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INVITED PAPER *Special Section on Wireless Distributed Networks*

Wireless Distributed Network: For Flexible Networking and Radio Resource Management

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SUMMARY This paper proposes a concept for a new technical field called wireless distributed network (WDN) as a strategic technical field to enable flexible networking and radio resource management (RRM) to cope with dynamic variation of spatially distributed traffic demands. As the core technical subject areas for the WDN, this paper identifies distributed networking for flexible network creation, cooperative transmission and reception for flexible link creation, and dynamic spectrum access for flexible radio resource management, and explains their technical features and challenges for constructing the WDN. This paper also discusses some already being studied application fields as well as potential future directions of the WDN applications.

key words: *wireless distributed network, heterogeneous network, autonomous distributed networks, cognitive radio, cooperative transmission, radio resource management*

1. Introduction

As the reliability and performances of wireless access systems become almost equivalent to those of the wired networks, the wireless network is recognized as very important social infrastructure, and its application field is getting diversified. Moreover, user preference of wireless access is diversified; some people prefer a wireless access with wider coverage whereas some other people prefer one with higher throughput. Thus, the networking is currently migrating to heterogeneous in which different types of wireless access systems are integrated according to the average spatial distribution of user preference and traffic demands [1], [2].

In addition to the migration of networks to heterogeneous, flexibility in the physical (PHY) and media access (MAC) layers in each link is also enhanced. Actually, it has been a strong motivation for evolution of new generation cellular systems [3]. Some examples are adaptive modulation and coding (AMC) [3], [4], transmit power control (TPC) [3], [5], multiple-input multiple-output (MIMO) transmission [3], [6], and two-dimensional scheduling [3], [7]. These techniques are actually effective in serving wide range of link quality to satisfy the user preference.

Although the heterogeneous networking and spectral efficiency enhancement techniques are effective in improving the situation of wireless networks to a better direction, they cannot be said to be strategic for flexibly coping with a more dynamic variation of spatial traffic distribution with a sufficient link quality; the heterogeneous networking cannot cope with occasional spatial traffic variation, and performances of the aforementioned spectral efficiency enhancement techniques are upper-limited by the channel state of each link. Thus, our challenges are how to flexibly control spatial distribution of radio resource in heterogeneous networks and how to overcome the upper-limitation of spectral efficiency enhancement techniques due to channel state of each link.

To solve these technical challenges, we have proposed a new technical field, the *wireless distributed network* (WDN) and organized the international workshop on WDN [8]. The keys are introduction of mutual cooperation of distributed networks and/or distributed wireless nodes [9]–[11], dynamic control of radio resource, and cognition of radio and traffic demand distribution. Obviously, it can be regarded as a future direction of heterogeneous networks.

For the WDN techniques, we also have to sophisticate the control mechanism. There are two migration paths for sophistication of control mechanisms; to more decentralized control for enhancement of flexibility in centralized systems like cellular systems [3], and to more cooperative control for introduction of flexibility in autonomously controlled systems like private wireless access systems [12], [13].

The strategic target of the WDN in this paper is flexible creation of wireless networks that can cope with dynamic variation of spatial distribution of traffic demands. Specifically, regarding the conventional heterogeneous networking [14] as a baseline, the WDN tries to enable more flexible controls of the spatial radio resource, link topology and/or link quality without changing node locations in the WDN.

For this purpose, this paper creates three technical subject areas, *distributed networking* in which radio resource and network topologies are controlled in a cooperative manner for flexible network creation, *dynamic link creation* in which stable links are created virtually by adaptive and cooperative control of physical links, and *dynamic spectrum access* in which spectrum allocation/acquisition is dynamically conducted in a decentralized and cooperative manner for flexible radio resource creation.

This paper is organized as follows: After the concept of WDN is explained in Sect. 2, this paper will explain each technical subject area for WDN in Sect. 3. Section 4 will give some WDN applications followed by conclusions in Sect. 5.

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2. Wireless Distributed Networks

Figure 1 shows the migration direction of heterogeneous networks. Although the conventional static heterogeneous network is effective in coping with average irregular distribution of spatial traffic, it is not so flexible to an occasional variation of spatial traffic distribution due to user mobility.

One of its solutions is the introduction of cooperative radio resource management (RRM) in heterogeneous networks. The most important difference between the static heterogeneous network and this scheme is that the cooperative RRM manager can control selection priority of wireless access systems for each user considering user preference, user location and traffic distribution, especially spatial traffic distributions for all the wireless access systems, so that spatial radio resource distribution can be coordinated in accordance with the spatial traffic demand distribution [15], [16]. This paper will call this scheme the *network selection type dynamic heterogeneous network*. This is actually the core concept of heterogeneous type cognitive radio, which is being standardized in the IEEE P1900.4 [17], [18].

