Study of an Iterative Resource Allocation Algorithm for a 2-hop OFDMA Virtual Cellular Network

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Abstract—Multi-hop networks can increase the data transmission rate in the next generation mobile network. A new resource allocation algorithm is required for this new type of network architecture. A multi-user resource allocation scheme has been proposed for a 2-hop OFDMA virtual cellular network (VCN). Using that scheme, the VCN can provide better channel capacity than the single hop network (SHN) for low transmission power. However, in the interference dominant transmission power region, the SHN performs better than the VCN. This paper proposes some iterative schemes to increase the channel capacity of the VCN. Using computer simulations, this paper shows that applying those iterative schemes can augment the ergodic channel capacity of the VCN in the interference dominant transmission power region.

Keywords-component: VCN, Resource allocation, SINR, Multi-hop network, Multi-user resource allocation, OFDMA, Channel capacity, Virtual cellular network, Iterative scheme.

I. INTRODUCTION

With the explosion of application services based multimedia content in wireless mobile networks, high data transmission rate is expected in the next generation mobile network. In the conventional single hop network, high data transmission rate requires high transmission power. Multi-hop networks can solve this problem of high transmission power [1-5]. In this context, a multi-hop virtual cellular network (VCN) has been proposed in [4-5]. In the VCN, a group of wireless ports (WP) and a central port (CP) constitute a virtual cell (VC). The CP acts as a gateway to the core network. The data transmitted from the CP can be relayed to the mobile terminals (MT) through multiple WPs.

OFDMA has been used in the conventional single hop network (SHN) to increase the user throughput because of its multiuser diversity and its resiliency to frequency selective channels. For the same reasons, it has also been studied extensively in multi-hop networks [6-8].

Based on the duplex method of the first-hop link and second-hop link used to relay data from the CP to the MTs, a resource allocation scheme for a 2-hop wireless network can be defined as a time division relaying scheme (TDRS) or a frequency division relaying scheme (FDRS). In a TDRS, the CP and the WPs are not allowed to transmit simultaneously because the frequency used between the CP and the WP is the same which is used to transmit data from the WP to the MT as illustrated in Figure 1a. As for in a FDRS, the CP and the WPs can transmit simultaneously in the same timeframe. Different frequencies are selected for data transmission between the CP and the WP, and between the WP and the MT (Figure 1b). Hence, a FDRS can increase the frequency diversity in the network.

In the literature, multiple resource allocation schemes have been proposed for 2-hop relaying networks [6, 9-10]. The authors of [9] have proposed a TDRS where they investigate the problem of route selection, power and subcarrier allocation using the dual Lagrandian method. The scheme in [6] simultaneously allocates subcarriers and routes to an MT while keeping a certain degree of fairness among the MTs. That scheme does not consider resource allocation in the first-hop link between the CP and the WPs. The FDRS in [10] simultaneously allocates the same subcarrier to multiple links. However, it does not take into account the problem of route allocation. The authors of [11] have proposed a parallel relaying scheme for a 2-hop OFDMA VCN. The parallel relaying scheme can provide route and frequency diversity by simultaneously allocating routes and subcarriers to an MT. In
the parallel relaying scheme, the data are transmitted simultaneously through multiple logical routes (LR). An LR is defined as a set combining a physical route and subcarriers allocated in each hop link of the physical route. A physical route can be a direct route between the CP and the MT or a 2-hop link route going through a WP. In Figure 2, three physical routes represented by dash dotted lines assure the data transmission to MT. An LR is constructed along the physical route going through WP, using subcarrier index 7 in the first-hop link and subcarrier index 3 in the second-hop link. The parallel relaying scheme was proposed for a single user.

The authors of [12] have proposed a FDRS for a 2-hop OFDMA VCN. That scheme considers the simultaneous allocation of the routes and subcarriers using the same concept of physical and logical routes previously described. The data are transmitted to the MTs using those LR. That scheme differs from [11] by the fact that it can be applied in a multuser environment and that multiple LR can reuse the same subcarrier simultaneously. Using that scheme, the VCN can provide better channel capacity and better degree of fairness than the SHN for low transmission power [12-13]. However, in the interference dominant transmission power region, the SHN performs better than the VCN.

