6

Multi Radio Resource Management over WiMAX-WiFi Heterogeneous Networks: Performance Investigation*

Alessandro Bazzi[1] and Gianni Pasolini[2†]
[1]*IEIIT-BO/CNR, Wilab*
[2]*DEIS-University of Bologna, Wilab*
Italy

1. Introduction

In an early future communication services will be accessed by mobile devices through heterogeneous wireless networks given by the integration of the radio access technologies (RATs) covering the user area, including, for instance, WiMAX and WLANs. Today, except for rare cases, it is a choice of the user when and how using one RAT instead of the others: for example, WiFi based WLANs (IEEE-802.11, 2005) would be the favorite choice if available with no charge, while WiMAX or cellular technologies could be the only possibility in outdoor scenarios.

The automatic selection of the best RAT, taking into account measured signal levels and quality-of-service requirements, is the obvious next step, and it has somehow already begun with modern cellular phones, that are equipped with both 2G and 3G technologies: depending on the radio conditions they are able to seamlessly switch from one access technology to the other following some adaptation algorithms. Indeed, all standardization bodies forecast the interworking of heterogeneous technologies and thus put their efforts into this issue: IEEE 802.21 (*IEEE802.21*, 2010), for instance, is being developed by IEEE to provide a protocol layer for media independent handovers; IEEE 802.11u (IEEE802.11u, 2011) was introduced as an amendment to the IEEE 802.11 standard to add features for the interworking with other RATs, and the unlicensed mobile access (UMA) and its evolutions have been included as part of 3GPP specifications ((3GPP-TS-43.318, 2007) and (3GPP-TR-43.902, 2007)) to enable the integration of cellular technologies and other RATs.

It appears clear that the joint usage of available RATs will be a key feature in future wireless systems, although it poses a number of critical issues mainly related to the architecture of future heterogeneous networks, to security aspects, to the signalling protocols, and to the

---

*©2008 IEEE. Reprinted, with permission, from "TCP Level Investigation of Parallel Transmission over Heterogeneous Wireless Networks", by A. Bazzi and G. Pasolini, Proceedings of the IEEE International Conference on Communications, 2008 (ICC '08).

†This chapter reflects the research activity made in this field at WiLAB (http://www. wilab.org/) over the years. Authors would like to acknowledge several collegues with which a fertile research environment has been created, including O. Andrisano, M. Chiani, A. Conti, D. Dardari, G. Leonardi, B.M. Masini, G. Mazzini, V. Tralli, R. Verdone, and A. Zanella.

multi radio resource management (MRRM) strategies to be adopted in order to take advantage of the multi-access capability.

Focusing on MRRM, the problem is how to effectively exploit the increased amount of resources in order to improve the overall quality-of-service provided to users, for instance reducing the blocking probability or increasing the perceived throughput.

Most studies on this topic assume that the generic user equipment (UE) is connected to one of the available RATs at a time, and focus the investigation on the detection of smart strategies for the optimum RAT choice, that is, for the optimum RAT selection and RAT modification (also called vertical handover); for example in (Fodor et al., 2004) the overall number of admitted connections is increased by taking into account the effectiveness of the various RATs to support specific services; the same result is also achieved in (Bazzi, 2010) by giving a higher priority to those RATs with smaller coverage, and in (Song et al., 2007) by using a load balancing approach.

Besides considering the different RATs as alternative solutions for the connection set-up, their parallel use is also envisioned, in order to take advantage of the multi-radio transmission diversity (MRTD) (Dimou et al., 2005) (Sachs et al., 2004), which consists in the splitting of the data flow over more than one RAT, according to somehow defined criteria. Different approaches have been proposed to this scope, having different layers of the protocol stack in mind: acting at higher layers, on the basis of the traffic characteristics, entails a lower capacity to promptly follow possible link level variations, whereas an approach at lower layers requires particular architectural solutions. In (Luo et al., 2003) the generation of different data flows at the application layer for video transmission or web-browsing (base video layer/enhanced video layer and main objects/in line objects, respectively) is proposed: the most important flow is then served through the most reliable link, such as a cellular connection, while the secondary flow is transmitted through a cheaper connection, such as a WiFi link. In (Hsieh & Sivakumar, 2005), separation is proposed at the transport layer, using one TCP connection per RAT. A transport layer solution is also proposed in (Iyengar et al., 2006), that introduces the concurrent multipath transfer (CMT) protocol based on the multihoming stream control transmission protocol (SCTP). A network level splitting is supposed in (Chebrolu & Rao, 2006; Dimou et al., 2005), and (Bazzi et al., 2008). Coming down through the protocol stack, a data-link frame distribution over two links (WiFi and UMTS) is proposed in (Koudouridis et al., 2005) and (Veronesi, 2005). At the physical layer, band aggregation is supposed for OFDM systems (for example, in (Batra et al., 2004) with reference to UWB) and other solutions that sense the available spectrum and use it opportunistically are envisioned in cognitive radios (Akyildiz et al., 2006).

Hereafter both the alternative and the parallel use of two RATs will be considered. In particular, a scenario with a point of access (PoA) providing both WiMAX and WiFi coverage will be investigated, and the performance level experienced by "dual-mode users" is assessed considering the three following MRRM strategies:

- *autonomous RAT switching*: the RAT to be used for transmission is selected on the basis of measurements (e.g, received power strength) carried out locally by the transmitter, hence with a partial knowledge of RATs'status;
- *assisted RAT switching*: the RAT to be used for transmission is selected not only on the basis of local measurements, but also on the basis of information exchanged with MRRM entities;
- *parallel transmission*: each UE connects at the same time to both RATs.

This chapter is organized as follows: the investigation outline, with assumptions, methodology and considered performance metric, is reported in Section 2; Section 3 and Section 4 introduce and discuss the MRRM strategies for multiple RATs integration; numerical results are shown in Section 5, with particular reference to the performance of an integrated WiFi-WiMAX network; the final conclusions are drawn in Section 6.

2. Investigation assumptions and methodology

Architectural issues

From the viewpoint of the network architecture, the simplest solution for heterogeneous networks integration is the so-called "loose coupling": different networks are connected through gateways, still maintaining their independence. This scenario, that is based on the mobile IP paradigm, is only a little step ahead the current situation of completely independent RATs; in this case guaranteeing seamless (to the end user) handovers between two RATs is very difficult, due to high latencies, and the use of multiple RATs at the same time is unrealistic.

At the opposite side there is the so-called "tight-coupling": in this case different RATs are connected to the same controller and each of them supports a different access modality to the same "core network". This solution requires new network entities and is thus significantly more complex; on the other hand it allows fast handovers and also parallel use of multiple RATs. For the sake of completeness, therefore, the scenario here considered consists of a tight-coupled heterogeneous network, that, for the scope of this chapter, integrates WiMAX and WiFi RATs.

Technologies. As already discussed, here the focus is on a WiMAX and WiFi heterogeneous network, where the following choices and assumptions have been made for the two RATs:

- *WiMAX.* We considered the IEEE802.16e WirelessMAN-OFDMA version (IEEE802.16e, 2006) operating with 2048 OFDM subcarriers and a channelization bandwidth of $7MHz$ in the $3.5GHz$ band; the time division duplexing (TDD) scheme was adopted as well as a frame duration of $10ms$ and a 2:1 downlink:uplink asymmetry rate of the TDD frame.
- *WiFi.* The IEEE802.11a technology (IEEE802.11a, 1999) has been considered at the physical level of the WLAN, thus a channelization bandwidth of 20 MHz in the 5 GHz band and a nominal transmission rate going from 6 Mb/s to 54 Mb/s have been assumed. At the MAC layer we considered the IEEE802.11e enhancement (IEEE802.16e, 2006), that allows the quality-of-service management.

