Ad-Hoc Behavior in Opportunistic Radio

Shahid Mumtaz, Paulo Marques, Atilio Gameiro, and Jonathan Rodriguez

Abstract: **The application of mathematical analysis to the study of wireless ad hoc networks has met with limited success due to the complexity of mobility, traffic models and the dynamic topology. A scenario based universal mobile telecommunications system (UMTS) time division duplex (TDD) opportunistic cellular system with an ad hoc behaviour that operates over UMTS frequency division duplex (FDD) licensed cellular network is considered. In this paper, we present a new routing metric which overall improves system performance in terms of interference and routing which operate in an ad hoc network in an opportunistic manner. Therefore we develop a simulation tool that addresses the goal of analysis and assessment of UMTS TDD opportunistic radio system with ad hoc behavior in coexistence with a UMTS FDD primary cellular networks.**

Index Terms: **Ad-hoc network, opportunistic radios (OR), routing.**

I. INTRODUCTION

Wireless communications play a very important role in military networks and networks for crisis management, which are characterized by their ad hoc heterogeneous structure. An example of a future network can be seen in Fig. 1. This illustrates a range of future wireless ad hoc applications. A common theme running throughout is the multiplicity of node types and capabilities, link capacities and potential for data aggregation. In this scenario we consider permanent presence of a high altitude platform (HAP) [1] or other form of aerial platform to provide communications support. The advantage of aerial platform based assets is the wide area coverage, which can be exploited when designing such networks. In the heterogeneous ad hoc network, it is difficult to develop plans that will cope with every eventuality, particularly hostile threats, due to the temporary nature. Thus, dynamic management of such networks represents the ideal situation where the new emerging fields of cognitive networking and cognitive radio can play a part. Here, we assume a cognitive radio is a radio that can change its transmitter parameters based on interaction with the environment where it operates [2], and additionally relevant here is the radio's ability to look for, and intelligently assign spectrum 'holes' on a dynamic basis from within primarily assigned spectral allocations. The detecting of holes and the subsequent use of the unoccupied spectrum is referred to as opportunistic use of the spectrum. An opportunistic radio (OR) is the term used to describe a radio that is capable of such operation [3]. In this paper we use the opportunistic radio system which was proposed in [4] that shares the spectrum with an universal mobile telecommunications system (UMTS) cellular network. This is motivated by the fact that UMTS radio frequency spectrum has become, in a significant number of countries, a very expensive commodity, and therefore the opportunistic use of these bands could be one way for the owners of the licenses to make extra revenue.

The OR system exploits the UMTS uplink (UL) bands, therefore, the UMTS base station, likely far from the opportunistic radio, creates local opportunities due to the path loss and shadowing between the OR transmitter and the UMTS base station. These potential opportunities in UMTS frequency division duplex (FDD) UL bands are in line with the interference temperature metric proposed by the federal communications commission (FCC) spectrum policy task force [5]. The interference temperature model manages interference at the receiver through the interference temperature limit, which is represented by the amount of new interference that the receiver could tolerate. As long as OR users do not exceed this limit by their transmissions, they can use this spectrum band. However, handling interference is the main challenge in code division multiple access (CDMA) networks, therefore, the interference temperature concept should be applied in UMTS licensed bands in a very careful way. In this paper we propose how an ad hoc behavior uses in an opportunities radio and with careful selections of routing schemes, we minimize overall interference level on the UMTS base station.

This paper is organized as follows: In Section II the scenario is defined. In Section III explains the opportunistic network with ad hoc topology. In Section IV explains coexistence analysis for a single opportunistic radio link. In Section V coexistence analysis for ad hoc opportunistic networks are explains and conclusions are made in Section VI.

II. SCENARIO DEFENITION

The UMTS is a direct sequence (DS)-CDMA system, thus all users transmit the information spreaded over 5 MHz bandwidth at the same time and therefore users interfere with one another. Fig. 2 shows a typical UMTS FDD paired frequencies. The asymmetric load creates spectrum opportunities in UL bands since the interference temperature (amount of new interference that the UMTS base station (BS) can tolerate) is not reached. In order to fully exploit the unused radio resources in UMTS, the OR network should be able to detect the vacant channelization codes using a classification technique [6]. Thus, the OR network could communicate using the remaining spreading codes which are orthogonal to the used by the UMTS network. However, classifying and identifying CDMA's codes is a very computational intensive task for real time applications.

Moreover, synchronization between UMTS UL signals and the OR signals to keep the ortogonality between codes will be a difficult problem. Our approach is to fill part of the available interference temperature raising the noise level above the

