation.

3.1 Superframe structure

As shown in Fig. 2, under the DFMAC scheme, time is partitioned into superframes of constant duration T . The duration T can be selected based on the delay requirement of local voice services [11, 16]. At the beginning of each superframe, there is a short beacon period T_B for synchronization, followed by a local voice phase, a dedicated phase, and a local data phase. These three phases are dedicated to the local voice services, delay tolerant data services, and local data services, respectively.

In order to achieve the deterministic delay guarantee for local voice services, the duration of the local voice phase within a superframe varies and depends on the number of voice sources at the ON states. Note that, if the local voice services can tolerate some loss, our work can be directly generalized to provide a stochastic delay guarantee by setting a maximum duration for the local voice phase according to the loss tolerance [16]. The dedicated phase can have a maximum duration $T_D(k)$ within each superframe, where k is the index of a hot spot. Each dedicated phase is divided into an uplink (UL) subphase for uplink delay tolerant data services and a downlink (DL) subphase for downlink delay tolerant data services with maximum durations $T_{UL}(k)$ and $T_{DL}(k)$, respectively. Obviously, we have $T_{UL}(k) + T_{DL}(k) = T_D(k)$. The remaining period in the

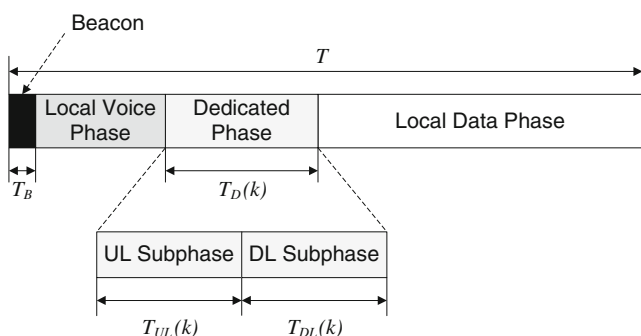


Fig. 2 Superframe structure of DFMAC

superframe is the local data phase. At any time, if there is no local voice node at the ON state, a dedicated phase will begin after the beacon period; if there is no nomadic node in the hot spot, the unutilized dedicated phase is merged to the local data phase. In this research, we assume a basic admission strategy which ensures that the local data phase has a non-zero share of each superframe [16], and that a maximum fraction $\beta_{UL}(k) = T_{UL}(k)/T$ and $\beta_{DL}(k) = T_{DL}(k)/T$ of each superframe can be guaranteed for the UL and DL subphases, respectively.

There is a token in each WLAN. Only the token holder can have an opportunity for packet transmission. The token is circulated among local voice nodes and the AP in the local voice phase, among nomadic nodes and the AP in the dedicated phase, and among local data nodes and the AP in the local data phase. Only nomadic nodes can access the UL subphase and only the AP can access the DL subphase. Since all downlink delay tolerant data service queues reside at the AP, when the AP holds the token in a DL subphase, the token is circulated among these queues. By introducing the dedicated phase, radio resources can be reserved for nomadic nodes since the time for them to travel through a hot spot is in general very brief.

For intra-phase token passing, three different mechanisms are adopted for the three phases. An inter-phase token passing mechanism is also provided to pass the token among different phases.

3.2 Deterministic token passing in the local voice phase

As discussed in Section 2, the delay guarantee of local voice services should be consistent regardless of the traffic load fluctuation caused by the occasional presence of nomadic nodes in a WLAN. The polling-based MAC can provide a deterministically bounded delay for voice services [16]. However, the polling overhead should be minimized to provide high resource utilization by considering voice multiplexing [11]. In this research, we use a deterministic token passing mechanism for the local voice phase to reduce the polling overhead in terms of the polling frames. Moreover, with a superframe structure, voice packet aggregation can be performed for overhead reduction, where the voice packets generated by a voice source during each superframe are combined and transmitted by a single MAC frame. Therefore, the overhead caused by RTP (real-time transport protocol)/UDP (user datagram protocol)/IP headers and physical (PHY) preambles can be reduced [11].

For deterministic token passing, each local node (including the AP) records the next token holder to

which the token should be passed. The next token holder is updated each time a local voice call arrives/completes, or a local voice node is switched from the OFF state to the ON state or vice versa. When a voice node holds a token, it aggregates all the voice packets backlogged and transmits them by a single MAC frame. The token is piggybacked to the packets and can be decoded by the next token holder through overhearing. Before each transmission, the current token holder should wait for the wireless channel to be idle for a fixed period of time τ_I . If the current token holder is switched from the ON state to the OFF state, it further piggybacks a VOICE OFF message to the current transmission. After overhearing the current transmission, the previous token holder changes the next token holder to the one indicated in the piggybacked token of the current transmission. On the other hand, a local voice node switching from the OFF state to the ON state transmits a voice packet with a piggybacked VOICE ON message after sensing the channel idle for a short period of time τ_{IV} ($\tau_{IV} < \tau_I$), and passes the token to the node whose transmission is delayed. Upon overhearing the current transmission, the previous token holder sets the local voice node (from the OFF state to the ON state) as the next token holder. If the local voice node switching from OFF to ON transmits a voice packet during a dedicated phase, the UL or DL subphase is delayed by the time of the voice packet transmission since the dedicated phase is reserved for nomadic nodes.