Service and performance metric. The main objective of this chapter is to derive and compare the performance provided by a WiFi-WiMAX integrated network when users equipped with dual-mode terminals perform downlink best effort connections. The performance metric we adopted is the throughput provided by the integrated WiFi-WiMAX network. As we focused our attention, in particular, on best effort traffic, we assumed that the TCP protocol is adopted at the transport layer and we derived, as performance metric, the TCP layer throughput perceived by the final user performing a multiple RATs download.

Let us observe, now, that several TCP versions are available nowadays; it is worth noting, on this regard, that the choice of the particular TCP version working in the considered scenario is not irrelevant when the *parallel transmission* strategy is adopted. For this reason in Section

4 the issue of interactions between the TCP protocol and the *parallel transmission* strategy is faced, and the expected throughput is derived.

Investigation methodology. Results have been obtained partly analytically and partly through simulations, adopting the simulation platform SHINE that has been developed in the framework of several research projects at WiLab. The aim of SHINE is to reproduce the behavior of RATs, carefully considering all aspects related to each single layer of the protocol stack and all characteristics of a realistic environment. This simulation tool, described in (Bazzi et al., 2006), has been already adopted, for example, in (Andrisano et al., 2005) to investigate an UMTS-WLAN heterogeneous network with a *RAT switching* algorithm for voice calls.

MRRM Strategies. In this chapter the three previously introduced MRRM strategies are investigated:

- *autonomous RAT switching*;
- *assisted RAT switching*;
- *parallel transmission*.

In the case of the *autonomous RAT switching* strategy, the decision on the RAT to be adopted for data transmission is taken only considering signal-quality measurements carried out by the transmitter. This the simplest solution: the RAT providing the highest signal-quality is chosen, no matter the fact that, owing to different traffic loads, the other RAT could provide a higher throughout.

As far as the *assisted RAT switching* is concerned, we assumed that an entity performing MRRM at the access network side periodically informs the multi-mode UE about the throughput that can be provided by the different RATs, which is estimated by the knowledge of the signal-quality, the amount of users, the scheduling policy, etc. This entails that in the case of UE initiated connections, the UE has a complete knowledge of the expected uplink throughput over the different RATs. In the case of network initiated connections all information is available at the transmitter side, hence the expected downlink throughput is already known.

The *parallel transmission* strategy, at last, belongs to the class of MRTD strategy, that acts scheduling the transmission of data packets over multiple independent RATs. This task can be accomplished either duplicating each packet, in order to have redundant links carrying the same information, or splitting the packet flow into disjointed sub-flows transmitted by different RATs. In this chapter we considered the latter solution, that is, the parallel transmission "without data duplication" modality. We made the (realistic) assumption that the entity performing MRRM is periodically informed on the number of IP packets transmitted by each technology as well as on the number of IP packets still waiting (in the data-link layer queues) to be transmitted; by the knowledge of these parameters a decision on the traffic distribution over the two RATs is taken, as detailed later on. Let us observe that this assumption is not critical since the entity performing MRRM and the front-end of the jointly used RATs are on the same side of the radio link, thus no radio resource is wasted for signalling messages.

3. RAT switching strategies

The adoption of *RAT switching* strategies (both the *autonomous RAT switching* and the *assisted RAT switching*) does not require significant modifications in the in the PoA/UE behavior except for what concerns vertical handovers. When a dual-mode (or multi-mode) UE or the PoA somehow select the favorite RAT, then they act exactly as in a single RAT scenario. Most of the research effort is thus on the vertical handovers management, in order to optimize the resource usage, maintaining an adequate quality-of-service and acting seamlessly (i.e., automatically and without service interruptions).

Although the tight coupling architecture is with no doubt the best solution to allow prompt and efficient vertical handovers, also loose coupling can be used. In the latter case some advanced technique must be implemented in order to reduce the packet losses during handovers: for example, packets duplication over the two technologies during handovers is proposed for voice calls in (Ben Ali & Pierre, 2009), for video streaming applications in (Cunningham et al., 2004), and for TCP data transfers in (Naoe et al., 2007) and (Wang et al., 2007). (Rutagemwa et al., 2007) and (Huang & Cai, 2006) suggest to use the old connection in downlink until the base-station's queue is emptied while the new connection is already being used for the uplink. Since the issue of vertical handover is besides the scope of this work, hereafter vertical handovers are assumed to be possible and seamless to the end user.

Independently on how multiple RATs are connected and how the vertical handover is performed, there must be an entity in charge of the selection of the best RAT. A number of metrics can be used to this aim, such as, for instance, the perceived signal level or the traffic load of the various RATs. The easiest way to implement a RAT switching mechanism is that each transmitter (at the PoA and the UE) performs some measurements on its own and then selects what it thinks is the best RAT. This way, no information concerning MRRM is exchanged between the UE and the network.

Let us observe, however, that the PoA and the UE have a different knowledge on RAT's status: the PoA knows both link conditions (through measurements of the received signal levels, for instance) and traffic loads of each RAT; the UE, on the contrary, can only measure the link conditions. It follows that without an information exchange between the PoA and the UE, the RAT choice made by the UE (in case of UE initiated connection) could be wrong, owing to unbalanced traffic loads. We define this simple, yet not optimal, MRRM strategy as *autonomous RAT switching*.

A more efficient MRRM is possible if some signalling protocol is available for the exchange of information between the UE and the PoA; a possible implementation could relay, for example, on the already mentioned IEEE 802.21 standard, as done for example in (Lim et al., 2009). The MRRM strategy hereafter denoted as *assisted RAT switching*, assumes that the PoA informs the UE of the throughput that can be guaranteed by each RAT, taking into account also the actual load of the network. It is obviously expected that the increased complexity allows a better distribution of UEs over the various RATs.

4. Parallel transmission strategy

From the viewpoint of network requirements, the adoption of the *parallel transmission* strategy is more demanding with respect to the two *RAT switching* strategies above discussed.

In this case, in fact, the optimal traffic distribution between the different RATs must be continuously derived, on the basis of updated information on their status. It follows that interactions between the entity performing the MRRM and the front-end of the RATs should be as fast as possible, thus making the tight coupling architecture the only realistic architectural solution. Apart from the need of updated information, the loose coupling architecture would introduce relevant differences in the delivery time of packets transmitted over the different technologies, thus causing reordering/buffering problems at the receiver.

Indeed, also in the case of tight coupling architecture, the different delivery delays that the *parallel transmission* strategy causes on packets transmitted by different RATs conflict with the TCP behavior.

For this reason in the following subsections the issue of interactions between the TCP and the *parallel transmission* strategy is thoroughly discussed.

4.1 TCP issues

The most widespread versions of the TCP protocol (e.g., New Reno (NR) TCP (Floyd & Henderson, 1999)) work at best when packets are delivered in order or, at least, with a sporadic disordering. A frequent out-of-order delivery of TCP packets originates, in fact, useless duplicates of transport layer acknowledgments; after three duplicates a packet loss is supposed by the transport protocol and the Fast Recovery - Fast Retransmit phase is entered at the transmitter side.