Even though the network selection type dynamic heterogeneous network is effective in flexibly controlling spatial distribution of radio resource, it is effective only in the network-covered area, which means it would also be desirable for terminals located in a non-network-infrastructure deployed area to autonomously construct a wireless networks to reach the core networks. It might sound similar to what is called an ad hoc network [19]. However, the concept is more strategic in that the autonomous networking is regarded as a self-organized network with at least one gateway to the IP network infrastructure. Specifically, wireless nodes located in a non-network-infrastructure deployed area mutually cooperate to each other to construct a new link topology for a network that reaches the existing heterogeneous networks. This paper will call integration of this scheme and the network selection type heterogeneous networks the *network selection and topology reconfigurable type heterogeneous network*, and this scheme will be considered as the basic networking configuration to supports dynamic and irregular distribution of spatial traffic demand for ubiquitous networks.

2.1 Concept of Wireless Distributed Networks

Figure 2 shows our classification of WDN technologies. Because the networks considered in this paper is composed by different types of sub-networks and autonomously constructed networks, we will call this networking related technical subject area the *distributed networking* for flexible network creation.

In the distributed networking, there is one important assumption: Quality of each link and its radio resource is sufficient to satisfy the required user services. Unfortunately, it is not really.

Quality of each link is subject to time-varying fading channel. Thus, it is mandatory to introduce cooperative transmission using plural physical links located on different spaces, because aggregation of plural physical links can enhance average link quality and can suppress its fluctuation. Moreover, if the aggregated links that transmit different user's signal cooperate to each other using cooperative coding, even if there exists link quality imbalance, quality of both links can be reached to the same level [13]. Thus, we will also create the second technical subject area called the *cooperative transmission/reception* (Tx/Rx) by which virtual link(s) with a required quality is flexibly created by cooperation of plural physical links in the distributed networks.

As for the radio resource limitation, dynamic spectrum access (DSA) techniques [20] would be the core techniques because the static spectrum allocation no longer has sustainability in coping with increasing demands for wireless connections. In the DSA, our challenges are, 1) how to dynamically obtain a necessary amount of spectrum, and 2) how to dynamically use the obtained spectrum. Thus, we will also create the third technical subject area called the *dynamic spectrum access* for flexible radio resource creation.

Among the three technical subject areas shown in

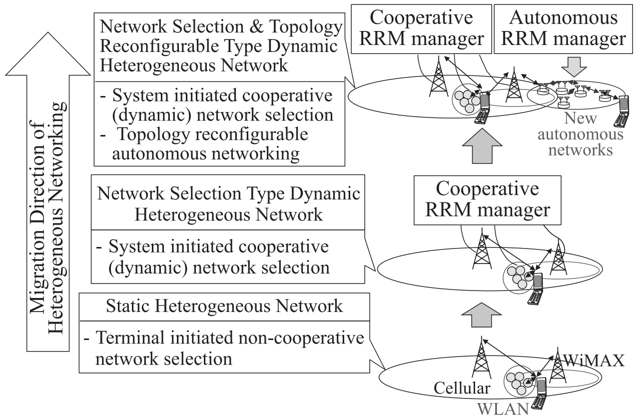

Fig. 1 Migration direction of heterogeneous networks.

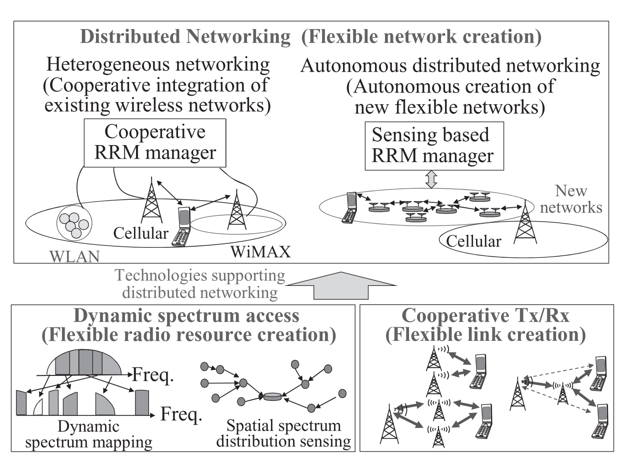

Fig. 2 Classification of WDN technologies.