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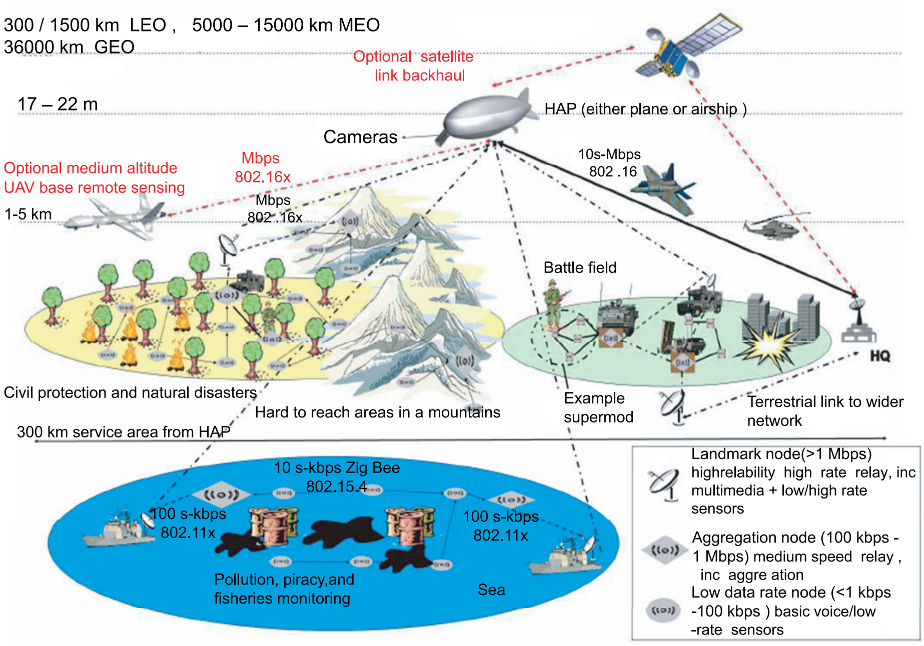

Fig. 1. Ad-hoc future network.

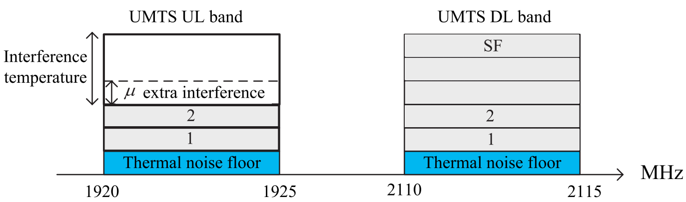

Fig. 2. UMTS FDD spectrum bands with asymmetric load

original noise floor. This rise is caused by the OR network activity, which aggregated signal is considered AWGN (e.g., CDMA, MC-CDMA, OFDM). We consider a scenario where the regulator allows a secondary cellular system over primary cellular networks. Therefore, we consider opportunistic radios entities as secondary users. The secondary opportunistic radio system can use the licensed spectrum provided they do not cause harmful interference to the owners of the licensed bands, i.e., the cellular operators. fSpecifically we consider as a primary cellular network an UMTS system and as secondary networks an ad hoc network with extra sensing features and able to switch its carrier frequency to UMTS FDD frequencies. For simplicity we consider that the aggregated signal coming from the OR network is AWGN and causes a noise rise equal to μ dB, as shown in Fig. 1.

Fig. 3 illustrates the scenario where an opportunistic radio network operates within an UMTS cellular system. We consider an ad hoc OR network of M nodes operating overlapped to the UMTS FDD cell. The OR network acts as a secondary system that exploit opportunities in UMTS UL bands. The OR network has an opportunity management entity which computes the maximum allowable transmit power for each OR node in order to not disturb the UMTS BS. In Fig. 3, the grey area represents the forbidden regions around the UMTS BS where, due the BS proximity, the allowed OR power level is insufficient to guarantee a specified QoS target.

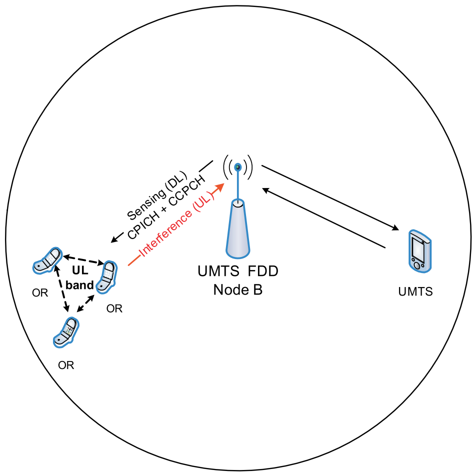

Fig. 3. Ad-hoc ORs networks operating in a licensed UMTS UL band.

III. THE OPPORTUNISTIC NETWORK WITH AD HOC TOPOLOGY

The opportunistic network, shown in Fig. 4, will interface with the link level simulator through look up tables (LUTs). It is possible to have one then one ad hoc networks in a given scenario, which is out of scope of this paper. We consider only one ad hoc network for simplistic purposes. The propagation models developed for the UMTS FDD network will be reused, and

