Resilient Opportunistic Forwarding: Issues and Challenges

RESILIENT OPPORTUNISTIC FORWARDING: ISSUES AND CHALLENGES

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ABSTRACT

Opportunistic networks, which are seen as one of the major evolutions from MANETs, have attracted many attentions recently. Generally speaking, opportunistic networks cover many similar aspects of Delay Tolerant Networks and Disruption Tolerant Network, which can be characterized by intermittent connectivity, frequent end-to-end path disruption and topology changes. In such challenging network scenarios, the end-to-end network resilience, or the effectiveness and efficiency of underlying network, becomes a very important topic.

To improve network resilience in opportunistic networks, a new breed of forwarding technologies, namely opportunistic forwarding, has been proposed recently. However, many of such works are developed independently and thereby following fairly different terminologies. In this paper, (i) we first give an overview of opportunistic networks; (ii) we then address the applicability, definition, and taxonomy of opportunistic forwarding technologies; next, (iii) we provide insights on fundamental ideas behind opportunistic forwarding, while walking through a few representative examples; finally, (iv) we conclude the paper with discussion on issues and challenges.

I. INTRODUCTION

After more than a decade of international research collaboration and thousands of publications, *Mobile Ad Hoc Networks* (MANETs) remains largely in the conceptual and prototype level, and can hardly be considered as a very mature and reliable network solution for real world applications. Although there are many reasons causing this harsh reality of MANETs, one challenge is particularly important. That is, *how to improve the currently fragile end-to-end network services in presence of interference-prone wireless communications and volatile network topology in MANETs?*

Traditional solutions tackle the network reliability and resilience by the concept of *fortifying* MANETs so that it behaves like wired networks. Particularly, for the reliability, (i) wireless links/hops are "fortified" by data link layer *automatic-repeat-request* (ARQ) and *forward-error-control* (FEC), (ii) end-to-end paths are "fortified" by transport layer ARQ and application erasure coding. As to the resilience, wired-like end-to-end forwarding paths are "fortified" by more frequency route updates, or by more than one redundant path (multi-path routing or flooding). The limitation of fortification approach is that it may work in benign MANET scenarios (e.g., low mobility, small network size in terms of the number of nodes and/or network diameter), but it is overwhelmed (e.g., poor scalability due to control overhead, slow response to mobility) in more challenging MANET environments, i.e. opportunistic networks.

As opposed to fighting against the volatile (bad) nature of MANETs by "fortification", a fairly new concept is to find a work-around by leveraging MANETs' good nature (e.g., broadcast medium, spatial and temporal path diversity) to compensate the volatility. This general design philosophy has inspired a few interesting works intending to improve MANET reliability and resilience performance. In this paper, we investigate a class of works, namely opportunistic forwarding.

The remainder of this paper is organized as follows. Section II gives an overview of opportunistic networks. Section III addresses applicability, definition, and taxonomy of opportunistic forwarding technologies. Section IV systematically walks through several representative works. Finally, Section V concludes this paper.

II. OPPORTUNISTIC NETWORKS

Before we dive into details of opportunistic forwarding, we would like to first discuss opportunistic networks, which have become a popular term recently. As an emerging concept, there is of course no crystal clear definition of opportunistic networks commonly agreed in the community. Nevertheless, some essential characteristics of opportunistic networks have been identified.

For example, Pelusi *et al.* provided an informative description of opportunistic networks in [1]. According to [1], opportunistic networks can be viewed as one of two main evolutions from MANETs (the other one is Wireless Mesh Networks. Note that we also consider sensor networks

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as the third major evolution). Moreover, opportunistic networks in most case are used as an interchangeable term for *Delay/Disruption Tolerant Networks* (DTNs) due to their common feature on intermittent network connectivity. However, opportunistic networks are more generic and not necessarily limited to the Internet-like architecture with gateways, as often assumed by DTNs.

Since connectivity is the most important criteria for defining opportunistic networks. One may wonder how to quantify network connectivity. In [2], Westphal recapitulated Hall's theoretical milestone of critical density, which statistically characterizes the network connectivity. Under the assumption of 2D Poisson node distribution and unit disk coverage, sub-critical node density (i.e. sparse network) leads to a disconnected network with probability one. On the other hand, for node density equal or higher than the critical threshold, there exists an infinitely large cluster of connected nodes.