The scheme in [12] assumes that an LR can also be allocated in the direct route between the CP and the MTs. Therefore, with an optimal allocation of the logical routes, the channel capacity of the VCN is expected to be superior or equal to that of the SHN whatever is the transmission power. Since, in [12], the allocation of the LRs is done successively to the MTs, interference from the latter LR was not considered when allocating the first LR. Interference between LR can degrade considerably the capacity of a wireless network. Therefore, this paper aims, by the means of some iterative schemes, to alleviate the effect of interference between the LRs and increase the channel capacity of the VCN in the interference dominant transmission power region.

The rest of this paper is presented as follows: Section II succinctly presents the algorithm in [12]; Section III details the study of the proposed iterative schemes; Section IV discusses the simulation results; and Section V concludes the paper.

II. RESOURCE ALLOCATION SCHEME IN [12]

a) Algorithm in [12]

The scheme in [12] considers a system with Q MTs and M WPs. The CP is considered to be WP. For each MT a set of LR candidates is constructed through each WP. FDRS is assumed in the downlink transmission. The CP can get the channel state information (CSI) between all nodes (MTs, CP, WPs) in a VC. The channel states do not vary during the communication time. To increase the spectrum efficiency, a subcarrier can be reused simultaneously in multiple LR if the following constraints are respected:

- A WP cannot transmit and receive in the same subcarrier simultaneously. Furthermore, multiple WPs cannot transmit to an MT using the same subcarrier.

- A subcarrier in use in a second-hop link can be reused simultaneously in a second-hop link to transmit data to another MT if the previous rule is respected.

- The total number of allocated LR in a VC cannot outnumber the subcarriers in that VC.

If a number of LRs is to be allocated to each MT, the objective is to find those LR which will maximize the total channel capacity of the VC. The optimal solution requires a combinatorial search of the LR and the MTs. Therefore, the paper in [12] proposes a successive allocation of the LR. The MTs are also selected in a successive order for LR allocation. The different steps of the algorithm are as follows:

1. For the current MT, construct the set of LR candidates for each WP based on the constraints previously listed.
2. For the current MT, find and allocate the LR candidate which maximizes the total channel capacity of the VC with respect to interference on and from existing communications.
3. For the current MT, remove unusable LR from the set of LR candidates based on the subcarrier reused constraints.
4. Repeat steps 2 and 3 until the total number of required LR is allocated to the current MT.
5. Repeat steps 1, 2, 3, and 4 for LR allocation to the next MT.

A more detailed description of the algorithm is available in [12].

b) Numerical expressions [12]

The propagation environment is modeled as the product of the instantaneous fading gain, log-normally distributed shadowing loss and the distance dependent path-loss. \( \delta_{x,y} \), \( M \), and \( H_{x,y} \) denote the log-normally distributed shadowing loss, the distance, and the instantaneous fading gain between node \( x \) and node \( y \), respectively. If \( P_x(k) \) is the transmission power of WP, at the \( k \)-th subcarrier, the signal-to-interference-plus-noise power ratio (SINR) of the \( k \)-th subcarrier at node \( x \), when the desired transmitted signal is from node \( x \), is given by [12]:

\[
SINR_{x,y}(k) = \frac{P_x(k) \cdot d_{x,y}^{-\alpha} \cdot 10^{-\delta_{x,y}/10} \cdot |H_{x,y}(k)|^2}{1 + \sum_{j \neq x} \frac{P_x(k) \cdot d_{j,y}^{-\alpha} \cdot 10^{-\delta_{j,y}/10} \cdot |H_{j,y}(k)|^2}{N}}
\]

\( N \) represents the noise power per subcarrier, \( \alpha \) is the path-loss exponent, and \( M \) is the number of WPs including the CP. WP, denotes any other WP transmitting on the \( k \)-th subcarrier.

If \( l_{MT,y,c}^{\ast}(WP_m \cdot k, k_j) \) is the \( e \)-th LR allocated to the \( p \)-th MT via the \( m \)-th WP, its SINR can be expressed as [12]:

\[
SINR_{(WP_m \cdot k, k_j)} = \begin{cases} 
SINR_{MT,y,c}(k) & \text{if direct route } (i = j) \\
\min \{SINR_{WP,y,c}(k)\} & \text{else}
\end{cases}
\]

\( k_i \) and \( k_j \) represent the subcarriers allocated in the first and second hop link, respectively. With \( D_p \) the number of LR
allocated to MT, the channel capacity of that MT is given by [12]:

$$C_p = \frac{1}{N_s} \sum_{i=1}^{D_p} \log_2 \left( 1 + SINR^{MT_p,i} \right).$$

(3) 

$N_s$ is the number of subcarriers in the related VC. With a VC of $Q$ MTs the total channel capacity $C$ is:

$$C = \sum_{p=1}^{Q} C_p.$$ 

(4) 

For more information regarding the numerical expressions, please refer to [12].

