Employing Ad Hoc Networks in WLANs: Trade-offs and Insights

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Abstract— **In this paper, the issues arising from the introduction of short-range, low-power, multi-hop, ad hoc networking in cellular networks are presented. The weaknesses of the widely proposed replacement – in essence – of the pure cellular paradigm by a pure ad hoc one in Wireless Local Area Networks (WLANs), are discussed and illustrated through some simulation results. The coexistence or integration of the cellular and the short-range, multi-hop, ad hoc networking paradigms is advocated, instead, and the notion of a dual mode of operation utilizing distinct frequency channels or bands is introduced. In this environment, the ad hoc networking efficiency is enhanced, as the coexisting cellular network helps mitigate inherent weaknesses of pure ad hoc networking.**

I. INTRODUCTION

THE design of wireless networks poses great challenges due to factors such as the limited bandwidth that is shared among users, interception- and error-prone medium, lack of secure transmissions, mobility and scarceness of energy resources. Recent advances in computing and wireless communications technologies have, on one hand, enabled efficient ways to address the aforementioned challenges and, on the other, make it feasible to design networks capable of accommodating high data rate applications, including multimedia. Moreover, due to the existence of different wireless standards and applications, these networks should support the accessibility by heterogeneous devices, as well as be possibly backward compatible.

In urban deployments, where the number of users and the traffic needs are potentially high (hotspots), WLANs appear to be a good candidate for a wireless bridge to the backbone network. The challenge is to make them adequate for supporting demanding future applications. The (infrastructure-based) WLANs allow for a centralized mode of operation, where the Access Point (AP) controls the transmissions inside its cell and provides for a single-hop network connecting Mobile Terminals (MTs) with the Internet. These networks provide for the extension of the fixed network infrastructure and the support of data rates at low cost and they are simple and capable of providing – even rather limited – Quality of Service (QoS) guaranties. On the other hand, WLANs have short coverage (limited by single-hop communication), they do not support direct peer-to-peer communication and the AP may always be a throughput bottleneck for its cell.

Current (infrastructure-based) WLANs do not scale to high data rates and increased number of users – as the growth of the Internet would require – due to the wireless data rate limitations. One way to increase the per user capacity of WLANs is by reducing the cell size (and, accordingly, the number of users per cell) and exploit spatial reuse. At the same time, the density of deployed APs should be increased to accommodate a large number of users, resulting in a higher cost and reduced overall efficiency. Besides, research has been directed toward smarter radio transmissions (adaptive or directional antennas), better channel access schemes or more efficient scheduling schemes (MAC protocols), faster/intelligent hand-offs and wireless-aware transport protocols to enhance wireless functionalities.

Ad hoc networks have recently been considered to provide for higher in-cell capacity and lower power consumption. Since ad hoc networks have been introduced as a network solution in emergency cases, they distribute the necessary functionalities of accessing the channel and routing among the MTs and typically involve multi-hop communication without the need for a coordinating node (such as the AP). They can extend the wireless infrastructure and allow for direct communication between two MTs. In addition, they are robust, flexible and require no administration or set-up cost. Nevertheless, the need for a higher node complexity, the challenges imposed by the applied distributed routing algorithms, the great impact of mobility and the lack of QoS and security may make the ad hoc networks unsuitable for meeting future user requirements.

The remainder of this paper is organized as follows. In the following section some trade-offs between using multi-hop networks instead of the traditional cellular networks are highlighted. Section III provides simulation results that shed light into the effectiveness of short-range, multi-hop paths inside WLANs for indoor applications. In section IV, a dual mode WLAN employing the ad hoc networking paradigm is advocated as a way to address the aforementioned issues and associated mechanisms are presented along with an investigation of the induced overhead. Finally, the paper is concluded in section V.

II. MULTI-HOP VERSUS PURE CELLULAR NETWORKS

The employment of the ad hoc networking paradigm in (infrastructure-based) WLANs has been motivated

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by the need to support high-rate applications, the capacity requirements in hotspots and the appeal of direct peer-to-peer communication between two MTs. It is basically introduced by reducing the transmission power of the MTs to decrease the transmission (communication) range and by allowing for peer-to-peer and multi-hop communication.

There are several benefits and possibilities arising from the transmission range reduction. First, the energy efficiency is improved and modulation schemes achieving higher data transmission rates can be employed. In addition, the transmission capacity of the resulting multi-hop cellular network is potentially increased due to the reduced interference and the potential for multiple simultaneous transmissions (spatial frequency reuse). These short-range, multi-hop, low-power transmissions can potentially provide for increased capacity (through spatial frequency reuse and higher data rates), increased coverage (by extending coverage away from the vicinity of the AP through multi-hop paths) and decreased power consumption (through reducing the transmission power) [1].