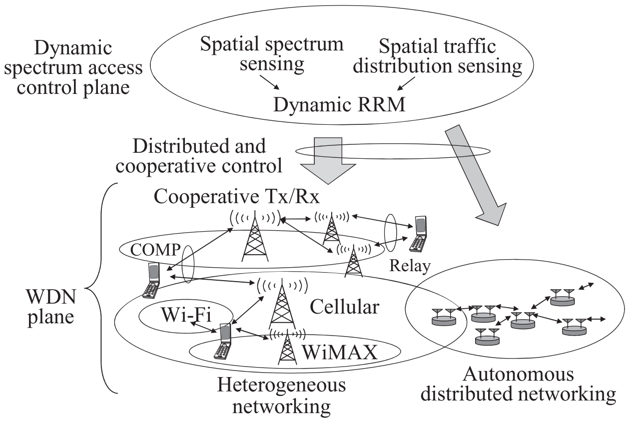

Fig. 3 Concept of wireless distributed networks.

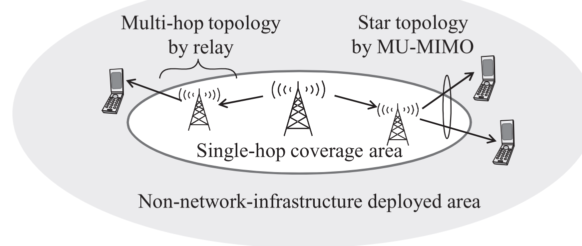

Fig. 4 Concept of autonomous distributed networking.

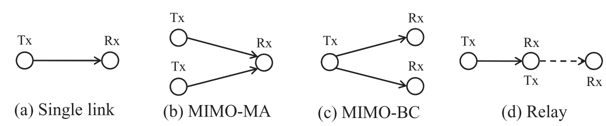

Fig. 5 Basic topologies in autonomous distributed networking.

Fig. 2, the dynamic spectrum access and cooperative Tx/Rx can be categorized as the supporting techniques for the distributed networking.

Figure 3 shows the relationship in more detail. The WDN consists of the WDN plane and dynamic spectrum access control plane. In the dynamic spectrum access control plane, based on identification of spatial distribution of available spectrum and traffic demand, dynamic RRM is conducted for each sub-network. In the WDN plane, while controlling quality of each link using cooperative Tx/Rx and dynamic RRM techniques, wireless networking is created.

3. Key Technical Subject Areas for the WDN

3.1 Network Selection Type Heterogeneous Networking

In the IEEE P1900.4, the network selection type heterogeneous networking is called the *heterogeneous type cognitive radio*, and it is currently being standardized in the committee. In the cooperative RRM, based on the spectrum operation policy and the context of each radio access network including its spectrum usage conditions, the spectrum usage is determined by the network-terminal distributed optimization. In more detail, please refer to Ref. [18].

3.2 Autonomous Distributed Networking

In autonomous distributed networking, wireless nodes located in a non-network-infrastructure deployed area mutually cooperate with each other to construct a new link topology for a network that reaches the existing heterogeneous networks as illustrated in Fig. 4. Therefore, the wireless network is used not only as a last hop of existing wired network but also as multi-hop, star, or mesh topologies to accommodate spatially distributed users out of the single-hop coverage. Key technologies used in such wireless networking are multi-user MIMO (MU-MIMO) [21] and relay.

Figure 5 illustrates basic topologies used in the autonomous distributed networking. Any combination of Tx and Rx nodes can form a wireless link. Since it is difficult for each node to simultaneously transmit and receive in the same frequency, the link should be directional at a certain timeslot.

The simplest topology is of course a single link as shown in Fig. 5(a). In the case of spatially distributed traffic, the MU-MIMO is effective to increase network capacity by introducing star topologies. There are two directions of the MU-MIMO. The first one is the MIMO multiple access (MIMO-MA) as shown in Fig. 5(b) in which multiple Txs access to an Rx at the same time, and the other one is the MIMO broadcast (MIMO-BC) as shown in Fig. 5(c) in which a Tx accesses to multiple Rxs. These two topologies enable functionalities of union and branching in autonomous distributed networking.

The relay is another important technique to virtually extend the length of a link by serial connection of multiple links as in Fig. 5(d). Although it is effective in enhancement of the coverage, there is another concern. Since the relay cannot transmit and receive simultaneously in the single-frequency reuse directional link topology, the relay requires additional radio resource, which results in degradation of network capacity.

The two-way relay [22] solves this problem by introducing the concept of MIMO-MA and MIMO-BC on the relay communication as shown in Fig. 6(a). At a certain timeslot, the relay node receives two-way flows at the same time by using MIMO-MA. At the next timeslot, the relay node transmits the two-way flows at the same time by using MIMO-BC. Owing to both benefits of MU-MIMO and relay, the two-way relay increases the coverage without sacrificing the network capacity.

Instead of using the MIMO-BC, network coding can be used to multiplex the two-way flows received in the previous MIMO-MA phase. At the end nodes, the desired inbound streams can be retrieved by subtracting the known outbound stream from received signals. Thus, the two-way relay is also achieved by using the network coding, thereby we can save radio resource as well.

