

DTCoop: Delay Tolerant Cooperative Communications in DTN/WLAN Integrated Networks

Hao Liang and Weihua Zhuang

Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, Ontario, Canada, N2L 3G1

Email: h8liang@ecemail.uwaterloo.ca, wzhuang@bcr.uwaterloo.ca

Abstract—In this paper, we consider a DTN/WLAN integrated network where nomadic nodes with high mobility comprise a delay tolerant network (DTN) while local nodes with low mobility reside in the coverage area of wireless local area networks (WLANs). A message dissemination service is considered, where data traffic is generated by a server in the Internet and destined to a group of nomadic nodes. In order to facilitate message dissemination, a delay tolerant cooperative communication (DT-Coop) scheme is proposed. The messages for dissemination are first pre-downloaded to a group of storage local nodes within a WLAN before the visit of a nomadic node, and then scheduled for transmission when a nomadic node comes into the transmission range. Analysis and simulation results are presented to evaluate the performance of the proposed DTCoop scheme. It is shown that our proposed scheme can significantly improve the message delivery performance from a WLAN to a nomadic node as compared with existing schemes without message pre-downloading or message scheduling.

I. INTRODUCTION

Wireless local area networks (WLANs) have been widely deployed in recent years at public and/or private areas such as libraries, cafeterias, classrooms, and residential houses, due to their inherently low implementation cost, in comparison with the wireless wide area networks (WWANs) such as cellular networks. In order to enlarge wireless service coverage, the notion of wireless metropolitan area sharing networks (WM-SNs) can be employed, where publicly and/or privately owned wireless Internet access points (APs) are shared [1]. Nomadic nodes (or mobile users) roaming in the network coverage area can obtain intermittent wireless access when they come into the transmission range of shared roadside APs.

On the other hand, message dissemination services have been extensively investigated in the context of vehicular ad hoc networks and mobile ad hoc networks because of a wide variety of practical application demands, such as traffic information downloading, entertainment content broadcasting, and commercial advertising [2] [3]. These services are typically generated by a server in the Internet and provided to the nomadic nodes when they come into the coverage area of infostations (or roadside units). However, as the number of infostations is limited, the performance of the message dissemination service is largely capped.

One straightforward solution for the aforementioned problem is the MobTorrent scheme which utilizes the roadside

APs and incorporates the store-carry-forward based delay tolerant network (DTN) routing for nomadic nodes [4]. As the bandwidth of the wireline connections is limited in many WLAN deployment environments (such as the ADSL broadband connections in residential areas), a message pre-fetching mechanism is implemented by the MobTorrent scheme where messages are transmitted to and stored by the roadside APs before the arrival of a nomadic node. However, as the buffer space is limited at the APs, the length of the pre-fetched messages is limited (a maximum of 6.5MB under the MobTorrent scheme). After the delivery of the pre-fetched messages, the bandwidth limitation of the wireline connections still caps the service quality. Another problem which cannot be solved by the MobTorrent scheme is the wireless channel variation. As the nomadic nodes with high mobility are considered, the wireless transmission error from an AP to a nomadic node caused by wireless channel fading cannot be mitigated. The same problem exists in other solutions based on the message pre-fetching at a single AP, such as the WiFi-based content distribution community infrastructure (CDCI) scheme [5].

In this work, we address the problem of message dissemination in the context of a DTN/WLAN integrated network where not only the AP within a WLAN is shared, but also the local nodes served by the WLAN can provide store-carry-forward routing capabilities. A delay tolerant cooperative communication (DTCoop) scheme is proposed to improve the message delivery performance from a WLAN to a nomadic node. Analytical and simulation results are presented to demonstrate the performance the proposed DTCoop scheme. Compared with conventional cooperative communication schemes without message pre-downloading [6] [7] and the MobTorrent scheme without message scheduling, the DTCoop scheme can significantly improve the average number of delivered messages upon each visit of a nomadic node to a WLAN.