Although critical density characterizes network connectivity in terms of spatial sparseness, it does not capture the temporal and protocol dynamics incurred by mobility and link failure due to other reasons. With high mobility, a persistent end-to-end path over certain period of time may not be possible even if the network is physically connected at any given time. In other words, network applications may still suffer from underlying intermittently connected network services due to *routing breakage*, even though it has high node density.

In [3], Li *et al.* investigated the relationship between "the time to route breakage" and node mobility (i.e. velocity). If the time to route breakage is too short due to high mobility, all traditional routing protocols will break down entirely or suffer from significant performance degradation, causing low delivery ratio and disproportionally high routing overhead.

Arguably, aforementioned two network scenarios (i.e., 1) sparse network with sub-critical density; and 2) fully-connected network with frequent topology changes) can be seen as different emphasis of DTN, delay tolerant or disruption tolerant. In this paper, we are particularly interested in the latter. More discussions on the former can be found in [4]. Issues for such scenarios are not necessarily the same with several ongoing projects as summarized in [1], including Pocket Switched Networks [5], ZebraNet [6], DakNet [7] and SNC [8]. These projects may focus more on the former.

III. OPPORTUNISTIC FORWARDING

A. Applicability

As mentioned in the previous section, high-mobility incurs fast route breakage, which in turn results in the failure of end-to-end data delivery. Evidently, such failure is caused by the mismatch between route breakage time and route adaptation time, which means that it takes a longer time to establish a new route than losing it again.

However, in a non-sparse high-mobility opportunistic network, a node potentially may have one or more connected neighboring nodes that can lead to the destination of the broken route all the time. If such neighboring nodes are not excluded from the end-to-end forwarding, fast route breakage does not necessarily lead to the failure of end-to-end delivery. Therefore, it is not surprise that flooding can be functioning in such challenging scenarios while routing cannot. In fact, uncontrolled flooding is the most primitive (and most conservative in terms of taking chances) form of opportunistic forwarding.

B. Definition

So what exactly is opportunistic forwarding?

Opportunistic forwarding represents a class of mechanisms for end-to-end data delivery. Compared to routing, there is a distinct characteristic that usually defines opportunistic forwarding. In opportunistic forwarding, the next-hop forwarding node may not be the same among all packets for the same source destination pair. To put this into a different perspective, the end-to-end traverse path of each packet is the collective result from per-hop forwarding decisions. It is worth noting that opportunistic forwarding is not limited to unicast (i.e., single-copy forwarding). Nevertheless, leveraging opportunistic forwarding to improve unicast performance does attract significant attention recently, with a variety of algorithms.

C. Taxonomy

As shown in Fig. 1, opportunistic forwarding can be classified according to various aspects.

In [1], Pelusi *et al.* had categorized opportunistic forwarding algorithms as *dissemination-based* and *context-based*. Dissemination-based algorithms essentially are various flooding schemes, while context-based algorithms are non-flooding schemes in which the best next-hop forwarding node is elected at each forwarding step. Although it sounds straightforward, certain algorithms reside in the gray area by following such categorization. For example, *Extremely Opportunistic Routing* (EXoR), which was proposed by Biswas and Morris in [9], intends to pick the best

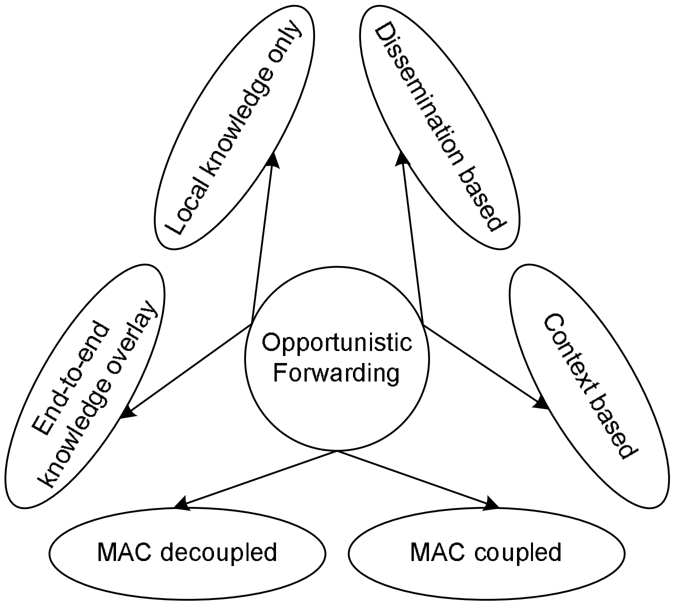

Figure 1. Taxonomy of opportunistic forwarding.

next-hop forwarder at each forwarding step based on local decision at all receiving nodes. However, due to the loss of signaling acknowledgement packets as well as possibility of different local views under multi-hop scenarios, multiple nodes may forward the same packet at a specific forward step. Therefore, EXoR possesses characteristics of both dissemination-based and context-based approaches.

