Cooperative Data Dissemination via Roadside WLANs

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Abstract

Data dissemination services embrace a wide variety of telematic applications where data packets are generated at a remote server in the Internet and destined to a group of nomadic users such as vehicle passengers and pedestrians. The quality of a data dissemination service is highly dependent on the availability of network infrastructures in terms of the access points (APs). In this article, we investigate the utilization of roadside wireless local area networks (RS-WLANs) as a network infrastructure for data dissemination. A two-level cooperative data dissemination approach is presented. With the network-level cooperation, the resources in the RS-WLANs are used to facilitate the data dissemination services for the nomadic users. The packet-level cooperation is exploited to improve the packet transmission rate to a nomadic user. Various techniques for the two levels of cooperation are discussed. A case study is presented to evaluate the performance of the data dissemination approach.

Introduction

Data dissemination services in wireless networks are becoming more and more important, as numerous telematic applications require the distribution of a certain amount of information in the network. In this article, we investigate one major category of data dissemination services where data packets are generated from a remote server in the Internet and destined to nomadic users such as vehicle passengers and pedestrians. Typical applications of data dissemination services include traffic information downloading, entertainment content distribution, and commercial advertising. For instance, a flyer can be created based on the most recent advertisements of a supermarket and uploaded to a content server. Then, the vehicle passengers and/or pedestrians can download the flyer when they travel through the coverage area of one or several access points (APs) deployed in the neighborhood of a local store.

The data dissemination services can be supported by the traditional cellular networks such as general packet radio service (GPRS) and 3G. However, as cellular networks aim at offering ubiquitous network coverage, providing the data dissemination services by cellular networks can suffer from low transmission rate and high cost [1]. An alternative is to make use of the existing wireless fidelity (Wi-Fi) based wireless local area networks (WLANs) which are worldwide deployed to provide high-speed Internet access for public and/or private communication hotspots such as cafes, restaurants, and residential houses. Typically, each WLAN serves a group of local users within the coverage area of the AP and has a potential to accept the nomadic users for network access [2] [3]. By delivering information packets to a nomadic user traveling through the coverage area of the roadside WLANs (RS-WLANs), the data dissemination services can be provided. However, in order to achieve efficient data dissemination via the RS-WLANs, two major problems should be resolved. Firstly, different from the data dissemination services which are generally delay tolerant, both delay sensitive voice/video and delay tolerant data services are normally provided to the local users within an RS-WLAN. Therefore, the resources in terms of bandwidth, buffer storage, and battery energy in each RS-WLAN should be efficiently shared between the nomadic users and local users. Secondly, since the duration of the wireless connection from a nomadic user to an RS-WLAN is short (e.g., several seconds for a vehicle passenger [1] and several minutes for a pedestrian [4]), a high packet transmission rate from the RS-WLAN to a nomadic user is indispensable to deliver a satisfactory service (in terms of the amount of information distribution).

In order to address the issues, we present a cooperative data dissemination approach based on two levels of cooperation, i.e., network level and packet level. For the network-level cooperation, the aim is to utilize publicly and/or privately owned RS-WLANs for services to nomadic users. The existing industrial application [2] and academic research [3] provide security, privacy, and incentive mechanisms to support the resource sharing between the nomadic users and local users in the RS-WLANs. In this article, we further investigate the resource management in each RS-WLAN by considering quality of service (QoS) requirements of both data dissemination services and local voice/data services. The packet-level cooperation is to achieve a high packet transmission rate, via techniques such as cooperative caching [1] [5] [6], cooperative transmission [7], and delay tolerant cooperation [4]. To evaluate the proposed data dissemination approach, a case study is presented.

Network Topology

Consider nomadic users (such as vehicle passengers and pedestrians) roaming in a network region, where RS-WLANs are deployed in communication hotspots and can be accessed by the nomadic users. An illustration of the network topology is shown in Fig. 1, where a section of a straight road is considered as an example. Each data dissemination service consists of a certain amount of packets destined to a group of nomadic users. Each destination nomadic user can successfully download a data dissemination service if and only if all the information packets are received.