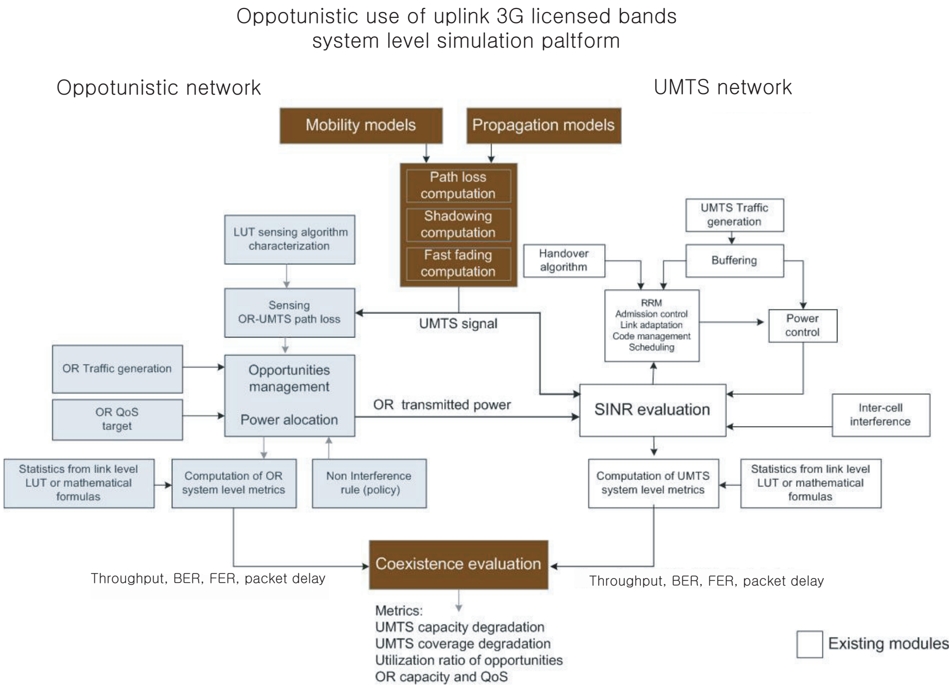

Fig. 4. Block diagram of the system level platform.

the entire channel losses (slow and fast fading) computed. The outputs will be the parameters that usually characterize packet transmissions: Throughput, block error rate (BLER), and packet delay.

In order to get the maximum allowable power for OR communications the OR nodes need to estimate the path loss between the UMTS BS and its particular location. Although we exploit opportunities in UL bands, we propose to sense DL signals; this is possible because there is a significant correlation between the average path loss of uplink and downlink bands of UMTS [7]. Since the BS antenna is typically situated in a high location, the DL signal is easier to detect than the multiple UL signals coming from different UMTS terminals. In addition, the DL signal arrives at the sensing antenna in a synchronized way, which facilitates detection through cyclo-stationary features of the UMTS signal. Moreover, sensing and transmiting in different bands avoid allocate special quiet periods for sensing as it is done in IEEE 802.22 [8] system, boosting the OR's spectrum efficiency.

The energy detector is a well-known technique to identify signal levels. However, realistic limitations of the detector's knowledge of the noise level power produce serious degradation in the energy detector performance [9]. In the UMTS case, due the low power spectrum density of spread spectrum signal, the signal presence causes a very small fractional increase in the total energy, thus, uncertainty in the measurement of the noise seriously degrades the radiometer performance. In addition, for this scenario, the best opportunities occurs when the OR nodes are near the UMTS cell border, where the sensed signal have usually negative SNR values, not detectable by a simple energy detector. To overcome this limitation, we propose to exploit the cyclo-stationary features of the DS-CDMA signal [10]. We assume that the OR knows a priori the UMTS carrier frequencies and bandwidths, which has been isolated and brought to the baseband.

DS-CDMA signals can be detected exploiting the baseband cyclo-stationary properties that come from the redundancy between frequency components separated by multiples of the symbol rate, i.e., the cyclic feature appears at $\alpha = 1/(\mathrm{SF}{\cdot}T_c)$, where T_c is the time chip duration. However UMTS FDD standard employs, in addition to user specific spreading, so called scrambling sequences, in order to improve the correlation characteristics of the signals and provide base station identification [11].

Scrambling takes place over multiple symbols, with a period equal to 10 ms, removing the cyclo-stationarity with the symbol rate. Nevertheless in UMTS standard, user signals have always the same chip rate, even if the individual SF and symbol rates differ. Thus, $a_c = 1/T_c$ (3.84 Mchip/s) is a common cyclic frequency to all UMTS channels and will be exploited to detect UMTS DL signals. An analytical formulation of the cyclic autocorrelation function for a UMTS FDD signal at $a_c = 1/T_c$ is detailed in [12].

Fig. 5 depicts the block diagram of the cyclo-stationary detector implemented. After an FFT operation a sliding window of samples performs frequency shifts of $+\alpha/2$ and $-\alpha/2$. The shifted spectrums are then multiplied to obtain the spectrum cyclic density (SCD) function. After that, a time smoothing operation is performed through an average process during the observation time. The complex values are then squared and integrated over the frequency domain. Finally, the detection statistic, d, is given by the ratio between the power of cyclo-stationary feature, measured at cyclic frequency, c, and the estimated noise floor, measured at α_n. In order to estimate this noise floor we take measurements of the noise at any cyclic frequency, α_n, where it is guaranteed to be no cyclic features present. Notice that as the UMTS chip rate is a known cyclic frequency, the algorithm needs to compute only two spectral lines of the SCD function, c and α_n, which keep this detector at a low complexity level.

