Double-Loop Receiver-Initiated MAC for Cooperative Data Dissemination via Roadside WLANs

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***Abstract*—In this paper, we investigate data dissemination in delay tolerant networks (DTNs) via roadside wireless local area networks (RS-WLANs). The data dissemination service is destined to a group of nomadic nodes roaming in a large network region with a low node density. The local nodes within the coverage area of an RS-WLAN can provide packet caching and relaying capabilities. We consider a cooperative data dissemination approach where information packets are first pre-downloaded to the local nodes within the RS-WLAN before the visit of a pedestrian nomadic node, and then opportunistically scheduled to transmit to the nomadic node upon its arrival. In order to resolve the channel contention among multiple direct/relay links and exploit the predictable traffic characteristics as a result of packet pre-downloading, a double-loop receiver-initiated medium access control (DRMAC) scheme is proposed. The MAC scheme can achieve spatial and temporal diversity via the outer-loop and inner-loop MAC, respectively. A receiver initiated mechanism is used to reduce the signalling overhead, where the ACK message is used as an invitation of channel contention. An analytical model is established to evaluate the performance of the proposed MAC scheme. Numerical results demonstrate that the proposed MAC scheme can significantly improve the number of delivered packets from an RS-WLAN to a nomadic node as compared with the existing MAC schemes.**

***Index Terms*—Cooperation, data dissemination service, delay tolerant network (DTN), diversity, medium access control (MAC), wireless local area network (WLAN).**

I. INTRODUCTION

Data dissemination services in wireless networks have been widely studied because of the intensive service demands such as traffic information downloading, entertainment content distribution, and commercial advertising [1]–[3]. The existing services are typically generated by a content server in the Internet and destined to a group of nomadic nodes roaming in the network region. Since the data dissemination services provided by wireless wide area networks such as GPRS and 3G cellular networks suffer from high capital expenditure and low speed, extensive research has been carried out to exploit the roadside WiFi access points (APs) for data delivery. For instance, the Drive-thru Internet architecture addresses the short-term network access problem when a mobile user walks, drives, or passes (by other means) through the coverage area of an AP [4]. To improve the availability of the roadside APs, the notion of wireless metropolitan area sharing network (WMSN) is introduced, where publicly and/or privately owned wireless local area networks (WLANs) are shared [5]. Following the same concept as WMSN, FON has successfully established a business model to stimulate the sharing of the WLANs [6]. Based on two kinds of incentives, i.e., direct payment and cooperative sharing among FON subscribers, the nomadic nodes can obtain permission to access the privately owned roadside WLANs (RS-WLANs) which are typically deployed at the roadside restaurants, cafes, and residential houses. However, in a rural area and/or an urban area with a low market penetration rate, the densities of the shared RS-WLANs as well as the nomadic nodes are low such that an end-to-end path from an AP to a nomadic node can hardly be established. Moreover, the data rate of the wireline connection between an AP and the content server may be limited[1], which further restricts the packet delivery rate from an RS-WLAN to a nomadic node.

To achieve efficient data dissemination in such a sparse network or delay tolerant network (DTN) [9], a cooperative approach (also referred to as DTCoop [10]) can be used, in which not only the AP within each RS-WLAN is shared, but also the local nodes connected to the AP can provide packet caching and relaying capabilities. Information packets are first pre-downloaded to a group of storage local nodes within an RS-WLAN. Upon the arrival of a nomadic node in the RS-WLAN, both direct links from storage local nodes and relay links via non-storage local nodes can be used for packet delivery. Although packet pre-downloading (or pre-fetching) has been investigated in literature to address the bandwidth limitation of the wireline connection between an AP and the content server [8], [10]–[12], how to efficiently schedule packet transmissions among multiple direct/relay links for potential cooperative diversity gain is still an open issue. Specifically, an efficient medium access control (MAC) scheme should be designed to exploit both spatial and temporal diversity in the cooperative communication paradigm for a high packet delivery rate. At the link layer, spatial diversity can be achieved by scheduling the local node with the highest average transmission rate to transmit, based on the geographic

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[1] For instance, the rate can be limited to a few Mbps for some residential Internet service subscribers, which is much lower than the maximum rate of the wireless connection (e.g., 54 Mbps for IEEE 802.11a based RS-WLANs) [7] [8].

locations of local nodes [13]. On the other hand, temporal (or user) diversity corresponds to the time-varying channel condition caused by the mobility of the nomadic node, and typically requires a time-dependent scheduling based on the instantaneous transmission rates from local nodes to the nomadic node [2] [14] [15]. However, the packet pre-downloading mechanism poses new technical challenges/opportunities in medium access control. A packet may have multiple copies at different storage local nodes and can be cooperatively relayed by multiple non-storage local nodes. In order to transmit a packet, high wireless channel contention should be resolved among multiple direct/relay links. On the other hand, the MAC scheme can take advantage of the packet pre-downloading mechanism. The traffic characteristics at the storage local nodes can be predicted (i.e., saturated) as the packets are already pre-downloaded before the visit of a nomadic node. The efficiency of medium access control can be potentially improved by reducing the signalling overhead.

In this paper, we propose a double-loop receiver-initiated MAC (DRMAC) scheme to achieve a high efficiency in cooperative data dissemination via RS-WLANs. Pedestrian nomadic nodes are considered, which correspond to the majority of the RS-WLAN users such as the FON subscribers [6]. This work extends our previous research [1] in improving the proposed MAC scheme for contention collision avoidance and multiuser support. The performance of the proposed MAC scheme is analyzed. To the best of our knowledge, this is the first work in literature to achieve the cooperative diversity gain based on receiver-initiated MAC and to utilize the time correlation of a wireless channel to reduce the signalling overhead. Specifically, the key features of this work include:

1) Two MAC loops are devised. The outer-loop MAC and inner-loop MAC are performed at relatively low and high frequencies to achieve spatial and temporal diversity, respectively;
2) In order to reduce the signalling overhead, a receiver-initiated MAC strategy is adopted to suppress the request-to-send/clear-to-send (RTS/CTS) message exchange by using the ACK message as an invitation of channel contention. The ACK message also carries the rate information of the previous transmission to reduce channel contentions among multiple storage and non-storage local nodes;
3) A novel analytical model is established using a finite-state Markov chain based channel model to characterize the time correlation between two consecutive transmissions. The analytical results are verified by extensive simulations for various visiting trajectories and speeds of a nomadic node. Compared with the IEEE 802.11 MAC, transmitter-initiated cooperative MAC, and receiver-initiated MAC, our proposed scheme can significantly improve the packet delivery rate from an RS-WLAN to a nomadic node.

The proposed MAC scheme improves quality of data dissemination services provided by RS-WLANs. Also, the resources within each RS-WLAN can be better utilized, which in turn stimulates the sharing of the roadside communication infrastructures in terms of the WiFi based WLANs.

The remainder of this paper is organized as follows. Section II provides an overview of the related work. Section III describes the system model. Section IV presents the proposed double-loop receiver-initiated MAC scheme. The performance of the proposed MAC scheme is analyzed in Section V. Numerical results are shown in Section VI. SectionVII concludes the research work.

II. RELATED WORK

Several MAC schemes have been proposed in literature to achieve spatial/temporal diversity in the context of cooperative communications. The CoopMAC can achieve spatial diversity based on the historic transmission observations [13]. Each low data rate node in the network maintains a table (i.e., the CoopTable) of potential relay nodes based on the overheard transmissions from other nodes. During packet transmission, each node of a low data rate selects either direct transmission mode or relay transmission mode (through a relay node) based on the information provided by the CoopTable. In this way, the packet transmission time can be reduced. Without predetermined network configuration, an adaptive distributed cooperative MAC (ADC-MAC) is proposed for spatial diversity in dynamic vehicular networks [14]. A heartbeat mechanism is devised so that the ADC-MAC can self-learn the geographic location information of the relay nodes and dynamically update the CoopTable. Since the source node adaptively selects the most suitable transmission mode and/or relay node based on the latest information in the CoopTable (which may not be up-to-date in comparison with the instantaneous information), temporal diversity can be potentially achieved. The distributed cooperative MAC achieves both spatial and temporal diversity [15]. The relay selection is completed in a distributed manner and the instantaneous channel quality is estimated during the RTS/CTS message exchange. These schemes are transmitter-initiated for communications among multiple pairs of traffic sources and destinations, and the exchange of RTS/CTS messages is required for the channel estimation and reservation before data transmission. As demonstrated in [16] [17], the receiver-initiated MAC schemes can reduce the signalling overhead for predictable traffic source. The RTS part of the RTS/CTS message exchange is suppressed, while the CTS part is used as an invitation by the receiver node for the transmitter node. However, when directly applied to RS-WLANs with pre-downloaded packets, these schemes do not exploit the potential diversity gain among multiple direct/relay links. Therefore, how to device a MAC scheme to reduce the signalling overhead while exploiting the diversity gain to facilitate the cooperative data dissemination in DTNs should be investigated.

III. SYSTEM MODEL

In this section, we first introduce the network topology. Then, the cooperative data dissemination approach is described, followed by a local information exchange mechanism to facilitate the cooperative data dissemination. As many symbols are used in this paper, Table I summarizes the important ones.