In addition to the previous categorization, opportunistic forwarding can also be divided into *end-to-end knowledge overlay based* and *local knowledge based* algorithms, as described in [10]. In the end-to-end knowledge overlay based algorithms, end-to-end routing information is still needed for forwarding decision making, which is likely to be the weakest link of these algorithms, because stale or incorrect routing information influences the forwarding decision. In the local knowledge based algorithms, routing protocols become unnecessary. Forwarding decisions are solely based on local information, which in turn can be adapted dynamically according to the results of the forwarding action. So far, it is challenging to design a local knowledge based algorithm without falling back to certain forms of flooding schemes.

The third way to classify opportunistic forwarding is whether the algorithm is *medium access control (MAC)-coupled* or *MAC-decoupled*. MAC-coupled algorithms aim to improve the signaling efficiency by combining/piggybacking certain information with MAC control overhead, such as 802.11 acknowledgement (ACK). In addition, MAC-coupled algorithms are often motivated by reducing the per-step forwarding latency incurred by opportunistic forwarding. Via customized MAC design that supports cross-layer operation, it is possible to apply opportunistic forwarding to a broad range of applications not limited to delay-tolerant traffic only. On the other hand, MAC-decoupled approaches may be more attractive if interoperability with legacy radios is required.

IV. NOVEL OPPORTUNISTIC FORWARDING TECHNIQUES

Instead of an exhausted survey of a myriad of algorithms strictly according to aforementioned taxonomy, we walk through several fundamental design ideas commonly shared by most algorithms, and provide some representative works for each, respectively. Some of the following techniques may be originated in DTN. Nevertheless, they can be applied to a broader scope of opportunistic networks with high density yet high mobility, as described in Section II.

A. Network layer temporally persistent (TP) forwarding

Generally speaking, in traditional network layer design, intermediate nodes are responsible of delivering each individual relay packet only once, which is applied to unicast, multicast and broadcast. In this sense, once a packet has been “delivered”, it is no longer qualify for further transmission as it would be counted as unnecessary duplication. Therefore, the temporal path diversity (i.e., topology changes over time) has been voluntarily abandoned at the network layer. Although failed delivery may be handled by persistent retries through per-hop ARQ at MAC or end-to-end ARQ at transport layer, both approaches are not effective, or efficient, in handling frequent topology/path changes due to mobility. MAC ARQ is bundled with designated unicast path, which is not very helpful if the path itself was lost. On the other hand, transport layer ARQ usually involves too much end-to-end latency and hence slow in response to path changes (i.e., the route breakage problem), and it consumes resource over the entire end-to-end path.

To combat the frequent topology/path changes and leverage temporal path diversity, *temporally persistent* (TP) network layer forwarding can be introduced, in which *a packet can be temporally delivered more than once to different neighboring nodes at the network layer, with buffering mechanism and according to proper forwarding decisions*. Although it resembles with flooding, temporally persistent forwarding possesses distinct features and should be taken as a separate class. In both techniques, each node forwards relay packets to all or multiple neighboring nodes. However, temporally persistent forwarding can be either unicast or broadcast, and multiple forwarding actions may be involved with topology changes over time.

A good example of temporally persistent forwarding protocol is *epidemic routing* [11], which is a dissemination based, local knowledge based, and MAC-decoupled opportunistic forwarding scheme. It adopts a so-called "store-carry-forward" paradigm in which packets may be buffered at an intermediate node and forwarded to any new neighbor it encounters later due to node mobility. Epidemic routing may adopt a combination of one or multiple forwarding mechanisms as follows:

- *K-hop forwarding*: in which any packet can only traverse in at most K-hops from the source node. In other words, if an intermediate node receives a packet having traversed K-1 hops from the source node, it will further forward the packet only if it meets the destination node.
- *Opportunistic forwarding*: a node may accept to relay a packet with a probability of p.
- *Limited-time forwarding*: a node only buffers a relay packet for a limited time.