The LUT sensing algorithm characterization block contains the cyclo-stationary detector's performance, i.e., the output detection statistic, d, as a function of the SNR measured at the sensing antenna for different observation times [4]. In order to estimate the path loss between the UMTS BS and the OR node, Fig. 6 acts as calibration curves to estimate the SNR of the total received DL signal. For more detail about pathloss sensing, see Reference [4]. For a particular detector outputs, d, and a fixed observation time, the estimated SNR is used by the OR node to compute the path loss between UMTS BS and the OR location trough,

$$\hat{L}_p = \min(P_{\mathrm{Tx}} + G_{\mathrm{BS}}) - \hat{P}_{\mathrm{Rx}},$$
$$\hat{P}_{\mathrm{Rx}} = \mathrm{SNR}(d - \mathrm{ObsTime}) + N_{\mathrm{th}}.$$

The path loss is estimated through the difference between the total BS transmitted power and the estimated received power given by the cyclo-stationary detector ($\hat{P}_{\mathrm{Rx}}$). $\hat{P}_{\mathrm{Rx}}$ is computed based on SNR plus the UMTS thermal noise floor, we consider the typical value $N_{\mathrm{th}} = -107$ dBm. Although the BS transmission power is determined by the UMTS network, we follow a conservative approach considering $\min(P_{\mathrm{Tx}} + G_{\mathrm{BS}}) = 26$ dBm. The sensing OR-UMTS path loss block estimates the path loss between UMTS BS and the OR location through the difference between the transmitted power and the estimated power given by cyclo-stationary detector (LUT sensing algorithm characterization block output). The OR traffic generation block contains real and non-real time service traffic models. OR QoS block defines the minimum data rate, the maximum bit error rate and the maximum transmission delay for each service class. The non-interference rule block computes the maximum allowable transmit power without disturbing the UMTS BS applying a simple non-interference rule (according to policy requirements). In the following, we briefly explain the opportunistic network blocks that was designed and implemented, using a C++ design methodology approach.

First of all, we assume that the OR knows a priori the UMTS carrier frequencies and bandwidths, which have been isolated and brought to the baseband. In order to get the maximum allowable power for OR communications, the OR nodes need to estimate the path loss from its location to the UMTS BS. The opportunistic user is interested in predefined services which should be available every time. This motivates the proposal of defining a set of usable radio front end parameters in order to support the demanded services classes under different channel conditions. Basically, at the beginning of each time step the opportunistic radio requires certain QoS guarantees including certain rate, delay and minimum interference to the primary user (non interference rule policy).

The opportunistic network has an opportunity management entity which computes the maximum allowable transmit power for each opportunistic node such that the aggregated interference does not disturb the UMTS BS. The aggregated transmit power does allowed at the opportunistic network can be computed using a simple non-interference rule

$$10\log\left(\sum_{k=1}^{K} 10^{\frac{P_{\mathrm{OR}}+G_{\mathrm{OR}}+G_{\mathrm{BS}}-\hat{L}_p(k)}{10}}\right) \le 10\log\left(10^{\frac{N_{\mathrm{th}}+\mu}{10}} - 10^{\frac{N_{\mathrm{th}}}{10}}\right) - \Gamma$$

where G_{OR} is the OR antenna gain, G_{BS} is the UMTS BS antenna gain, L_p is the estimated path loss between the OR node and the UMTS BS, K is the number of ORs performed by a sensing algorithm, and N_{th} is the thermal noise floor. μ is a margin of tolerable extra interference that, by a policy decision, the UMTS BS can bear. Finally, Γ is a safety factor to compensate shadow fading and sensing s impairments. Notice if the margin of tolerable interference $\mu = 0$ the OR must be silent. Γ is a safety factor margin (e.g., 6–10 dB) to compensate the mismatch between the downlink and uplink shadow fading and others sensing's impairments. The margin of tolerable interference is defined according to policy requirements.

[*Power Management*]

There are two suggested approaches for power management in mobile ad hoc networks:

- No power adjustment.
- Power adjustment.

The basic difference between the two schemes is that in the former scheme, the power needed to communicate with the farthest node in the ad hoc network is also used to communicate with any closer node in the ad hoc network. On the other hand, the latter scheme suggests communicating with each node using the minimum power it needs for reliable communication. This introduces less interference on the UMTS base station in our scenario to simultaneous transmissions of other nodes.

The objective of defining a ad hoc netowork is to reduce interference and thereby improve the end-to-end network throughput. We assume a minimum required level of received power, denoted $MinRecvPower$, that is necessary to guarantee a non-interference rule as mention earlier. The minimum power level to be transmitted by OR-node i such that at least the $MinRecvPower$ level is achieved at node j (UMTS base station)for a given network configuration is given by

$$P_{tij} = P_{\max}\frac{MinRecvPower}{P_{rji}}.$$

- $P_{tij} =$ power transmitted by OR- node i such that the transmission range does not exceed node j (UMTS BS).
- $P_{rji} =$ power received by node j when node i transmits at $P_{\max}$.

Employing scheduling algorithms, we can provide a good trade-off between maximizing capacity, satisfying delay constraint, achieving fairness and mitigating interference to the primary user. In order to satisfy the individual QoS constraints of the opportunistic radios, scheduling algorithms that allow the best user to access the channel based on the individual priorities of the opportunistic radios, including interference mitigation, have to be considered. The objective of the scheduling rules is to achieve the following goals:

- Maximize the capacity.