TABLE I: Summary of important symbols used.

Symbol	Definition
B	The number of packets in data dissemination service
$f(\cdot)$	A bijective function which maps each CG member to its rank in the CG notification message
$g(\cdot)$	A bijective function which maps each potential CG member to its rank in the deterministic backoff
i_{Tx}	The ID of the previous transmitter node
L	The group of local nodes
L_C	The group of CG members
L_{CP}	The group of potential CG members
L_S (L_N)	The group of storage (non-storage) local nodes
M	The number of transmission rates
m_{Tx}	The rate index of the previous transmission piggybacked in the ACK message
N_C	The number of CG members
$\overline{R}_i^e$	The estimated average transmission rate of local node i
$R'_{i,R_{Tx}}$	The one-step higher transmission rate of the potential CG member i with respect to R_{Tx}
T	The duration of a superframe
T_D	The duration of a dedicated phase
T_S	The duration of a slot in deterministic backoff
γ_m^{th}	The SNR threshold of the mth transmission rate
$\zeta_i(m)$	The packet transmission rate of local node i under rate index m

A. Network Topology

Consider a service area where a number of RS-WLANs are deployed. Local nodes reside in the coverage area of an RS-WLAN, while the nomadic nodes are roaming in the entire network region. We consider pedestrian nomadic nodes which can be disconnected for hours and walk through the coverage area of an RS-WLAN within several minutes. The densities of the RS-WLANs and nomadic nodes are low, which results in a DTN scenario [9]. Focusing on MAC, we consider a single RS-WLAN (e.g., in a residential house) with a group, L, of local nodes (including the AP), as shown in Fig. 1.

The RS-WLAN provides services to both local and nomadic nodes. For the resource sharing, we consider a superframe structure as shown in Fig. 2 [18]. Time is partitioned into superframes with constant duration T. Each superframe begins with a beacon period with duration T_B. Following the beacon period, a dedicated phase with duration T_D ($T_D < T - T_B$) is reserved for the data dissemination service upon the arrival of a nomadic node. The remaining period in the superframe is used to serve the local nodes. For the resource allocation among multiple nomadic nodes which are simultaneously present in an RS-WLAN, a time sharing mechanism is used, in which each dedicated phase is assigned to a nomadic node. The AP notifies the local nodes about the assignment during the beacon period. At the beginning of each dedicated phase, a dedicated phase assignment message is broadcasted by one of the local nodes to notify the nomadic node.

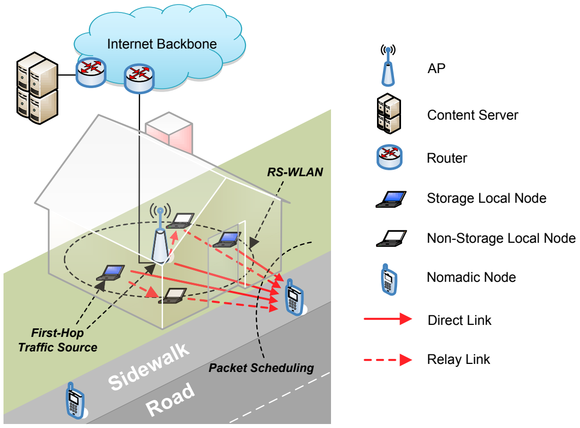

Fig. 1: Network topology and the cooperative data dissemination approach.

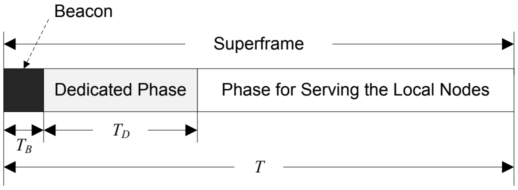

Fig. 2: The superframe structure.

Suppose a data dissemination service (e.g., to distribute a flyer of a supermarket or a video clip of a commercial advertisement) is initiated and destined to a group of nomadic nodes[2]. The data file for dissemination is segmented to B packets with equal size. Without loss of generality, we consider an IEEE 802.11 based RS-WLAN with M transmission rates at the physical layer [7]. The mth rate is selected for wireless transmission if the instantaneous received signal-to-noise ratio (SNR) is within $[\gamma_m^{th}, \gamma_{m+1}^{th})$, where γ_m^{th} $(m = 1, 2, \cdots, M)$ is the SNR threshold of the mth rate such that the wireless transmission can be considered as error free [19]. The Mth rate is selected when the SNR is above γ_M^{th} (i.e., $\gamma_{M+1}^{th} = \infty$), while no wireless transmission is established when the SNR is below γ_1^{th}. The RS-WLAN under consideration is fully

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[2] If there are multiple data dissemination services, they are served according to a first-in-first-out (FIFO) policy.

connected. In order to efficiently utilize the radio resources, we assume that a neighbor discovery mechanism is in place, which admits a nomadic node to the RS-WLAN when a non-zero transmission rate can be supported with a high probability.

B. The Cooperative Data Dissemination Scheme

The cooperative data dissemination scheme consists of two phases, i.e., packet pre-downloading and packet scheduling. Because of the buffer space limitation, the packets of the data dissemination service is pre-downloaded to a group L_S of storage local nodes, while another group L_N ($L_N \cap L_S = \emptyset$) of non-storage local nodes can provide relaying capabilities. Assuming that the packet pre-downloading procedure is completed based on an existing approach[3], we focus on the scheduling of packet transmission to a visiting nomadic node. The buffer space of the AP is sufficiently large, so that the AP can also serve as a storage local node, i.e., $\{AP\} \subset L_S$. In order to achieve a high packet transmission rate, an opportunistic scheduling scheme is applied by considering both direct links from the storage local nodes and the relay links from the non-storage local nodes. Among these links, the one with the highest transmission rate is selected.

C. Local Information Exchange

Each non-storage local node is paired with a storage local node for the highest link transmission rate. The storage local node is the first-hop traffic source for the non-storage local node. As shown in Fig. 1, the two non-storage local nodes select one of the storage local nodes and the AP as their first-hop traffic sources, respectively. For a non-storage local node i ($i \in L_N$), denote the rate index of the first-hop transmission from the traffic source as m_i^1. The local information, in terms of the IDs of the storage/non-storage local nodes (in L_S/L_N) and the source selection results of the non-storage local nodes (with respect to $m_i^1, i \in L_N$), is stored at all local nodes and is transmitted to a visiting nomadic node during its neighbor discovery procedure. With low mobility of local nodes (e.g., laptops or normal users of the RS-WLANs), we assume that the local information does not change during the visiting period of a nomadic node.

When a nomadic node comes into the RS-WLAN, let m denote the index of the direct transmission rate if the source node is a storage local node or the second-hop transmission rate otherwise. Then the packet transmission rate from local node i (including the transmission of the ACK message and cooperative relaying overhead) to the visiting nomadic node is a function of m, denoted by $\zeta_i(m)$ (in packet/s) and given by [13]

$$\zeta_i(m) = \begin{cases} \frac{1}{T_P(m)+T_{ACK}+2T_{SIFS}}, & \text{if } i \in L_S \\ \frac{1}{T_{HR}+T_P(m_i^1)+T_P(m)+T_{ACK}+4T_{SIFS}}, & \\ & \text{if } i \in L_N \end{cases} \tag{1}$$

where $T_P(m)$ is the packet transmission time at the mth transmission rate, while T_{SIFS}, T_{HR}, and T_{ACK} are the time durations of short interframe space (SIFS), helping request message, and ACK message, respectively. The helping request message is sent by a non-storage local node to request a packet from the selected first-hop traffic source. All signalling messages (other than the data packet) are transmitted at the basic rate to ensure the transmission accuracy. Without loss of generality, we denote the case that the wireless transmission cannot be established by $m = 0$ with $\zeta_i(0) = 0$. Since $T_P(m)$ is monotonic with respective to m according to the transmission rate definition, $\zeta_i(m)$ is a bijective function. Therefore, if the packet transmission rate of local node i is denoted by R, we can obtain its rate index m as $m = \zeta_i^{-1}(R)$ based on the local information L_S, L_N, and m_i^1 for $i \in L_N$. For notation clarity, we use the symbols in $\{i, j, n\}$ and $\{m, l, h\}$ to denote the local nodes and the rate indices, respectively, in the following sections.

IV. THE DOUBLE-LOOP RECEIVER-INITIATED MAC SCHEME

To provide high quality data dissemination services, our main objective is to minimize the service delivery delay which is mainly caused by the intermittent network connectivity. For instance, the flyer of a supermarket should be delivered to a pedestrian walking towards the supermarket as soon as possible. From the link layer point of view, this objective can be achieved by increasing the number of data packets (or data volume [4]) delivered to the nomadic node upon its visit to each RS-WLAN, or equivalently, improving the packet transmission rate from the local nodes to the nomadic node during the dedicated phase of each superframe. Towards the goal, a DRMAC scheme is proposed. In this section, we first give an overview of the proposed MAC scheme, and then present the details of its operation.