Nevertheless, when traffic is destined to the backbone Internet, the destination within the wireless cell is always the AP. As a result, the channel around the AP becomes a bottleneck, limiting the throughput performance of the multi-hop network to even below that of the pure cellular network [2]. Moreover, the throughput of a multi-hop cellular network is compromised by the vulnerability of multi-hop paths due to topology changes caused mainly by mobility (link failures). Even under low mobility conditions, the paths consisted of shorter-range hops are short-living and frequent route discoveries are required to maintain paths wasting, at the same time, a significant part of the available bandwidth. Since a shorter transmission range impacts negatively on connectivity, the density of MTs within a cell and the topology can affect the effectiveness of the multi-hop network. Besides, the distributed nature of the routing protocols and QoS support in such networks further compromise the potential benefits that the ad hoc networking paradigm may introduce in WLANs.

The quality of a multi-hop connection depends strongly on the transmission power, the propagation characteristics of the frequency used, as well as the distance between the source and the destination. As the transmission power – and thus the transmission range – decreases, the number of hops needed to reach a certain destination increases. In this case, higher signal-to-noise-ratio values are achieved as interference is reduced but, at the same time, the more frequent link failures, the additional delay and the protocol overhead reduce the potential benefits [3]. As shown in [4], more than half of the transmission capacity is spent on routing, medium access and protocol control packets in a typical ad hoc network.

By reducing the transmission range and allowing for peer-to-peer and multi-hop communication, the ad hoc networking paradigm may increase substantially the nominal network capacity. When single-hop, peer-to-peer communications take place, both the transmission rate (due to the shorter distance) and the potential for spatial frequency reuse are maximized. If most of the transmissions are of this type and uniformly spread within the cell, the network capacity is greatly increased. The picture may be different though if the aforementioned uniformity is absent and most of the traffic is directed toward the AP and the spatial frequency reuse potential disappears, as discussed before. Moreover, if multi-hop (as opposed to single-hop) transmissions dominate, then the potential for spatial frequency reuse is drastically reduced, as the needed transmissions associated with the path cover a potentially large part of the cell. The higher transmission rate achieved over a shorter-range-hop, single-hop path is also significantly compromised in multi-hop paths, due to the need for relaying through intermediate nodes; relaying requires the MT to switch between receiving and transmitting modes, which further reduces the end-to-end throughput. The employed multi-hop network is hard to fairly allocate resources among the MTs, as well as avoid frequent network partitions and route failures.

In addition, although the reduction of the transmission power can result in decreased overall energy consumption, short-range-hop, multi-hop paths may induce additional transmissions – as a result of the more frequent link failures – that can negate the potential energy savings benefits.

III. PERFORMANCE OF SHORT-RANGE-HOP, MULTI-HOP NETWORKS

Multi-hop networks typically employ ranges of no more than 15m in WLAN cells for indoor hotspot applications, where the coverage of the AP does not exceed 50m. In typical pure ad hoc networks, ranges of 150m-250m have been considered [4]. Consequently, it is expected that shorter-range-hop, multi-hop paths deployed within a WLAN are short-living and more vulnerable to mobility. Moreover, the feasibility of multi-hop paths is questionable.

To address all the above issues taking into consideration the potential spatial reuse and higher capacity induced by multi-hop networks, a cell of 100mX100m with 50 moving MTs has been simulated in ns-2 [5]. Simulations were run for 300 seconds. The results were averaged over 5 runs for each scenario.

Four different *levels*, l, of short-range communication have been defined and considered inside a WLAN cell based on the physical distance (in m) between the MTs; $l \in \{6, 8, 12, 15\}$. Two MTs that are d meters apart can establish a level l communication as long as $0.8l \leq d \leq 1.2l$. A sequence of n MTs each of which is away from the preceding MT by some distance in *(0.8l, 1.2l)* is said to form a level l path of length *(n-1)* hops.