II. SYSTEM MODEL

Consider a DTN/WLAN integrated network with isolated WLANs scattered around a large network region [8]. Wireless Internet APs attached to the Internet backbone provide wireless access to the local nodes in the WLANs. Nomadic nodes roaming randomly within the entire network region comprise a DTN. All local nodes, nomadic nodes, and APs are equipped with a short range radio transceiver. The nomadic nodes can

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stay disconnected for hours and travel through a WLAN within several minutes.

A message dissemination service is considered, which delivers data traffic generated by a server in the Internet to a group of nomadic nodes. Messages can be delivered to a nomadic node when it comes into the coverage area of a WLAN. In this work, we consider a long message dissemination session with sufficient messages and focus on the message delivery from a single WLAN to a tagged nomadic node. The interactions between different WLANs and the store-carry-forward routing among nomadic nodes are left for our further work.

For efficient service to both local nodes and nomadic nodes, a DTN-friendly medium access control (DFMAC) scheme is assumed for each WLAN [8]. Under the DFMAC scheme, time is partitioned into superframes of constant duration. A certain period of each superframe is reserved for the message dissemination service. Denote the channel bandwidth dedicated to the message dissemination service as W_D . The wireless transmission rate at instantaneous signal-to-noise ratio (SNR) γ is $R_D(\gamma)$, while the wireline transmission rate from a server in the Internet to the AP is R_{WL} . The wireless and wireline transmissions are considered as error free at rates $R_D(\gamma)$ and R_{WL} , respectively. In order to facilitate the message dissemination service, it is imperative to increase the number of messages delivered to a nomadic node when it visits a WLAN, to be discussed in the following section.

III. THE DTCoop SCHEME

An illustration of the DTCoop scheme is given in Fig. 1, which includes two procedures: message pre-downloading and message scheduling. The message dissemination session is first transmitted to and stored by a group of local nodes within a WLAN before the arrival of a destination nomadic node. Then upon a visit of the nomadic node to the WLAN, an opportunistic message scheduling is performed to exploit channel diversity for a high message delivery rate.

A. Message Pre-Downloading

Fig. 1(a) illustrates the message pre-downloading. Both WWAN based on-demand pre-downloading [4] and mobility history based stochastic pre-downloading [5] can be implemented in the DTCoop scheme. However, because of the buffer space limitation, only a group of local nodes (denoted by set G_L) within the WLAN can accept the message dissemination session under consideration. The local nodes with and without pre-downloaded messages are defined as the storage and non-storage local nodes, respectively. Note that we do not consider the message pre-downloading to an AP since its buffer space is generally limited and should be reserved for the local services within a WLAN [8].

Under the assumption of stationary local nodes, the reception SNR from the AP to a storage local node j ($\gamma_{AP,j}$, $j \in G_L$) is fixed and can be obtained accurately. In order to achieve reliable message pre-downloading, the rate of wireless broadcasting from the AP to storage local nodes is given by $R_{pre} = \min \{R_{WL}, R_D(\gamma_{AP,j}), j \in G_L\}$. Note that different

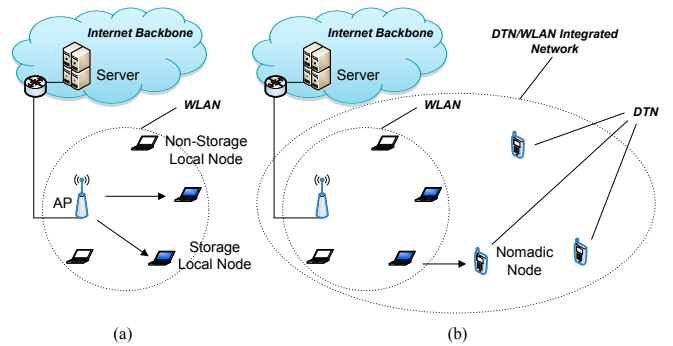


Fig. 1: An illustration of the DTCoop scheme: (a) Message pre-downloading. (b) Message scheduling.