A. Overview

A function diagram of the DRMAC scheme is shown in Fig. 3, where the contention group (CG) is defined as a group of local nodes which can participate in the wireless channel contention for packet transmission to the nomadic node. The DRMAC scheme consists of two MAC loops. The outer-loop MAC is performed at a low frequency to determine the CG membership for spatial diversity based on the average transmission rate, while the inner-loop MAC is performed at a high frequency to select the transmitter for temporal diversity based on the instantaneous transmission rate.

Several new messages are introduced for our proposed MAC scheme. The dedicated phase assignment message is defined in Subsection III-A. Correspondingly, a receiving request message is introduced as a response to the dedicated assignment message by a nomadic node. Similar to the existing cooperative MAC schemes [13]–[15], we introduce a helping request message which is used by a non-storage local node (or equivalently, a relay node) to request a packet from the first-hop traffic source. Since the first-hop traffic source is already determined based on local information exchange, only

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[3] For instance, on-demand packet pre-downloading exploits the instantaneous mobility information (which is delivered via a cellular network) to pre-download data packets to the RS-WLANs on the movement trajectory of a nomadic node [8], while stochastic packet pre-downloading uses the historic mobility information to pre-download data packets to the RS-WLANs to be visited by a nomadic node with a high probability [11].

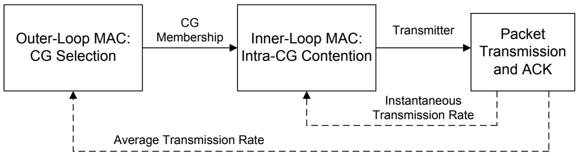

Fig. 3: A function diagram of the DRMAC scheme.

the non-storage local node address is included in the helping request message. The storage local nodes which are selected as the first-hop traffic sources are required to decode all helping request messages for potential first-hop transmissions. By definition, the formats of dedicated phase assignment message, receiving request message, and helping request message are the same as that of the CTS message, with their RA fields being given by the addresses of the nomadic node, the local node sending the dedicated phase assignment message, and the non-storage local node requesting the packet, respectively. The ACK message sent by the nomadic node piggybacks the instantaneous transmission rate index, m_{Tx}, estimated based on the previous transmission and the packet sequence number [7]. Note that the sequence number is used to identify the packet for the next transmission, taking into account that identical packets may be stored at multiple storage local nodes in packet pre-downloading. Similar message format is used by a rate notification message for a local node to indicate its instantaneous transmission rate.

Taking account of the superframe structure as shown in Fig. 2, the critical operation steps of the proposed MAC scheme can be briefly summaries as follows. Here, we consider a single nomadic node which is admitted by the RS-WLAN.

1) A standard beacon mechanism [7] is used with an additional information being broadcasted by the AP to notify the local nodes about the CG membership (which is determined based on the outer-loop MAC for spatial diversity, to be discussed in Subsection IV-B);
2) At the beginning of a dedicated phase, a CG attachment procedure is performed to initiate the inner-loop MAC. The procedure begins with one of the CG member sending a dedicated phase assignment message to notify the nomadic node. After the CG attachment, a CG member with the highest instantaneous transmission rate to the nomadic node is identified as the transmitter node for temporal diversity;
3) A contention-by-invitation procedure is performed for the remaining period of the dedicated phase after the CG attachment. The side information provided by the ACK message is used to reduce the MAC overhead while achieving temporal diversity.

Step 2 and Step 3 constitute the inner-loop MAC, to be discussed in Subsection IV-C.

B. The Outer-Loop MAC

Each local node, $i \in L$, estimates its instantaneous transmission rate (R_i^e) to the nomadic node based on the SNR of each ACK message it received. From the received SNR, if the corresponding rate index is m_i^e, we have $R_i^e = \zeta_i(m_i^e)$. The average transmission rate $\overline{R}_i^e$ can be calculated based on the previous estimates of R_i^e.

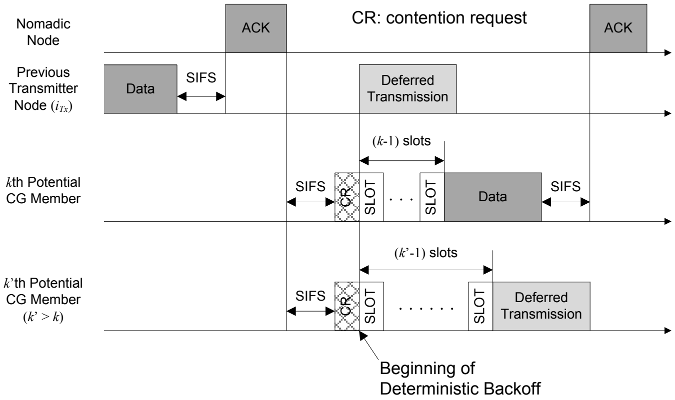

Fig. 4: Signalling in the contention-by-invitation.

From the periodic reports of $\overline{R}_i^e$ by all local nodes, the AP selects a group L_C of local nodes with the highest average transmission rates as the CG members, and then broadcasts a CG notification message (during the beacon period) to inform all local nodes about the IDs of the CG members in a descending order of the average transmission rate. When two or more local nodes have the same average transmission rate to the nomadic node, the ordering among them is in accordance with their IDs. For a clear presentation, we define a bijective function $f : L_C \rightarrow \{1, 2, \cdots, N_c\}$, which maps each CG member ID to its rank in the CG notification message, where $N_C = |L_C|$ is the number of CG members. Obviously, for $i, j \in L_C$, if $f(i) < f(j)$, we have $\overline{R}_i^e \geq \overline{R}_j^e$. For a larger N_C, more local nodes can participate in the channel contention for a higher temporal diversity gain.

C. The Inner-Loop MAC

The two components of the inner-loop MAC are presented as follows.

1) Contention-by-Invitation: If a CG member i ($i \in L_C$) can correctly decode the ACK message from the previous transmission, the value of m_{Tx} can be obtained. Then the rate of the previous transmission can be calculated as $R_{Tx} = \zeta_{i_{Tx}}(m_{Tx})$ based on the receiver address field of the ACK message (corresponding to the ID of the previous transmitter node i_{Tx} [7]). If $R_i^e > R_{Tx}$, node i is invited and will join the channel contention.

To select a transmitter node, a contention-based procedure is used based on the side information provided by the ACK message, as shown in Fig. 4. Each invited CG member sends a short burst, as a contention request, T_{SIFS} after the reception of the ACK message. The previous transmitter node (i_{Tx}) overhears the contention request burst and defers its transmission. Since a CG member cannot obtain the instantaneous transmission rate information of other CG members, we denote L_{CP} as the group of all potential (invited) CG members, which is a subgroup of L_C and is given by

$$L_{CP} = \{j | \max_{1 \leq l \leq M} \{\zeta_j(l)\} > R_{Tx}, j \in L_C \setminus i_{Tx}\}. \quad (2)$$

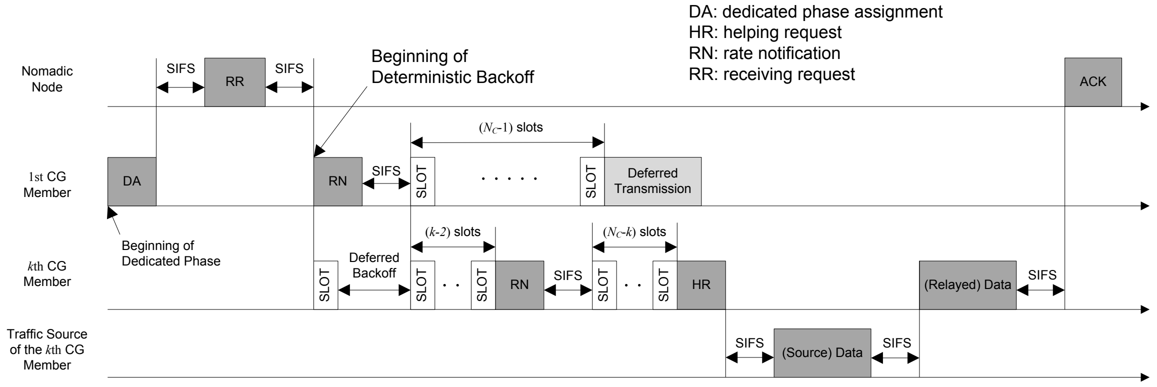

Fig. 5: Signalling in the CG attachment.

Note that a CG member is potentially invited only when it can support a transmission rate higher than R_{Tx}. Then, a deterministic backoff (with the kth potential CG member backoffs for $(k-1)$ slots before its transmission) is established by sorting all potential CG members according to the descending order of the one-step higher transmission rate, which is defined as

$$R'_{i,R_{Tx}} = \min_{l}\{\zeta_i(l) | \zeta_i(l) > R_{Tx}\}, \ i \in L_{CP}. \tag{3}$$

The slot duration in the deterministic backoff is T_S [7]. The rationale behind the one-step higher transmission rate based deterministic backoff is to utilize the time correlation of a wireless channel to reduce contentions. For pedestrian mobility, the value of m_{Tx} given in the ACK message is up-to-date with a high probability and a transmission rate change to a non-adjacent index during a round of packet transmission and ACK is unlikely. Since all nodes in L_{CP} have a lower transmission rate than R_{Tx} during the previous transmission, if node i ($i \in L_{CP}$) is invited to join the channel contention, its current transmission rate equals the one-step higher transmission rate ($R'_{i,R_{Tx}}$) with a high probability. As a result, by ordering the potential CG members based on $R'_{i,R_{Tx}}$, the CG member with the highest instantaneous transmission rate can be selected as the transmitter node with a high probability.