This causes a significant reduction of the TCP congestion-window size and, as a consequence, a reduction of the throughput achievable at the transport layer.

This aspect of the TCP behavior has been deeply investigated in the literature (e.g. (Bennett et al., 1999) and (Mehta & Vaidya, 1997)) and modern communication systems, such as WiMAX, often include a re-ordering entity at the data-link layer of the receiver in order to prevent possible performance degradation.

Let us observe, now, that when the *parallel transmission* strategy is adopted, each RAT works autonomously at data-link and physical layers, with no knowledge of other active RATs. During the transmission phase, in fact, the packets flow coming from the upper layers is split into sub-flows that are passed to the different data-link layer queues of the active RATs and then transmitted independently one of the others.

It follows that the out-of-order delivery of packets and the consequent performance degradation are very likely, owing to possible differences of the queues occupation levels as well as of the medium access strategies and to the transmission rates of active RATs.

The independency of the different RATs makes very difficult, however, to perform a frame reordering at the data-link layer of the receiver and, at the same time, it would be preferable to avoid, for the sake of simplicity, the introduction of an entity that collects and reorders TCP packets coming from different RATs. For this reason, the adoption of particular versions of TCP, especially designed to solve this problem, is advisable in multiple RATs scenarios.

Here we considered the adoption of the Delayed Duplicates New Reno version of TCP (DD-TCP) (Mehta & Vaidya, 1997), which simply delays the transmission of TCP acknowledgments when an out-of-order packet is received, hoping that the missing packet is already on the fly.

The DD-TCP differs from the NR-TCP only at the receiving side of the transport layer peer-to-peer communication; this implies that the NR-TCP can be maintained at the transmitter side. Thus, this solution could be adopted, at least, on multi-mode user terminals, where the issue of out-of-order packet delivery is more critical owing to the higher traffic load that usually characterizes the downlink phase.

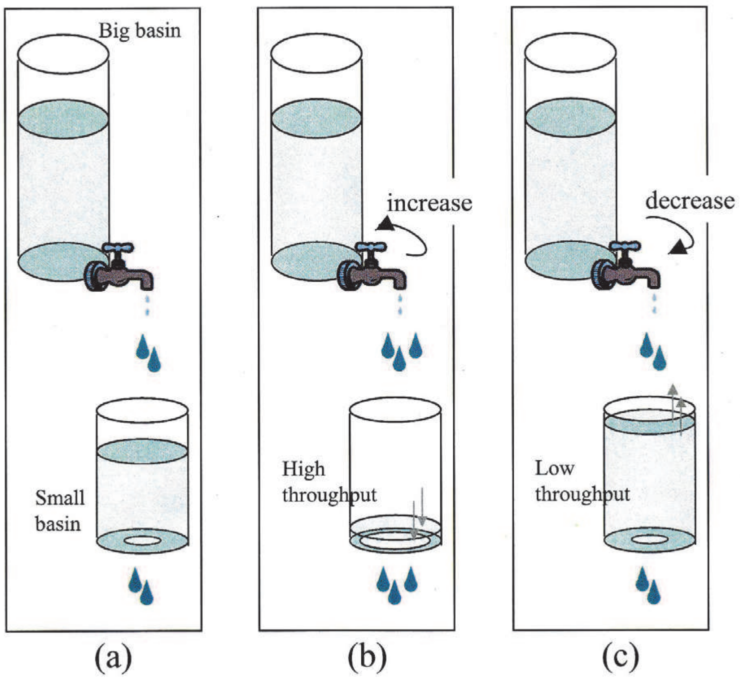


Fig. 1. Representation of the TCP mechanism.

The above introduced critical aspects of the TCP protocol and its interaction with the MRRM strategy in the case of *parallel transmission* are further investigated in the following, where an analytical model of the throughput experienced by the final user is derived.

Let us consider, to this aim, an heterogeneous network which is in general constituted by RATs whose characteristics could be very different in terms, for instance, of medium access strategies and transmission rates.

It is straightforward to understand that, in the case of *parallel transmission*, the random distribution of packets with uniform probability over the different RATs would hardly be the best solution. Indeed, to fully exploit the availability of multiple RATs and get the best from the integrated access network, an efficient MRRM strategy must be designed, able to properly balance the traffic distribution over the different access technologies.

In order to clarify this statement, a brief digression on the TCP protocol behavior is reported hereafter, starting from a simple metaphor.

Let us represent the application layer queue as a big basin (in the following, big basin) filled with water that represents the data to be transmitted (see Fig. 1-a). Another, smaller, basin (in the following, small basin) represents, instead, the data path from the source to the receiver: the size of the data-link layer queue can be represented by the small basin size and the transmission speed by the width of the hole at the small basin bottom.

In this representation the TCP protocol works like a tap controlling the amount of water to be passed to the small basin in order to prevent overflow events (a similar metaphor is used, for example, in (Tanenbaum, 1996)). It follows that the water flow exiting from the tap represents the TCP layer throughput and the water flow exiting from the small basin represents the data-link layer throughput.

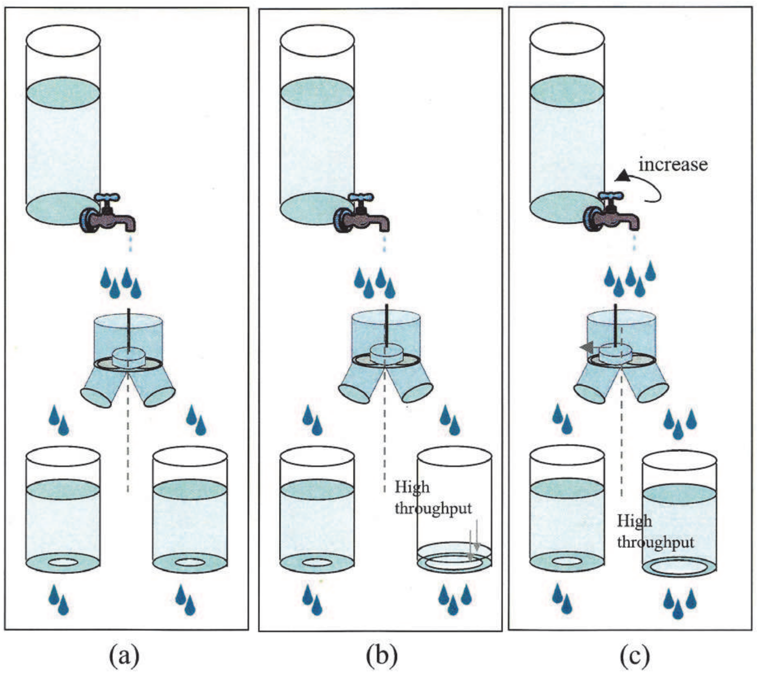


Fig. 2. Representation of the TCP mechanism with parallel transmission over two RATs.

As long as the small basin is characterized by a wide hole, as depicted in Fig. 1-b, the tap can increase the water flow, reflecting the fact that when a high data-link layer throughput is provided by the communication link, the TCP layer throughput can be correspondingly increased.