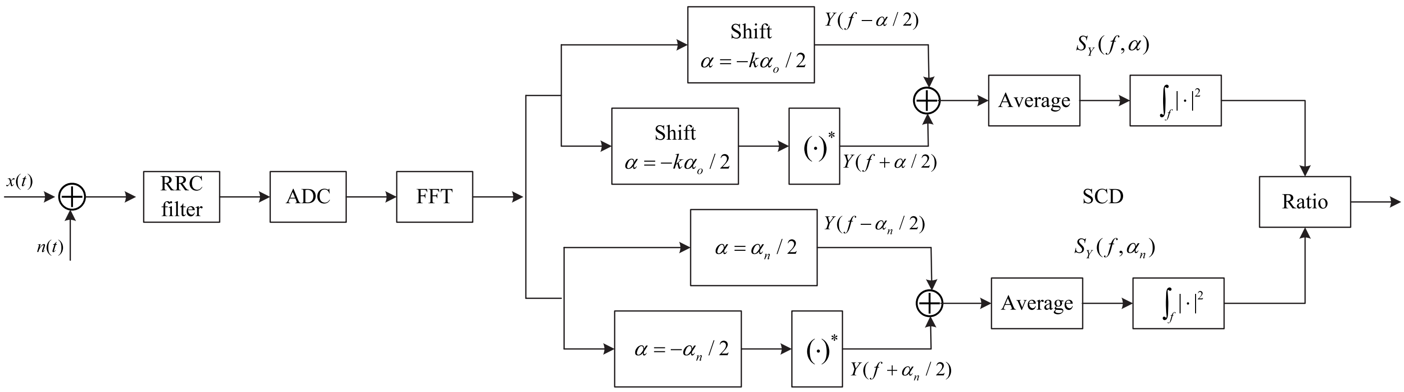

Fig. 5. Cyclo-stationary detector of the UMTS signal.

- Satisfy the time delay guarantees.
- Achieve fairness.
- Minimize the interference caused by the opportunistic radios to the primary user.

A power control solution is required to maximize the energy efficiency of the opportunistic radio network, which operates simultaneously in the same frequency band with an UMTS UL system. Power control is only applied to address the non-intrusion to the services of the primary users, but not the QoS of the opportunistic users.

A distributed power control implementation which only uses local information to make a control decision is of our particular interest. Note that each opportunistic user only needs to know its own received SINR at its designated receiver to update its transmission power. The fundamental concept of the interference temperature model is to avoid raising the average interference power for some frequency range over some limit. However, if either the current interference environment or the transmitted underlay signal is particularly non uniform, the maximum interference power could be particularly high.

IV. COEXISTENCE ANALYSIS FOR A SINGLE OPPORTUNISTIC RADIO LINK

In this section, we consider the simplest case where a single OR link operates within a UMTS FDD cell. Simulations were carried out to compute the coexistence analysis between the OR link and the UMTS network. The main parameters used for the simulations are summarized in Table 1. We consider an omni directional cell with a radius of 2000 m. Each available frequency, in a maximum of 12, contains 64 primary user terminals. Each of these primary users receives the same power from the UMTS base station (perfect power control). We assume the primary users data rate equal to 12.2 kbps (voice call); the E_b/N_o target for 12.2 kbps is 9 dB. Thus, and since the UMTS receiver bandwidth is 3840 kHz, the signal to interference ratio required for the primary users is sensibly -16 dB. There is (minimum one) opportunistic radio in the cell coverage area, which has a transmitted power range from -44 to 10 dBm. The opportunistic radio duration call is equal to 90 seconds. We furthermore consider load characteristics. Identical in every UMTS cellular system and the frequencies are close enough so that the same statistical models apply.

[*Simulation Results for a Single UMTS Frequency*]

In order to calculate cumulative distribution function (CDF) for the interference at UMTS BS we consider 64 UMTS licensed UMTS terminals in each cell (with radius equal to $R = 2000$ m), as shown in the following Fig. 7. The OR receiver gets interference from the PUs located in the central UMTS cell and in 6 adjacent cells. The ORs are within an ad hoc network service area (with radius equal to $R = 100$ m); the OR receiver is 10 m away from the OR transmitter. The OR transmitter is constrained by the non-interference rule.

Based on the capacity's Shannon formula, the OR's link capacity that can be achieved between two OR nodes is given by

$$C_{\text{Mbps}} = B \log_2 \left(1 + \frac{L_2 P_{\text{ORTx}}}{N_{\text{th}} + I_{\text{UMTS}}} \right)$$

where $B = 5$ MHz, L_2 is the path loss between the ORTx and the ORRx, $N_{\text{th}} = -107$ dBm is the average thermal noise power and IUMTS is the amount of interference that the UMTS terminals cause on the ORRx. On the other hand, the total interference at the UMTS BS caused by the OR activity can not be higher than the UMTS BS interference limit, -116 dBm [13].

The Fig. 8 shows the CDF of the interference computed at the UMTS BS due the OR network activity. The results show that an 8 Mbps OR's link capacity is guaranteed for approximately 98% of the time without exceeding the UMTS BS interference limit (-116 dBm). However, this percentage decreases to 60% when an OR link with 32 Mbps is established

V. COEXISTENCE ANALYSIS FOR AD HOC OPPORTUNISTIC NETWORKS

In the previous section we have considered a single link between two nodes ORs, now we extend the coexistence analysis to the case of an ad hoc OR network with several nodes, multiple hop communication and routing mechanisms.