More sophisticated forwarding rules have been proposed in MV routing as well as PROPHET routing protocols [1].

B. Network layer temporally diverse (TD) forwarding

Temporally diverse (TD) forwarding is a different concept from temporally persistent (TP) forwarding. In fact, TD and TP can co-exist. TP specifies that multiple forwarding actions can take place for the same data packet, while TD specifies different forwarding actions can take place for different data packets.

Unlike traditional routing, where all data packets are forwarded over the same next-hop path (paths in case of multi-path routing) unless route changes, there is no explicit path(s) that dictates the forwarding actions of all data packets in TD. In other words, traditional routing can be seen as voluntarily abandoning the temporal diversity over the lifetime of the route, which evidently is slower in response to various network environment changes than packet-by-packet based TD forwarding.

A few representative TD forwarding mechanisms are shown as follows:

1) MAC Anycasting: MAC anycasting [12] is one of the early attempts on opportunistic forwarding. According to aforementioned taxonomy, it is a context-based, end-to-end knowledge overlay based, MAC-coupled scheme. It assumes that there is an overlay routing protocol that is able to provide multiple candidate forwarding nodes, i.e. an anycast group, at each forwarding step. Given any packet and the overlaid knowledge of anycast group, the MAC protocol selects one candidate node at a time to attempt delivery, until it successfully transmits the packet. The forwarding selection algorithm may be dictated by routing algorithm (i.e., ordered anycasting), or by simple round robin link probing at MAC. Note that unlike later TD mechanism, MAC anycasting does not leverage the broadcast nature of wireless medium, as it resorts to multiple separate MAC transmission attempts in the forwarding selection process, which appears to be wasteful. However, [12] may have a good reason for such design choice because it had a focus on MAC with directional antennas.

2) Self-Selective Routing (SSR): SSR, formerly named Routeless Routing, was proposed by Chen *et al.* in [13]. SSR adopts a context-based, end-to-end knowledge overlay based, MAC-decoupled design approach. First of all, SSR is a network layer protocol that can operate with *commercial off-the-shelf* (COTS) wireless MACs, such as 802.11. Data are always sent in broadcast at MAC (and therefore without MAC ARQ). At the network layer, SSR employs a backoff algorithm and signaling handshakes to handle broadcast reception and autonomously select the next-hop relay node. Generally, the receiver with the shortest broadcast backoff and hence acknowledging the sender first will be selected as the winner for the next-hop forwarding. The broadcast acknowledgment is also used to implicitly inform other potential relay nodes not to forward this particular packet (they are still able to forward if they win any of future packets). To handle hidden terminal problem where some potential relay nodes may not hear from the winner, the original sender has to explicitly repeat the acknowledgement in a *ready-to-send/clear-to-send)* RTS/CTS fashion as commonly used by MAC layer acknowledgements.

Regarding the autonomous next-hop winner selection, the random broadcast backoff timer is essentially associated with the cost (hop-count in their implementation) to the destination node, which is an end-to-end knowledge overlay collected via an AODV-like initial route discovery process. Furthermore, traffic congestion is taken into account implicitly as the backlogged traffic may further delay the transmission of broadcast acknowledgement even if the timer expires.

It is worth noting that although SSR employs per-hop opportunistic forwarding, it still relies on end-to-end knowledge obtained via traditional routing process. Without such knowledge, a relay node is unlikely to be selected as the winner due to very large backoff timer even if it becomes a good choice due to topology change. On the other hand, a relay node with obsolete knowledge may be frequently selected as the winner given its stale knowledge. Although SSR claims to be able to dynamically update/correct stale end-to-end knowledge, such correction occurs only by luck when a relay node overhears from the destination due to its own traffic delivery. Therefore, SSR may still experience poor forwarding performance under frequent or dramatic topology changes. In addition, it has to pay the latency price of additional per-hop backoff latency compared with traditional routing. Nevertheless, it is one-step further in terms of improving forwarding resilience over AODV.