from the cooperative broadcast/multicast applications from a single AP to several clusters of well connected relay and destination nodes [2] [9] [10], a conservative rate R_{pre} is considered in the DTCoop scheme for a reliable first-hop broadcasting. The reason is that, in a DTN/WLAN integrated network, the storage local nodes are always connected to the AP, while the destination nodes of the message dissemination service are disconnected from the storage local nodes (or the AP) for most of the time. In a typical scenario, there is a sufficient time for message pre-downloading, but each message disseminated session should be stored at the non-destination local nodes for a considerably long period of time before delivery. Therefore, the message pre-downloading procedure of the DTCoop scheme is buffer limited rather than time (or bandwidth) limited.

Compared with conventional cooperative communication schemes without message pre-downloading, the bandwidth limitation of the wireline connection is less influential on the message delivery rate of the DTCoop scheme since the pre-downloaded messages do not need to be fetched from a server in the Internet directly. Moreover, the rate loss of the cooperative communications caused by the half-duplex transmission constraints of the relay nodes [6] can be reduced by implementing the DTCoop scheme since the first-hop message pre-downloading procedure is executed before the visit of a nomadic node.

B. Message Scheduling

The message scheduling is shown in Fig. 1(b). Different from the message pre-downloading procedure, the message scheduling is considered as bandwidth limited since the sojourn duration of a nomadic node in a WLAN is typically short. Compared with the MobTorrent (or CDCI) scheme, since messages are pre-downloaded to a group (G_L) of storage local nodes in the DTCoop scheme, channel diversity (or multi-user diversity) can be exploited for transmission rate improvement.

When the destination nomadic node comes into the coverage area of the WLAN, among the group of storage local nodes and the AP (denoted by $G_S = G_L \cup \{AP\}$), the one with the maximum instantaneous SNR is scheduled to transmit. Because of the bandwidth limitation of the wireline connection, it

is possible that R_{WL} is smaller than the instantaneous wireless transmission rate from the AP to the nomadic node. Therefore, we consider an equivalent SNR for the AP with a maximum value γ_{WL} . Since the wireless transmission rate $R_D(\gamma)$ is discontinuous with respect to γ if adaptive modulation and coding (AMC) are adopted at the physical layer [9], we have $\gamma_{WL} = \arg \max_{\gamma} \{R_D(\gamma) \leq R_{WL}\}$.

After all pre-downloaded messages are transmitted to the visiting nomadic node, if the message delivery is not completed, the remaining messages can be delivered by directed transmissions from the AP to the nomadic node.

IV. PERFORMANCE ANALYSIS

For performance evaluation of the proposed DTCoop scheme, we focus on the analysis of the average number of delivered messages when a tagged nomadic node visits the WLAN. For analytical tractability, the following assumptions are made:

- The movement of nomadic nodes follow a random direction (RD) mobility model, and the density of nomadic nodes is low [11] [12]. Each WLAN covers a circular region with radius r ;
- The wireless channel condition of different links are independent. The maximum transmission range from a local node (or the AP) to a nomadic node is d_{max} , beyond which the wireless transmission rate is negligible.

As both storage local nodes and AP can be scheduled for message transmission, we consider an approximated wireless coverage area of the WLAN with radius $r + d_{max}$. Under the RD mobility, the visiting trajectory of a tagged nomadic node i to the WLAN is defined by two parameters β and δ , where β represents the incident angle of nomadic node i , and δ is the angle between the polar axis (x) and the direction of the vertical line from the polar to the visiting trajectory, as demonstrated in Fig. 2. With the RD mobility, the distributions of β and δ can be found in [11] [12]. Note that given the visiting trajectory parameters β and δ , the two opposite movement directions (counterclockwise and clockwise) have the same probability to be chosen. The speed of nomadic node i when it visits the the WLAN is denoted by v .