3.3 Probabilistic token passing for local data phase

The framework of probabilistic token passing proposed in [12] is adopted for the local data phase, due to its good performance and its capability of supporting service differentiation. For a group G of nodes (or queues) contending for wireless channel access, the token passing scheme can be characterized by two parameters: $\mathbf{p} = \{p_i, 1 \leq i \leq |G|\}$ and $\mathbf{P} = \{P_{i,j}, 1 \leq i, j \leq |G|\}$, where p_i denotes the token holding probability of node i , $P_{i,j}$ represents the token passing probability from node i to node j , and $|G|$ is the size of G . Without service differentiation among local data nodes, the values of p_i and $P_{i,j}$ are given by

$$p_i = 1/|G|, \quad i \in \{1, 2, \dots, |G|\} \tag{1}$$

$$P_{i,j} = \begin{cases} 1/(|G| - 1), & \text{if } i \neq j, \quad i, j \in \{1, 2, \dots, |G|\} \\ 0, & \text{otherwise.} \end{cases} \tag{2}$$

Specifically, when $|G| = 1$, the only node will always hold the token by letting $p_i = 1$ and $P_{i,i} = 1$. If a token holder has a data packet to transmit, the token is piggybacked to the data packet; otherwise, it simply passes the token to the next node.

3.4 Truncated token passing for the dedicated phase

For the dedicated phase, a truncated token passing policy is adopted. It is based on the framework of probabilistic token passing as discussed in Section 3.3. However, if the queue of a certain nomadic node is drained, the token will not be passed on to that node anymore within the current superframe. In the UL subphase, suppose a set G_{UL} of nomadic nodes in a hot spot are contending for channel access. If node $m, m \in G_{UL}$, has an empty queue, it broadcasts a DRAINED message to all other nodes and passes the token to one of them with equal probabilities. For the remaining nodes, upon receiving the DRAINED message, they recalculate the token passing probability by replacing G_{UL} with $G_{UL} \setminus \{m\}$. The above procedure continues until there is only one nomadic node left in the UL subphase and its queue is also drained or the boundary of UL subphase is reached or crossed. In such cases, inter-phase token passing is initiated to pass the token to the DL subphase, to be discussed in Section 3.5. The truncated token passing policy is virtually adopted in the DL subphase for downlink delay tolerant data queues, where the AP always holds the token. The truncated token passing procedures for the UL and DL subphases are restarted after the beacon period of each superframe. Obviously, when the message arrival rate of delay tolerant data services is low, the probability for a message to arrive during a dedicated phase is low accordingly since the duration of each dedicated phase is short. By using the truncated token passing policy, unnecessary token passing within each dedicated phase can be reduced when the uplink or downlink delay tolerant data service queue is empty, and the unutilized proportion of the superframe can be passed on to the local data phase for local data services.

3.5 Inter-phase token passing

For inter-phase token passing, each node (including the AP) keeps three synchronized timers to track how much time has elapsed within the current superframe, UL subphase, and DL subphase. These timers are restarted accordingly at the beginning of each superframe, UL subphase, and DL subphase.

After the beacon period, the local voice phase starts with the AP transmitting its aggregated voice packets.

At the end of a voice phase, the next token holder of the last local voice node is set to a nomadic node (or a queue) belonging to the dedicated phase with the same probability as the token holding probability of the target node.

In the dedicated phase, before each packet transmission, the token holder checks the synchronized timer and compares it with the boundary of each subphase, i.e., $T_{UL}(k)$ and $T_{DL}(k)$ in hot spot k . After the current transmission is finished, if the boundary is reached or crossed, the next token holder is set to a node belonging to the next phase with the same probability as the token holding probability of the target node in that phase.

As data transmissions in the beacon period are not allowed, if the time left in the local data phase within the superframe is not sufficient for transmitting one more packet after the current transmission, the current token holder passes the token through the current transmission to a node belonging to the next phase or subphase. A voice node switching from OFF to ON during a local data phase defers its current transmission if the time left in the current superframe is not enough for the transmission of a voice packet. The new token holder will not start its transmissions until the beacon period of the new superframe is finished.

3.6 Node (call) arrivals and departures (completions)

When a node arrives at or departs from the WLAN (or a voice/data call arrives or completes), the source node sends an ARRIVAL or DEPARTURE message after sensing the channel idle for a short period of time τ_{AD} ($\tau_{AD} < \tau_{IV}$). After receiving the message, the current token holder discards the token, and the AP recalculates the durations ($T_{UL}(k)$ and $T_{DL}(k)$) and token passing parameters (\mathbf{p} and \mathbf{P}) for all the phases and subphases. If the new call is a local voice call, the node is put at the end of the deterministic token passing list. Then the AP broadcasts a NOTE message to inform all nodes of the updated information as well as the node to which a new token is issued. The new token holder starts transmission τ_1 after the beacon signal from the AP.

3.7 Failure recovery

The current token holder monitors the current token passing procedure. If a new transmission does not begin from the next token holder i after τ_F , where τ_F is slightly larger than τ_1 , a new token will be issued and passed to node i again. This procedure will continue for at most N_F times. After that, if there is still no trans-

mission initiated by node i , the node is considered to be inactive in the system due to battery depletion or hardware impairments. A NOTE message is then broadcasted by the current token holder, treating node i as a leaving node. (Note that the node mobility is not considered as a cause of failure since the node departure procedure can be applied when a node tends to move out of a hot spot, as discussed in Section 3.6.) During the recovery procedure, the passing of a new token by the current token holder is considered the same as a normal token passing. If the inter-phase token passing condition is satisfied according to the discussion given in Section 3.5, the current token holder stops the recovery procedure and, at the same time, generates a new token and passes it to a node belonging to the new phase accordingly.