3) Holistic Routing: To quote [14], the name of holistic routing stands for opportunistically forwarding packets considering "*all causes - [interference-related] transmission failures, [mobility-related] link failures, and network congestion - in a holistic way*". Similar to SSR, Holistic Routing adopts a context-based, end-to-end knowledge overlay based, MAC-decoupled design approach. To reflect the idea of holistic approach, it includes a brief discussion on formulating the end-to-end cost from the simple hop-count to more "holistic" metric that covers historical successful delivery ratio, interference level, remaining energy, etc. However, without substantiating such complex cost metric, it falls back to the simple hop-count metric in actual implementation.

There are two major differences between Holistic Routing and SSR. First, in Holistic routing algorithm, a relay node is excluded from further forwarding only if its cost to destination is higher than the last-hop sender. Second, in terms of collecting/updating cost knowledge, Holistic routing theoretically can start from ground zero and adapt cost knowledge autonomously without end-to-end AODV-like handshakes, as adopted by SSR. Nevertheless, initial knowledge flooding may be much faster and more efficient overall with less wasted message transmissions.

Holistic Routing also investigated an important issue that plagues opportunistic forwarding, which is the dilemma in setting the retransmission delay. It is possible that the last-hop sender does not receive any acknowledgement, which may be due to (i) loss of all potential receivers, (ii) loss of acknowledgement message(s). Therefore, retransmission may be needed at each forwarding step. While a larger transmission delay will increase end-to-end delay, a smaller one may incur unnecessary retransmissions. Due to various factors, such as network congestion, there is no close-form formulation of the delay upper bound at the network layer. Therefore the proper retransmission timeout has to be case specific.

4) Extremely Opportunistic Routing (ExOR): ExOR [9] is an end-to-end knowledge based, MAC-coupled technology. As mentioned in Section II, ExOR [9] is arguably a context based scheme since it intends to collaboratively select one winner for the next-hop forwarding. However, as a design choice by trade study, ExOR forsakes the RTS/CTS-like two-way acknowledgement of the winner, as adopted by RSS, and opts to let multiple copies of the same data packet being forwarded due to occasional exception of coordination failures. Therefore, it also possesses certain feature of dissemination based scheme.

ExOR proposed to modify 802.11 MAC so that the format of data frame includes ($N > 1$) next-hop candidate nodes as MAC destination addresses. In addition, every data transmission is followed by N consecutive acknowledgement transmissions before the release of current channel access cycle. Assuming the end-to-end knowledge (i.e., weighted hop count prioritized by delivery rates) is predetermined, a node selects the best N next-hop candidates in the order of their priorities for each data transmission. Upon receiving the data packet, each selected candidate response in their corresponding acknowledgement opportunities with the winner's node ID. The winner ID is the node with highest sender selected priority whose acknowledgement has been overheard so far, not necessarily the acknowledging candidate itself.

Compared with MAC anycasting, ExOR is more efficient in general omni-directional MAC because multiple anycasting transmissions are reduced into one. Compared with RSS, ExOR may incur shorter and bounded forwarding latency given its MAC-coupled approach. However, like both SSR and MAC anycasting, its weakest link may be its reliance on predetermined end-to-end routing knowledge. This makes it difficult to apply ExOR to mobile scenarios. Nevertheless, the concept of packet based forwarding decision was proved to be valid in static scenarios where transient link loss makes ExOR outperform traditional routing with the best possible route.

C. Emerging supplemental forwarding techniques

Several emerging techniques have been developed independently from opportunistic forwarding, yet to be found feasible and/or particular suitable when being used in conjunction with opportunistic forwarding. Such techniques include erasure coding, networking coding, cooperative (or collaborative) communications.

1) Erasure coding based forwarding: Using erasure coding technology, each original data packet is converted into a large set of code blocks such that the original data packet can be reconstructed with any sufficiently large subset of code blocks. It is originally designed as an end-to-end application layer concept to improve the delivery ratio of large data and improve the recovery efficiency for multicast. Interestingly, erasure coding can be integrated with opportunistic forwarding in various ways such that the end-to-end resilience can be further improved.

First, the conventional end-to-end erasure coding can be directly imposed on top of a dissemination based opportunistic forwarding scheme. As a result, multiple code blocks received from different relay nodes can be used to recover the original data, as described in [15].

Second, erasure coding can also be used on a per-hop basis with opportunistic forwarding. In such a scheme, the relay node that is able to assemble and recover the original data may either have higher probability of forwarding, or generate additional code blocks. An attempt to combine per-hop erasure coding and opportunistic forwarding can be found in [16]. In this work, code blocks are delivered through an end-to-end "river", which consists of path diversity but without explicitly specifying next-hop paths at each forwarding step. Therefore, coding diversity and path diversity can be freely combined at any relay nodes to recover the original uncoded data. In addition, coding redundancy can be dynamically adjusted (either increase or decrease) on a per-hop basis. Another work for DTN can be found in [17].