Mobility has been modelled using the *random waypoint model*. Each MT starts its journey from a random location and moves toward a random des-

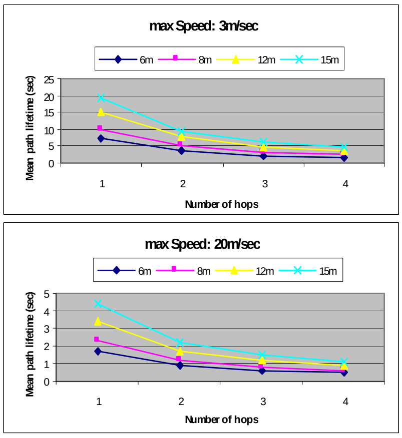

Fig. 1. Mean path lifetime versus the number of hops

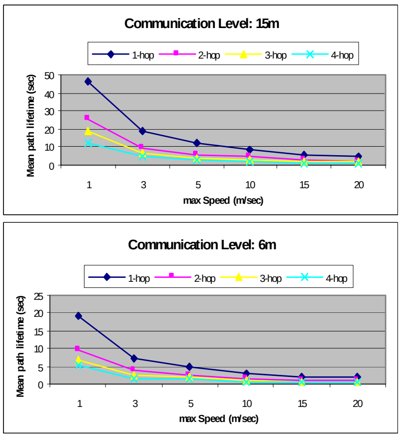

Fig. 2. Mean path lifetime versus MT speeds

tination at a randomly chosen speed v (uniformly distributed between 0 and v_{max} (in m/sec), where $v_{max} \in \{1, 3, 5, 10, 15, 20\}$). Once the destination is reached, another random destination is targeted after a pause. In indoor applications, low max MT speeds (less than 3-5m/sec) are expected. Nevertheless, the attenuation is higher in low-power transmissions and, thus, such transmissions are more vulnerable to indoor environments (where signals would have to penetrate obstacles to reach a destination). Higher values for v_{max} (up to 20m/sec) have also been used to capture this latter vulnerability. For the same reason, all results that are presented here correspond to a pause time of 0sec.

Fig. 1 presents the mean lifetime of paths for different levels of communication as a function of their length (in number of hops) and for v_{max} equal to 3m/sec and 20m/sec; paths of up to four hops are considered. As expected, for a given communication level the mean path lifetime decreases with the path length and, for a given path length, it increases with the communication level. It decreases by a factor of one half for two-hop paths and significantly less for longer-hop paths. While higher communication level paths last longer on the average, it should be noted that the associated power consumption increases and the potential for spatial reuse decreases. If the latter two factors are not of a concern, then in such an environment higher communication levels should be considered to construct longer-living paths. Notice that paths of level 15m last more than 2-3 times longer than those of level 6m, depending on their length.

The impact of MT speed on the mean path lifetime is shown in Fig. 2. It may be observed that under low MT speeds ($v_{max} \leq 5m/sec$) the decrease rate of the mean path lifetime is much higher than under higher speeds ($10m/sec \leq v_{max} \leq 20m/sec$). Consequently, mobility is expected to impact significantly on the lifetime of the paths expected in indoor environments (low MT speed). Paths of more than two hops have low lifetime even for high communication levels and low mobility.

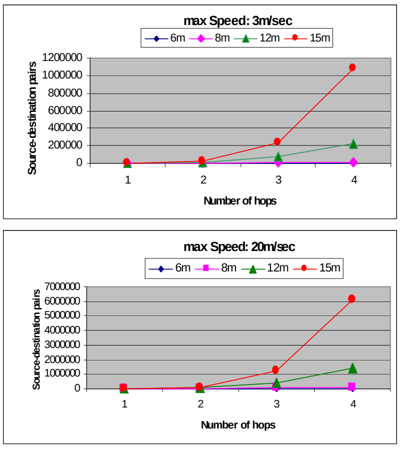

Fig. 3. Source-destination pairs versus the number of hops

The results of Fig. 3 show the efficiency of a multi-hop network in terms of the number of source-destination pairs that can be supported over time for different communication levels. The number of source-destination pairs measures the network's capability to satisfy traffic requirements inside the cell. The more the source-destination pairs a communication level is capable of supporting, the higher the potential throughput achieved by the WLAN.

In Fig. 3, the number of source-destination pairs of each level of communication is illustrated as a function of the number of hops in a path for max MT speeds of 3m/sec and 20m/sec and for 50 MTs inside a cell. These pairs have been measured for the entire simulation duration of 300secs. As the number of considered hops or the speed increases, more source-destination pairs can be served. For short distances (6m and 8m), the increase of source-destination pairs is not apparent since there are only few available paths.

The number of destinations a multi-hop network may reach represents the level of connectivity; as the speed increases more paths can be established but, at the same time, their lifetime is shorter. While short distances provide for the potential for a higher spatial reuse (and capacity) inside the cell, connectivity may be compromised and network partitions occur, as shown in Fig. 4 and Fig. 5.