Path loss and Rayleigh fading are considered for the wireless channel [7]. The probability density function (PDF) of the instantaneous SNR for a distance d between the transmitter and receiver is given by $f_{\Gamma(d)}(\gamma) = (1/\bar{\Gamma}(d))e^{-\gamma/\bar{\Gamma}(d)}$ ($0 \leq \gamma < \infty$), where $\bar{\Gamma}(d)$ is the average SNR depending on the path loss effect [9]. Note that a generalization of our analytical model is straightforward to other PDFs of the instantaneous SNR. In this work, we consider $R_D(\gamma)$ being represented by the wireless channel capacity, i.e., $R_D(\gamma) = W_D \log_2(1 + \gamma)$. The investigation of the message scheduling overhead at the MAC layer [6] and the AMC at the physical layer [9] is left for our further work. The length of each message is L bytes including all packetization overhead. Upon the visit of nomadic node i to the WLAN, the number of messages already pre-downloaded to the storage local nodes is denoted by K_{pre} . In a network-wide analysis, the value of K_{pre} can be calculated based on

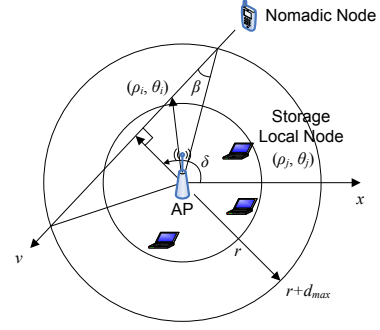


Fig. 2: An illustration of the visit of a nomadic node to the wireless coverage area of a WLAN

the message pre-downloading rate R_{pre} and the inter-visiting time of nomadic node i to the WLAN [3] which is beyond the scope of this work.

The performance analysis of the DTCoop scheme consists of two parts. In Subsection IV-A, the average transmission rate is calculated for each specific location of the tagged nomadic node. Then, in Subsection IV-B, an integration of the average transmission rate over the visiting trajectory is performed to obtain the average number of delivered messages. In the following analysis, the polar coordinate system is used.

A. Performance Analysis for a Tagged Nomadic Node at a Specific Location

Suppose the AP is located at the pole, and the position of storage local node j is (ρ_j, θ_j) for $j \in G_L$. When the tagged nomadic node is at position (ρ_i, θ_i) , denote the equivalent SNR of the transmissions from local node j (or the AP) to nomadic node i as $\Gamma_L(j, i)$. For $j \in G_L$, the PDF of $\Gamma_L(j, i)$ is given by $f_{\Gamma_L(j, i)}(\gamma) = f_{\Gamma(d(j, i))}(\gamma)$, where $d(j, i) = \sqrt{\rho_i^2 + \rho_j^2 - 2\rho_i\rho_j \cos(\theta_i - \theta_j)}$ is the distance between nomadic node i and storage local node j . However, as the transmission rate of the wireline connection is limited by R_{WL} , the equivalent SNR of the transmission from the AP to nomadic node i ($\Gamma_L(AP, i)$) is bounded by γ_{WL} . Obviously, $\Gamma_L(AP, i)$ is a hybrid (discrete and continuous) random variable whose PDF can be calculated as

$$f_{\Gamma_L(AP, i)}(\gamma) = \begin{cases} (1 - \int_0^{\gamma_{WL}} f_{\Gamma(d(AP, i))}(x)dx) \delta(\gamma - \gamma_{WL}) \\ \quad + f_{\Gamma(d(AP, i))}(\gamma), & \text{if } 0 \leq \gamma \leq \gamma_{WL}; \\ 0, & \text{otherwise} \end{cases} \quad (1)$$

where $\delta(t)$ is the Dirac delta function with properties $\delta(t) = 0$ for $t \neq 0$ and $\int_{t_0-\varepsilon}^{t_0+\varepsilon} \delta(t-t_0)dt = 1$ for $\varepsilon > 0$. The cumulative distribution function (CDF) of $\Gamma_L(j, i)$ ($j \in G_S$) is given by $F_{\Gamma_L(j, i)}(\gamma) = \int_0^{\gamma} f_{\Gamma_L(j, i)}(x)dx$, $0 \leq \gamma < \infty$.