The nomadic users and local users have different mobility patterns. A nomadic user moves at a high speed. While traveling from one location to another, the user likely will pass several RS-WLANs. On the other hand, a local user moves at a low speed and can stay within the coverage area of an RS-WLAN for a considerably long duration. There are two types of transceivers used by the local users, i.e., storage and non-storage local transceivers, where the storage local transceivers can buffer information packets for the data dissemination services for nomadic users.

The wireless connection between a local user and a nomadic user can be established when they come into the transmission range of each other. The packet transmission rate of the connection depends on the channel quality. For the wireline connection between an AP and a server in the Internet, the rate depends on the Internet services subscribed by the RS-WLAN. For instance, in a typical residential RS-WLAN, the rate of the wireline connection can be limited to a few Mbps which is much lower than the maximum rate of the wireless connection (e.g., 54Mbps for IEEE 802.11a based RS-WLANs) [1].

Network-Level Cooperation

The network-level cooperation is to make use of RS-WLAN resources in a network-wide manner for efficient data dissemination to nomadic users. To this end, the resources within each RS-WLAN in terms of bandwidth, buffer storage, and battery energy should be managed efficiently among the nomadic users and local users. Moreover, security and privacy should be guaranteed for both nomadic users and local users, while some incentives are required to stimulate the cooperation.

Resource Management

The essential resources are the radio bandwidth which allows both nomadic users and local users to access an RS-WLAN. For bandwidth allocation, a medium access control (MAC) scheme is considered, where time is partitioned into superframes with equal durations as shown in Fig. 2 [8]. Each superframe begins with a beacon period followed by a local voice phase to support voice services to local users. After the local voice phase, there is a period called the dedicated phase which is reserved for the data dissemination services when nomadic users come into the coverage area of the RS-WLAN. The reserved dedicated phase is to guarantee network access opportunities for the nomadic users during their short periods of connectivity while eliminating the interference between the data dissemination services and local services. When multiple nomadic users are present in an RS-WLAN, each nomadic user obtains a reserved period within the dedicated phase for medium access. At the end of each superframe, there is a local data phase to support the data services to local users. The duration of the local voice phase depends on QoS requirements (e.g., packet delay) of the local voice services. The duration of the dedicated phase should be controlled to achieve a throughput tradeoff between the data dissemination services and local data services.

Different from the bandwidth resource sharing which is a fundamental step of cooperative data dissemination, the sharing of buffer storage resources is auxiliary to achieve a high packet transmission rate to nomadic users. There are two potential storage locations within each RS-WLAN, i.e., the AP and the local transceivers. For an AP, the buffer space is generally limited to several megabytes [1]. One solution is to connect each AP with a local file server, such as in the Wi-Fi based content distribution community infrastructure (CDCI) [5]. However, an extra cost is inevitable for the file servers. On the other hand, by exploiting the buffer space at the local transceivers, no extra capital expenditure is required [6]. A certain amount of buffer space from the local transceivers can be shared within the RS-WLANs. As shown in Fig. 1, the local transceivers with and without shared buffer space are referred to as storage and non-storage local transceivers, respectively. Different transmission techniques can be adopted based on the shared buffer storage. For instance, when a nomadic user comes into the coverage area of an RS-WLAN, packets can be delivered by direct transmissions from the AP and the storage local transceivers, or by relaying transmissions via the non-storage local transceivers.

With respect to energy resources, two categories of local users (transceivers) may exist in each RS-WLAN. The first category includes the local terminals (such as laptops) which are connected to the power supplies and have no obvious energy constraints, while the second category includes the local handsets (such as PDAs and smart phones) which are powered by batteries with stringent energy constraints. Since the packet transmission consumes energy, the local users with a stringent energy constraint may not participate in the packet relaying. Generally, there is no energy constraint for the AP.

Security, Privacy, and Incentives in Cooperation

In the RS-WLANs, security and privacy should be guaranteed for both nomadic users and local users to prevent misuse of network resources and personal information. The APs of FON use traditional password authentication when a nomadic user tries to access an RS-WLAN, without a privacy protection mechanism [2]. In order to provide efficient mutual authentication between a nomadic user and an RS-WLAN, a localized and distributed authentical approach is proposed in [3]. The user anonymity and identity privacy can be protected by the proposed scheme.