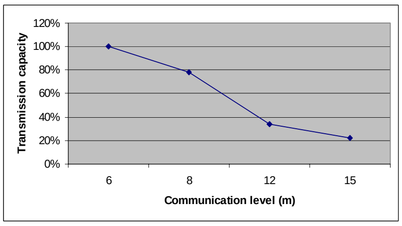

Fig. 4. Transmission capacity versus the communication level

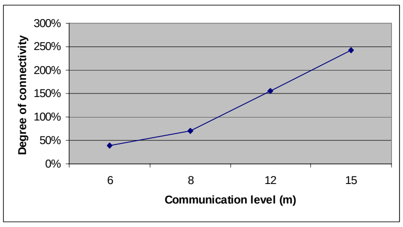

Fig. 5. Degree of connectivity versus the communication level

In Fig. 4, the transmission capacity is defined as the percentage of the MTs inside the cell that can concurrently transmit without interfering with any other MT. The transmission capacity has been calculated based on the dimensions of the simulated area and the MT coverage range for each communication level. As it is expected, with the increase of the communication range, the interference increases and the potential simultaneous transmissions decrease.

In Fig. 5, the degree of connectivity is defined as the average (over all 50 MTs) of the fraction of time that a MT can communicate with a neighbor multiplied by the number of neighbors. Thus, if a MT had 1 neighbor for 5% and 2 neighbors for 10% of the total simulation time then its degree of connectivity would be 25%. The results of Fig. 5 have been derived by averaging results from all mobility scenarios used. For shorter ranges, where the potential for frequency reuse is increased, connectivity is harder to maintain and partitions are more frequent. On the other hand, longer ranges may induce higher level of network connectivity and increase the potential for alternate routes (through other one-hop away neighbors), but they limit the potential for frequency reuse since the interference is increased.

The number of source-destination pairs were measured for 10, 20, 30, 40 and 50 MTs inside a cell, a communication level of 15m and a max MT speed of 3m/sec. As depicted in Fig. 6 – where results are shown for a time interval of 10secs – the number of supported source-destination pairs is very limited in low-density cells, to the point of questioning the effectiveness of a multi-hop network of any range. For the one or two-hop paths, the number of source-destination pairs in low-density cells is negligible.

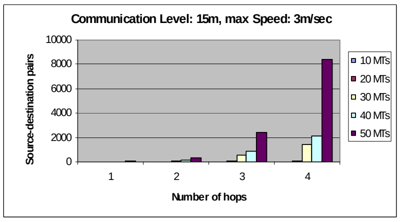

Fig. 6. Number of source-destination pairs versus the number of hops and the number of MTs in a cell

From the above results and discussion, it is evident that the introduction of a short-range-hop, multi-hop paradigm in a WLAN may lead to serious inefficiencies and a compromised performance compared to that of a typical longer-range-hop, pure, ad hoc network. On one hand, the short ranges result in higher transmission rates and benefits of spatial frequency reuse but, on the other, they lead to more unstable and error-prone paths and a lower degree of connectivity that is less of a problem in high density cells.

IV. INTEGRATING AD HOC NETWORKS IN (INFRASTRUCTURE-BASED) WLANS

Although short-range-hop, multi-hop networks turn out to be very ineffective under inter-cell traffic conditions [2], enabling peer-to-peer direct communication between MTs is of value. It would be necessary to support rare, heavy load, bursty, peer-to-peer communications over short-range-hop, one-hop or even multi-hop paths, that take advantage of spatial frequency reuse of the shared medium and offload the main resources in the cellular network.

One way of enhancing the performance of WLANs through the ad hoc networking paradigm is by maintaining the infrastructure of the WLAN (centralized mode of operation) and enabling peer-to-peer communications (ad hoc mode of operation) inside the cell by using different channels of the same frequency band, or other frequency bands that can provide for ample bandwidth and high rates. This way, two non-interfering modes of operation will be possible. Such a dual mode system is currently under development utilizing the 60 GHz band for the ad hoc mode of operation [6].

The induced dual mode of operation may be better managed if the AP controls the resources for both the centralized and the ad hoc frequency channels. One can take advantage of the existing AP to also improve the employed ad hoc network within its cell by implementing synchronization, power-saving mechanisms and resource allocation in a centralized manner. The network performance can be further enhanced by allowing for more than one ad hoc channels. The main challenge to address, in order to take advantage of the potential benefits of the short-range-hop, multi-hop networks in the (infrastructure-based) WLANs, is the efficient management of the dual mode of operation.