When two or more nodes have the same one-step higher transmission rates, the ordering among them is according to the one indicated in the CG notification message (with respect to the average transmission rate). For illustration clarity, we define a bijective function $g : L_{CP} \rightarrow \{1, 2, \cdots, |L_{CP}|\}$ which maps each CG member ID in L_{CP} to a positive integer representing its rank in the deterministic backoff. Obviously, two cases should be taken into account for any $i, j \in L_{CP}$: 1) If $R'_{i,R_{Tx}} > R'_{j,R_{Tx}}$, then $g(i) < g(j)$; 2) If $R'_{i,R_{Tx}} = R'_{j,R_{Tx}}$, then $g(i) < g(j)$ if and only if $f(i) < f(j)$. Therefore, $g(i)$ is given by

$$\begin{aligned} g(i) = 1 + \sum_{\substack{j\in L_{CP}\\ j\neq i}} & \left[I\left(R'_{i,R_{Tx}} < R'_{j,R_{Tx}}\right) \right. \\ & \left. + I\left(R'_{i,R_{Tx}} = R'_{j,R_{Tx}}\right) I\left(f(i) > f(j)\right)\right], \ i \in L_{CP} \end{aligned} \tag{4}$$

where $I(A)$ is an indication function which equals 1 if A is true and 0 otherwise, while the constant 1 corresponds to each potential CG member itself.

As the parameters L_C, i_{Tx}, and R_{Tx} are known by all the CG members which have correctly decoded the ACK message, the set L_{CP} can be accurately determined. Moreover, for each contending CG member i, the value of $R'_{j,R_{Tx}}$ for $j \in L_{CP} \backslash i$ can also be obtained accurately since the local information is available for all local nodes within the RS-WLAN. Therefore, contention collision is avoided in the deterministic backoff.

After the backoff is finished, the invited storage local node sends a data packet while the invited non-storage local node sends a helping request message. If any transmission is detected during the backoff procedure, an invited CG member defers its transmission since there exists another node with a higher packet transmission rate. If no contention request burst is detected, the previous transmitter node starts a new transmission immediately. In the example shown in Fig. 4, the kth and k'th potential CG members participate in the channel contention. Since $k < k'$, the kth potential CG member is the first node to finish the backoff. Data transmission starts given the kth potential CG member is a storage local node, while the transmission of the k'th potential CG member is deferred.

2) CG Attachment: At the beginning of a new dedicated phase, the value of m_{Tx} indicated in the ACK message becomes out-of-date because of the transmission of local traffic in between the dedicated phases. Therefore, a CG attachment mechanism is needed for the first transmission in the new dedicated phase to identify a CG member with the highest instantaneous transmission rate to the nomadic node, as shown in Fig. 5. Each dedicated phase begins with a dedicated phase assignment message broadcasted by the CG member with the highest average transmission rate. Upon the reception, the nomadic node replies a receiving request message to the CG member. If there is no reply from the nomadic node, the dedicated phase assignment message is retransmitted. Here, we consider the retransmission continues until the end of the dedicated phase. However, a retransmission limit may be set for better utilization of the resources within an RS-WLAN.

Upon the reception of the request message, a deterministic backoff (with the kth CG member backoffs for $(k-1)$ slots before its transmission) is established. The CG members are ordered according to the CG notification message. The first

CG member sends out a rate notification message to notify the other CG members about its instantaneous transmission rate which is estimated based on the receiving request message. When the backoff is finished, another CG member (except the N_Cth CG member) sends a rate notification message only if it has a higher instantaneous transmission rate than the previously indicated ones. The kth CG member starts data (or receiving request message) transmission only if no other transmission is received in the $(N_C - k)$ slots after its rate notification. In the example shown in Fig. 5, the kth CG member is a non-storage local node and is the only CG member which has a higher instantaneous transmission rate than that of the first CG member. The CG attachment procedure also identifies a new transmitter node when wireless transmission cannot be established from any of the CG members, possibly caused by (temporary) deep fading or interference.

By using the receiver-initiated mechanism, no RTS/CTS message exchange is necessary before each packet transmission. Moreover, by exploiting the transmission rate indicated in the ACK message as side information, the transmitter selection (by deterministic backoff) does not need to be performed after each ACK message, which further reduces the signalling overhead.

V. PERFORMANCE ANALYSIS

In this section, the performance of the DRMAC scheme is analyzed. The performance metric under consideration is the number of data packets that can be delivered from an RS-WLAN to a nomadic node following a certain movement trajectory at a given speed. The existing analytical model [14] [21] can evaluate the performance of the transmitter-initiated MAC schemes under a saturated traffic condition, similar to the cooperative data dissemination approach considered here where data packets are already pre-downloaded to the storage local nodes. However, it cannot be applied to model the receiver-initiated mechanism and the time correlation of a wireless channel utilized in the DRMAC scheme. In the following, we present a novel analytical model by using a finite-state Markov chain based channel model to characterize the wireless channel condition [23] [24].

Path loss and Rayleigh fading are considered for a typical WLAN scenario [13]. The cumulative density function (CDF) of the instantaneous SNR, $\Gamma(d)$, for a distance d between the transmitter and receiver is given by $F_{\Gamma(d)}(\gamma) = 1 - e^{-\gamma/\overline{\Gamma}(d)}$ $(0 \leq \gamma < \infty)$, where $\overline{\Gamma}(d)$ is the average SNR at d depending on the path loss effect [22]. Denote $p^t_{i,m,m'}(\tau)$ as the transition probability of the wireless transmission rate index of local node i from m to m' during τ. Based on the finite-state Markov chain channel model, we have

$$p^t_{i,m,m+1}(\tau) = \frac{\tau N_{m+1}}{P_{i,m}}, \quad m = 0, \cdots, M-1 \tag{5}$$

$$p^t_{i,m,m-1}(\tau) = \frac{\tau N_m}{P_{i,m}}, \qquad m = 1, \cdots, M \tag{6}$$

where $N_m = f_{\max} \exp\left(-\frac{\gamma^{th}_m}{\overline{\Gamma}(d_i)}\right)\sqrt{2\pi \frac{\gamma^{th}_m}{\overline{\Gamma}(d_i)}}$ is the cross-rate of rate index m, and $f_{\max}$ is the maximum Doppler frequency which depends on the movement speed of the nomadic node. For the analysis of DRMAC scheme, τ corresponds to the duration of one packet transmission. Therefore, we have

$$p^t_{i,m,m}(\tau) = 1 - p^t_{i,m,m+1}(\tau) - p^t_{i,m,m-1}(\tau). \tag{7}$$

The probability of any other state transition equals zero. For analytical tractability, the following assumptions are made:

1) The RS-WLAN covers a circular region with radius r and a neighbor discovery mechanism is in place which admits a nomadic node when it comes within a distance r_V from the AP. The value of r_V can be greater than the transmission range the AP because of the extended coverage by the local nodes;
2) The nomadic node visits the RS-WLAN along a straight line (e.g., a sidewalk as shown in Fig. 1). The local nodes are stationary during the visiting period, while the speed v of the visiting nomadic node is constant. The movement speed of the nomadic node (e.g., a pedestrian) is relatively low such that $p^t_{i,m,m+1}(\tau)$ and $p^t_{i,m,m-1}(\tau)$ are much smaller than $p^t_{i,m,m}(\tau)$;
3) The wireless channels among different local nodes are independent;
4) The average transmission rate $(\overline{R}^e_i)$ can be accurately estimated by the outer-loop MAC, while the CG member with the highest instantaneous transmission rate can always be selected as the transmitter node by the inner-loop MAC.

The performance analysis consists of four parts. In Subsection V-A, we derive an explicit expression for the average number of delivered packets over the visiting trajectory of a nomadic node, while the components in the expression are evaluated in the following subsections. In Subsection V-B, the average packet transmission rate is calculated for a specific location of a nomadic node. In Subsection V-C and Subsection V-D, the signalling overhead in terms of the durations of contention-by-invitation and CG attachment is evaluated, respectively.

A. Average Number of Delivered Packets over Visiting Trajectory

Suppose the AP is located at the pole, and the position of local node i $(i \in L)$ is (ρ_i, θ_i). In order to represent the movement of a nomadic node along the roadside (a straight line), we define the visiting trajectory based on two parameters, i.e., δ and β, which are the angles related to the slope of the visiting trajectory and the shortest distance between the AP and the visiting trajectory, respectively. An illustration of the visiting trajectory is shown in Fig. 6 for the network topology in Fig. 1. If the nomadic node enters the neighbor discovery range of the RS-WLAN at time 0, then at time t, the positions of the nomadic node for the two opposite moving directions are given by[4]

$$\rho(t) = \sqrt{v^2t^2 + r_V^2 - 2vtr_V \cos\beta} \tag{8}$$

$$\theta(t) = \pm \arccos \frac{r_V - vt\cos\beta}{\rho(t)} + \delta \mp (\frac{\pi}{2} - \beta). \tag{9}$$

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[4] An extension of our analytical model to an arbitrary visiting trajectory is straightforward by using a different set of functions $\rho(t)$ and $\theta(t)$.