In order to stimulate the network-level cooperation, incentives are necessary. Direct payment is one of the most straightforward incentives. For a non-owner/subscriber nomadic user who wants to access an RS-WLAN, FON utilizes the paid access pass to assure the network access [2]. The access pass can be bought directly from the portal page of an RS-WLAN or pre-purchased before the usage. To improve the efficiency of the billing procedure, U-tokens are introduced and can be bought from the third parties (called the roaming brokers) [3]. A U-token is a kind of electronic currency which is untraceable, divisible, and can be cashed back after the usage. There are also some nonpayment incentives to stimulate the sharing of RS-WLANs. For instance, according to the business model of FON, the owners of the shared RS-WLANs (called Foneros) can access all the shared RS-WLANs owned by other Foneros in a worldwide scale.

Cooperation with Cellular Networks and among Nomadic Users

In addition to utilizing RS-WLANs for cooperative data dissemination, the cellular networks such as GPRS and 3G can also be used as an auxiliary network infrastructure. With ubiquitous network coverage, the cellular networks can provide control channels for the cooperative data dissemination [1]. The request and acknowledgement of a data dissemination service can be exchanged between a remote server and a nomadic user through a cellular network. Moreover, the location and trajectory of a nomadic user can be obtained from a cellular network to facilitate the packet-level cooperation, to be discussed in the following section.

Extensive research has been done on the cooperative data dissemination among the nomadic users, such as content broadcasting in vehicular networks based on vehicle-to-vehicle communications [9]. These techniques can be directly incorporated into our proposed cooperative data dissemination approach for better service provisioning.

Packet-Level Cooperation

With the network-level cooperation, a certain amount of resources from the RS-WLANs can be used by nomadic users. In order to efficiently utilize the resources, packet-level cooperation can be adopted to improve the packet transmission rate when a nomadic user visits an RS-WLAN. Two techniques are considered, i.e., cooperative caching and cooperative transmission. For cooperative caching, packets are pre-downloaded to the AP and/or storage local transceivers within an RS-WLAN before the visit of a destination nomadic user [1] [5] [6]. The cooperative caching can solve the problem of limited bandwidth of the wireline connection. On the other hand, even if the wireline connection is not the bottleneck, a high packet transmission rate can be achieved by exploiting channel diversity among multiple local transceivers. In cooperative transmission, the local transceivers within RS-WLANs are used as relays for packet delivery to the nomadic users [7]. With a focus on the cooperation in a typical WLAN scenario, we discuss only the decode-and-forward cooperation here.

For clarity in comparing different packet-level cooperation schemes, in the following, we consider an illustrative scenario where an RS-WLAN is serving a nomadic user with the help from a single local user, as shown in Fig. 3. In the figure, R_{WL} denotes the wireline transmission rate from a server in the Internet to the AP, R_{AR} and R_{AD} the wireless transmission rate from the AP to the local user and nomadic user, respectively, and R_{RD} the wireless transmission rate from the local user to the nomadic user. For simplicity, neglect the wireless transmission error and the overhead for packet scheduling and acknowledgement.

Direct Transmission

As shown in Fig. 3a, the direct transmission relies only on the packet transmission from the AP to the nomadic user. The direct transmission can be applied to most RS-WLANs based on the IEEE 802.11 standard. Because of a potential bandwidth limitation of the wireline connection, especially in a residential area, the packet transmission rate to a nomadic user is capped since the packets have to be retrieved from a server in the Internet. The direct transmission rate is given by $\min\{R_{WL}, R_{AD}\}$. Such scheme uses the bandwidth resources of an RS-WLAN mainly upon the visit of the nomadic user.

Cooperative Caching at the AP

As a solution to the bandwidth limitation of the wireline connection, cooperative caching at the AP can be implemented [1]. Data packets are pre-download to the RS-WLAN AP prior to the visit of the nomadic user, and then delivered to the user from the AP directly, as illustrated in Fig. 3b. The packet pre-downloading procedure is shown by the dashed line, since it is already done during the visit of the nomadic user.