When, on the contrary, a small hole (→ a low data-link layer throughput) is detected, the tap (→ the TCP protocol) reduces the water flow (→ the TCP layer throughput), as described in Fig. 1-c. This way, the congestion control is performed and the saturation of the data-link layer queues is avoided.

Now the question is: what happens when two basins (that is, two RATs) are available instead of one and the water flow is equally split between them?

Having in mind that the tap has to prevent the overflow of either of the two small basins, it is easy to understand that, in the presence of two small basins with the same hole widths, the tap could simply double the water flow, as depicted in Fig. 2-a.

In the presence of a small basin with a hole wider than the other (see Fig. 2-b), on the other hand, the tap behavior is influenced by the small basin characterized by the lower emptying rate (the leftmost one in Fig. 2-b), which is the most subject to overflow. This means that the availability of a further "wider holed" basin is not fully exploited in terms of water flow increase. Reasoning in terms of TCP protocol, in fact, the congestion window moves following the TCP layer acknowledgments related to packets received in the correct order. This means that, as long as a gap is present in the received packet sequence (one or more packets are missing because of a RAT slower than the other), the congestion window does not move at the transmitter side, thus reducing the throughput provided.

Coming back to the water flow metaphor, it is immediate to understand that, in order to fully exploit the availability of the further, "more performing", small basin, the water flow splitting modality must be modified in such a way that the water in the two small basins is kept at almost the same level (see Fig. 2-c). This consideration introduces in our metaphor the concept of resource management, which is represented in Fig. 2-c by the presence of a valve which dynamically changes the sub-flows discharge.

This concept, translated in the telecommunication-correspondent MRRM concept, will be thoroughly worked out in Section 4.4. To do this, however, an analytical formulation of the expected throughput in the case of multiple RATs adopting the *parallel transmission* strategy is needed, which is reported in the following subsection.

4.2 Throughput analytical derivation

Starting from the above reported considerations, we can derive a simple analytical framework to model the average throughput T perceived by the final user in the case of two heterogeneous RATs, denoted in the following as RAT_A and RAT_B, managed by an MRRM entity which splits the packet flow between RAT_A and RAT_B with probabilities P_A and $P_B = 1 - P_A$, respectively.

Focusing the attention on a generic user, let us denote with T_i the maximum data-link layer throughput supported by RAT_i in the direction of interest (uplink or downlink), given the particular conditions (signal quality, network load due to other users, ...) experienced by the user. Dealing with a dual mode user, we will denote with T_A and T_B the above introduced metric referred to RAT_A and RAT_B respectively.

Let us assume that a block of N transport layer packets of B bits has to be transmitted and let us denote with O the amount of overhead bits added by protocol layers from transport to data-link. After the MRRM operation the N packet flow is split into two sub-flows of, in average, $N \cdot P_A$ and $N \cdot P_B$ packets, which are addressed to RAT_A and RAT_B.

It follows that, in average, RAT_A and RAT_B empty their queues in $D_A = \frac{N\cdot(B+O)\cdot P_A}{T_A}$ and $D_B = \frac{N\cdot(B+O)\cdot P_B}{T_B}$ seconds, respectively.

Thus, the whole N packets block is delivered in a time interval that corresponds to the longest between D_A and D_B.

This means that the average TCP layer throughput provided by the integrated access network to the final user can be expressed as:

$$T = \begin{cases} \frac{N\cdot B}{D_A} = \frac{T_A}{P_A}\xi & \text{when } D_A > D_B\text{, that is when } \frac{T_A}{P_A} < \frac{T_B}{P_B}; \\ \frac{N\cdot B}{D_B} = \frac{T_B}{P_B}\xi & \text{in the opposite case, when } \frac{T_A}{P_A} \geq \frac{T_B}{P_B}\ , \end{cases} \tag{1}$$

or, in a more compact way, as:

$$T = min\left\{\frac{T_A\xi}{P_A}, \frac{T_B\xi}{P_B}\right\}, \tag{2}$$

where the factor $\xi = B/(B+O)$ takes into account the degradation due to the overhead introduced by protocol layers from transport to data-link.

Let us observe, now, that the term $T_A\xi/P_A$ of (2) is a monotonic increasing function of $P_B = 1 - P_A$, while the term $T_B\xi/P_B$ is monotonically decreasing with P_B.

Since $\frac{T_A}{P_A} < \frac{T_B}{P_B}$ when P_B tends to 0 and $\frac{T_A}{P_A} > \frac{T_B}{P_B}$ when P_B tends to 1, it follows that the maximum TCP layer throughput T_{max} is achieved when $\frac{T_A}{P_A} = \frac{T_B}{P_B}$, that is when:

$$P_A = P_A^{(max)} = \frac{T_A}{T_A + T_B}\ , \tag{3}$$

and consequently

$$P_B = P_B^{(max)} = 1 - P_A^{(max)} = \frac{T_B}{T_A + T_B}, \tag{4}$$

having denoted with $P_A^{(max)}$ and $P_B^{(max)}$ the values of P_A and P_B that maximize T.

Recalling (2), the maximum TCP layer throughput is immediately derived as:

$$T_{max} = min\left\{\frac{T_A\xi}{P_A}, \frac{T_B\xi}{P_B}\right\}\Bigg|_{P_A=P_A^{(max)}} = (T_A + T_B)\xi, \tag{5}$$

thus showing that a TCP layer throughput as high as the sum of the single TCP layer throughputs can be achieved.

Eqs. (3) and (4) show that an optimal choice of P_A and P_B is possible, in principle, on condition that accurate and updated values of the data-link layer throughput T_A and T_B are known (or, equivalently, accurate and updated values of the TCP layer throughput $T_A\xi$ and $T_B\xi$).

4.3 Parallel transmission strategy: Throughput model validation

In order to validate the above described analytical framework, a simulative investigation has been carried out considering the integration of a WiFi RAT and a WiMAX RAT, which interact according to the *parallel transmission* strategy.

The user is assumed located near the PoA that hosts both the WiMAX base station and the WiFi access point, thus perceiving a high signal-to-noise ratio.

Packets are probabilistically passed by the MRRM entity to the WiFi data-link/physical layers with probability P_{WiFi} (which corresponds to P_A in the general analytical framework) and to the WiMAX data-link/physical layers with probability $1 - P_{WiFi}$ (which corresponds to P_B in the general analytical framework), both in the uplink and in the downlink.

The simulations outcomes are reported in Fig. 3, where the average throughput perceived at the TCP layer is shown as a function of P_{WiFi} (see the curve marked with the circles).

In the same figure we also reported the average throughput predicted by (2), assuming $T_A\xi$ referred to the WiFi RAT and $T_B\xi$ to the WiMAX RAT.

The values of $T_A\xi$ and $T_B\xi$ adopted in (2) have been derived by means of simulations for each one of the considered technologies, obtaining $T_{WiFi} = T_A\xi = 18.53$ Mb/s and $T_{WiMAX} = T_B\xi = 12.76$ Mb/s.

With reference to Fig. 3, let us observe, first of all, the very good matching between the simulation results and the analytical curves derived from (2), which confirms the accuracy of the whole framework. Moreover, from (3) and (5) it is easy to derive $P_A^{(max)} = P_{WiFi} = 0.59$ and $T_{max} = 31.29$ Mb/s, in perfect agreement with the coordinates of the maximum that can be observed in the curve reported in Fig. 3.