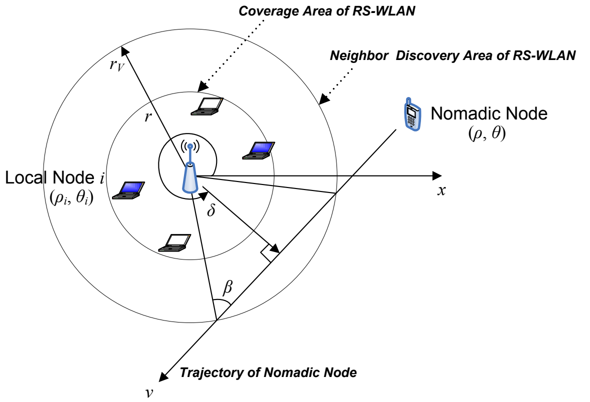

Fig. 6: The visiting trajectory of a nomadic node to an RS-WLAN.

Based on the DRMAC scheme, the overhead of CG attachment should be calculated at the beginning of each dedicated phase, while the overhead of contention-by-invitation should be evaluated before each packet transmission. For analytical tractability, we consider both overhead at the beginning of each superframe since the average channel condition does not change significantly within a superframe for pedestrian nomadic nodes. With the kth superframe ($k \geq 1$) starting at time t_k ($t_k = (k-1)T$), we denote the durations of contention-by-invitation and CG attachment as $\overline{T}_{CI}(t_k)$ and $\overline{T}_{AT}(t_k)$, respectively. Then the average number of packets delivered to the nomadic node during superframe k is given by

$$B_k^s = \frac{T_D - \overline{T}_{AT}(t_k)}{\left[1/\overline{R}_V(t_k)\right] + \overline{T}_{CI}(t_k)} \tag{10}$$

where $\overline{R}_V(t_k)$ is the average packet transmission rate without signalling overhead, given location $(\rho(t_k), \theta(t_k))$ of the nomadic node. For a sufficiently large B value such that the data dissemination service cannot be completely delivered within a single RS-WLAN, the average number of delivered packets over the visiting trajectory is given by $B_V = \sum_{k=1}^{N_F} B_k^s$, where $N_F = \left\lfloor \frac{2r_V \cos\beta}{vT} \right\rfloor$ is the number of superframes during the visiting period of the nomadic node. Note that the same average number of delivered packets is obtained for the two opposite moving directions as given in (9).

In order to obtain B_V, the values of $\overline{R}_V(t_k)$, $\overline{T}_{CI}(t_k)$, and $\overline{T}_{AT}(t_k)$ should be calculated for all $k \in \{1, 2, \cdots, N_F\}$, to be discussed in the following subsections. Without loss of generality, consider the beginning time of a tagged superframe with the position of the nomadic node given by (ρ, θ).

B. Average Packet Transmission Rate

We first derive the average packet transmission rate of each local node. The probability that the mth ($0 \leq m \leq M$) rate is chosen by the (one-hop) wireless transmission from local node i to the nomadic node is given by

$$P_{i,m} = \begin{cases} F_{\Gamma(d_i)}(\gamma_1^{th}), & \text{if } m = 0 \\ 1 - F_{\Gamma(d_i)}(\gamma_M^{th}), & \text{if } m = M \\ F_{\Gamma(d_i)}(\gamma_{m+1}^{th}) - F_{\Gamma(d_i)}(\gamma_m^{th}), & \text{otherwise} \end{cases} \tag{11}$$

where $d_i = \sqrt{\rho^2 + \rho_i^2 - 2\rho\rho_i \cos(\theta - \theta_i)}$ is the distance between the nomadic node and local node i. Denoting the instantaneous transmission rate from local node i to the nomadic node as R_i, the average transmission rate can be calculated as

$$\overline{R}_i = \sum_{m=0}^{M} \zeta_i(m) P\left(R_i = \zeta_i(m)\right) = \sum_{m=0}^{M} \zeta_i(m) P_{i,m}. \tag{12}$$

Based on the estimated average transmission rate ($\overline{R}_i^e = \overline{R}_i$), the CG memberships ($L_C$) can be determined for spatial diversity. According to assumption 4), we have $R_V = \max_{j \in L_C} \{R_j\}$ with its CDF given by

$$\begin{aligned} F_{R_V}(a) &= P\left(\max_{j \in L_C} \{R_j\} \leq a\right) \\ &= \prod_{j \in L_C} P\left(R_j \leq a\right) \\ &= \prod_{j \in L_C} \left[\sum_{m=1}^{M} P_{j,m} I\left(\zeta_j(m) \leq a\right)\right] \end{aligned} \tag{13}$$

where the second equality holds as the channels are independent. From (11) and (13), the probability mass function (PMF) of R_V and the average packet transmission rate $\overline{R}_V$ can be obtained numerically.

C. Duration of Contention-by-Invitation

In addition to a constant T_{CR}, the duration of contention-by-invitation mainly consists of the duration of deterministic backoff, which depends on the the current transmitter node and the group of CG members in the channel contention. The probability that CG member n is the transmitter node and the transmission rate index is m ($m \geq 1$) can be derived as

$$\begin{aligned} P_{n,m}^s = P_{n,m} \prod_{j \in L_C \setminus n} \sum_{l=0}^{M} &\left[P_{j,l} I\left(\zeta_j(l) < \zeta_n(m)\right)\right. \\ &\left. + P_{j,l} I\left(\zeta_j(l) = \zeta_n(m)\right) I\left(f(j) > f(n)\right)\right] \end{aligned} \tag{14}$$

where j denotes a CG member other than n and l the transmission rate index. The first and second terms in the summation of (14) are based on the temporal diversity and correspond to the two cases in the definition of $g(\cdot)$ in (4), respectively.

Given that the current transmitter node n is transmitting at the rate indexed m, the (conditional) probability for the rate index of a potential CG member i to be l is given by

$$\begin{aligned} P_{i,l|n,m} = \frac{P_{i,l}}{\sum_{l=0}^{\zeta_i^{-1}(R'_{i,\zeta_n(m)})-1} P_{i,l}}, \; i \in L_{CP}, \\ l \in \{0, 1, \cdots, \zeta_i^{-1}(R'_{i,\zeta_n(m)}) - 1\} \end{aligned} \tag{15}$$

where L_{CP} can be calculated based on (2) by replacing i_{Tx} and R_{Tx} with n and $\zeta_n(m)$, respectively. In (15), we have $0 \leq l \leq \zeta_i^{-1}(R'_{i,\zeta_n(m)}) - 1$ since the rate of CG member i cannot exceed that of the current transmitter node. Given the current transmitter node n and its rate index m, the probability for a potential CG member $i \in L_{CP}$ to participate in the channel contention is given by

$$\begin{aligned} P^c_{i|n,m} = & \sum_{l=0}^{\zeta_i^{-1}(R'_{i,\zeta_n(m)})-1} \sum_{h=\zeta_i^{-1}(R'_{i,\zeta_n(m)})}^{M} [P_{i,l|n,m} \\ & \cdot p^t_{i,l,h}(1/\zeta_n(m))] \\ = & P_{i,[\zeta_i^{-1}(R'_{i,\zeta_n(m)})-1]|n,m} \\ & \cdot p^t_{i,[\zeta_i^{-1}(R'_{i,\zeta_n(m)})-1],\zeta_i^{-1}(R'_{i,\zeta_n(m)})}(1/\zeta_n(m)) \end{aligned} \tag{16}$$

where $1/\zeta_n(m)$ corresponds to the duration of one packet transmission from the current transmitter node. Based on assumption 2), the probability for two or more CG members to change their transmission rate (and join the channel contention) during the time of a packet transmission is negligible. Therefore, given the current transmitter node n and its rate index m, the probability for CG member i to be the next transmitter is

$$P^x_{i|n,m} = P^c_{i|n,m} \prod_{\substack{j \in L_{CP} \\ j \neq i}} (1 - P^c_{j|n,m}). \tag{17}$$

Then, the duration (in s) of contention-by-invitation before each packet transmission can be calculated as

$$\overline{T}_{CI} = T_{CR} + \sum_{n \in L_C} \sum_{m=1}^{M} P^s_{n,m} \cdot \sum_{i \in L_{CP}} [(g(i)-1)\,T_S]\, P^x_{i|n,m} \tag{18}$$

where $g(i)$ is given by (4), and the second term of the product represents the conditional expectation of the deterministic backoff duration, given the current transmitter node n and its rate index m.