For packet pre-downloading, both cellular network based on-demand pre-downloading [1] and mobility history based stochastic pre-downloading [5] can be implemented. For the on-demand pre-downloading, when a nomadic user requests a data dissemination service, the request message is sent through a cellular network to notify the server in the Internet as well as the RS-WLANs on the trajectory of the nomadic user. Then, the data packets are sent to and stored at the APs of the notified RS-WLANs before the visit of the nomadic user. For stochastic pre-downloading, the visiting history of the nomadic users to the RS-WLANs is needed. For a specific nomadic user, since different trajectories have different probabilities to occur, data packets are pre-downloaded to RS-WLANs on trajectories which are most likely to be visited by the nomadic user.

In order to avoid packet duplication in the pre-downloading, erasure coding can be used in packet pre-downloading [5]. Suppose a specific data dissemination service consists of M packets, by erasure coding, the M packets are encoded into $\tilde{M}$ blocks ($\tilde{M} > M$) which are pre-downloaded to the RS-WLANs. By visiting a certain number of RS-WLANs, a nomadic user can successfully decode the message after receiving M out of $\tilde{M}$ distinct blocks. The redundancy factor is given by $\eta = \frac{\tilde{M}}{M}$ ($\eta > 1$). For a larger η, as more encoded blocks are generated, the probability for a nomadic user to obtain distinct blocks is higher upon visiting one of the RS-WLANs, at the cost of an increased decoding complexity.

The cooperative caching at the AP can greatly reduce the negative impact of the limited bandwidth of the wireline connection. The packet transmission rate to the nomadic user in Fig. 3b mainly depends on R_{AD}. Obviously, in order for the direct transmission scheme to achieve the rate, the transmission rate of the wireline connection (R_{WL}) should be at least equal to the wireless transmission rate (R_{AD}), which can be difficult for RS-WLANs in a residential area. For the resource usage, cooperative caching at the AP consumes more bandwidth and buffer storage resources at the AP as compared with the direct transmission, because of the packet pre-downloading procedure. Moreover, as the buffer space is generally limited at an AP if no external file server is used, the number of pre-downloaded packets is capped and thus the transmission rate improvement by implementing packet pre-downloading may not be significant [5].

Cooperative Caching at the Local Transceivers

In order to obtain extra buffer storage for packet pre-downloading, the resources of the local transceivers should be exploited [6]. As shown in Fig. 3c, by pre-downloading packets not only to the AP but also to the local transceivers, the number of pre-downloaded packets can be increased. With more pre-downloaded packets, the probability that the AP needs to retrieve packets from the server in the Internet is reduced. The packet transmission rate is $\frac{R_{AD}+R_{RD}}{2}$ if the AP and storage local transceiver are equally likely to transmit to the nomadic user. Compared with the cooperative caching only at the AP, the rate improvement by cooperative caching at both the AP and the local transceiver is not obvious, as it depends on the channel quality between the storage local transceiver and nomadic user. In pre-downloading packets to and transmitting packets from the storage local transceiver, not only the bandwidth and buffer storage but also the energy resources are needed at the storage local transceiver, which may prevent some energy constrained local transceivers (e.g., PDAs and smart phones) from participating in the cooperation.

Cooperative Transmission

Cooperative transmission relies on channel diversity among non-storage local transceivers which can act as relays in packet transmission [7]. The wireless link (either direct link or relay link) with the higher rate is selected for packet delivery to the nomadic user, as shown in Fig. 3d. With the half duplex mode, the transmission rate of the relay link is given by $[\frac{1}{\min\{R_{WL},R_{AR}\}} + \frac{1}{R_{RD}}]^{-1}$. Overall, the rate of the cooperative transmission scheme is $\max\{\min\{R_{WL}, R_{AD}\}, \frac{\min\{R_{WL},R_{AR}\}R_{RD}}{\min\{R_{WL},R_{AR}\}+R_{RD}}\}$. Compared with the direct transmission, an advantage of the cooperative transmission scheme is the potential to offer a higher transmission rate to the nomadic user, which depends on the wireline transmission rate as well as the channel quality of the direct and relay links.