To enable the centralized control in the dual mode of operation, two main processes are needed: one process that allows the AP to discover the ad hoc network topology (called *Neighborhood Discovery*) and one process that provides for the routing information (establishment of paths for both modes) needed for the in-cell traffic (called *Path Selection*).

In case there are multiple transmitters, the communication between the MTs and the AP is always possible. In the case of MTs with one transmitter – to keep the device cost low – MTs are tuned to one frequency channel at a time and have to occasionally switch between different frequencies at the cost of the induced switching time. The AP can have multiple transmitters to participate in both topologies.

A. Neighborhood Discovery (ND)

The ND process provides information about the ad hoc topology to the AP by discovering the directly reachable neighbors (one-hop away) of all MTs inside the cell and measuring the quality of the corresponding links. Every MT and the AP participate in ND by exchanging *hello* messages and maintain neighborhood information in the form of a list containing the neighbors and the status of the corresponding links. This information is sent to the AP, which is responsible for the path selection.

The AP decides when ND should be performed. It may be done periodically or be event-driven based on several criteria such as: the available bandwidth at the centralized frequency, the density of users inside the cell, the number of new users in the system, the detected link breakages at the ad hoc frequency and time elapsed since the last ND process. The AP sends a broadcast message to inform all MTs inside its coverage area indicating the frequency channel that is used for ND (in case of more than one), the time instant at which this procedure is initiated and potentially the transmission schedule of the hello messages.

The MTs and the AP exchange hello messages based on their MAC IDs, in order to determine their one-hop away neighbors and construct their *link state tables.* After receiving its neighbors' hello messages, each MT can determine the state of each link with their one-hop away neighbors by measuring the signal-to-noise-ratio provided by the physical layer. Depending on the measured link state, different transmission rates (and communication levels) may be achieved. At the end, the MTs forward the collected information to the AP.

B. Path Selection

The AP makes routing decisions based on the information collected during the ND process. This information is stored in a table and is updated at the end of the ND process. The AP manages all resource requests from the MTs inside the cell by looking up this table and establishes connections either at the centralized frequency channel or at the ad hoc channels. The connections at the centralized frequency are more reliable while the shorter-range ad hoc links can offer substantially higher rates. Moreover, the availability of the WLAN bandwidth is limited in hotspots and, consequently, paths at the ad hoc channels will have to be used. The AP selects a path considering the associated link states for the ad hoc mode of operation. Other quality metrics such as the remaining battery lifetime of the involved MTs may be considered.

Upon a resource request arrival, the AP determines the candidate ad hoc paths for the specific source-destination pair. If there is ad hoc connectivity, the most efficient path is identified; efficiency may be defined based on metrics such as: the number of hops, the link states, the present allocation of resources for the ad hoc channels and the kind of application to support (required bit rates). In case there is no WLAN bandwidth available, the most efficient ad hoc path identified is utilized. In case there is WLAN bandwidth available, it may be utilized instead of the most efficient ad hoc path identified. Such a decision could be based on criteria such as the quality and bandwidth of the identified ad hoc path (number of hops, link states, achievable transmission rates, etc.) and the amount of unutilised WLAN bandwidth. If there is neither ad hoc connectivity nor WLAN bandwidth available, the connection cannot be established and the resource request is resubmitted in the future.

C. Overhead of the ND process in a dual-band, single-transmitter WLAN

The performance and effectiveness of the dual mode of operation is affected by the additional required control overhead. This overhead is due to the ND process and the extra messages needed to establish an ad hoc connection. For the results that are presented in this section, the framework of [6] has been considered where the MTs have to switch between frequencies in order to guarantee connectivity within a HiperLAN/2 cell and allow for the establishment of ad hoc paths. The ND process is responsible for most of control overhead since – unlike in pure ad hoc networks – it requires that the system remains inactive until it is completed. For this reason, it should not be executed frequently. On the other hand, this process needs to be repeated frequently as it provides useful information for the establishment of ad hoc paths. Clearly, there is a trade off here that needs to be considered carefully. In typical ad hoc networks, information regarding the MTs' neighborhood may be obtained in a similar way like the one described for the ND process, here. The difference is that the exchange of control packets is distributed and relies on the synchronization of each MT and the specific parameters of each algorithm applied. In case the synchronization of MTs is centralized, the exchange of hello messages is scheduled so that they do not interfere with on-going data transmissions – as may be the case in typical ad hoc networks; the need for switching between the ad hoc and the centralized channel may further increase the induced overhead although, at the same time, it separates control from data packets.