4 Performance analysis

For analysis tractability, the following assumptions are made:

1. All mobile nodes and APs are equipped with the same radio transceivers with a transmission range R_{TR} . The transmission range is much smaller than the dimension of network coverage area ψ . Each hot spot covers a circular region with diameter ϕ ($\phi^2 \ll \psi$). There is no node failure.
2. The movement of nomadic nodes follows a random direction (RD) mobility model [17], and the density of nomadic nodes is low.
3. Packet arrivals of local data service and message arrivals of delay tolerant data service are independent Poisson processes. Each message is composed of K packets.

For a nomadic node, define inter-visiting time as the duration between its two consecutive visits to a hot spot, and sojourn duration as the period that it stays within a hot spot in each visit. Based on assumptions (1) and (2), the inter-visiting time is approximately exponentially distributed [17]. We denote the rate that a nomadic node visits a hot spot (inter-visiting rate) by γ_V , which is the reciprocal of inter-visiting time. Although the distribution of sojourn duration is not obtainable, its expectation T_{SJ} can be derived as a special case of the average contact duration between two mobile nodes by letting one of them stationary [17]. The probability that there are two or more nomadic nodes simultaneously within a hot spot is negligible with a low nomadic node density and $\phi^2 \ll \psi$.

The average packet arrival rate of local data node i within hot spot H_k is denoted by $\lambda_{i,k}$ ($0 \leq i \leq M_{LD,k}$,

$1 \leq k \leq M_H$), where $M_{LD,k}$ is the number of local data nodes within hot spot H_k , M_H is the number of hot spots, and $\lambda_{0,k}$ represents the packet arrival rate at the AP of hot spot H_k and destined for the local data nodes. For nomadic nodes, the average message arrival rates of uplink and downlink delay tolerant data services are denoted by $\lambda_{U,i}$ and $\lambda_{D,i}$ ($1 \leq i \leq M_N$), respectively, where M_N is the number of nomadic nodes. The buffer size for uplink delay tolerant data service at nomadic node i is $B_{U,i}$, and the buffer size for downlink delay tolerant data service at the AP for nomadic node i is $B_{D,i}$.

Let $M_{LV,k}$ denote the number of local voice nodes within hot spot k . The ON and OFF periods of local voice traffic flows are exponentially distributed with average value of $1/\alpha$ and $1/\beta$, respectively. At the ON

state, voice packets arrive with a constant inter-arrival time τ_V .

4.1 Fraction of channel time for local voice services

As discussed in Section 3.2, the MAC scheme is designed to guarantee a deterministic delay bound for local voice services. Therefore, we focus on the channel time occupancy by local voice services in this subsection. At the beginning of each superframe, a voice source is at the OFF state with probability $\frac{\alpha}{\alpha+\beta}$ and at the ON state with probability $\frac{\beta}{\alpha+\beta}$ [11]. The joint probability mass functions (PMFs) of the voice sources at the OFF/ON states at the beginning of a superframe and the number of voice packet arrivals during the superframe are given respectively by

$$P_{OFF,i} = \begin{cases} \frac{\alpha}{\alpha+\beta} [\exp(-\beta(T - i\tau_V)) - \exp(-\beta(T - (i - 1)\tau_V))], & \text{if } 1 \leq i \leq N_V - 1 \\ \frac{\alpha}{\alpha+\beta} [1 - \exp(-\beta\tau_V)], & \text{if } i = N_V \\ \frac{\alpha}{\alpha+\beta} - \sum_{i=1}^{N_V} P_{OFF,i}, & \text{if } i = 0 \end{cases} \tag{3}$$

$$P_{ON,i} = \begin{cases} \frac{\beta}{\alpha+\beta} [\exp(-\alpha(i - 1)\tau_V) - \exp(-\alpha i\tau_V)], & \text{if } 1 \leq i \leq N_V - 1 \\ \frac{\beta}{\alpha+\beta} [\exp(-\alpha(T - \tau_V))], & \text{if } i = N_V \\ \frac{\beta}{\alpha+\beta} - \sum_{i=1}^{N_V} P_{ON,i}, & \text{if } i = 0 \end{cases} \tag{4}$$

where $N_V = T/\tau_V$ is the maximum number of voice packets that can be generated by a voice source during each superframe. $P_{OFF,i}$ and $P_{ON,i}$ are the probability that there are i voice packet arrivals during a superframe, and at the beginning of this superframe the voice source is at OFF and ON states, respectively.

Since under the DFMAC scheme, a local voice node switching from the OFF state to the ON state transmits the first voice packet with waiting time τ_{IV} for channel idle, the average channel time occupied by local voice services in a superframe is given by

$$\begin{aligned} \bar{T}_V(k) = & \sum_{i=1}^{N_V} [P_{OFF,i} \cdot (2T_O - \tau_I + \tau_{IV} + i \cdot T_{PL,V}) \\ & + P_{ON,i} \cdot (T_O + i \cdot T_{PL,V})] \cdot M_{LV,k} \\ & + \sum_{i=1}^{N_V} (P_{OFF,i} + P_{ON,i}) \cdot (T_O + i \cdot T_{PL,V}) \cdot M_{LV,k} \end{aligned} \tag{5}$$

where the first and second summations correspond to the fractions of channel time occupied by uplink and downlink voice services, respectively; T_O is the duration for transmitting the overhead of a voice packet, including τ_I , PHY preamble, and RTP/UDP/IP headers

[12]; $T_{PL,V}$ is the duration for the payload transmission of a voice packet; k is the index of a hot spot. Then, the fraction of channel time for local voice services can be calculated as $\eta_V(k) = \bar{T}_V(k)/T$.