This scheme can be easily extended to a general 2D

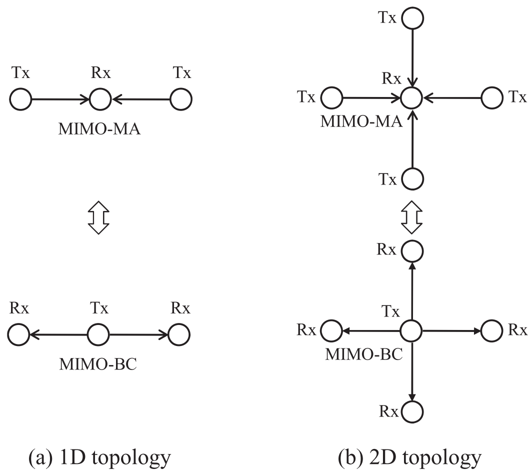

Fig. 6 Topologies in two-way relay networks.

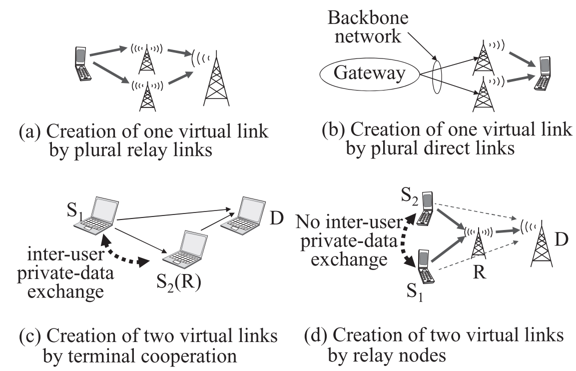

Fig. 7 Concept of cooperative Tx/Rx.

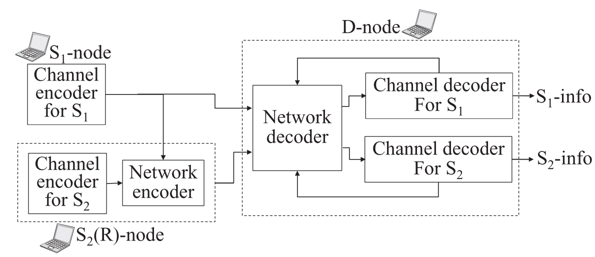

Fig. 8 System model for network coding introduced cooperative relay. In this figure, interleavers and deinterleavers are not shown to prevent this figure complex.

case by increasing the number of antennas at the relay node as shown in Fig. 6(b). The 2D two-way relay acts as a junction of wireless flows in the autonomous distributed networking. The network coding is also applicable in this 2D two-way relay topology and can obtain radio resource saving as well [23].

Combining the aforementioned key components, i.e. MIMO-MA, MIMO-BC, one-way and two-way relays, can create wide variety of topologies so that it is able to accommodate spatially distributed users out of the single hop coverage without sacrificing the network capacity. That is important feature of the proposed WDN. Moreover, a dynamic link creation to be described in the next section can also be formed via cooperative combinations of these topologies.

3.3 Dynamic Link Creation by Cooperative Transmission and Reception

When a point-to-point single hop transmission is conducted by a pair of wireless modems, a very limited amount of omni-directionally radiated radio energy is reached to the receiver, which strictly restricts the upper-limit of user throughput. Thus, if we would like to further increase user throughput without increasing transmit power, we have to consider a method to gather the spatially radiated signal and transfer the signal to the destination by some means. Cooperative relaying is the very suitable technique for this mechanism.

Figure 7 shows the concept. In the case of Fig. 7(a), a spatially radiated source node (terminal) signal is received by two relay nodes, and the relays transfer the signal to the destination (base station (BS)). With this process, the destination node can gather more radiated energy from the source node, which gives the spatial (site) diversity gain. Moreover, when the relay nodes employ different channel encoding in a cooperative manner, channel coding gain can also be obtained, which is called *distributed coding* [12].

A modification of this configuration is shown in Fig. 7(b), where source to relay links in Fig. 7(a) are replaced by the backbone networks. In the Third Generation Partnership Project Long Term Evolution (3GPP LTE) specification, this configuration is called the coordinated multi-point transmission (CoMP).

Another configuration to enhance link quality is the terminal-cooperated relaying in which plural terminals having the same destination node are operated in a cooperative manner, so that both nodes can be successfully detected at the destination nodes. For maximally utilize capacity of cooperated links, cooperative coding is mandatory [12]. Some examples are shown in Figs. 7(c) and (d). When each terminal is allowed to detect the other user's signal, each terminal can mutually assist the other one by relaying the other terminal's signal in addition to its own signal as shown in Fig. 7(c). On the other hand, when the detection of the other user's signal is not allowed to secure privacy as in the case of cellular systems, the configuration shown in Fig. 7(d) is taken, where relaying is conducted by dedicated relay node(s) so that user privacy is secured. In this case, although terminals are not directly cooperating, the repeater is equivalently building their cooperative relationship [24].