III. PROPOSED SCHEMES

a) Sequential and random iterative schemes (SIS, RIS)

In [12], the LRs allocation to the MTs is done in a successive order of the MTs. Since frequency reuse is applied, the possible interference from the LRs of the $(p+t)$-th MT is not considered when allocating LRs to the $p$-th MT, $t \geq 1$. Reallocating LRs to the $p$-th MT after allocating LRs to the $(p+t)$-th MT can, therefore, provide some improvements in the channel capacity of the VCN. This paper considers two methods to reallocate LRs, after allocation has been done to all MTs. In the first method, reallocation is done in a sequential order, starting from the first MT (Sequential Iterative Scheme, SIS). As for in the second method, an MT is selected randomly for reallocation (Random Iterative Scheme, RIS). For reallocation, this paper only applies steps 2, 3, and 4. This paper compares the channel capacity provided by all iterations, and keeps the combination of LRs which provides the best channel capacity. At each reallocation, the maximum number of combinations $B$ to be evaluated to allocate $D$ LRs to an MT is given by:

$$B(v) = \sum_{i=0}^{D-1} \left( \left( N_s - v - i \right) \times \left( N_s - v - i \right) \times \left( N_s - v - i \right) \times \left( N_s - v - i \right) \right),$$

(4) 

with $0 \leq v = \sum_{i=0}^{D_p} \leq N_s$, $D_p$ is the number of LRs in used by the $p$-th MT. The complexity is linear on the number $J$ of iterations, $O(JB)$.

b) Permutational scheme (PS)

In [12], the MTs are selected in a successive order for resource allocation. Since frequency reuse is applied, the order in which the MTs are selected influences the result of the algorithm. In a system with $Q$ MTs, there exist $Q!$ ways to arrange the MTs. Each of these arrangements is defined as a permutation of the MTs. In a system where $Q$ is large, evaluate the channel capacity of all of these arrangements, by applying the algorithm in [12] to each of them, is not practical. Therefore, this paper evaluates the channel capacity for some permutations of the MTs, randomly generated. The algorithm in [12] is applied to each permutation. The permutational scheme keeps track of the permutation which provides the highest channel capacity. The Knuth shuffle method is used to generate a random permutation with equal probability. The complexity is linear on the number $Q$ of MTs and the number $P$ of random permutations generated, $O(EB)$. $E$ is calculated by:

$$E = Q \times P.$$ 

(5) 

The permutational scheme has a higher degree of complexity than the SIS and the RIS because one iteration of the permutational scheme requires reallocation for all MTs while the SIS and the RIS would reallocate only one MT.

c) Permutational combined iterative scheme (PCIS)

Applying the PS can help to find some permutations of the MTs for which the level of interference between the MTs is low. However, the PS does not solve the interference issue discussed in III-a). Hence, the permutational combined iterative scheme (PCIS) combines the PS and the SIS. A random permutation of the MTs is generated, resource allocation is done for all MTs using the scheme in [12], and reallocation is performed starting from the first MT. In brief, the PCIS applies the SIS of III-a) to each random permutation. The complexity is $O(ZB)$ with:

$$Z = P \times (Q + J).$$ 

(6) 

This scheme has a higher degree of complexity than the PS, the SIS, and the RIS.