D. Duration of CG Attachment

Since retransmission mechanism is considered in CG attachment, its duration can be calculated iteratively based on the success/failure of transmitting each dedicated phase assignment message. At the beginning of a dedicated phase, denote $\vec{\mathbf{m}} = \{\mathbf{m}_1, \cdots, \mathbf{m}_{N_c}\}$ as a vector of the rate indices of all CG members, where $\mathbf{m}_i$ is a random variable representing the rate index of the ith CG member according to the CG notification message. Conditioned on the success/failure of the first transmission of the dedicated phase assignment message, the average duration of CG attachment is given by

$$\begin{aligned} \overline{T}_{AT} &= \overline{T}^{at}_{\vec{\mathbf{m}}|\mathbf{m}_1 \neq 0} P(\mathbf{m}_1 \neq 0) + \overline{T}^{at}_{\vec{\mathbf{m}}|\mathbf{m}_1 = 0} P(\mathbf{m}_1 = 0) \\ &= \overline{T}^{at}_{\vec{\mathbf{m}}|\mathbf{m}_1 \neq 0} \sum_{m=1}^{M} P_{f^{-1}(1),m} + \overline{T}^{at}_{\vec{\mathbf{m}}|\mathbf{m}_1 = 0} P_{f^{-1}(1),0} \end{aligned} \tag{19}$$

where the inverse function $f^{-1}(\cdot)$ is used to map the rank in CG attachment to the ID of each CG member. In (19), $T^{at}_{\vec{\mathbf{m}}|\mathbf{m}_1 \neq 0}$ and $T^{at}_{\vec{\mathbf{m}}|\mathbf{m}_1 = 0}$ are the average durations of CG attachment given the first transmission of the dedicated phase assignment message is successful and fails, respectively. The expressions of $T^{at}_{\vec{\mathbf{m}}|\mathbf{m}_1 \neq 0}$ and $T^{at}_{\vec{\mathbf{m}}|\mathbf{m}_1 = 0}$ are given in Appendix. When no wireless transmission can be established from any of the CG members, the CG attachment procedure is also performed, which happens with a low probability (according to the neighbor discovery mechanism) and is neglected in (19).

VI. NUMERICAL RESULTS

Our proposed MAC scheme can be applied to different WLAN standards. Here, the IEEE 802.11a standard with $M = 8$ is considered as an example [7]. By definition, the sizes of the dedicated phase assignment message, receiving request message, and helping request message are equal to the size of the CTS message, while the size of the rate notification message is equal to the size of the ACK message which piggybacks the instantaneous transmission rate index (4 bits) and the packet sequence number (12 bits) [7]. For the wireless channel condition, the pathloss exponent is 3 for a typical WLAN environment [13], and the Rayleigh fading is simulated based on the widely used Jake's model to reflect the time correlation [25]. The SNR threshold of each transmission rate (γ^{th}_m, $m = 1, \cdots, M$) is given in [19]. The RS-WLAN is fully connected with radius $r = 25$ m and neighbor discovery range $r_V = 50$ m. We consider a data dissemination service with a sufficiently large K value and let the size of each packet be 1000 bytes. The durations of the superframe and dedicated phase are $T = 150$ ms and $T_D = 50$ ms, respectively. Using a first-order autoregressive moving average (ARMA) model, the estimated average transmission rate from local node i to the nomadic node is updated by $\overline{R}^{e*}_i = (1-\xi)\overline{R}^e_i + \xi R^e_i$, where $\overline{R}^e_i$ and $\overline{R}^{e*}_i$ are the estimated average transmission rate before and after the update, respectively, and ξ is an aging factor to keep a partial memory of the historic estimations and is set to $\xi = 0.1$. To simplify simulations with respect to the stationary local nodes, we investigate a ring topology [26] which achieves approximately uniformly distributed node locations for different numbers of local nodes ($|L|$). The local nodes are evenly distributed on two circles with radius $\frac{r}{2}$ and $\frac{3r}{4}$, respectively. The two circles include the same number of nodes, and half of them can provide packet caching capabilities. Consider two visiting trajectories of the nomadic node with parameter sets $(\frac{\pi}{8}, 0)$ and $(\frac{\pi}{16}, \frac{3\pi}{4})$, and corresponding shortest distances between the AP and the nomadic node 19.13 m and 9.75 m, respectively. To incorporate the visiting trajectories of the nomadic node and the physical layer channel model (i.e., the Jake's model) into the MAC simulation, we develop our own event-driven simulator based on MATLAB. A similar simulator is used in previous research [15] without taking account of the trajectories and the time correlation of a wireless channel.

For performance comparison, we consider five MAC schemes, i.e., IEEE 802.11 MAC [7], direct transmission, transmitter-initiated cooperative MAC [15], receiver-initiated MAC [17], and the proposed DRMAC. For the IEEE 802.11 MAC scheme, all storage local nodes participate in the channel contention to deliver packets to the visiting nomadic node. The direct transmission scheme can be considered as a special case of the IEEE 802.11 MAC scheme, where a data packet is transmitted from the AP to the nomadic node after the RTS/CTS exchange. For fair comparison, we modify the transmitter-initiated cooperative MAC scheme by limiting the number of contending local nodes after the RTS/CTS exchange to N_C and ordering them based on the inner-loop MAC of the proposed scheme. In this manner, the channel contention can be reduced among multiple direct/relay links but still exists during the RTS message transmissions. Although the receiver-initiated MAC scheme (without multiple storage local nodes as traffic sources) is not applicable for RS-WLANs with pre-downloaded packets, we modify the scheme by always inviting the storage local node with the highest average transmission rate. Finally, for the newly proposed DRMAC scheme, the value of N_C is chosen from the set $\{1, 2, 3, 4\}$.

A. Performance Evaluation of the DRMAC Scheme

The effect of N_C on the performance of the proposed MAC scheme is shown in Fig. 7, without the signalling overhead. The nomadic node has a visiting trajectory with parameter set $(\frac{\pi}{8}, 0)$ at a speed of 1.5 m/s. We can see that the analytical results match well with the simulation results. As N_C increases, the average number of delivered packets increases, with a higher temporal diversity gain. However, the increment dwindles with a further increase of N_C because the temporal diversity gain becomes saturated. Moreover, for a given N_C, the average number of delivered packets increases with the number of local nodes, which offers more spatial diversity.

Taking account of the signalling overhead, the effect of N_C on the performance of the proposed MAC scheme is shown in Fig. 8, with accurate estimation of the average transmission rate. Although the signalling overhead slightly reduces the average number of delivered packets, the basic trends of the curves are the same as those in Fig. 7, thanks to both spatial and temporal diversity gains. With pedestrian nomadic nodes and the IEEE 802.11a based physical layer, the channel coherent time is in the order of tens of milliseconds, while the transmission duration of an ACK message is in the order of tens of microseconds. Therefore, the instantaneous transmission rate given in the ACK message is up-to-date with a high probability [23]. This observation confirms the utilization of the ACK message as a receiver-initiated contention invitation, which reduces the signalling overhead. Moreover, the analytical and simulation results agree with each other well, with a slight difference caused by the Markov chain based channel model and the one-step higher transmission rate based approximation.

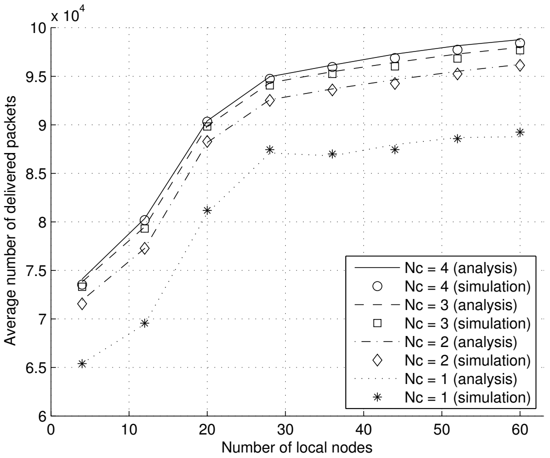

Fig. 7: The average number of delivered packets using the proposed MAC scheme, without signalling overhead.

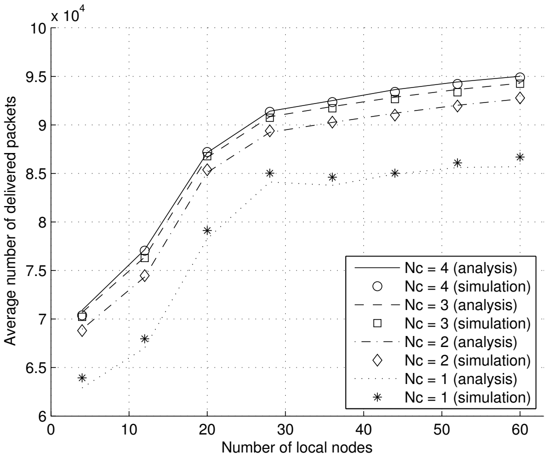

Fig. 8: The average number of delivered packets using the proposed MAC scheme, taking account of the signalling overhead.