In the cooperated relaying, the most important challenge is how to flexibly create plural virtual links with a required quality even if there is dynamically varying link quality imbalance between the physical links in cooperation. A method to solve this problem is the introduction of network coding in the relay node.

Figure 8 shows the network coding introduced cooperative relay for the Fig. 7 (c) configuration, where network coding is introduced in S_2 [25]. The transmitted signal from

S_1 node is directly received at the D-node. At the same time, it is received by the S_2 node. When the signal is correctly detected by the S_2 node, the coded data for S_1 node and that for S_2 node are network-encoded and it is transmitted to the D-node. Thus, this system model is equivalent to concatenated coding of the channel coding and network coding.

In the D-node, network decoding is conducted using both the directly received signal from S_1 and network-encoded signal from S_2 to discriminate S_1 and S_2 signal using a maximum a-posteriori (MAP) estimation followed by individual channel decoding, where MAP-based joint detection is conducted by the iterative process between the network decoder and channel decoder based on extrinsic log-likelihood ratio (LLR) exchange.

3.4 Usable Spectrum Creation by DSA

Currently, spectrum for a wireless access system is allocated as a licensed (dedicated) band, or competitively acquired on the unlicensed bands. However, these two spectrum allocation/acquisition schemes can no longer sufficiently cope with the aforementioned flexible link creation, especially for broadband wireless access systems. To overcome this limitation, the dynamic spectrum access (DSA) is extensively studied, in which a wireless access system is granted a spectrum access right on the condition that the use of the spectrum does not cause harmful interference to the other systems with higher access priority.

Figure 9 shows classifications of the spectrum access schemes. The spectrum access schemes can be classified into centralized control-type and decentralized control-type. The conventional dedicated spectrum access is located at the leftmost place, whereas the competitive spectrum acquisition is located at the rightmost place in this figure. Between these two schemes, there are various types of DSA schemes.

In the case of the network selection type dynamic heterogeneous networks explained in Sect. 2.1, wireless access selection for each terminal is conducted based on centralized control in cooperation with terminals. In this case, because dynamic selection of wireless access systems is equivalent to dynamic selection of spectrum to carry out balancing of the spectrum efficiency, this scheme is called a *DSA for heterogeneous-type cognitive radio* [16], [17].

When unused spectrum (white space) is detected by a

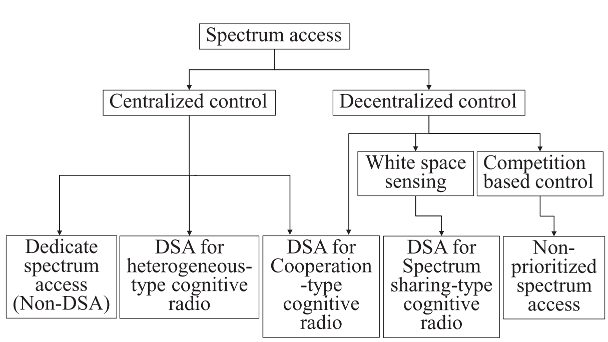

Fig. 9 Classifications of the spectrum access schemes.

spectrum sensing technique and it is used with a lower priority access right, it is called a *DSA for spectrum sharing-type cognitive radio* [17]. For this scheme, spectrum sensing is mainly conducted by the secondary users. Moreover, the purpose of spectrum sensing is not the detection of the interference at the position but the assessment of whether or not the radio signal transmission from the position causes any harmful interference to the primary systems or not. For this purpose, various types of cooperative spectrum sensing schemes are proposed [26].

A more effective way for a secondary system to get spectrum access opportunity is the *DSA for cooperative type cognitive radio* in which a secondary system obtains a spectrum access right when link quality of the primary system becomes temporarily lower than a preliminarily determined level on the condition that the secondary system assists primary system's transmission first, and then can utilize the spectrum if its surplus radio resource is still remaining [27]. In this case, spectrum access opportunity can be obtained in cooperation with the primary system with a centralized control and a secondary system with decentralized control.

This scheme is actually beneficial for both primary and secondary systems because it can enhance transmission quality of the primary system by a cooperative transmission with a secondary system, and the secondary system itself can get more opportunistic spectrum access right than the conventional spectrum sharing-type cognitive radio, because signal faded period for the primary system can also be used as the white space period.