Delay Tolerant Cooperation

The cooperative caching at the local transceivers can address the bandwidth limitation of the wireline connections. On the other hand, the cooperative transmission exploits the channel diversity but the packet transmission rate can be capped by the limited bandwidth of the wireline connection. To take the advantage of both approaches, a delay tolerant cooperation (DTCoop) scheme is proposed [4]. Based the DTCoop scheme, data packets are pre-downloaded to not only the AP but also the storage local transceivers within an RS-WLAN, and the channel diversity is exploited in scheduling the transmission of the pre-downloaded packets upon each visit of a nomadic user. An illustration of the packet scheduling under the DTCoop scheme is shown in Fig. 4. Within an RS-WLAN, there are three entities which can participate in the cooperation, i.e., the AP, storage local transceivers, and non-storage local transceivers. There are four possible transmission links to deliver a packet to a nomadic user, i.e., the direct links from the AP and a storage local transceiver, and the relay links from the AP and a storage local transceiver with the help of a non-storage local transceiver. Among the links, the one with the maximum transmission rate is selected. After all pre-downloaded packets are delivered, the remaining packets of the data dissemination service are delivered to the nomadic user by the cooperative transmission scheme. Since the packet pre-downloading procedure of the DTCoop scheme is the same as the cooperative caching at the local transceivers, in Fig. 3d, the transmission rate is given by $\max\{R_{AD}, R_{RD}\}$ if the DTCoop scheme is adopted. The DTCoop scheme achieves the highest packet transmission rate with both packet pre-downloading and channel diversity via packet scheduling.

A Case Study

Consider data dissemination from an RS-WLAN to a nomadic user. The RS-WLAN coverage area is a circle centered at the AP with radius 50 m. The local users are randomly located within the coverage area and are stationary during the visiting period of a nomadic user. The nomadic user is a pedestrian, moving at a speed of 1 m/s along a straight line with a minimum distance of 13.1 m to the AP. For the wireless channel condition, a pathloss exponent equal to 3 and Rayleigh fading are considered for a typical WLAN scenario [4] [7]. The wireless transmission power of local users, nomadic users, and AP is 100 mW, while the noise power is 0.001 mW. The wireless transmission follows the 802.11a standard with 8 possible rates range from 6 Mbps to 54 Mbps. The packet transmission under a certain rate is considered as error free when the signal-to-noise ratio at the receiver is above a threshold as given by [10]. The maximum wireless transmission range under the channel condition is 50.4 m, corresponding to a connectivity period of 97.2 s from the nomadic user to the AP. The size of each data packet is 10 KBytes.

Fig. 5 shows a comparison among the packet-level cooperation schemes in terms of the average number of packets delivered to the nomadic user as a function of the bandwidth of the wireline connection. There are 10 local users, and half of them have a storage transceiver. The number of pre-downloaded packets is 15000 while the fraction of channel time for the dedicated phase is 0.3. The direct transmission scheme delivers the minimum number of packets to the nomadic user during the visit when the bandwidth of the wireline connection is extremely limited (e.g., below 7 Mbps). By pre-downloading 15000 packets to the AP, the cooperative caching increases the number of delivered packets from that of the direct transmission scheme. However, if the 15000 packets are also pre-downloaded to all the storage local transceivers and scheduled equally likely, slightly less packets are delivered to the nomadic user. Indeed, as the storage local transceivers are scattered within the coverage area of the RS-WLAN, the storage local transceiver with a poor channel condition may be selected as a transmitter node, which degrades the packet delivery performance. The cooperative transmission may deliver less packets than the two cooperative caching schemes if the bandwidth of the wireline connection is extremely limited. The delay tolerant cooperation can significantly increase the average number of delivered packets as compared with all the other schemes. Note that the cooperative caching at the AP does not deliver more packets when the bandwidth of the wireline connection increases. The reason is that the 15000 pre-downloaded packets are sufficient for the packet delivery to the nomadic user and not much packet retrieval from the server is required during the visiting period.

