Chapter 11

POWER CONSUMPTION AND SPECTRUM USAGE PARADIGMS IN COOPERATIVE WIRELESS NETWORKS

The way out of the energy trap!

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Abstract: One of the most important and challenging topics for future wireless communications is the power consumption of wireless and mobile handheld devices. In Chapter 14 we underlined the importance of this issue and predicted that future terminals will consume even more power. The dramatic increase of power consumption can ultimately be attributed to the emergence of advanced services and it may result in an energy trap following the linear extension approach for future wireless communication systems. Therefore we address the problem of increased power consumption and introduce some solutions. In Chapter 18 the power consumption is also considered and solutions are given by means of task splitting in cooperative networks. Here we focus on the power that is consumed in the wireless transmission and reception process. Once more we advocate the use of cooperation, but this time the target is to reduce the power consumption for the receiving process of multicast services. The potential power saving using

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cooperation is not limited to multicast services, but they are used in this chapter for illustrative purposes.

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1. Motivation

As shown in Chapter14, the ever-increasing power consumption of future wireless terminals may be one of the most limiting factors for future wireless communication systems. New services as well as new transmission techniques will use more and more power. Moreover, future wireless communications are likely to take place at higher and less congested frequency bands, where path loss is larger, and higher transmission powers are needed to keep the same coverage area. In this chapter we introduce one possible solution to reduce the power consumption at the transmission level using cooperative strategies. As we will see in the following, the proposed solution is fully in line with the designing rule of 4G ($S_{4G} \sim 1/P_{4g}$) suggested in Chapter 14. For purely illustrative purposes, we present our approach in the context of multicast services supported by multiple description coding (MDC), but we stress that the concept is not limited to that particular application and it can be applied in any field of cooperative communication.

2. System under Investigation

The system under investigation follows the architecture of omnipresent cellular systems adding cooperation among wireless terminals. We assume the setup of Figure 11.1: A number of wireless terminals (WTs) are distributed over a given coverage area of an access point (AP). All terminals in a given group (A, B, or C) are interested in the same multicast service. The multicast service is provided using multiple description coding as described in Chapter 16. The MDC example is not a necessary condition, but it helps us to illustrate the idea. Furthermore MDC introduces robustness to the cooperative group allowing cooperative entities to leave and join the group whenever they want. Terminals may join or leave seamlessly the group without stopping the service for the other group members. The MDC sub–streams are transmitted to the terminals from the access point. We focus on J wireless terminals that are in close proximity and form a particular cooperative group. In general there are multiple cooperating groups with different numbers of cooperating terminals in each. For clarity, but without loss of generality, we assume that the number of transmitted sub–streams is also set to J. We investigate now different scenarios in terms of service quality and power consumption. We distinguish two possible operating strategies for the terminals:

- Autonomous Operation (No Cooperation)

  The J terminals do not cooperate and try to receive all J sub–streams in a stand alone fashion over the multicast downlink communication. This

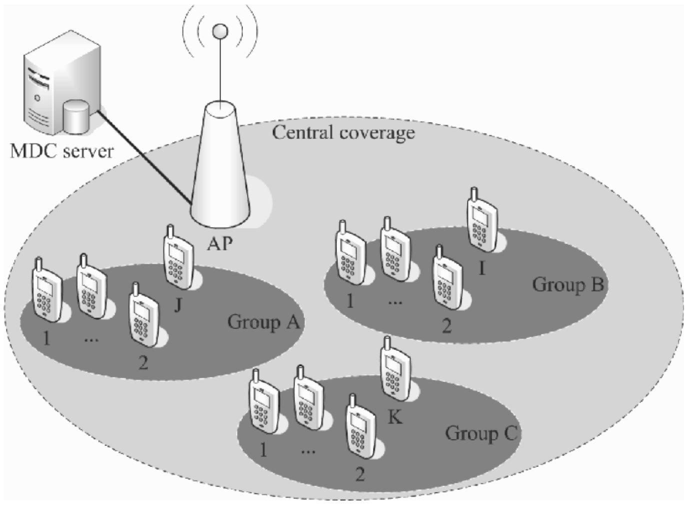

Figure 11.1. Example of cooperative groups with one central access point.

strategy is related to a certain service quality referred to as S_{NoCoop} and the power required to provide such a service P_{NoCoop}. P_{NoCoop} is the overall power consumed by a given terminal including cellular and short range communication.

- Cooperative Operation (Terminals Cooperate With Each Other)

  Each terminal receives one out of J MDC sub–streams, and the terminals within a cooperating group exchange these among each other. For this purpose the terminals need an additional connection to communicate with each other, and the connections will take place over *short–range communication* links. The target is to provide the same service quality as in the non–cooperative case ($S_{NoCoop} = S_{Coop}$). The power consumed in this case P_{Coop} may be different from P_{NoCoop}. We are only interested in the power consumption of the terminals without considering any power issues at the access point, which is assumed to be powered by a fixed line.