3.5 Dynamic Spectrum Utilization for Created Spectrum

When multimedia traffic is transferred via a wireless network, because holding time for each spectrum block may be different, the available spectrum obtained by the DSA becomes spot-wise rather than contiguous. Thus, the first important issue is how to efficiently utilize spot-wise spectra to create a wireless channel with a necessary amount of bandwidth.

Figure 10 shows several types of spectrum assignment techniques. In the conventional dynamic spectrum assignment (DCA) [28], after available spot-wise spectra are identified, one of the spectra is allocated to a user as shown in Fig. 10(a). In this case, however, the assigned bandwidth is upper-limited by the maximum bandwidth among all the available spot-wise spectra.

When spectrum splitting [29] is employed, the transmitted spectrum is split into sub-blocks, and they are mapped onto spot-wise spectra as shown in Fig. 10 (b). With this process, a wider bandwidth is more probable to be allocated to each user.

Even if the spectrum splitting is employed, if the bandwidth of the aggregated spectrum is still narrower than the transmitted signal bandwidth, we usually have to reduce the signal bandwidth by reducing the user rate.

A technique to reduce the transmitted signal bandwidth without reduction of the user rate is the spectrum clipping

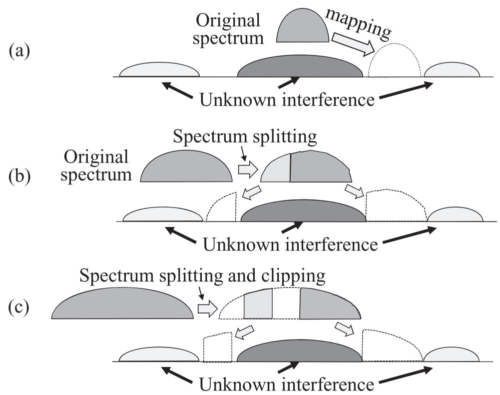

Fig. 10 Spectrum assignment techniques. (a) DCA, (b) Spectrum splitting, (c) spectrum splitting and clipping.

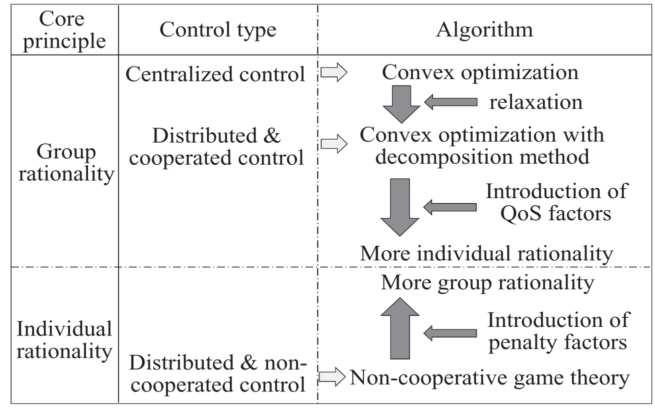

Fig. 11 Relationship between the control type and suitable control algorithm.

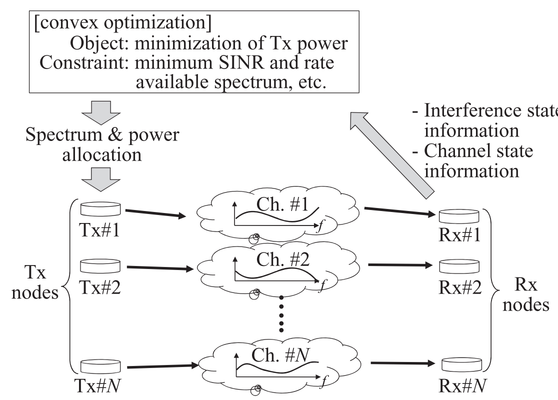

Fig. 12 An example of convex optimization for a centralized RRM.

[30] as shown in Fig. 10(c). In this process, a part of spectrum is intentionally eliminated in the transmitter, and the rest of the spectrum is mapped onto the available spot-wise spectra. In this process, although a part of transmitted spectrum is eliminated, the total transmitted power is still kept to the same level as that before spectrum clipping.

Distortion by the spectrum clipping and frequency selective fading is compensated for by a non-linear equalizer. Thus, the spectrum clipping enables it to adjust the bandwidth of transmitted signal spectrum, whereas the spectrum-splitting and non-contiguous spectrum mapping enables it to flexibly utilize available spectrum.

3.6 Distributed Control for the RRM

Because available radio resource composed by spectrum and/or power is very limited, introduction of efficient RRM algorithm is the most important to share the radio resource with the other users. Moreover, distributed control rather than the centralized control is more preferable for the distributed networking.