For the network-level cooperation, Fig. 6 shows the average number of delivered packets versus the fraction of channel time for the dedicated phase when the bandwidth of the wireline connection is 10 Mbps. Half of the local users have a storage transceiver. For clarity, we only show the results for the cooperative transmission and delay tolerant cooperation which provide the highest packet delivery performance. With an increase of the fraction of channel time for the dedicated phase, the average number of delivered packets increases for both cooperation schemes since more bandwidth resources are allocated to the data dissemination service for the visiting nomadic user. Moreover, with more local users participating in the cooperation process, the average number of delivered packets increases for both schemes since the channel diversity can be exploited from a larger number of local transceivers. In addition, with more pre-downloaded packets, the average number of delivered packets increases for the delay tolerant cooperation scheme. The increment is more obvious when the fraction of channel time for the dedicated phase is large since more packet retrieval from the server is required, especially for the case where less packets are pre-downloaded. In summary, with more resources dedicated to nomadic users in the network-level cooperation, better performance can be achieved in the data dissemination.

Conclusions

In this article, a two-level cooperative data dissemination approach is presented. In the network-level cooperation, the resources of the RS-WLANs are allocated to facilitate the data dissemination services to nomadic users. The packet-level cooperation with cooperative caching and/or cooperative transmission is further investigated to improve the packet transmission rate. Cooperative caching at the AP and/or local transceivers can reduce the negative impact of the limited bandwidth of the wireline connection, whereas cooperative transmission can exploit channel diversity to further improve the packet transmission rate. As demonstrate in a case study, with more resources dedicated to nomadic users in the network-level cooperation, more packets can be delivered when a nomadic user visits an RS-WLAN. The DTCoop scheme achieves the best packet delivery performance among all packet-level cooperation schemes by exploiting both cooperative caching and cooperative transmission.

In order to better utilize the buffer storage of the local transceivers, optimal pre-downloading should be investigated by considering user mobility and content popularity. Moreover, as multiple storage and non-storage local transceivers may reside in an RS-WLAN, an efficient MAC scheme should be designed to resolve the channel contention while achieving channel diversity. In addition, how to provide a network-level delay analysis for cooperative data dissemination by considering the mobility of nomadic users is still an open issue.

Acknowledgment

This research was supported by a research grant from the Natural Science and Engineering Research Council (NSERC) of Canada.

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Biographies

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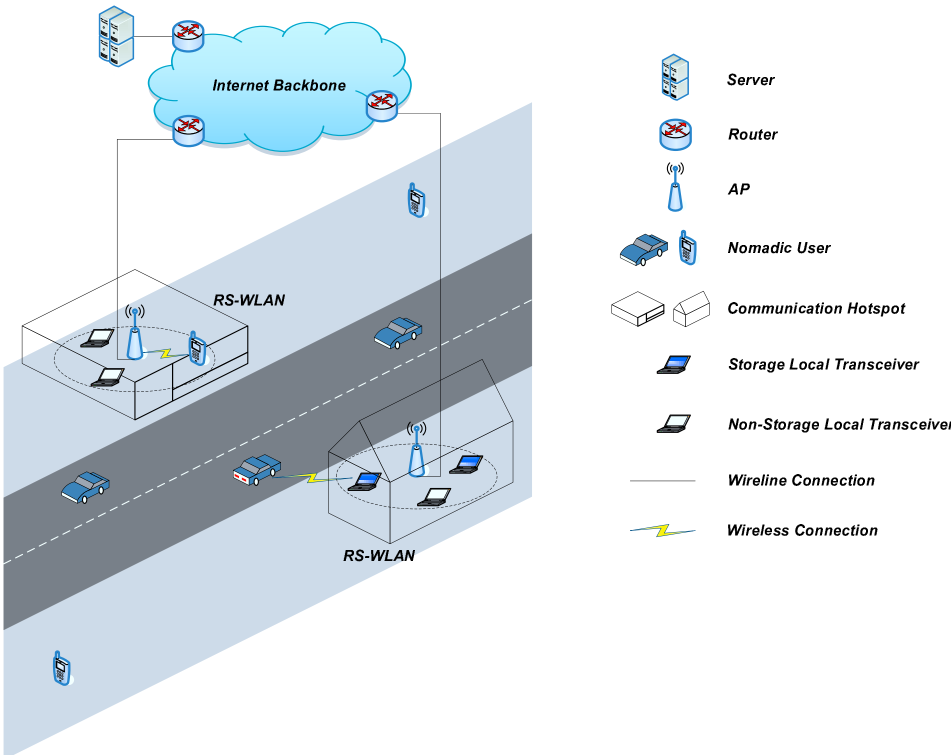

Fig. 1: An illustration of the network topology for data dissemination.