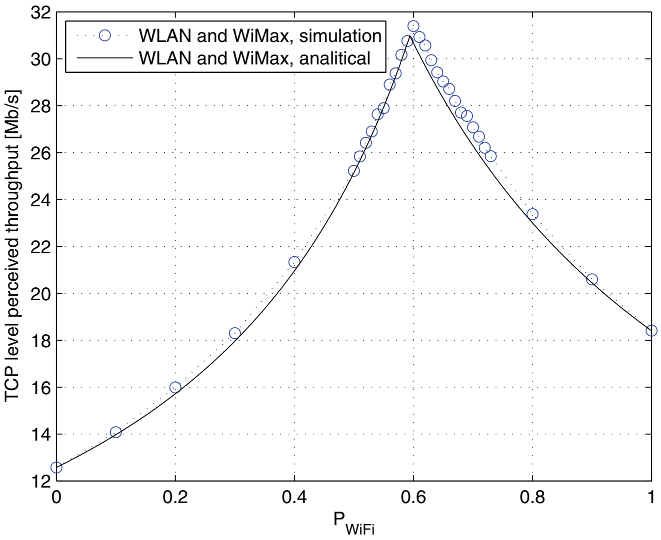


Fig. 3. TCP layer throughput provided by a WiFi-WiMAX heterogeneous network, as a function of the probability that the packet is transferred through the WiFi.

Let us observe, moreover, the rapid throughput degradation resulting from an uncorrect choice of P_{WiFi}. This means that the correct assessment of P_{WiFi} heavily impacts the system performance.

4.4 Traffic-management strategy

The results reported in Fig. 3 showed that in the case of *parallel transmission* the random distribution of packets with uniform probability over the two technologies is not the best solution. On the contrary, to fully exploit the availability of multiple RATs, an efficient traffic-management strategy must be designed, able to properly balance the traffic distribution over the different access technologies.

In order to derive the throughput realistically provided to the final user adopting the *parallel transmission* strategy, we must therefore check whether the optimum traffic balance can be actually achieved or not. In other words, we need to check whether a really effective traffic-management strategy, allowing the user terminal to automatically “tune and track” the optimal traffic distribution, exists or not.

For this reason we conceived an original traffic-management strategy, that we called *Smoothed Transmissions over Pending Packets (Smooth-Tx/Qu)*, that works as follows: packets are always passed to the technology with the higher ratio between the number of packets transmitted up to the present time and the number of packets waiting in the data-link queue; thus, system queues are kept filled proportionally to the transmission speed. The number of transmitted packets is halved every T_{half} seconds (in our simulations we adopted $T_{half} = 0.125$ s) in order to reduce the impact of old transmissions, thus improving the achieved performance in a scenario where transmission rates could change (due to users mobility, for instance).

The performance of such strategy have been investigated evaluating the throughput experienced by a single user in a scenario consisting of a heterogeneous access network with one IEEE802.11a-WiMAX PoA. Transmission *eirp* of 20 dBm and 40 dBm have been assumed for IEEE802.11a and WiMAX, respectively. The throughput provided by each technology

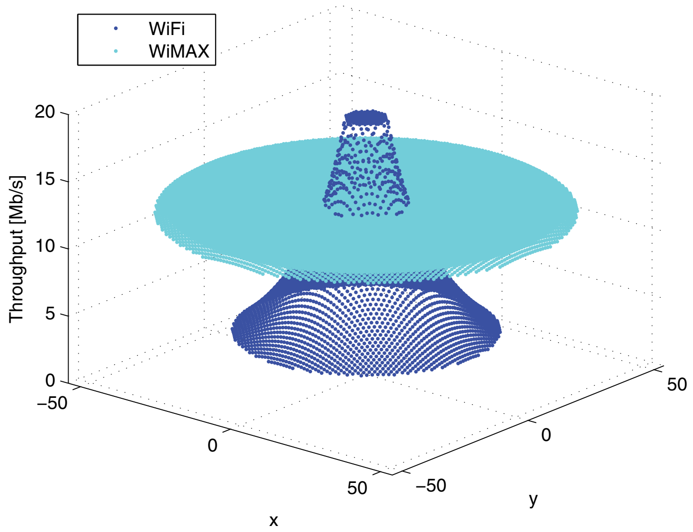


Fig. 4. The investigated scenario.

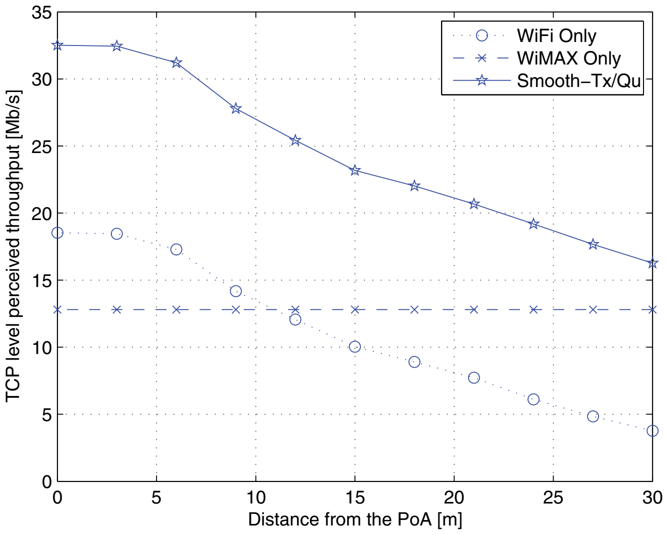


Fig. 5. WiFi-WiMAX heterogeneous networks. TCP layer throughput varying the distance of the user from the access point/base station, for different MRRM schemes. No mobility.

within the area of overlapped coverage is depicted in Fig. 4, where the couple $(x, \ y)$ represents the user's coordinates.

The user is performing an infinite file download and does not change its position. The outcomes of this investigation are reported in Fig. 5, that shows the average perceived TCP layer throughput as a function of the distance from the PoA.

Before discussing the results reported in Fig. 5, a preliminary note on the considered distance range $(0 - 30 \text{ m})$ is needed.

Let us observe, first of all, that WiMAX is a long range communications technology, with a coverage range in the order of kilometers. Nonetheless, since our focus is on the heterogeneous WiFi-WiMAX access network, we must consider coverage distances in the

User position/behavior	WiFi only	WiMAX only	Smooth Tx/Qu
1 Still, near the PoA	18.53	12.76	32.37
2 Still, 30 m far from the PoA	3.81	12.76	16.40
3 Moving away at 1 m/s, starting from the PoA	11.83	12.76	25.01
4 Near the PoA for half sim., then 30 m far away	10.04	12.61	21.03

Table 1. TCP layer average throughput. Single user, 1 WiFi access point and 1 WiMAX base station co-located. 10 seconds simulated.

order of few dozens of meters (i.e., the coverage range of a WiFi), where both RATS are available; for this reason the x-axis of Fig. 5 ranges from 0 to 30 meters.

The different curves of Fig. 5 refer, in particular, to the traffic-management strategy above described and, for comparison, to the cases of a single WiFi RAT and of a single WiMAX RAT.

Of course, when considering the case of a single WiMAX RAT, the throughput perceived by an user located in the region of interest is always at the maximum achievable level, as shown by the flat curve in Fig. 5. As expected, on the contrary, the throughput provided by WiFi in the same range of distances rapidly decreases for increasing distances.