When nomadic node i is at position (ρ_i, θ_i) , denote the SNR of the message transmission under the proposed scheduling scheme as Γ_S . Then the CDF of Γ_S can be calculated as

$$F_{\Gamma_S}(\gamma) = P(\max \{\Gamma_L(j, i), j \in G_S\} \leq \gamma) = \prod_{j \in G_S} F_{\Gamma_L(j, i)}(\gamma). \quad (2)$$

Note that the second equality in (2) holds because of the channel independency among different links. Then the PDF of Γ_S is given by

$$f_{\Gamma_S}(\gamma) = \sum_{j \in G_S} f_{\Gamma_L(j,i)}(\gamma) \prod_{m \in G_S \setminus \{j\}} F_{\Gamma_L(m,i)}(\gamma). \quad (3)$$

The average transmission rate from both storage local nodes and the AP to nomadic node i at position (ρ_i, θ_i) can be calculated by a piecewise integration given as follows

$$\begin{aligned} & \bar{R}_V(\rho_i, \theta_i) \\ &= \int_0^\infty R_D(\gamma) f_{\Gamma_S}(\gamma) d\gamma \\ &= \int_0^{\gamma_{WL}} R_D(\gamma) \left[\sum_{j \in G_S} \frac{1}{\bar{\Gamma}(d(j,i))} e^{-\frac{\gamma}{\bar{\Gamma}(d(j,i))}} \right. \\ & \quad \cdot \left. \prod_{m \in G_S \setminus \{j\}} \left(1 - e^{-\frac{\gamma}{\bar{\Gamma}(d(m,i))}} \right) \right] d\gamma \\ & \quad + R_D(\gamma_{WL}) e^{-\frac{\gamma_{WL}}{\bar{\Gamma}(d(AP,i))}} \prod_{m \in G_S \setminus \{AP\}} \left(1 - e^{-\frac{\gamma_{WL}}{\bar{\Gamma}(d(m,i))}} \right) \\ & \quad + \int_{\gamma_{WL}}^\infty R_D(\gamma) \left[\sum_{j \in G_S \setminus \{AP\}} \frac{1}{\bar{\Gamma}(d(j,i))} e^{-\frac{\gamma}{\bar{\Gamma}(d(j,i))}} \right. \\ & \quad \cdot \left. \prod_{m \in G_S \setminus \{AP,j\}} \left(1 - e^{-\frac{\gamma}{\bar{\Gamma}(d(m,i))}} \right) \right] d\gamma. \quad (4) \end{aligned}$$

When all of the preloaded messages are transmitted to nomadic node i but the message dissemination session is still not completed, the remaining messages can be delivered by direct transmissions from the AP. Since the equivalent SNR is given by (1), the average transmission rate when nomadic node i is at position (ρ_i, θ_i) is given by

$$\begin{aligned} \bar{R}_{VO}(\rho_i, \theta_i) &= \int_0^{\gamma_{WL}} \frac{R_D(\gamma)}{\bar{\Gamma}(d(AP,i))} e^{-\frac{\gamma}{\bar{\Gamma}(d(AP,i))}} d\gamma \\ & \quad + R_D(\gamma_{WL}) e^{-\frac{\gamma_{WL}}{\bar{\Gamma}(d(AP,i))}}. \quad (5) \end{aligned}$$