2) Network coding based forwarding: Network coding improves network forwarding efficiency by intelligently processing data packets at the network layer so that information of multiple data packets can be delivered in a single transmission yet recovered by corresponding receiver(s) of transmitted data packets.

Katti *et al.* proposed COPE [18], which is able to practically leverage the low-complexity XOR-based network coding to opportunistically reduce the number of unicast data transmissions. With minimum customization to solve the lack of collision avoidance of 802.11 MAC broadcast, COPE generally transmits all data packets in broadcast so that multiple corresponding receivers can extract wanted information from a single broadcast transmission. This work is still in conceptual stage. It requires all nodes to broadcast (either piggybacked with data or sent explicitly) their reception report, which consists of which packets they have received and stored. Unfortunately, such reception report may be substantial in size and hence cancel the benefit of network coding. Nevertheless, some features of COPE, such as broadcast transmission, post-reception processing and buffering, make it a natural match with certain opportunistic forwarding mechanisms.

Another forwarding approach, namely MISTRAL [19], is actually a genuine combination of opportunistic forwarding and network coding. MISTRAL is a controlled flooding mechanism, which can be classified as dissemination based opportunistic forwarding. MISTRAL aims to improving the data delivery ratio over typical opportunistic flooding with the minimal amount of redundancy overhead, which is achieved via efficient XOR-based network coding. Results shown that, compared with opportunistic flooding, MISTRAL can achieve equal delivery ratio with less overhead. Improvement of forwarding efficiency can be also viewed as improvement of resilience since more redundancy can be afforded towards resilience due to improved efficiency.

3) Cooperative (collaborative) communications: Cooperative communication has received significant attention in both communication and networking communities. It resides mainly on a new communication paradigm in which a functional physical layer communication link can be originated from more than one transmitter collaboratively, so that the receiver can leverage the multipath diversity from all signals in a positive manner rather than treating them as interference. It is envisioned that cooperative communications technology can be used in either an ordered or a randomized (opportunistic) manner. However, to the best of our knowledge, cooperative communication remains largely at conceptual level, with significant practical or architectural issues across layers towards technological maturity. A few proof-of-concept MAC schemes including SSRA, OCRA [20] and CSSRA [21] have been proposed recently. Please also refer to [22] for more discussion in MANETs.

Solely based on speculation, we believe that there are natural merits to marriage opportunistic forwarding with cooperative communications for improving the end-to-end multipath diversity at two fronts. First, in order to achieve cooperative communications, temporally persistent forwarding with buffering mechanism is most likely needed so that more than one node may share and collaboratively transmit copies of the same data packet. Second, the traditional concept of next-hop route may be potentially blurred by the uncertain range heterogeneity introduced by collaborative transmitters. In a very popular illustrative example demonstrating the benefit of cooperation communications, two transmitters may collaboratively reach a receiving node that is outside the 1-hop connectivity of either transmitter individually. In summary, opportunistic forwarding is potentially a natural choice due to the implications of cooperative communications paradigm.

V. CONCLUSIONS

In this paper, we have investigated a breed of forwarding technologies, namely opportunistic forwarding. We discuss applicability, definition, taxonomy, and fundamental underlying ideas of opportunistic forwarding, as well as potential merits in conjunction with other emerging forwarding technologies, which include erasure coding, network coding and cooperative communications. As we discussed in Section IV-B, one of the weaknesses of many existing schemes are their reliance on end-to-end routing knowledge overlay. While independent algorithms entirely forsaking routing yet being adaptive to end-to-end topology changes are highly desirable in terms of network resilience and forwarding efficiency, how to achieve this remains unclear. The second challenge is the appropriate design balance and trade off in terms of cross-layer (MAC and network) forwarding co-operation. More MAC-intrusive design may lead to smaller forwarding latency but it also limits the applicability of the technology. The third potential issue is how to integrate opportunistic forwarding with the emerging multi-channel multi-radio (MCMR) networks, where additional spectrum diversity has to be coordinated with the spatial and temporal diversity provided by opportunistic forwarding.

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