Scalability is commonly considered as one of the greatest challenges in ad hoc networks. Intuitively, the scalability constraint is caused by the relaying burden on the intermediate nodes in the system. Because of the intrinsic competition for bandwidth resource, the relaying traffic sometimes stifles the originating traffic, and this leads to constraining effect on the

Table 1. Main parameters used for the simulations.

Parameter name	Value
UMTS system	
Time transmission interval (T_{ti})	2 ms
Cell type	Omni/single cell approach (one cell)
Cell radius	2000 m
Radio resource management	
Nominal bandwidth (W)	5 MHz
Maximum number of available frequencies	12
($N_{[\max]}$)	
Data rate (R_b)	12.2 kbps
E_b/N_o target	9 dB
SIR target (γ)	−16 dB
Spreading factor	16
Spectral noise density (N_o)	−174 dBm/Hz
Step size PC	Perfect power control
Channel model	Urban
Carrier frequency	2 GHz
Shadowing standard deviation (σ)	8 dB
Decorrelation length (D)	50 m
Channel model	ITU vehicular A
Mobile terminals velocity	30 km/h
Primary user (PU)	
Number of primary user(s) terminals per cell/frequency (K)	64
Sensibility/power received	−117 dBm
UMTS BS antenna gain	16 dBi
Noise figure	9 dB
Orthogonally factor	0
Opportunistic radio (OR)	
Number of opportunistic radio(s) in the cell coverage area	2
Maximum/minimum power transmitted ($P_{o[\max/\min]}$)	$10/-44$ dBm
Antenna gain	0 dBi
Duration call	90 s

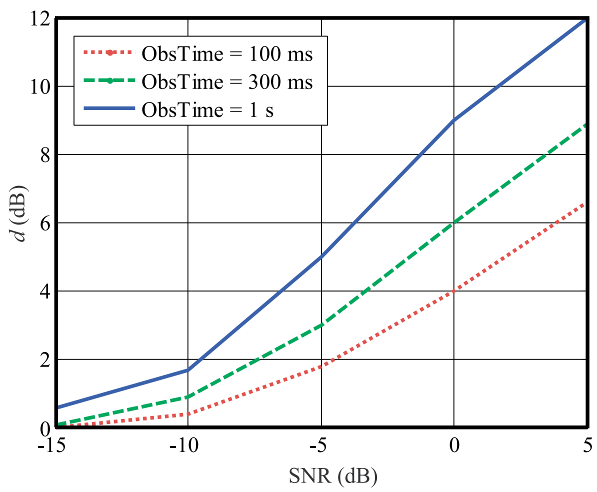

Fig. 6. Cyclo-stationary detector's characterization.

overall achievable traffic load within the system. Since it is a wireless system, it is also important to consider the interference impact on the receivers in the ad hoc network. Interference information is useful when making higher-layer decisions such as routing. Conventional routing metrics such as hop count, ETX and ETT [14] fail to take interference impact into account. Our goal is to explore a way to utilize emerging cognitive radio technology and techniques to select better routes for ad-hoc communications and consequently improve the scalability of such an ad hoc network.

In a cognitive radio context, the cognitive entities in an ad hoc network are the nodes. This leads to a node-centric paradigm discussed later in this paper. Given the cognitive capability of a node, it can behave in an autonomous fashion. Collectively the cognitive nodes in the system operate cooperatively in order to meet end-to-end QoS requirement of users. This node-centric paradigm is different from the conventional link-centric model in which the link from the transmitter to the receiver is often regulated rather than an individual node. Based on the node-centric paradigm, radio links in the ad hoc network are considered in master-slave fashion. Here, we discriminate between some important capacity related terminologies used in this paper. 'Originating capacity' (C_o) of a node is the 'goodput' generated from the node. 'Relaying capacity' (C_r) of the node refers to the relaying burden the node needs to carry for communications initiated by other nodes in the system. 'Requested capacity' of a node is the level of capacity that is able to satisfy all the requested traffic that needs to be transmitted by the node, including both originating traffic and relaying traffic:

$$C_{\text{req}} = C_o + C_r$$

where C_{req}, C_o, and C_r are the requested capacity, originating capacity and relaying capacity, respectively. 'Maximum capacity' of a node denotes the maximum capacity level that can be transmitted by the node regarding the capability constraint of the node. This capability constraint of the node refers to the ability to find and utilize the spectrum resource, the power level it uses to transmit to its receiver(s) and interference mitigation technology and techniques it is capable of using, e.g., 'smart' receive antenna. 'Available capacity' is the capacity achieved by request under the maximum capacity constraint. We have:

$$C_a = \min(C_{\text{req}}, C_{\max})$$

where C_a is the available capacity, $C_{\max}$ is the maximum capacity. The last term introduced here is 'virtual capacity' (C). It is defined as the capacity allocated to the node for a specific routing task. It is a portion of the available capacity on the node ($C \in C_a$).