Figure 11 shows the relationship between the control type and its suitable algorithm. There are two main core principles for the RRM, *group rationality basis* or *individual rationality basis*. In the case of cellular systems, centralized control with its core principle of group rationality is employed, because most of the controls including RRM are conducted in the network (operator) side to maximize operational rationality. The convex optimization [31] is the most popular optimization algorithm by which a global solution is theoretically obtainable, as long as the objective function and constraint functions are convex.

Figure 12 shows an example of convex optimization application to the centralized RRM. When a fixed transmission rate is required for each user, transmission (Tx) power is minimized according to the channel state information and interference state information fed back from the Rx nodes with its constraint of minimum signal to interference plus noise power ratio (SINR), user rate and the available spectrum.

With diversification of the network granularity in distributed networks, introduction of distributed control is inevitable because centralized control is no longer applicable. Actually, the RRM conducted in the RNC in the wideband code division multiple access (W-CDMA) is distributed to the BSs while inter-BS links called X_2 interface are introduced in the case of 3GPP LTE.

Figure 13 shows an example of this scheme. In this case, decomposition method [32], [33] is introduced in the convex optimization, where the decomposition method is an approach to solving a problem by breaking it up into smaller sub-problems and solving each sub-program individually, either in parallel or sequential. In Fig. 13, each sub-problem corresponds to the RRM in each BS. Each sub-program has an interface with the master program (it corresponds to X_2 interface in the case of 3GPP LTE) via which, information on mutual interference between BSs are exchanged.

In either centralized or partially decentralized control cases, their main purpose is still maximizing group rationality, and individual rationality (user-centric requirements) has been put on relatively a low level. Quite recently, the public systems try to pay more attention to considering user rationality, which is the introduction of quality of service (QoS) factors in the RRM.

On the other hand, maximization of the individual rationality is another core principle in the RRM, where group

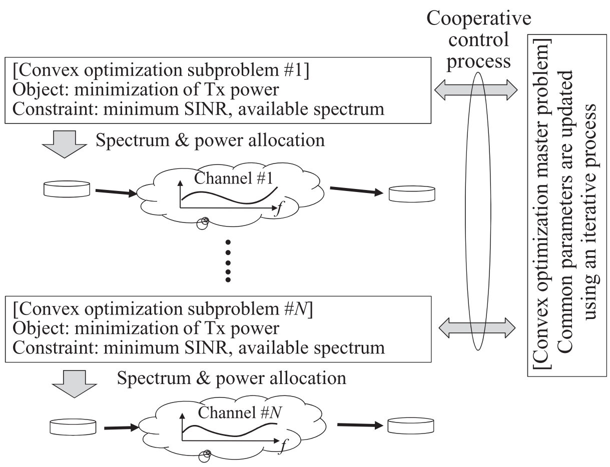

Fig. 13 An example of decomposition method introduced convex optimization in the decentralized RRM.

rationality is put on relatively a lower level. The non-cooperative game theory [34] is very useful at understanding such RRMs. In the non-cooperative game, all players choose their best response without any knowledge on the final decision of the other players' strategies. Such non-knowledge on the other player's strategy choices is the most distinct difference between the non-cooperative game and single-objective or multi-objective optimization algorithms like convex optimizations. The solution is called a Nash equilibrium that gives no incentive for all players to change their strategies. Because the Nash equilibrium maximizes individual utility by changing his/her strategy while the other players are assumed to act on their selfish manner, it might be different from the maximum social utility. The cost due to such a selfish operation is called a *price of anarchy* (PoA), which is defined as the social optimum welfare to the welfare obtained by the Nash equilibrium. When the PoA is 1, Nash equilibrium is optimal, whereas when PoA > 1, the selfish Nash solution is worse than the optimal one.

A key to increase individual welfare in the non-cooperative game is how to introduce factors of inter-player interaction into a utility function while individual rationality is maintained as the core principle. For example, introduction of penalty factors is proposed in a potential game [35]; when a selfish manner increases his penalty, the penalty discourages the player's avaricious pursuit of welfare, by which group rationality is indirectly taken into consideration. When the potential function is a convex function, the best response is converged to the Nash equilibrium.

In this section, we do not want to say which we should take, group rational based RRM, or individual rational RRM. Rather we should understand that both RRM is introducing the other's rationality factor, and enhancing their flexibility and efficiency in control.

3.7 Other Technical Subject Areas

In the above discussions, we have shown major three technical subject areas for the WDN. Of course, the technical subject areas for the WDN are not limited to them. The core keywords for the WDN are, distributed and cooperative control, distribution of functions and their strategic integration, spatial distribution monitoring and control, etc., those of which may propose new technical subject areas to create a new directions for future wireless networking. We are expecting to accommodate new technical subject areas in Fig. 2.