4.2 Throughput of local data services

The main system performance measure for local data services is normalized system throughput, which is defined as the fraction of channel time used for packet payload transmissions. Consider the worst-case throughput for local data services when the dedicated phase is fully occupied by nomadic nodes. Note that under the truncated token passing policy described in Section 3.4, the actual normalized system throughput can be better than the worst-case value if the message arrival rate of delay tolerant data service is low.

Let $T_{R,i,k}$ be the token rotation time of local data node i within hot spot H_k , which is the time duration between two consecutive token holdings of the node. Then, the queue utilization of node i within hot spot H_k can be calculated by

$$\rho_{i,k} = \lambda_{i,k} E [T_{R,i,k}]. \tag{6}$$

When nomadic nodes are present in hot spot H_k , define a random variable $D_{i,k}$, where $D_{i,k} = 1$ when

the local voice phase and dedicated phase are included in the token rotation cycle of node i within hot spot H_k , and $D_{i,k} = 0$ otherwise. We have $P(D_{i,k} = 0) = 1 - P(D_{i,k} = 1)$. Therefore, the average token rotation time is given by

$$E[T_{R,i,k}] = E[T_{R,i,k}|D_{i,k} = 0]P(D_{i,k} = 0) + E[T_{R,i,k}|D_{i,k} = 1]P(D_{i,k} = 1), \quad 0 \leq i \leq M_{LD,k}, 1 \leq k \leq M_H \tag{7}$$

where

$$E[T_{R,i,k}|D_{i,k} = 0] = \sum_{n=0}^{M_{LD,k}} [T_P \rho_{n,k} + T_T(1 - \rho_{n,k})] \tag{8}$$

$$E[T_{R,i,k}|D_{i,k} = 1] = E[T_{R,i,k}|D_{i,k} = 0] + T_B + \bar{T}_V(k) + T_D(k) \tag{9}$$

T_P and T_T being the time needed for data packet transmission and token passing, respectively. Note that for analysis tractability, an approximation is made in (9) by using the result of (5) which includes the packet transmission time of local voice nodes switching from OFF to ON. The accuracy of this approximation will be shown in Section 5.2. Since there is only one token rotation cycle with $D_{i,k} = 1$ in each superframe, the average time occupied by token rotation cycles with $D_{i,k} = 0$ in a superframe is $T - E[T_{R,i,k}|D_{i,k} = 1]$. Then, we have

$$P(D_{i,k} = 1) = \frac{1}{1 + \frac{(T - E[T_{R,i,k}|D_{i,k} = 1])}{E[T_{R,i,k}|D_{i,k} = 0]}} = \frac{E[T_{R,i,k}|D_{i,k} = 0]}{T - T_B - \bar{T}_V(k) - T_D(k)} \tag{10}$$

From (6)–(10), we can find the queue utilizations $\rho_{i,k}$ ($0 \leq i \leq M_{LD,k}, 1 \leq k \leq M_H$). Then the normalized system throughput of local data services within hot spot H_k in the presence of nomadic nodes can be derived as

$$Th_k = \frac{T - T_B - \bar{T}_V(k) - T_D(k)}{T} \cdot \frac{\sum_{i=0}^{M_{LD,k}} T_{PL,D} \rho_{i,k}}{\sum_{i=0}^{M_{LD,k}} [T_P \rho_{i,k} + T_T(1 - \rho_{i,k})]} \tag{11}$$

where $T_{PL,D}$ is the time used for data packet payload transmission.

When nomadic nodes are not present in hot spot H_k , we have $T_D(k) = 0$ and $P(D_{i,k} = 1) = 0$. Since $E[T_{R,i,k}|D_{i,k} = 0] = E[T_{R,i,k}]$ with $P(D_{i,k} = 0) = 1$, from (6) and (8) we can obtain another set of queue

utilizations $\rho_{i,k}^*$ ($0 \leq i \leq M_{LD,k}, 1 \leq k \leq M_H$). Then, the normalized system throughput is given by

$$Th_k^* = \frac{T - T_B - \bar{T}_V(k)}{T} \cdot \frac{\sum_{i=0}^{M_{LD,k}} T_{PL,D} \rho_{i,k}^*}{\sum_{i=0}^{M_{LD,k}} [T_P \rho_{i,k}^* + T_T(1 - \rho_{i,k}^*)]} \tag{12}$$

4.3 Delivery probability of delay tolerant data services

Since the inter-visiting time is exponentially distributed and is expected to be much larger than the sojourn duration under assumptions (1) and (2), the queuing behaviors of both uplink and downlink delay tolerant data services can be described by continuous time Markov chains (CTMCs). Without loss of generality, consider the uplink delay tolerant data service. For a tagged nomadic node with message arrival rate λ_U and mobility parameters γ_V and T_{SJ} , define a CTMC $X_U(t)$, where $X_U(t) \in [0, B_U]$ denotes the number of delay tolerant data messages in the uplink queue and B_U is the maximum queue length. The transition rate $q_{i,j}^U$ ($0 \leq i, j \leq B_U$) from state i to state j of the uplink queue can be calculated as follows.