B. Performance Comparison among Different MAC Schemes

A performance comparison among all the five MAC schemes is shown in Fig. 9, using the first-order ARMA model based estimation of the average transmission rate. For the DRMAC scheme, we present the results for $N_C = 1$ and $N_C = 3$, respectively. The performance of the proposed MAC scheme slightly degrades as compared with that in Fig. 8, because of the estimation error of the average transmission rate, which results in an occasionally inaccurate selection of CG members. The performance of the direct transmission scheme is low in the absence of spatial and temporal diversity. The IEEE 802.11 MAC scheme performs poorly with packet pre-downloading, since the inherent random backoff before the RTS transmission is not based on the wireless channel condition of the storage local nodes. As the local nodes are scattered within the coverage area of the RS-WLAN, the storage local node with a poor channel condition may be selected as a transmitter, which degrades the packet delivery performance. Moreover, the number of packets delivered by the IEEE 802.11 MAC scheme decreases as the number of local nodes increases, because of a more intensive channel contention among the storage local nodes. By exploiting the diversity gain, the transmitter-initiated cooperative MAC scheme (with $N_C = 4$) can increase the average number of delivered packets. However, the performance improvement is not significant because of the RTS/CTS message exchange, and random backoff which does not adapt to the wireless channel condition. The average number of delivered packets first increases and then decreases with the number of local nodes, demonstrating a tradeoff between the spatial/temporal diversity gain and the intensity of the channel contention

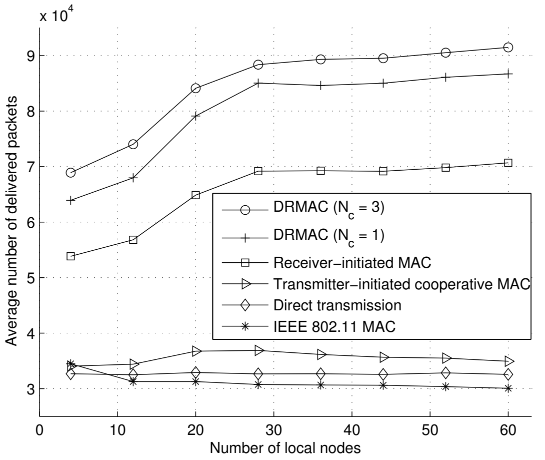

Fig. 9: A comparison among different MAC schemes.

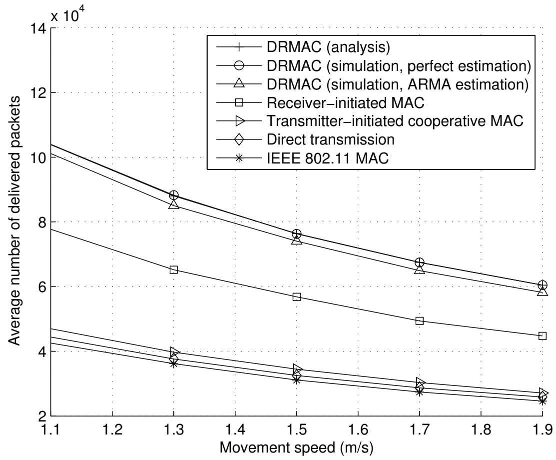

Fig. 10: The effect of movement speed on different MAC schemes, 12 local nodes, $(\beta, \delta) = (\frac{\pi}{8}, 0)$.

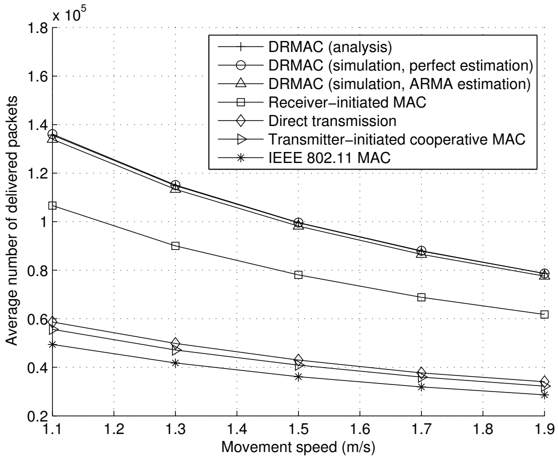

Fig. 11: The effect of movement speed on different MAC schemes, 20 local nodes, $(\beta, \delta) = (\frac{\pi}{16}, \frac{3\pi}{4})$.

among multiple storage local nodes. The receiver-initiated MAC scheme can significantly increase the average number of delivered packets without RTS messages. When the number of local nodes increases, the average number of delivered packets increases with a higher spatial diversity gain. However, the performance of the receiver-initiated MAC scheme is inferior to the DRMAC scheme with $N_C = 1$ due to the overhead of CTS (or ready-to-receive (RTR) [17]) message transmission. By exploiting both spatial and temporal diversity gain and reducing the signalling overhead, the DRMAC scheme achieves the best performance among all the MAC schemes.

To study the effect of the movement speed and trajectory parameters of the visiting nomadic node, Figs. 10-11 show the average number of delivered packets versus movement speed for the different numbers of local nodes and visiting trajectory parameters. As the movement speed increases, the average number of delivered packets decreases with a shorter visiting period. However, the decrement is not linear since the movement speed also affects the channel fading statistics in terms of the maximum Doppler frequency. The relative performance among different schemes is the same as that in Fig. 9. More packets can be delivered by all the MAC schemes in Fig. 11, which has a longer visiting duration with the visiting trajectory closer to the AP. The transmitter-initiated cooperative MAC scheme delivers slightly less packets to the nomadic node as compared with the direct transmission scheme since the channel contention is higher for an RS-WLAN with 20 local nodes and a visiting trajectory closer to the AP. In both Fig. 10 and Fig. 11, the analytical results of the DRMAC scheme match well with the simulation results with accurate average transmission rate information, and slightly better than the simulation results based on the first-order ARMA model for channel rate estimation.

VII. CONCLUSIONS AND FURTHER WORK

In this paper, we consider a cooperative data dissemination approach for DTN applications via RS-WLANs. A DRMAC scheme is proposed to improve the packet delivery rate from an RS-WLAN to a pedestrian nomadic node. The proposed MAC scheme exploits both spatial and temporal diversity gain while reducing the signalling overhead. An analytical model is derived for the proposed MAC scheme by using a finite-state Markov chain to characterize the time correlation of a wireless channel. Analytical and simulation results indicate that our proposed MAC scheme can achieve the best performance, in terms of the average number of delivered packets from an RS-WLAN to a nomadic node, as compared with the existing IEEE 802.11 MAC, transmitter-initiated cooperative MAC, and receiver-initiated MAC schemes.

This work focuses on pedestrian nomadic nodes. An extension to vehicular nomadic nodes is very interesting but challenging, in which the wireless channel is highly dynamic such that it is difficult to obtain the transmission rate information for temporal diversity and use the time correlation of a wireless channel for signalling overhead reduction. Moreover, joint design for packet pre-downloading to the storage local nodes and medium access control based on mobility statistics [8] [11] needs further investigation.

APPENDIX: DERIVATION OF $\overline{T}^{at}_{\vec{\mathbf{m}}|\mathbf{m}_1\neq 0}$ AND $\overline{T}^{at}_{\vec{\mathbf{m}}|\mathbf{m}_1=0}$

We first derive the duration of CG attachment with respect to a deterministic set $\{m_1,\cdots,m_{N_c}\}$ of rate indices, given $m_1\neq 0$. Define an indication function $A_{\{m_1,\cdots,m_{N_c}\},k}$ which equals to 1 if the kth CG member has a higher transmission rate than all other CG members with lower ranks and 0 otherwise, given by

$$\begin{aligned} A_{\{m_1,\cdots,m_{N_c}\},k} = I(&\zeta_{f^{-1}(k)}(m_k) > \zeta_{f^{-1}(h)}(m_h),\\ &\forall\ 1\le h<k),\quad 2\le k\le N_c. \end{aligned} \tag{20}$$

In the DRMAC scheme, the kth CG member ($2\le k\le N_c-1$) sends a rate notification message (with duration T_{RN}) only when $A_{\{m_1,\cdots,m_{N_c}\},k}=1$; Otherwise, it waits for an idle slot with duration T_S. Therefore, the duration of CG attachment with respect to the deterministic set of rate indices is given by

$$\begin{aligned} T^{at}_{\{m_1,\cdots,m_{N_c}\}|m_1\neq 0} &= T_{DA}+T_{RR}+T_{RN}+3T_{SIFS}\\ &+\sum_{k=2}^{N_c-1}\left[(T_{RN}+T_{SIFS})\,A_{\{m_1,\cdots,m_{N_c}\},k}\right.\\ &\qquad\left.+T_S\left(1-A_{\{m_1,\cdots,m_{N_c}\},k}\right)\right]\\ &+T_S\left(1-A_{\{m_1,\cdots,m_{N_c}\},N_c}\right). \end{aligned} \tag{21}$$