B. Performance Analysis over Visiting Trajectory

Assume that nomadic node i enters the wireless coverage area of the WLAN (with radius $r + d_{max}$) at time 0. Given the sojourn trajectory parameters β and δ , after time t , the position of nomadic node i is given by $(\rho_i^1(t), \theta_i^1(t))$ and $(\rho_i^2(t), \theta_i^2(t))$ for the two opposite directions (counterclockwise and clockwise) and can be calculated as

$$\begin{aligned} \rho_i^l(t) &= \sqrt{v^2 t^2 + (r + d_{max})^2 - 2vt(r + d_{max}) \cos \beta} \\ \theta_i^l(t) &= (-1)^{l-1} \arccos \frac{r + d_{max} - vt \cos \beta}{\rho_i(t)} \\ & \quad + \delta + (-1)^l \left(\frac{\pi}{2} - \beta \right), \quad l = 1, 2. \quad (6) \end{aligned}$$

Given the number of the pre-downloaded messages K_{pre} , the average number of messages that can be delivered from the storage local nodes (or the AP) to nomadic node i over

the visiting trajectory is given by

$$\bar{K}_V = \begin{cases} \bar{K}_V^M, & \text{if } 0 \leq \bar{K}_V^M \leq K_{pre}; \\ K_{pre} + \frac{1}{2} \sum_{l=1}^2 \left\lfloor \frac{\int_0^{T_l} \bar{R}_{VO}(\rho_i^l(t), \theta_i^l(t)) dt}{L} \right\rfloor, & \text{otherwise} \end{cases}, \quad (7)$$

where $T_V = \frac{2(r+d_{max}) \cos \beta}{v}$ is the sojourn duration of nomadic node i , T_l ($l = 1, 2$) is the delivery completion time of the pre-downloaded messages which satisfies $\int_0^{T_l} \bar{R}_V(\rho_i^l(t), \theta_i^l(t)) dt = K_{pre} L$, $\bar{K}_V^M = \left\lfloor \frac{\int_0^{T_V} \bar{R}_V(\rho_i^l(t), \theta_i^l(t)) dt}{L} \right\rfloor$ is the maximum number of messages that can be delivered over the visiting trajectory from both storage local nodes and the AP to nomadic node i .

V. NUMERICAL RESULTS

In this section, numerical results are presented to demonstrate the performance of the proposed DTCoop scheme. The radius of the WLAN under consideration is $r = 100$ m, and the speed of the tagged nomadic node is $v = 1$ m/s. For a typical WLAN scenario, the wireless transmission power of local nodes, nomadic nodes, and AP is 100 mW, while the noise power is 0.001 mW [13]. The bandwidth dedicated to message dissemination service under the DFMA scheme is $W_D = 10$ MHz. The length of each message is $L = 10$ Kbytes. For the wireless channel condition, we consider a pathloss exponent $\alpha = 4$ with a maximum transmission range $d_{max} = 200$ m. Since the storage local nodes are assumed to be stationary within each WLAN, for fair comparison, we consider a ring topology as an example where the storage local nodes are evenly distributed on a circle with the AP located at the center. The distance between the storage local nodes and the AP is r_L .

The performance of the proposed DTCoop scheme is shown in Fig. 3. The visiting trajectory and WLAN topology parameters are given by $\beta = \frac{\pi}{12}$, $\delta = 0$, and $r_L = \frac{r}{2}$, respectively. Over this visiting trajectory, the shortest distance between the tagged nomadic node and the AP is 77.6 m. The transmission rate of the wireline connection is $R_{WL} = 1$ Mbps. We can see that the analytical results match well with the simulation results. As expected, with an increase of K_{pre} , the average number of delivered messages increases. The reason is that, with more pre-downloaded messages, more message transmissions can benefit from the channel diversity in terms of the opportunistic scheduling among multiple storage local nodes and the AP. However, the increment dwindles as $|G_L|$ increases because of the saturation of channel diversity gain.