In Fig. 7 and Fig. 8, the dependence of the overhead of the ND process from the number of hops that constitute a path, the number of MTs inside the cell and mobility is shown. The ND overhead is defined as the fraction of time during which ND is performed (including the required switching time to tune at the

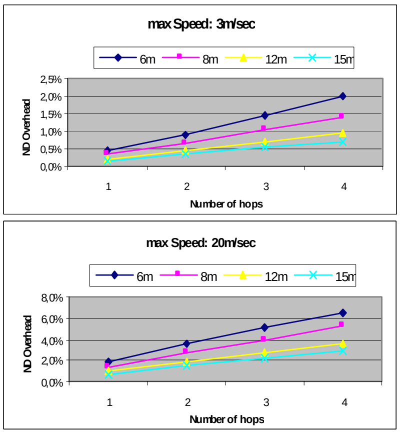

Fig. 7. ND overhead versus the number of hops (for 200 users in a cell)

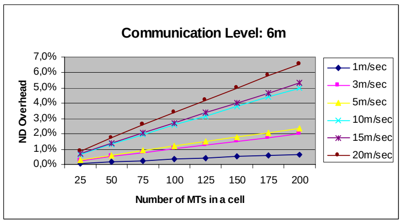

Fig. 8. ND overhead of four-hop paths of level 6m versus the number of MTs inside a cell (for different MT speeds)

predefined frequency channel of the ND process [6]). The number of MTs inside a cell affects the ND overhead since it affects its duration. ND is assumed to be periodically performed with such a period that more than 90% of the calculated paths do not break between two consecutive NDs for the specific speed and communication level. Fig. 7 illustrates the cases for a max speed of 3m/sec and 20m/sec and for 200 users in the cell. Since the paths that consist of more hops have shorter lifetime, more overhead is required to support them (the ND process is performed more frequently).

The minimum (maximum) ND overhead is calculated to be approximately 0,17% (below 7%) for the case of 200 users for one-hop (four-hop) communication of level 15m (6m) and max MT speed of 1m/sec (20m/sec). In Fig. 8, the ND overhead of four-hop paths of level 6m (most vulnerable) is illustrated for all max MT speeds considered. As the speed increases, more overhead is required to maintain 90% of the paths due to the higher probability of link failure.

In Fig. 9, the percentage of increase of the source-destination pairs as a function of the overhead of the ND process is shown for the case of max MT speed of 3m/sec, for the paths of communication level 15m and for 50 MTs inside a cell. It is shown that a low increase in the induced ND overhead can result in a huge increase in the number of source-destination pairs.

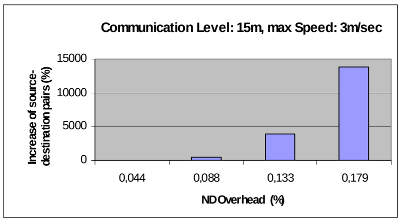

Fig. 9. Increase of source-destination pairs versus ND overhead

V. CONCLUSIONS

Present WLANs need to be enhanced to accommodate the demanding emerging applications in densely populated areas. Current proposals suggest the introduction of the ad hoc networking paradigm drifting away from the cellular paradigm towards short-range-hop, multi-hop networks. As it has also been argued recently elsewhere, it is shown through simulations that such an approach is ineficient and is expected to lead to a worse performance under typical traffic conditions. The benefits of the increased transmission rate (due to the shorter-transmission range) and spatial reuse, may be more than compensated for by the instability of (and overhead in managing) the multi-hop paths, the error-prone conditions under low-power transmissions, as well as the non-uniformity of source-destination (within the cell) pairs that is very likely to create a bottleneck at the AP.

For the aforementioned reasons, it is argued in this paper that the cellular networking paradigm should coexist with an introduced ad hoc networking one and rely on the support of the former to mitigate the inherent weaknesses of the latter. Thus, a coexistence and synergy between the two paradigms is advocated in this paper and it is proposed that different frequency channels or bands be utilized to allow for it. In addition to the apparent benefits of a centralized path establishment and routing in the ad hoc network (supported by the maintained cellular infrastructure), it is shown through simulations that the Neighborhood Discovery overhead (including MT switching time between the different frequencies, as an operation at one frequency at a time is assumed for cost reduction) is low. Thus, an integration of a second (ad hoc) mode of operation inside the traditional cellular mode is a promising approach for enhancing current WLAN capabilities.

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