The most important result reported in Fig. 5, however, is related to the upper curve, that refers to the previously described traffic-management strategy when applied in the considered heterogeneous WiFi-WiMAX network. As can be immediately observed, the throughput provided by this strategy is about the sum of those provided by each single RAT, which proves the effectiveness of the proposed traffic-management strategy.

The impact of the user's position and mobility has also been investigated: the results are reported in Table 1 and are related to four different conditions:

1. the user stands still near the PoA (optimal signal reception),
2. the user stands still at 30 m from the access PoA (optimal WiMAX signal, but medium quality WiFi signal),
3. the user moves away from the PoA at a speed of 1 m/s (low mobility),
4. the user stands still near the PoA for half the simulation time, then it moves instantaneously 30 m far away (reproducing the effect of a high speed mobility).

Results are shown for the above described traffic-management strategy as well as for the benchmark scenarios with a single WiFi RAT and a single WiMAX RAT and refer to the average (over the 10 s simulated time interval) throughput perceived in each considered case.

As can be observed the proposed strategy provide satisfying performance in all cases, thus showing that the optimum traffic balance between the different RATs can be achieved.

5. Performance comparison

In the previous section we derived the throughput provided to a single user when the *parallel transmission* strategy is adopted; in this section we also derive the performance of the *autonomous RAT switching* strategy and the *assisted RAT switching* strategy and we extend the investigation to the case of more than one user.

To this aim we considered the same scenario previously investigated, with co-located WLAN access point and WiMAX base station. The resource is assumed equally distributed among connections within each RAT; this assumption means that the same number of OFDMA-slots is given to UEs in WiMAX and that the same transmission opportunity is given to all UEs in WiFi (i.e., they transmit in average for the same time interval, as permitted by IEEE802.11e, that has been assumed at the MAC layer of the WiFi).

In Fig. 6, the complementary cumulative distribution function ($ccdf$) of the perceived throughput is shown when $N = 1, 2, 3, 5, 10$, and 20 users are randomly placed in the coverage area of both technologies: for a given value $\overline{T}$ of throughput (reported in the abscissa), the corresponding $ccdf$ provides the probability that the throughput experienced by an user is higher than $\overline{T}$.

For each value of N, 1000 random placements of the users were performed; the already discussed MRRM strategies are compared:

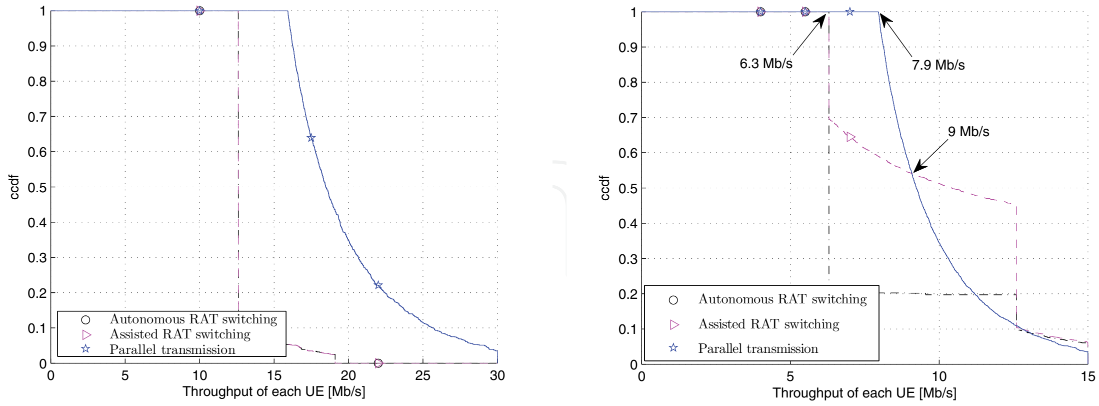
- *autonomous RAT switching*;
- *assisted RAT switching*;
- *parallel transmission*.

With reference to Fig. 6(a), that refers to the case of a single user, there is obviously no difference adopting the *autonomous RAT switching* strategy or the *assisted RAT switching* strategy. In the absence of other users the choice made by the two strategies is inevitably the same: WiFi is used at low distance from the PoA, while WiMAX is preferred in the opposite case.

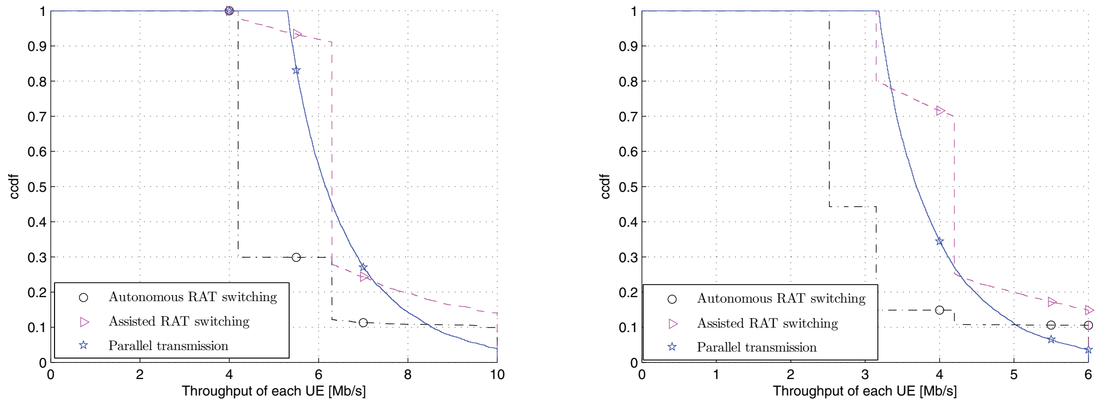
The results reported in Fig. 6(a) also confirm that in the case of a single user the perceived throughput can significantly increase thanks to the use of the *parallel transmission* strategy, as discussed in Section 4.4. The significant improvement provided in this case by the *parallel transmission* strategy is not surprising: in the considered case of a single user, in fact, both the *autonomous RAT switching* strategy and the *assisted RAT switching* strategy leave one of the two RATs definitely unused, which is an inauspicious condition.

This consideration suggests that the number of users in the scenario plays a relevant role in the detection of the best MRRM strategy, thus the following investigations, whose outcomes are reported in figures from 6(b) to 6(f), refer to scenarios with $N = 2, 3, 5, 10$, and 20 users, respectively. As can be observed, when more than one user is considered the *dynamic RAT switching* always outperforms the *no RAT switching* and the advantage of using the *parallel transmission* strategy becomes less clear.