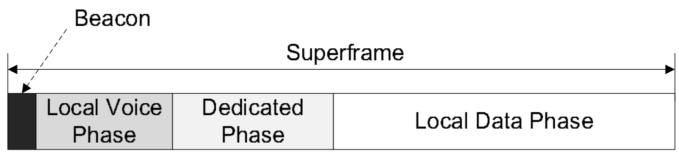

Fig. 2: The MAC superframe structure.

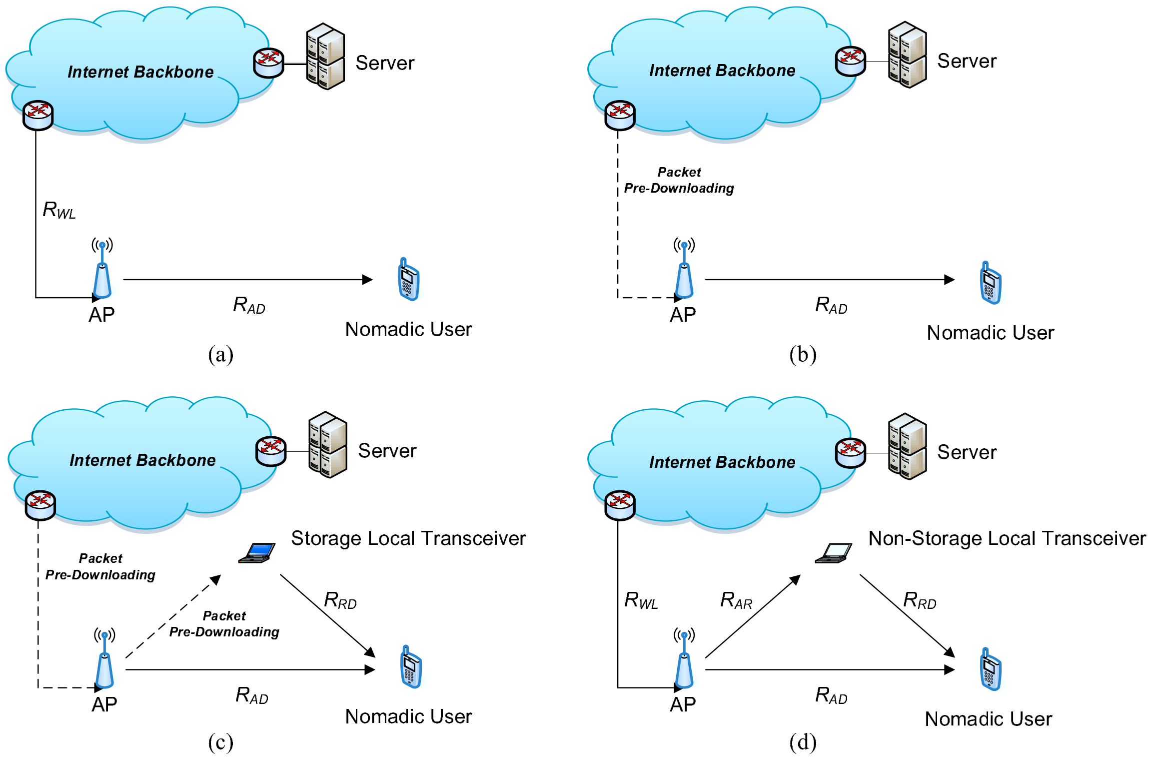

Fig. 3: The packet-level cooperation: (a) Direct transmission. (b) Cooperative caching at the AP. (c) Cooperative caching at a local transceiver. (d) Cooperative transmission.