A comparison among the DTCoop scheme and other existing schemes is shown in Fig. 4. The visiting trajectory and WLAN topology parameters are given by $\beta = \frac{\pi}{36}$, $\delta = 0$, and $r_L = \frac{r}{4}$, respectively. The shortest distance between the tagged nomadic node and the AP over this visiting trajectory is 26.1 m. The number of storage local nodes is $|G_L| = 10$. We can see that the average number of the delivered messages increases as R_{WL} increases. The direct transmissions from the

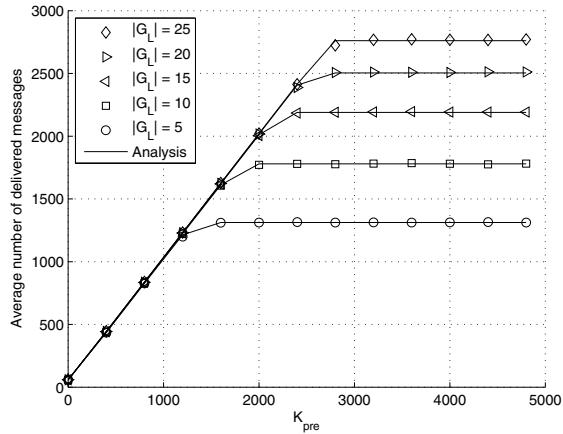


Fig. 3: Performance evaluation of the DTCoop scheme.

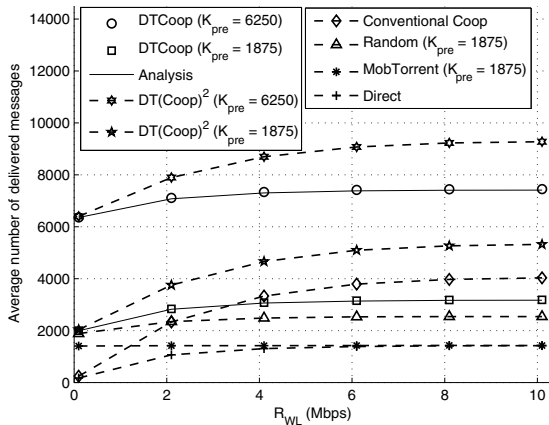


Fig. 4: Performance comparison among the DTCoop scheme and other related schemes.

AP to the nomadic node provides the lowest performance. By utilizing the MobTorrent (or CDCI) scheme, since messages are pre-downloaded to the AP, the average number of delivery messages can be improved when R_{WL} is low. Note that for fair comparison, we assume that the AP under the MobTorrent scheme has a sufficient buffer space, which may not be practical for privately owned WLANs. In order to further improve the message delivery performance, the storage local nodes can be utilized for message relaying. We can see that, the DTCoop scheme outperforms the random scheduling scheme (such as 802.11 MAC) for the same value of K_{pre} since the channel diversity can be exploited by messages scheduling among storage local nodes and the AP. The conventional cooperative communication scheme [6] [7] outperforms the DTCoop scheme when K_{pre} is small and R_{WL} is large. The reason is that, under the DTCoop scheme, when all of the pre-downloaded messages are delivered, the remaining messages are transmitted to the nomadic node by direct transmissions from the AP. For fair comparison, we further consider a $DT(Coop)^2$ scheme where conventional cooperative communications is utilized to deliver the remaining messages.

Obviously, the $DT(Coop)^2$ outperforms the conventional cooperative communication scheme for different values of R_{WL} . A significant performance gain is observed when more messages are pre-downloaded to storage local nodes ($K_{pre} = 6250$). In addition, a good agreement can be seen between the analytical and simulation results for different values of R_{WL} .

VI. CONCLUSIONS AND FURTHER WORK

In this paper, we investigate the message dissemination service in a DTN/WLAN integrated network. A DTCoop scheme consisting of message pre-downloading and message scheduling is proposed to improve the message delivery performance, when a nomadic node comes into the coverage area of a WLAN. An analytical model is derived for the performance evaluation of the DTCoop scheme and the accuracy is verified by simulations. Numerical results indicate that the DTCoop scheme can significantly increase the average number of delivered messages to a nomadic node. However, as this improvement is achieved with a storage overhead at local nodes, when multiple message dissemination sessions are considered, the group of storage local nodes (G_L) should be carefully determined by considering the buffer space of each local node and will be investigated in our further work.

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