With the message arrival rate λ_U , we have

$$q_{i,i+1}^U = \lambda_U, 0 \leq i \leq B_U - 1. \tag{13}$$

When the tagged nomadic node visits one of the hot spots, messages can be transmitted to the destination via the AP. If after the current visit, the uplink delay tolerant data service queue is still not empty, the transition rate is given by

$$q_{i,j}^U = \sum_{k=1}^{M_H} \gamma_V I(S_{UL}(k), i - j), 1 < i \leq B_U, 1 \leq j < i \tag{14}$$

where $I(i, j)$ is an indication function which equals 1 if i is equal to j , and 0 otherwise. The function $S_{UL}(k)$ denotes the maximum number of uplink delay tolerant data messages that can be transmitted during the sojourn duration when hot spot k is visited, and is given by

$$S_{UL}(k) = \left\lfloor \text{round} \left(\frac{T_{SJ}}{T} \right) \frac{T_{UL}(k)}{T_{PK}} \right\rfloor. \tag{15}$$

Note that we make an approximation on the fractional superframe in the calculation of $S_{UL}(k)$ by considering the fact that the duration of a superframe is much shorter than the sojourn duration. For the same reason, the time spent on the arrival and departure procedures of a nomadic node is ignored.

After the current visit, if the uplink delay tolerant service queue of the node is empty, the transition rate is given by

$$q_{i,0}^U = \sum_{k=1}^{M_H} \gamma_V C(S_{UL}(k), i), \quad 1 \leq i \leq B_U \quad (16)$$

where $C(i, j)$ is a comparison function which equals 1 if $i \geq j$ and 0 otherwise. For any other state transitions not mentioned precedingly, the transition rate is equal to 0.

Obviously, the CTMC is a finite state irreducible Markov chain; therefore it is ergodic, and the stationary probability exists. Denote the stationary probability by $\pi_U = \{\pi_i^U, 0 \leq i \leq B_U\}$. It can be calculated by solving a set of balance equations [18].

The delivery probability of uplink delay tolerant data service is given by $P_{D,UL} = 1 - \pi_{B_U}^U$. Similarly, we can obtain the stationary probability $\pi_D = \{\pi_i^D, 0 \leq i \leq B_D\}$ and the delivery probability $P_{D,DL}$ for the downlink.

5 Numerical and simulation results

In this section, numerical and simulation results are presented to demonstrate the performance of the DF-MAC. Performance comparisons with the modified HCF scheme [11] and probabilistic token-based scheme [12] are also provided to show the efficiency of our proposed scheme. Note that a comparison between the DFMAC and the IEEE 802.11e MAC is not provided since the advantage of the modified HCF scheme over IEEE 802.11e MAC is already demonstrated in [11].

The system parameters used in analysis and simulation are shown in Table 2 and are in accordance with

Table 2 System parameters used in analysis and simulation

Parameter	Value
τ_I	40 μ s
τ_{IV}	20 μ s
τ_{AD}	10 μ s
τ_V	20 ms
T	100 ms
T_B	0.3920 ms
T_P	0.9793 ms
T_T	0.3960 ms
$T_{PL,D}$	0.7273 ms
$T_{PL,V}$	0.024 ms
T_O	0.2858 ms
$1/\alpha$	352 ms
$1/\beta$	650 ms

previous work [11, 12]. There are two non-overlapping hot spots ($M_H = 2$) with arbitrary deployment locations in the network region. For illustration clarity, we consider the two hot spots are equivalent with $\beta_{UL}(1) = \beta_{UL}(2) = \beta_{UL}$ and $\beta_{DL}(1) = \beta_{DL}(2) = \beta_{DL}$. The tagged nomadic node is considered as a pedestrian with RD mobility speed 1.5 m/s and radio transmission range $R_{TR} = 250$ m. The diameter of each hot spot is $\phi = R_{TR}$. Using typical RD mobility parameters [17], for network coverage area $\psi = 2,000 \times 2,000$ m², we have $\gamma_V = 9.1912 \times 10^{-5}$ s⁻¹, $T_{SJ} = 107.1038$ s; for $\psi = 2,500 \times 2,500$ m², we have $\gamma_V = 5.8824 \times 10^{-5}$ s⁻¹, $T_{SJ} = 107.1038$ s. Note that the same sojourn duration is obtained since it only depends on the RD mobility parameters and is not affected by the size of network. For delay tolerant data services, each message consists of $K = 100$ packets.

5.1 Fraction of channel time for local voice services

The fraction of channel time used by local voice services versus the number of local voice nodes is shown in Fig. 3 for the three MAC schemes. We can see that, the analytical and simulation results match well with each other for our proposed DFMAC scheme. As the number of local voice nodes increases, the fraction of channel time used by the local voice services increases since more voice packets per unit time need to be transmitted. However, for different number of local voice nodes, the DFMAC scheme requires a minimal channel time. Compared with the probabilistic token-based scheme, the DFMAC scheme incorporates a

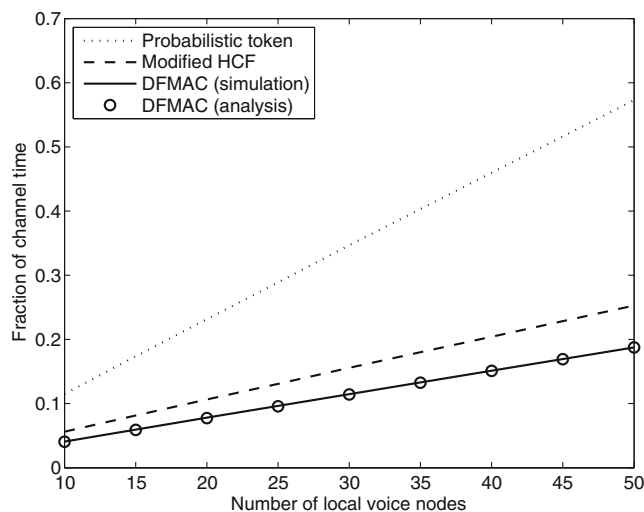


Fig. 3 The fraction of channel time for the local voice services versus the number of local voice nodes

superframe structure and exploits the voice packet aggregation to reduce the packetization overhead. Although the delay experienced by each voice packet may be slightly larger under the DFMAC scheme than under the probabilistic token-based scheme, the delay is bounded and can be tuned by selecting different superframe duration T [11, 16]. Compared with the modified HCF scheme, the DFMAC scheme has a lower channel occupancy time for local voice services since the polling frames for local voice nodes at the ON state are eliminated.