IV. SIMULATION PERFORMANCE

a) System model

In order to evaluate the performance of the proposed iterative schemes, this paper considers a single VC with 6 WPs and a CP located at the center of the VC. The VC is of a hexagonal shape. The WPs are placed at an equal distance from the CP (Figure 3). The Monte Carlo simulation method is used to evaluate the ergodic channel capacity of the VCN and the SHN. With $d_0$ being the radius of the VC, $d/d_0$ defines the distance ratio between the CP and the WPs. The paper in [14] shows that an optimal distance ratio to place the WPs can be found in the interval 0.2–0.3. Hence, this paper considers a distance ratio $d/d_0 = 0.3$. $P/P_0$ denotes the normalized transmission power. $P$ represents the total transmission power in the VC. $P_0$ is the average power of the CP for which the SNR at $d_0$ is 0dB. The total transmit power is equally shared among the allocated LRs. The allocated power of a 2-hop link LR is equally distributed among each link of the LR. The bandwidth is divided into $N_s = 32$ subcarriers. 14 MTs are generated randomly in a VC. $D_s = 2$ logical routes are allocated per MT. This paper considers a path-loss exponent $\alpha = 4$, a standard deviation of the lognormally distributed shadowing loss $\sigma = 8$, and $L = 8$ propagation paths independently distributed Rayleigh fading.
between the LRs, its channel capacity does not change. The SHN does not suffer interference and choose the LRs which will cause the less interference in the network. Since the SHN does not suffer interference, it does not solve the interference between the LRs, and the SIS which can solve the interference does not change because the SHN does not suffer interference between the MTs. The PS and the PCIS can also provide some light increases of the channel capacity of the SHN. As already explained, there exist some permutations of the MTs for which the level of interference between the MTs is less than for others. Applying the scheme in [12] to some random permutations can therefore show some ameliorations in the channel capacity of the VCN. Figure 6 also shows that further enhancement can be achieved if 30 iterations of the SIS are applied to each permutation (PCIS). This is because though the PS can improve the channel capacity of the VCN by providing the permutations of the MTs with the lowest interference between the LRs, it does not solve the problem which is discussed in section III-a). Therefore, combining the SIS with the PS can help to further increase the ergodic channel capacity of the VCN. The channel capacity of the SHN does not change because the SHN does not suffer interference between the MTs. The PS and the PCIS can also provide some light increases of the channel capacity of the VCN in the interference non-dominant transmission power region. The scheme in [12] is a suboptimal algorithm which allocates the LRs to the MTs in a sequential order. The PS and PCIS, by randomly permutating the MTs, can approximate the global solution of the optimal allocation of the LRs.

Applying the PCIS in a running system presents some practical challenges; because the PCIS requires deallocation of all MTs. This means that transmissions to all MTs would need to be stopped if the PCIS has to be applied. Despite this practical challenge, the PCIS can be considered as a valuable candidate to evaluate the performance of the proposed iterative schemes. This is because it incorporates both the PS, which can provide some permutations of the MTs with low interference between the LRs, and the SIS which can solve the interference

\[ \alpha = 4, D_1 = 2 \text{ LRs}, \quad Q = 14 \text{ MTs}, \quad L = 8, \sigma = 8, N = 32, \quad d/d_0 = 0.3 \]

\[ P_s = 20 \text{ dB} \]

\[ P_t = 0.3 \]

\[ N_s = 2 \text{ LRs}, \quad N_t = 32, \quad d/d_0 = 0.3 \]

\[ \text{Normalized Transmission Power} \]

\[ \text{Ergodic Channel Capacity (Bits/s/Hz)} \]

\[ \text{Number of iterations} \]

\[ \text{Normalized Transmission Power} \]

\[ \text{Ergodic Channel Capacity (Bits/s/Hz)} \]

\[ \text{Number of iterations} \]
issue discussed in section III-a). Though some values of $B$ in the PCIS are greater than those in the SIS, to simplify the evaluation of the performance of the SIS, this paper assumes that the values of $B$ between the SIS and the PCIS do not vary considerably. Then, in case of 14 MTs, $J = 500$ iterations in the case of the SIS can be compared with $P = 10$ random permutations and $J' = 36$ iterations in the PCIS, $Z = 10(4+36)$. The simulation results of this configuration is plotted in Figure 7. According to Figure 7, the SIS can approximate the performance of the PCIS. Hence, the SIS can be a suitable candidate to alleviate the effect of interference in the VCN.

V. CONCLUSION

The authors of [12] have proposed a multiuser resource allocation scheme for a 2-hop OFDMA VCN. In that scheme, the SHN performs better than the VCN in the interference dominant transmission power region. This paper proposes a sequential and a random iterative scheme to enhance the channel capacity of the VCN in the interference dominant transmission power region. Using computer simulations, this paper shows that high improvement can be achieved if those iterative schemes are applied and that the sequential scheme converges faster than the random one. This paper also investigates a permutational combined iterative scheme which of the sequential iterative scheme. The simulation results show that the performance of the sequential iterative scheme approaches the performance of the permutational combined iterative scheme.

REFERENCES