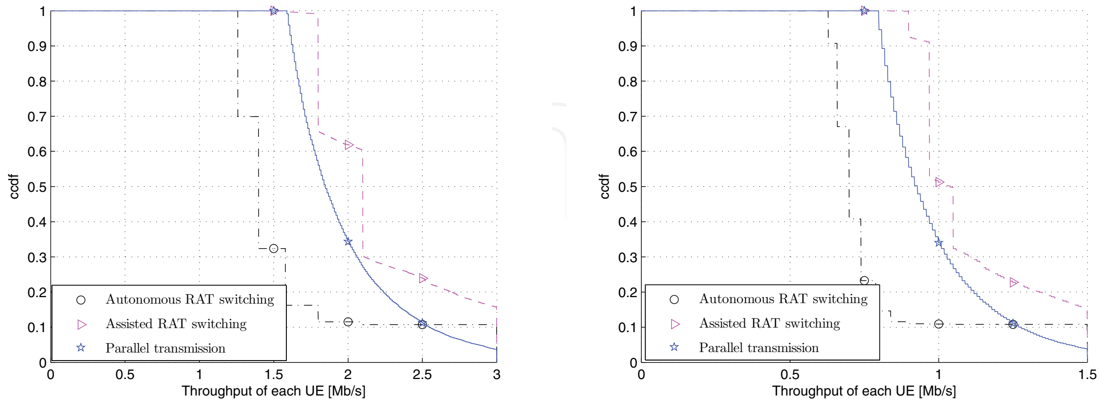
Let us focus our attention, now, on Fig. 6(b), that refers to the case of $N = 2$ users randomly placed within the scenario. When the *parallel transmission* strategy is adopted, the 100% of users perceive a throughput no lower than 7.9 Mb/s, whereas the *autonomous RAT switching* strategy and the *assisted RAT switching* strategies provides to the 100% of users a throughput no lower than 6.3 Mb/s. It follows that, at least in the case of $N = 2$ users, the *parallel transmission* strategy outperforms the other strategies in terms of minimum guaranteed throughput. Fig. 6(b) also shows that with the *parallel transmission* strategy the probability of perceiving a throughput higher than 9 Mb/s is reduced with respect to the case of the *assisted RAT switching* strategy. This should not be deemed necessarily as a negative aspect:



(a) One user. (b) Two users.



(c) Three users. (d) Five users.



(e) Ten users. (f) Twenty users.

Fig. 6. $Ccdf$ of the throughput perceived by N users randomly placed in the scenario.

everything considered we can state, in fact, that the parallel transmission strategy is fairer than the assisted RAT switching strategy (at least in the case of N = 2 users), since it penalizes lucky UEs (those closer to the PoA) providing a benefit to unlucky users.

Increasing the number of users to $N = 3, 5, 10$, and 20 (thus referring to Figs. 6(c), 6(d), 6(e), and 6(f), respectively), the *autonomous RAT switching* strategy confirms its poor performance with respect to both the other strategies, while the $ccdf$ curve related to the *assisted RAT switching* strategy moves rightwards with respect to the *parallel transmission* curve, thus making the *assisted RAT switching* strategy preferable as the number of users increases.

Let us observe, however, that passing from $N = 10$ to $N = 20$ users, the relative positions of the $ccdf$ curves related to the *parallel transmission* strategy and the *assisted RAT switching* strategy do not change significantly and the gap between the two curves is not so noticeable. It follows that in scenarios with a reasonable number of users the *parallel transmission* strategy could still be a good (yet suboptimal) choice, since, differently from the *assisted RAT switching* strategy, no signalling phase is needed.

6. Conclusions

In this chapter the integration of RATs with overlapped coverage has been investigated, with particular reference to the case of a heterogeneous WiFi-WiMAX network.

Three different MRRM strategies (*autonomous RAT switching*, *assisted RAT switching* and *parallel transmission*) have been discussed, aimed at effectively exploiting the joint pool of radio resources. Their performance have been derived, either analytically or by means of simulations, in order to assess the benefit provided to a "dual-mode" user. In the case of the *parallel transmission* over two technologies a traffic distribution strategy has been also proposed, in order to overcome critical interactions with the TCP protocol.

The main outcomes of our investigations can be summarized as follows:

- in no case the *autonomous RAT switching* strategy is the best solution;
- in the case of a single user the *parallel transmission* strategy provides a total throughput as high as the sum of throughputs of the single RATs;
- the *parallel transmission* strategy generates a disordering of upper layers packets at the receiver side; this issue should be carefully considered when the parallel transmission refers to a TCP connection;
- as the number of users increases the *assisted RAT switching* strategy outperforms the *parallel transmission* strategy.

7. References

3GPP-TR-43.902 (2007). Technical specification group gsm/edge radio access network; enhanced generic access networks (egan) study; v10.0.0; (release 10).

3GPP-TS-43.318 (2007). Technical specification group gsm/edge radio access network; generic access network (gan); v10.1.0; stage 2 (release 10).

Akyildiz, I. F., Lee, W.-Y., Vuran, M. C. & Mohanty, S. (2006). Next generation/dynamic spectrum access/cognitive radio wireless networks: a survey, *Computer Networks* 50(13): 2127 – 2159.

Andrisano, O., Bazzi, A., Diolaiti, M., Gambetti, C. & Pasolini, G. (2005). Umts and wlan integration: architectural solution and performance, *Personal, Indoor and Mobile Radio*

Communications, 2005. PIMRC 2005. IEEE 16th International Symposium on, Vol. 3, pp. 1769 –1775 Vol. 3.

Batra, A., Balakrishnan, J. & Dabak, A. (2004). Multi-band OFDM: a new approach for UWB, *Circuits and Systems, 2004. ISCAS '04. Proceedings of the 2004 International Symposium on*.

Bazzi, A. (2010). Wlan hot spots to increase umts capacity, *Personal Indoor and Mobile Radio Communications (PIMRC), 2010 IEEE 21st International Symposium on*, pp. 2488 –2493.

Bazzi, A., Pasolini, G. & Andrisano, O. (2008). Multiradio resource management: Parallel transmission for higher throughput?, *EURASIP Journal on Advances in Signal Processing* 2008. 9 pages.

Bazzi, A., Pasolini, G. & Gambetti, C. (2006). Shine: Simulation platform for heterogeneous interworking networks, *Communications, 2006. ICC '06. IEEE International Conference on*, Vol. 12, pp. 5534 –5539.

Ben Ali, R. & Pierre, S. (2009). On the impact of soft vertical handoff on optimal voice admission control in PCF-based WLANs loosely coupled to 3G networks, *IEEE Transactions on Wireless Communications* 8: 1356 – 1365.

Bennett, J., Partridge, C. & Shectman, N. (1999). Packet reordering is not pathological network behavior, *Networking, IEEE/ACM Transactions on* 7(6): 789 –798.

Chebrolu, K. & Rao, R. (2006). Bandwidth aggregation for real-time applications in heterogeneous wireless networks, *Mobile Computing, IEEE Transactions on* 5(4): 388 – 403.

Cunningham, G., Perry, P. & Murphy, L. (2004). Soft, vertical handover of streamed video, *5th IEE International Conference on Mobile Communication Technologies, 2004. (3G 2004).*, IEE, London, UK, pp. 432 – 436.

Dimou, K., Agero, R., Bortnik, M., Karimi, R., Koudouridis, G., Kaminski, S., Lederer, H. & Sachs, J. (2005). Generic link layer: a solution for multi-radio transmission diversity in communication networks beyond 3G, *Vehicular Technology Conference, 2005. VTC-2005-Fall. 2005 IEEE 62nd*.

Floyd, S. & Henderson, T. (1999). The newreno modification to tcp's fast recovery algorithm, *Request for Comments: 2582*, pp. 1 –11.

Fodor, G., Furuskär, A. & Lundsjö, J. (2004). On access selection techniques in always best connected networks, *In Proc. ITC Specialist Seminar on Performance Evaluation of Wireless and Mobile Systems*.