Routing by definition is a process of selecting paths. Conventional routing algorithms normally find the route with shortest path to improve efficiency [15]. However, in a wireless ad hoc network, shortest path routing is not necessarily the best solution. In such a wireless scenario, other criteria, such as interference, capacity, etc., should be considered while making the routing decisions. We assume a cognitive network is a network with a cognitive process that can perceive current network conditions, and then plan, decide, and act on those conditions [16]. For the routing mechanism to be 'cognitive,' it must have three elements of processes: Observing, reasoning and acting [17], [18]. The observing process refers to how necessary information is gathered for implementation. The reasoning process is where the cognitive entity, e.g., a node (ORs), considers (orient, plan, decide, and learn) the way to behave for its various goals based on the information gathered from observing. The acting process is about how to implement the decision made by reasoning. We focus on the reasoning process mainly, assuming necessary information for each node is available through observing and different adjustment can be carried out in terms of acting. In order to serve a goal of the network level (e.g., finding the shortest path), there must be a certain mechanism to comprehensively link the nodes in the system and enable them to function in a collective way. For a routing problem, the route discovery algorithm is required to find the ideal route in the system. The classic Dijkstra's algorithm [19] is chosen for this work for the route discovery problem. It is originally derived for solving the single-source shortest path problem for a graph with non-negative path costs. The functionality of Dijkstra's original algorithm can be extended for various purposes. For example, OSPF (open shortest path first) protocol is an implementation of Dijkstra's algorithm for Internet routing [19]. Dijkstra's algorithm can effectively choose the route with lowest accumulative cost. In order

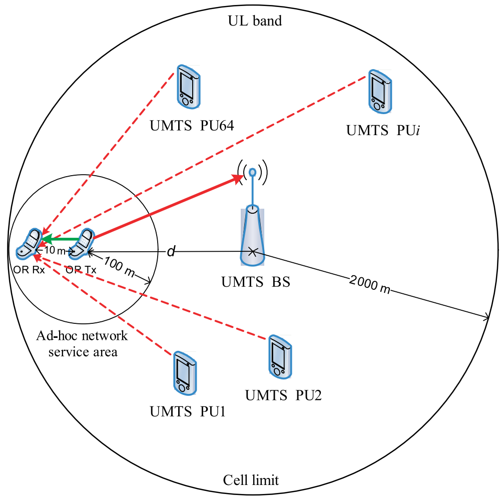

Fig. 7. Ad-hoc single link scenario.

to achieve higher level goals in the system, we can exploit the optimization function of Dijkstra's algorithm by redefining the cost. That is to say, the definition of cost is manipulated in order to serve a different purpose other than finding the 'shortest' path. In the following sections, we demonstrate how this algorithm can be used for OR system operating over the licensed UMTS band and routing strategies base on hop count and capacity information are investigate and compare.

[*Hop Based Routing*]

To find the shortest path for a routing mission in terms of hop count, the cost can be defined as:

$$W_{\text{ORTx,ORRx}} = 1, \ \forall \text{ORTx}, \ \text{ORRx} \in N \tag{1}$$

where $W_{\text{ORTx,ORRx}}$ denotes the cost to transmit from link ORTx to ORRx.

N is the total number of ad hoc nodes in the OR system This routing scheme is often known as the 'hop count' or 'shortest path routing,' and is the most commonly used routing metric in existing routing protocols.

[*Capacity-Based Routing*]

With an ad hoc wireless network in our UMTS system, the scalability of the network is a major constraint due to the relaying burden each OR node has to carry. Heterogeneous OR nodes in the system can potentially improve the scalability of the network if the higher capacity OR nodes are placed in the right positions where more traffic has to be relayed. Intuitively, it is desirable to divert relaying traffic away from the OR nodes which have limited capacity to ones which are more capable to relay. For this purpose, we can define the cost as follows:

$$W_{\text{ORTx,ORRx}} = \frac{1}{C_{\text{ORRx}}}, \ \forall \text{ORTx}, \ \text{ORRx} \in N \tag{2}$$

C_{ORRx} denotes the virtual capacity of the receiving node ORRx a node with higher capacity will be more likely to be chosen for the object route because the cost is less compared with a lower capacity node. If we consider that the transmission power of each OR node is identical, then C_{ORRx} is determined by two factors:

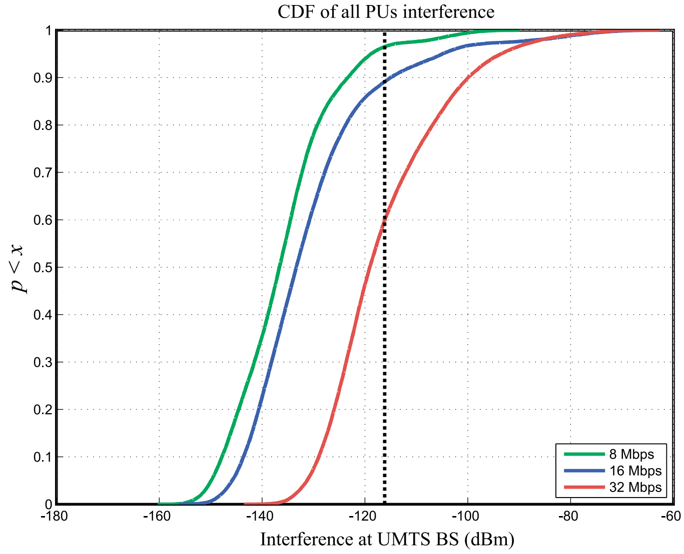

Fig. 8. Interference at UMTS BS.

- The interference suffered by the UMTS base station.
- The spectrum resource that can be utilized by the OR.