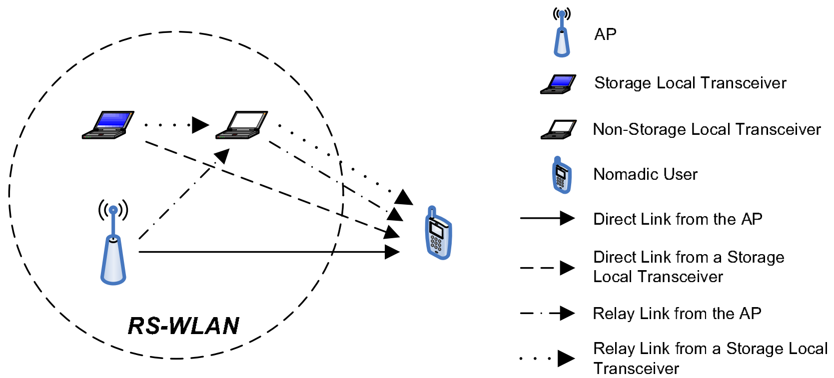

Fig. 4: An illustration of packet scheduling under the DTCoop scheme.

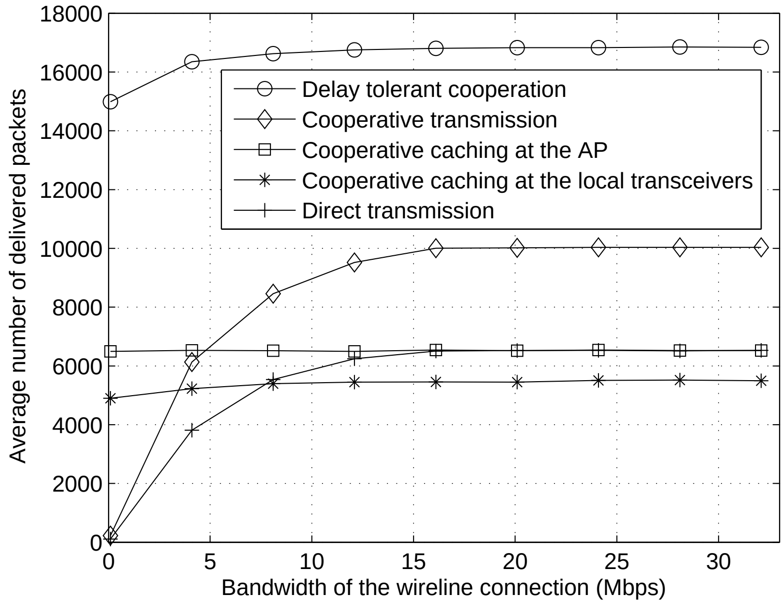

Fig. 5: Performance evaluation of the packet-level cooperation.

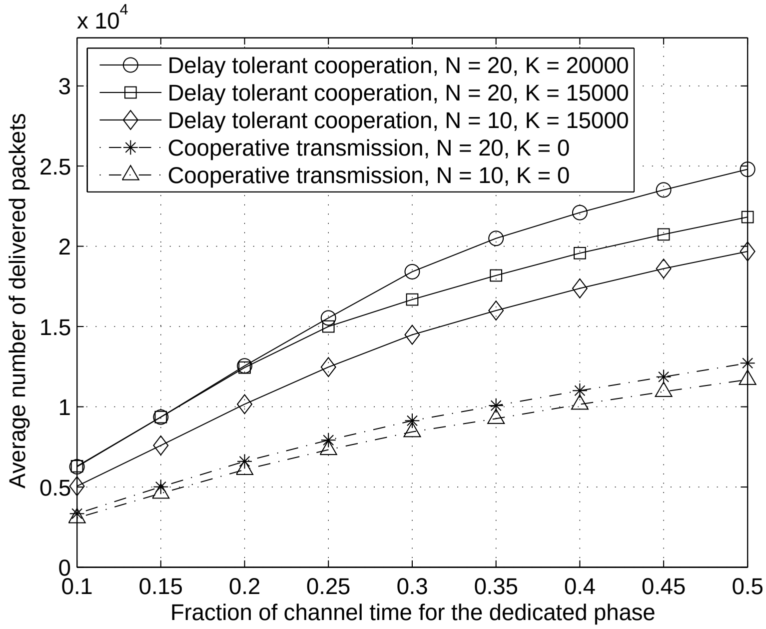

Fig. 6: Performance evaluation of the network-level cooperation (with N local users and K pre-downloaded packets).