Taking account of the randomness in transmission rates and independent channels, the value of $\overline{T}^{at}_{\vec{\mathbf{m}}|\mathbf{m}_1\neq 0}$ is given by

$$\begin{aligned} \overline{T}^{at}_{\vec{\mathbf{m}}|\mathbf{m}_1\neq 0} &= \sum_{\substack{1\le m_1\le M\\ 0\le m_2,\cdots,m_{N_c}\le M}} [T^{at}_{\{m_1,\cdots,m_{N_c}\}|m_1\neq 0}\\ &\qquad\cdot P(\vec{\mathbf{m}}=\{m_1,\cdots,m_{N_c}\}|\mathbf{m}_1\neq 0)]\\ &=\sum_{m_1=1}^{M}\sum_{m_2=0}^{M}\cdots\sum_{m_{N_c}=0}^{M}[T^{at}_{\{m_1,\cdots,m_{N_c}\}|m_1\neq 0}\\ &\qquad\cdot\prod_{n=1}^{N_c}P(\mathbf{m}_n=m_n|\mathbf{m}_1\neq 0)]\\ &=\sum_{m_1=1}^{M}\sum_{m_2=0}^{M}\cdots\sum_{m_{N_c}=0}^{M}[T^{at}_{\{m_1,\cdots,m_{N_c}\}|m_1\neq 0}\\ &\qquad\cdot P(\mathbf{m}_1=m_1|\mathbf{m}_1\neq 0)\prod_{n=2}^{N_c}P(\mathbf{m}_n=m_n)]\\ &=\sum_{m_1=1}^{M}\sum_{m_2=0}^{M}\cdots\sum_{m_{N_c}=0}^{M}[T^{at}_{\{m_1,\cdots,m_{N_c}\}|m_1\neq 0}\\ &\qquad\cdot\frac{P_{f^{-1}(1),m_1}}{\sum_{m=1}^{M}P_{f^{-1}(1),m}}\prod_{n=2}^{N_c}P_{f^{-1}(n),m_n}]. \end{aligned} \tag{22}$$

Define $\vec{\mathbf{m}}'=\left\{\mathbf{m}'_1,\cdots,\mathbf{m}'_{N_c}\right\}$ as the rate indices of CG members during the second transmission of the dedicated phase assignment message. Then, $\overline{T}^{at}_{\vec{\mathbf{m}}|\mathbf{m}_1=0}$ is given by

$$\begin{aligned} \overline{T}^{at}_{\vec{\mathbf{m}}|\mathbf{m}_1=0} &= T_{DA}+T_{SIFS}\\ &+\overline{T}^{at}_{\vec{\mathbf{m}}'|\mathbf{m}_1=0,\mathbf{m}'_1\neq 0}\cdot p^t_{f^{-1}(1),0,1}\left(T_{DA}+T_{SIFS}\right)\\ &+\overline{T}^{at}_{\vec{\mathbf{m}}'|\mathbf{m}_1=0,\mathbf{m}'_1=0}\cdot p^t_{f^{-1}(1),0,0}\left(T_{DA}+T_{SIFS}\right) \end{aligned} \tag{23}$$

where $\overline{T}^{at}_{\vec{\mathbf{m}}'|\mathbf{m}_1=0,\mathbf{m}'_1\neq 0}$ is the average duration of CG attachment after the first attempt (with duration $T_{DA}+T_{SIFS}$), given that the first and second transmissions of the dedicated phase assignment messages fail and are successful, respectively. Similar to (22), we have

$$\begin{aligned} \overline{T}^{at}_{\vec{\mathbf{m}}'|\mathbf{m}_1=0,\mathbf{m}'_1\neq 0} &= \sum_{m'_1=1}^{M}\sum_{m'_2=0}^{M}\cdots\sum_{m'_{N_c}=0}^{M}[T^{at}_{\{m'_1,\cdots,m'_{N_c}\}|m'_1\neq 0}\\ &\cdot\frac{P_{f^{-1}(1),m'_1|m_1=0}}{\sum_{m=1}^{M}P_{f^{-1}(1),m|m_1=0}}\prod_{n=2}^{N_c}P_{f^{-1}(n),m'_n}] \end{aligned} \tag{24}$$

where the value of $T^{at}_{\{m'_1,\cdots,m'_{N_c}\}|m'_1\neq 0}$ is given by (21) with $\{m_1,\cdots,m_{N_c}\}$ and $m_1\neq 0$ being replaced by $\{m'_1,\cdots,m'_{N_c}\}$ and $m'_1\neq 0$, respectively. In (24), $P_{f^{-1}(1),m|m_1=0}$ is the conditional PMF of the rate index of the second transmission of the dedicated phase assignment message, given that the first transmission fails. By considering the transition probabilities of the transmission rate indices in the finite-state Markov chain, we have

$$P_{f^{-1}(1),m|m_1=0}=\begin{cases} p^t_{f^{-1}(1),0,m}\left(T_{DA}+T_{SIFS}\right),\\ \quad\text{if } m=0 \text{ or } m=1\\ 0,\ \text{otherwise} \end{cases} \tag{25}$$

where the values of $p^t_{f^{-1}(1),0,0}(\cdot)$ and $p^t_{f^{-1}(1),0,1}(\cdot)$ are given by (5) and (7), respectively. Then, (24) can be simplified to

$$\begin{aligned} \overline{T}^{at}_{\vec{\mathbf{m}}'|\mathbf{m}_1=0,\mathbf{m}'_1\neq 0} &= \sum_{m'_2=0}^{M}\sum_{m'_3=0}^{M}\cdots\sum_{m'_{N_c}=0}^{M}[T^{at}_{\{1,m'_2,\cdots,m'_{N_c}\}|m'_1\neq 0}\\ &\qquad\cdot\prod_{n=2}^{N_c}P_{f^{-1}(n),m'_n}]. \end{aligned} \tag{26}$$

In (23), $\overline{T}^{at}_{\vec{\mathbf{m}}'|\mathbf{m}_1=0,\mathbf{m}'_1=0}$ is the average duration of CG attachment after the first attempt (with duration $T_{DA}+T_{SIFS}$), given that both first and second transmissions of the dedicated phase assignment messages fail. Define $\vec{\mathbf{m}}''=\left\{\mathbf{m}''_1,\cdots,\mathbf{m}''_{N_c}\right\}$ as the rate indices of CG members during the third transmission of the dedicated phase assignment message. We have

$$\begin{aligned} \overline{T}^{at}_{\vec{\mathbf{m}}'|\mathbf{m}_1=0,\mathbf{m}'_1=0} &= T_{DA}+T_{SIFS}+[\overline{T}^{at}_{\vec{\mathbf{m}}''|\mathbf{m}_1=0,\mathbf{m}'_1=0,\mathbf{m}''_1\neq 0}\\ &\qquad\cdot p^t_{f^{-1}(1),0,1}\left(T_{DA}+T_{SIFS}\right)]\\ &\quad+[\overline{T}^{at}_{\vec{\mathbf{m}}''|\mathbf{m}_1=0,\mathbf{m}'_1=0,\mathbf{m}''_1=0}\\ &\qquad\cdot p^t_{f^{-1}(1),0,0}\left(T_{DA}+T_{SIFS}\right)]\\ &= T_{DA}+T_{SIFS}+[\overline{T}^{at}_{\vec{\mathbf{m}}'|\mathbf{m}_1=0,\mathbf{m}'_1\neq 0}\\ &\qquad\cdot p^t_{f^{-1}(1),0,1}\left(T_{DA}+T_{SIFS}\right)]\\ &\quad+[\overline{T}^{at}_{\vec{\mathbf{m}}'|\mathbf{m}_1=0,\mathbf{m}'_1=0}\\ &\qquad\cdot p^t_{f^{-1}(1),0,0}\left(T_{DA}+T_{SIFS}\right)] \end{aligned} \tag{27}$$

where the second equality of (27) is due to the one-step memory of finite-state Markov chain. By rearranging (27), we have

$$\begin{aligned} \overline{T}^{at}_{\vec{\mathbf{m}}'|\mathbf{m}_1=0,\mathbf{m}'_1=0} &= \frac{T_{DA}+T_{SIFS}}{p^t_{f^{-1}(1),0,1}\left(T_{DA}+T_{SIFS}\right)}\\ &\qquad+\overline{T}^{at}_{\vec{\mathbf{m}}'|\mathbf{m}_1=0,\mathbf{m}'_1\neq 0}. \end{aligned} \tag{28}$$

Substituting (28) into (23), we get

$$\begin{aligned}\overline{T}^{at}_{\vec{\mathbf{m}}|\mathbf{m}_1=0} &= T_{DA} + T_{SIFS} + \overline{T}^{at}_{\vec{\mathbf{m}}'|\mathbf{m}_1=0,\mathbf{m}'_1\neq 0} \\ &\quad \cdot p^t_{f^{-1}(1),0,1}\left(T_{DA}+T_{SIFS}\right) \\ &\quad + [\frac{T_{DA}+T_{SIFS}}{p^t_{f^{-1}(1),0,1}\left(T_{DA}+T_{SIFS}\right)} + \overline{T}^{at}_{\vec{\mathbf{m}}'|\mathbf{m}_1=0,\mathbf{m}'_1\neq 0}] \\ &\quad \cdot p^t_{f^{-1}(1),0,0}\left(T_{DA}+T_{SIFS}\right) \\ &= \frac{T_{DA}+T_{SIFS}}{p^t_{f^{-1}(1),0,1}\left(T_{DA}+T_{SIFS}\right)} + \overline{T}^{at}_{\vec{\mathbf{m}}'|\mathbf{m}_1=0,\mathbf{m}'_1\neq 0}\end{aligned} \tag{29}$$

where $\overline{T}^{at}_{\vec{\mathbf{m}}'|\mathbf{m}_1=0,\mathbf{m}'_1\neq 0}$ is given by (24).

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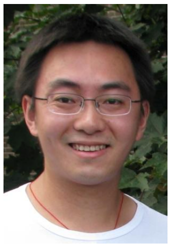

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