In a cognitive radio context, having more available spectrum for the OR node implies that the OR node is capable of finding a larger spectrum hole (or more spectrum holes) and exploiting it for transmission. If we only consider a system without bandwidth constraint at each node as a special case, interference is then the only concern. It is a worst-case scenario, in which the interference problem is dealt with in the most conservative way and has the most severe impact on capacity. Assuming power levels and available bandwidth at each OR node, we let both of them equal to 1,

$$W_{\mathrm{ORTx,ORRx}} = \frac{1}{\frac{1}{I_{\mathrm{ORRx}}+1}} < -116\,\mathrm{dBm}, \forall \mathrm{ORTx}, \mathrm{ORRx} \in N$$

$$I_{\mathrm{ORRx}} = 10\log\left(\sum_{k=1}^{M} 10^{\frac{P_{\mathrm{OR}}+G_{\mathrm{OR}}+G_{\mathrm{BS}}-\hat{L}_p(k)}{10}}\right)$$

I_{ORRx} represents aggregated interference from the UMTS base station which node ORRx suffers.

[*Routing Performance Analysis*]

We show the effectiveness of different routing mechanisms proposed in Section V. An uniform geographic distribution of traffic is assumed to be generated by the ORs nodes simultaneously in the UMTS system (multiple tiers of surrounding cells). This is a worst scenario, where the system is running at its maximum overall capacity and most severe interference level is experienced from the UMTS base station. We define the capacity required to serve one route end-to-end without the impairment caused by interference and sharing with other routes as one Erlang. By using Erlang as the capacity unit, we can simply focus on the theoretic capacity performance without loosing the generality.

First, we look at the scenario without capacity constraint in the system. In other words, there is no shortage of bandwidth for each transmission in the system and all the originating traffic of each node will be delivered without constraint. We look at a case where the sink (landmark node) of the system is placed in the corner as shown in the Fig. 9 using hop-based routing. (1) is used in the route discovery process. We can see that the closer a node is to the sink, the more traffic going through the node and most severe interference level is experienced with the UMTS base station, as indicated by higher requested capacity of the node. It shows the requested capacity of each node is dependent on the topological location of the OR node in respect of the topological location of the sink. Instead of using conventional hop-based routing mechanism, we can implement the capacity-based routing in the previous scenario. In a system without capacity constraints, (2) is utilized in route discovery. Fig. 10 shows the requested capacity performance for the case in which the sink is in the corner. We can see that this time the routing pattern has been dramatically changed compared with the one with hop-based routing strategy. The route discovery process in this scenario tends to choose the routes along the edge of the system, in order to reduce severe interference from UMTS base station. It shows that by adjusting the cost function based on

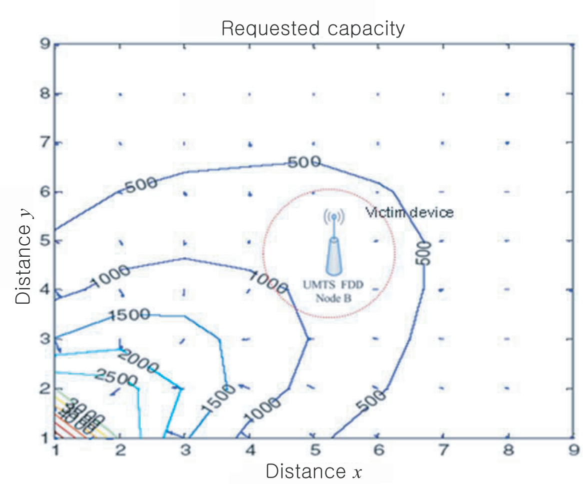

Fig. 9. Contour plot with gradient arrows to show the requested capacity performance using hop-based routing strategy in a system.

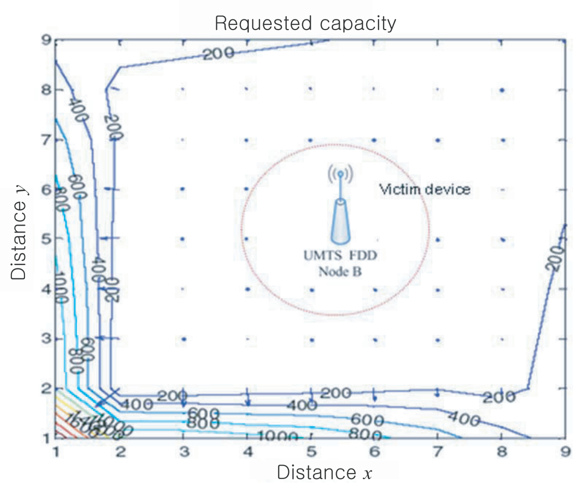

Fig. 10. Contour plot with gradient arrows to show the requested capacity performance using capacity-based routing strategy in a system.

interference, the capacity-based routing strategy can effectively reduce the overall interference level in the system by shifting traffic to the edge of the network.

VI. CONCLUSION

In this paper, we have considered an ad hoc behavior in the ORs and suggested that by implementing ad hoc features in the ORs will improve the overall performance of system. We implemented routing feature of an ad hoc network in ORs, which dramatically reduce the server interference from the UMTS BS. Routing strategies based on hop count and capacity information are investigated and compared. The capacity-based routing strategy can reduce the overall interference level in the system by shifting traffic to the edge of the network. OR networks with fully implemented an ad Hoc features are the areas of future research.

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