4. Applications of WDN

In the 3G cellular systems, quality of each user signal is controlled in each cell based on a centralized control, where interference in a cell is regarded as unknown, uncontrollable and undesired signal. In this situation, inter-cell interference is mitigated by interference avoidance by scheduling, or desired signal level control by the TPC [3], all of which are conducted individually in each cell. However, due to increasing demands on performance improvement for cell-edge users, inter-cell interference coordination and relays, which are part of WDN techniques, are to be introduced in the 3GPP LTE and LTE-Advanced (LTE-A).

Figure 14 shows the concept. Because radio resource distribution control using a network selection type heterogeneous networking is effective only for users in the coverage area (non-overlapped coverage area in Fig. 14), it is helpless for the coverage extension.

The BS cooperation which is classified in the cooperative Tx/Rx techniques in Fig. 2 is extensively studied for the 3GPP LTE-A, where it is called CoMP [3]. When plural BSs transmit a user's signal simultaneously in a cooperative manner, we can expect user throughput enhancement for the cell edge users due to the received signal level enhancement by the site diversity effect, the received signal level control by the TPC, and co-channel interference reduction effect by non-usage of the same spectrum in the adjacent cell. Thus, although plural link aggregation by the BS coordination requires extra radio resource, these techniques could offset the radio resource loss and get more enhancement of spectral efficiency. Moreover, when multiuser MIMO (MU-MIMO) techniques are introduced to the BS cooperation, because the MU-MIMO can increase total radio resource in each cell, we can further enhance user throughput for the cell edge [36]. Although BS cooperation is effective in coverage extension, the effect is limited only to the cell edge areas.

Cooperative relaying, especially two-way relaying explained in Sect. 3.2 is another technique to further extend coverage in cellular systems. Up to the third generation in cellular systems, wireless links are introduced only at the last one-hop. Thus, the direction of packet flow in the wireless links is only uplink or down link. In the case of relay extension, on the other hand, the packet flow becomes bi-directional and the network topology could be two-dimensional when mesh topology is employed as explained in Sect. 3.2.

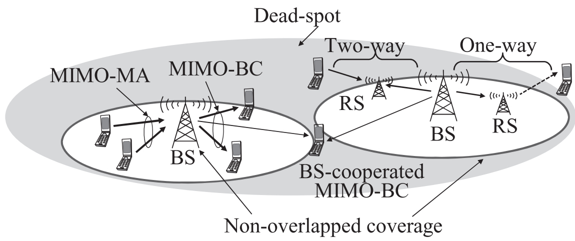

Fig. 14 Potential WDN applications in LTE and LTE-A.

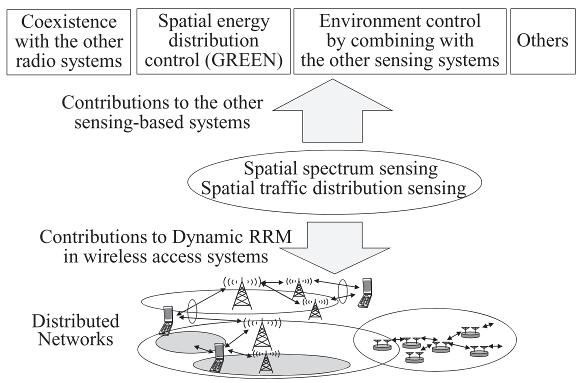

Fig. 15 New application fields for the WDN.

Moreover, ad hoc/mesh network [37], sensor network [38], cognitive radio network [39] and multi-hop cellular network [40], [41] are currently under development.

In addition to the cellular systems, the WDN techniques have wider application fields. Figure 15 shows some examples for new application fields for the WDN. Among many technologies in the WDN, sensing of spatial spectrum and traffic distributions has very wide application areas. For example, when the sensing data is combined with the other sensing data related to our social and living environments, it can be applied to various types of our environment monitoring and control.

One more application field is the energy saving. At present, energy consumption by the information and communications technology (ICT) industries are already quite high. Spatial energy distribution control for wireless access infrastructure in conjunction with the spatial traffic distribution is proposed by a GREEN communication project [42].

5. Conclusions

This paper discussed the concept of WDNs as a strategic technical field to enable flexible networking, link quality control and radio resource management to cope with dynamic variation of spatially distributed traffic demands. As its technical subject areas, we have identified distributed networking, cooperative transmission and reception, and dynamic spectrum access as the core technical subject areas, and explained their technical features and challenges for constructing WDNs. This paper also discussed some already studied application fields as well as potential future directions of the WDN applications. Especially, we have pointed out the importance of spatial spectrum and traffic distributions sensing not only for wireless networking but also for much wider applications, such as GREEN communications.

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