5.2 Throughput of local data services

To evaluate the throughput of local data services, we take hot spot H_1 as an example. For illustration clarity, the same value of packet arrival rate is chosen for all local data nodes and the AP. Since the influence of β_{UL} and β_{DL} on the local throughput is equivalent, we set β_{DL} to 0.1 and tune the value of β_{UL} to show its effect. Figures 4, 5 and 6 show the normalized system throughputs for 10 local voice nodes ($M_{LV,1} = 10$) and 10 local data nodes ($M_{LD,1} = 10$), 10 local voice nodes and 30 local data nodes, and 30 local voice nodes and 30 local data nodes, respectively. As the packet arrival rate of each node increases, the normalized system throughput increases almost linearly before saturation, and the speed of increment is much higher for the case of 30 local nodes. For the DFMAC with a larger value of β_{UL} , the saturation occurs at a smaller packet arrival rate. But the normalized saturated throughput does not

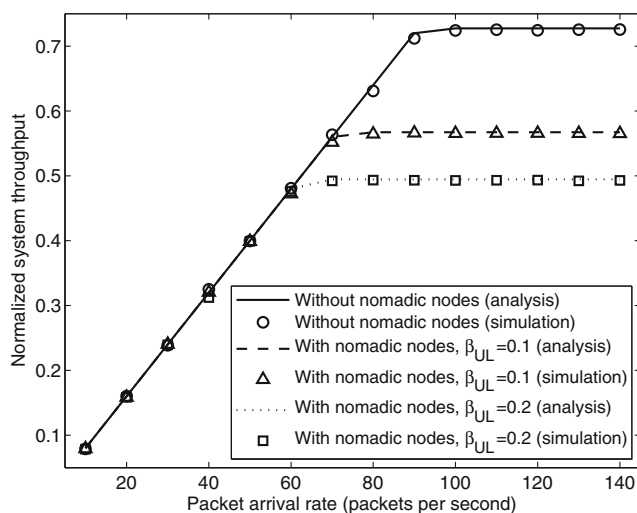


Fig. 4 The normalized system throughput of local data services versus packet arrival rate (10 local voice nodes, 10 local data nodes)

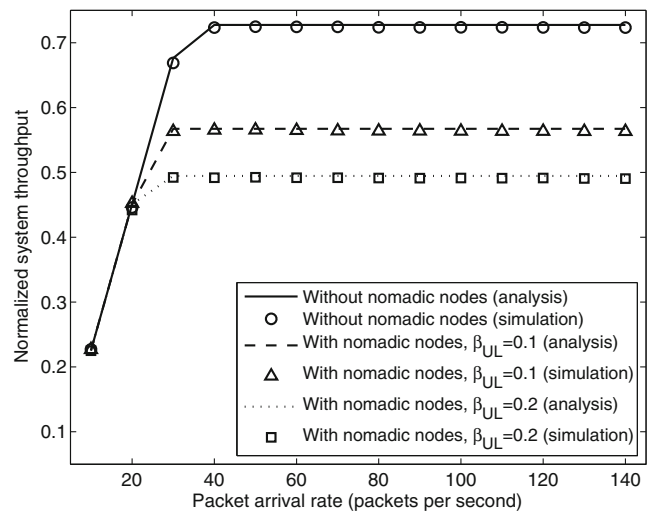


Fig. 5 The normalized system throughput of local data services versus packet arrival rate (10 local voice nodes, 30 local data nodes)

change much with the number of local nodes for a given β_{UL} value, since the local data phases are already fully occupied by packet transmissions, no matter how many local nodes are present. This phenomenon can also be explained by (11): As all $\rho_{i,k}$ approaches one, the second factor on the right hand side remains unchanged even if the value of $M_{LD,k}$ increases. As a result, the normalized system throughput depends only on the first factor which is a non-increasing function of β_{UL} . From these three figures we can also observe that, for different system configurations, our analytical model

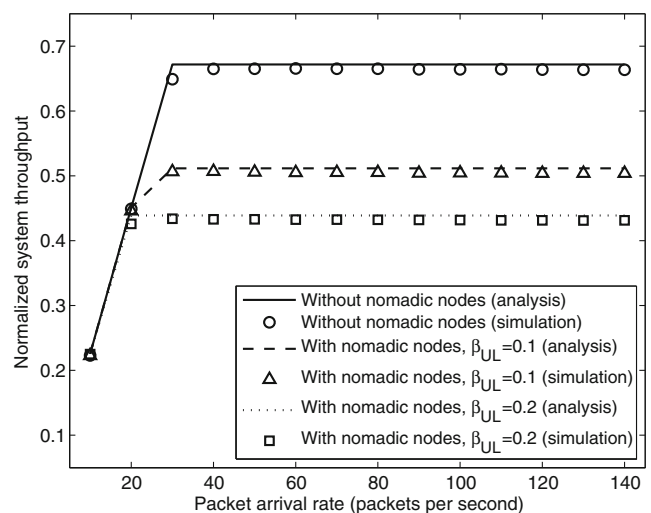


Fig. 6 The normalized system throughput of local data services versus packet arrival rate (30 local voice nodes, 30 local data nodes)

provides a good estimation of the normalized system throughput of local data services.