Hsieh, H.-Y. & Sivakumar, R. (2005). A transport layer approach for achieving aggregate bandwidths on multi-homed mobile hosts, *Wireless Networks* 11: 99–114.

Huang, H. & Cai, J. (2006). Adding network-layer intelligence to mobile receivers for solving spurious TCP timeout during vertical handoff., *IEEE Network* 20: 24 – 31.

IEEE-802.11 (2005). Iso/iec standard for information technology - telecommunications and information exchange between systems - local and metropolitan area networks - specific requirements part 11: Wireless lan medium access control (mac) and physical layer (phy) specifications (includes ieee std 802.11, 1999 edition; ieee std 802.11a.-1999; ieee std 802.11b.-1999; ieee std 802.11b.-1999/cor 1-2001; and ieee std 802.11d.-2001), *ISO/IEC 8802-11 IEEE Std 802.11 Second edition 2005-08-01 ISO/IEC 8802 11:2005(E) IEEE Std 802.11i-2003 Edition* pp. 1 –721.

IEEE802.11a (1999). Supplement to ieee standard for information technology - telecommunications and information exchange between systems - local and metropolitan area networks - specific requirements. part 11: Wireless lan medium access control (mac) and physical layer (phy) specifications: High-speed physical layer in the 5 ghz band, *IEEE Std 802.11a-1999* p. i.

IEEE802.11u (2011). Ieee standard for information technology-telecommunications and information exchange between systems-local and metropolitan networks-specific requirements-part ii: Wireless lan medium access control (mac) and physical layer (phy) specifications: Amendment 9: Interworking with external networks, *IEEE Std 802.11u* p. i.

IEEE802.16e (2006). Ieee standard for local and metropolitan area networks part 16: Air interface for fixed and mobile broadband wireless access systems amendment 2: Physical and medium access control layers for combined fixed and mobile operation in licensed bands and corrigendum 1, *IEEE Std 802.16e-2005 and IEEE Std 802.16-2004/Cor 1-2005 (Amendment and Corrigendum to IEEE Std 802.16-2004)* pp. 1 –822.

IEEE802.21 (2010).
URL: *http://www.ieee802.org/21/*

Iyengar, J., Amer, P. & Stewart, R. (2006). Concurrent multipath transfer using SCTP multihoming over independent end-to-end paths, *Networking, IEEE/ACM Transactions on* 14(5): 951 –964.

Koudouridis, G., Karimi, H. & Dimou, K. (2005). Switched multi-radio transmission diversity in future access networks, *Vehicular Technology Conference, 2005. VTC-2005-Fall. 2005 IEEE 62nd*.

Lim, W.-S., Kim, D.-W., Suh, Y.-J. & Won, J.-J. (2009). Implementation and performance study of ieee 802.21 in integrated ieee 802.11/802.16e networks, *Computer Communications* 32(1): 134 – 143.

Luo, J., Mukerjee, R., Dillinger, M., Mohyeldin, E. & Schulz, E. (2003). Investigation of radio resource scheduling in WLANs coupled with 3G cellular network, *Communications Magazine, IEEE* 41(6): 108 – 115.

Mehta, M. & Vaidya, N. (1997). Delayed duplicate acknowledgments: A proposal to improve performance of tcp on wireless links, *Tech. Rep., Texas A&M University* .

Naoe, H., Wetterwald, M. & Bonnet, C. (2007). IPv6 soft handover applied to network mobility over heterogeneous access networks., *IEEE 8th International Symposium on Personal, Indoor and Mobile Radio Communications, 2007. (PIMRC 2007).*, IEEE, Athens, Greece, pp. 1–5.

Rutagemwa, H., Pack, S., Shen, X. & Mark, J. (2007). Robust cross-layer design of wireless-profiled TCP mobile receiver for vertical handover., *IEEE Transactions on Vehicular Technology.* 56: 3899 – 3911.

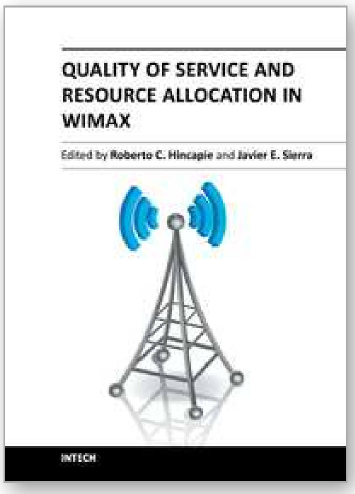
Sachs, J., Wiemann, H., Lundsjo, J. & Magnusson, P. (2004). Integration of multi-radio access in a beyond 3g network, *Personal, Indoor and Mobile Radio Communications, 2004. PIMRC 2004. 15th IEEE International Symposium on*, Vol. 2, pp. 757 – 762 Vol.2.

Song, W., Zhuang, W. & Cheng, Y. (2007). Load balancing for cellular/wlan integrated networks, *IEEE Network* 21: 27–33.

Tanenbaum, A. S. (1996). *Computer Networks*, Prentice Hall, Upper Saddle River, NJ.

Veronesi, R. (2005). Multiuser scheduling with multi radio access selection, *Wireless Communication Systems, 2005. 2nd International Symposium on*, pp. 455 –459.

Wang, N.-C., Wang, Y.-Y. & Chang, S.-C. (2007). A fast adaptive congestion control scheme for improving TCP performance during soft vertical handoff., *IEEE Wireless Communications and Networking Conference, 2007. (WCNC 2007).*, IEEE, Hong Kong, pp. 3641–3646.



QUALITY OF SERVICE AND RESOURCE ALLOCATION IN WIMAX

Edited by Roberto C. Hincapie and Javier E. Sierra

INTECH

Quality of Service and Resource Allocation in WiMAX
Edited by Dr. Roberto Hincapie

ISBN 978-953-307-956-1
Hard cover, 376 pages
Publisher InTech

Published in print edition February, 2012

This book has been prepared to present state of the art on WiMAX Technology. It has been constructed with the support of many researchers around the world, working on resource allocation, quality of service and WiMAX applications. Such many different works on WiMAX, show the great worldwide importance of WiMAX as a wireless broadband access technology. This book is intended for readers interested in resource allocation and quality of service in wireless environments, which is known to be a complex problem. All chapters include both theoretical and technical information, which provides an in depth review of the most recent advances in the field for engineers and researchers, and other readers interested in WiMAX.

Alessandro Bazzi and Gianni Pasolini (2012). Multi Radio Resource Management over WiMAX-WiFi Heterogeneous Networks: Performance Investigation, Quality of Service and Resource Allocation in WiMAX, Dr. Roberto Hincapie (Ed.), ISBN: 978-953-307-956-1, InTech, Available from: http://www.intechopen.com/books/quality-of-service-and-resource-allocation-in-wimax/multi-radio-resource-management-over-wimax-wifi-heterogeneous-networks-performance-investigation

InTech Europe
University Campus STeP Ri
Slavka Krautzeka 83/A
51000 Rijeka, Croatia
Phone: +385 (51) 770 447
Fax: +385 (51) 686 166
www.intechopen.com

InTech China
Unit 405, Office Block, Hotel Equatorial Shanghai
No.65, Yan An Road (West), Shanghai, 200040, China
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
Fax: +86-21-62489821