The relation between the fraction of channel time occupied by delay tolerant data services and the normalized system throughput of local data services is demonstrated in Fig. 7 for 10 local voice nodes and 30 local data nodes case and in Fig. 8 for 30 local voice nodes and 30 local data nodes case. Using the DFMAC scheme, the fraction of channel time occupied by delay tolerant data services is equivalent to $\beta_{UL} + \beta_{DL}$. The packet arrival rates of local data node and the AP are fixed to 15 packets per second. Note that this packet arrival rate does not result in throughput saturation when there is no nomadic node in a hot spot, as shown in Figs. 5 and 6. From Figs. 7 and 8, we observe that, as the fraction of channel time increases, the normalized system throughput under the DFMAC scheme is almost unchanged when the fraction is small. This is because, when the queue utilization of local data nodes is low, the probability for local data queues to be empty is high, and a considerable portion of channel time is occupied by pure token passing. On the other hand, as the fraction of channel time increases, the queue utilization of local data nodes increases and the overhead on the pure token passing decreases. However, when the fraction of channel time further increases, the normalized system throughput degrades dramatically due to throughput saturation in the local data phase. In a saturation condition, the local data phases are fully occupied by packet transmissions, therefore the normalized system throughput only depends on the duration of local data phases. With nomadic nodes in

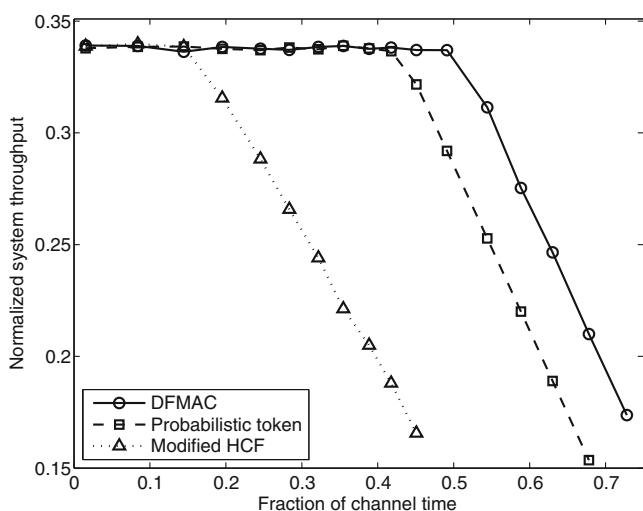


Fig. 7 The normalized system throughput of local data services versus the fraction of channel time occupied by delay tolerant data services (10 local voice nodes, 30 local data nodes)

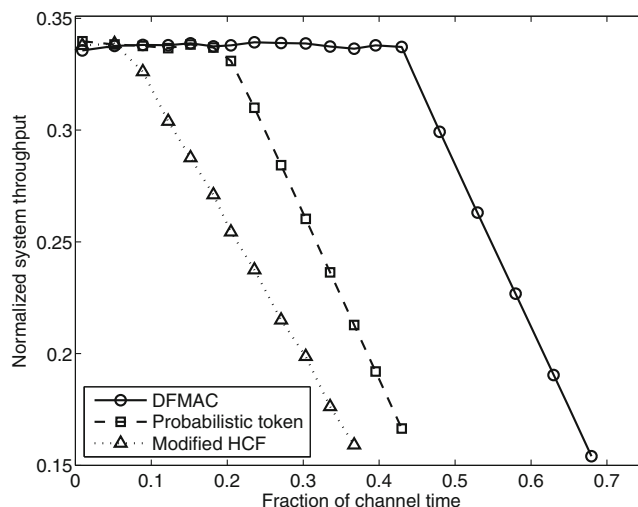


Fig. 8 The normalized system throughput of local data services versus the fraction of channel time occupied by delay tolerant data services (30 local voice nodes, 30 local data nodes)

hot spots, the only possibility to facilitate delay tolerant data services is to sacrifice the throughput of local data services. A theoretical explanation can also be given from (11), since the normalized system throughput depends only on the first factor on the right hand side as all $\rho_{i,k}$ approaches one.

A comparison among the DFMAC scheme, the probabilistic token-based scheme, and the modified HCF scheme is also demonstrated in Figs. 7 and 8. Before throughput saturation, the three schemes achieve similar normalized system throughput of local data services. However, in a saturation condition, the DFMAC scheme outperforms the other two schemes and thus can achieve a better tradeoff between the delay tolerant data services and local data services. For instance, for a given normalized system throughput of local data services, a larger fraction of channel time can be occupied by the delay tolerant data services under the DFMAC scheme. Compared with the probabilistic token-based scheme, the performance improvement obtained by utilizing the DFMAC scheme increases with the increase of the number of local voice nodes, since the performance gain of the DFMAC scheme over the probabilistic token-based scheme is obtained by reducing the channel occupancy of local voice services. On the other hand, although the modified HCF scheme can provide a relatively efficient resource allocation for local voice services as shown in Fig. 3, it cannot achieve an efficient tradeoff between the delay tolerant data services and local data services compared with the DFMAC scheme, since the contention-based MAC of the modified HCF scheme for local data services is not efficient when the channel contention

among local data nodes is high (i.e., in a saturation condition).

5.3 Delivery probability of delay tolerant data services

Consider the uplink transmission. The delivery probability is evaluated in four cases with different configurations of network coverage area (ψ), uplink delay tolerant data service arrival rate (λ_U), and buffer size (B_U), given as follows:

- Case 1 $\psi = 2,000 \times 2,000 \text{ m}^2$, $\lambda_U = 0.03$ messages per second, $B_U = 800$ messages;
- Case 2 $\psi = 2,000 \times 2,000 \text{ m}^2$, $\lambda_U = 0.03$ messages per second, $B_U = 300$ messages;
- Case 3 $\psi = 2,500 \times 2,500 \text{ m}^2$, $\lambda_U = 0.03$ messages per second, $B_U = 300$ messages;
- Case 4 $\psi = 2,500 \times 2,500 \text{ m}^2$, $\lambda_U = 0.06$ messages per second, $B_U = 300$ messages.

Figure 9 shows the message delivery probability of uplink delay tolerant data service versus β_{UL} . It is observed that, the delivery probability increases as β_{UL} increases, since more radio resources are provided to a nomadic node when it comes into a hot spot. The delivery probability can also be improved with a larger buffer size or a lower message arrival rate because of the lower chances for the buffer to be fully occupied. On the other hand, the network area has a negative effect on the delivery probability. For a given set of RD mobility parameters, the sojourn duration is independent of the network area, but the inter-visiting time becomes longer for a network with a larger area, resulting in a lower delivery probability. It is observed that

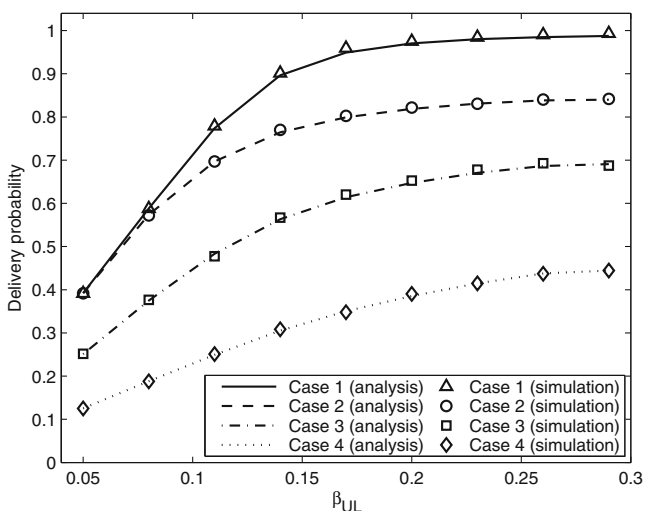


Fig. 9 The delivery probability of uplink delay tolerant data service versus β_{UL}

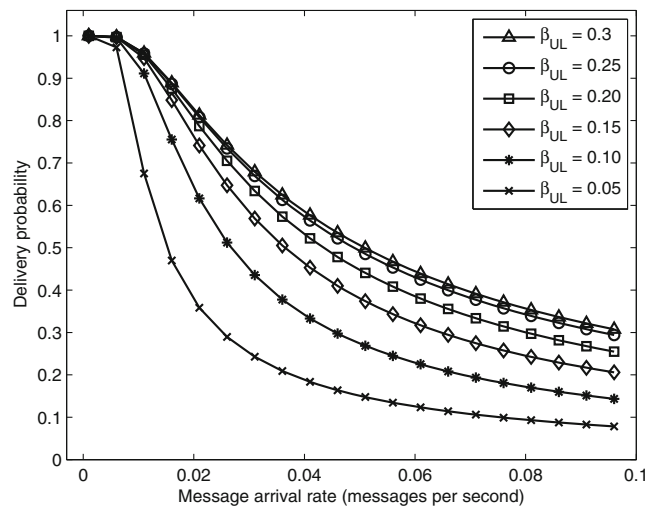


Fig. 10 The delivery probability of uplink delay tolerant data service versus message arrival rate

the analytical and simulation results closely match with each other.

In order to evaluate how the effectiveness of DFMAC changes with the uplink delay tolerant data service arrival rate, we fix the values of ψ and B_U to $2,500 \times 2,500 \text{ m}^2$ and 300 messages, respectively. As shown in Fig. 10, with an increase of the message arrival rate, the delivery probability of uplink delay tolerant data service decreases. As expected, the delivery probability can be increased by choosing a larger β_{UL} value. Nonetheless, for a fixed message arrival rate, the degree of the message delivery improvement dwindles when the value of β_{UL} increases. The rationale is that, as β_{UL} increases, the limited buffer size gradually becomes the bottleneck of message delivery.

6 Conclusions

In this paper, a DTN/WLAN interworking scenario is considered. A DTN-friendly MAC (DFMAC) scheme is proposed to facilitate link-layer resource allocation for local nodes and nomadic nodes in a hot spot. By tuning the phase duration parameters of the DFMAC, the performance balance between local services and delay tolerant data services can be achieved. The performance of the proposed MAC scheme is evaluated by mathematical analysis and further validated by simulations. Our results show that, by properly choosing the value of phase duration parameters, we can achieve satisfactory system performance for both nomadic nodes and local nodes. Further work includes the extension of the DFMAC scheme to joint design with different

store-carry-forward routing protocols and the investigation of wireless channel impairments.

Acknowledgements The authors wish to thank Mr. Ho Ting Cheng for his helpful suggestions which improved the quality of this paper. This work was supported by a research grant from the Natural Science and Engineering Research Council (NSERC) of Canada.

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