3. Time Division Multiple Access Cooperation

Our reference scenario is multicast downlink transmission, referred hereafter as Scenario 1. The MDC sub–streams are transmitted from the access point over a given radio interface at a given transmission rate R_c (where c stands for central or cellular) using the time division multiple access principle. The terminals receive the service at the same rate investing the power $P_{c,rx}$ (this power is consumed in the circuitry in order to perform all the operations necessary for the signal down–conversion and amplification, as well as the signal processing). In the following we indicate transmitted packets with solid lines and received

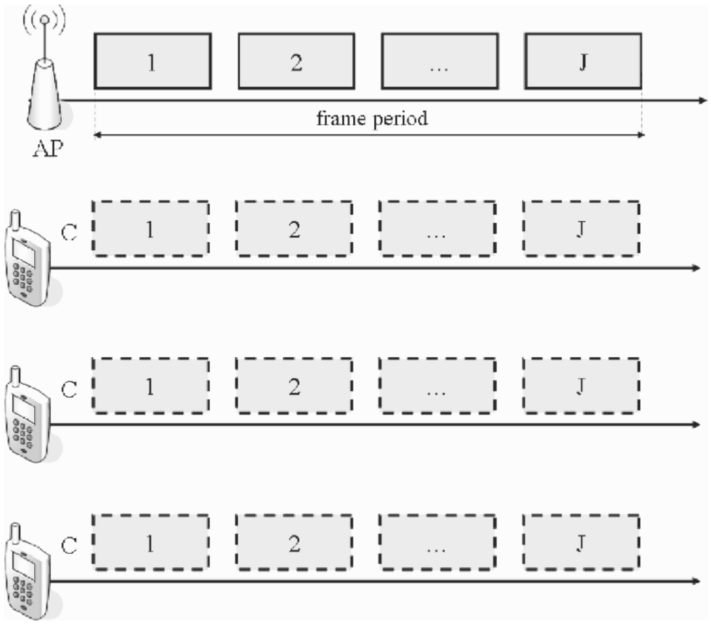

Figure 11.2. Scenario 1: Non cooperative reception of the J sub–streams.

packets with dashed lines. Figure 11.2 shows the non–cooperative transmission: the sub–streams are transmitted in a packetized form using time division. Within one *frame period* each sub–stream sends one packet as given in Figure 11.2. To receive the best service quality, each terminal needs to receive all packets of the sub–streams transmitted by the central air interface.

In the case of J cooperating terminals, only one packet per terminal per frame is received over the central air interface. The terminals have to agree on the disjoint reception of the J packets. For the exchange within the cooperating group we will consider two possible mechanisms. The first possible mechanism, referred to as Scenario 2, is shown in Figure 11.3 and assumes that the terminals are capable of using the central and the short–range communication interface at the same time. The second option (Scenario 3) assumes that only one radio link can be active for transmission or reception at any given time, and therefore activity alternates between the central and the short– range communication link, as shown in Figure 11.4.

In Figure 11.3 the first terminal receives one packet from the access point and forwards this packet within its cooperating group. The exchange of the cooperative packets need to be done in the next frame (after all J packets have been received). This has to be taken into account for the resulting delay, but this aspect is beyond the scope of this chapter. As all the other terminals do the same, the missing $J-1$ packets are received over the short–range communication link.

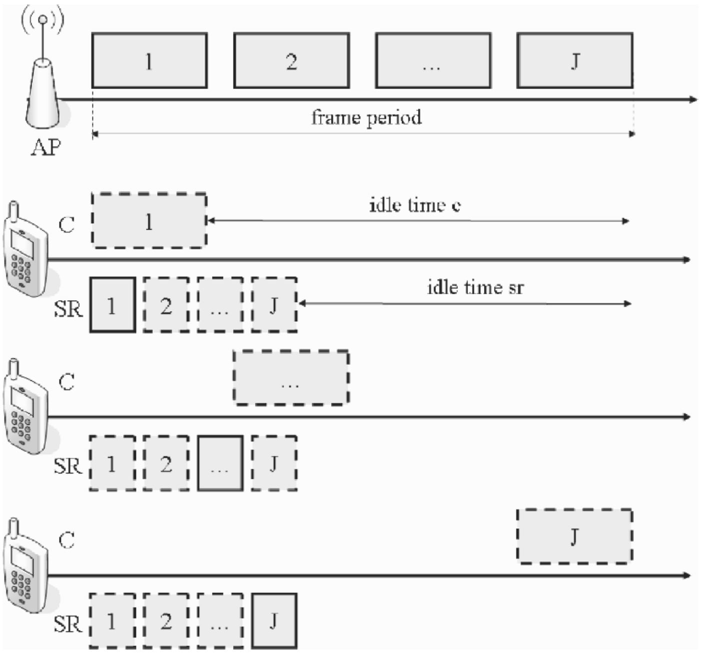

Figure 11.3. Scenario 2: Cooperative reception of the J sub–streams.

In order to compute the power levels, we assume that for the packet reception from the central access point a power level of $P_{c,rx}$ is needed. Furthermore power levels $P_{sr,tx}$ and $P_{sr,rx}$ are needed to send and receive a packet over the short range (sr), respectively. As given in the figures, the time to send or receive on the short–range is assumed to be shorter than the time needed to receive from the central AP. This is motivated by rate adapted systems such as IEEE802.11a/g. We inherently assume that higher rates can be achieved on the short–range link relative to the central link, because we expect that user proximity implies lower loss links among the members of a cooperative group. This assumption is essential for the success of the proposed cooperation scheme. In contrast to the example given in Figure 11.4, the central entity (AP) does not need to be aware of this kind of cooperation.

The cooperation scheme given in Figure 11.4 distinguishes two phases for the data transmission/reception. The first phase is dedicated to communication between the terminals and the AP. During this phase, the terminals receive the disjoint packets. The second phase is dedicated to inter-terminal communication, and it is during this phase that the exchange takes place. During this phase, the central entity stops its transmission and waits for the exchange to be completed. It is therefore obvious that the central entity needs to be aware of this kind of cooperation.

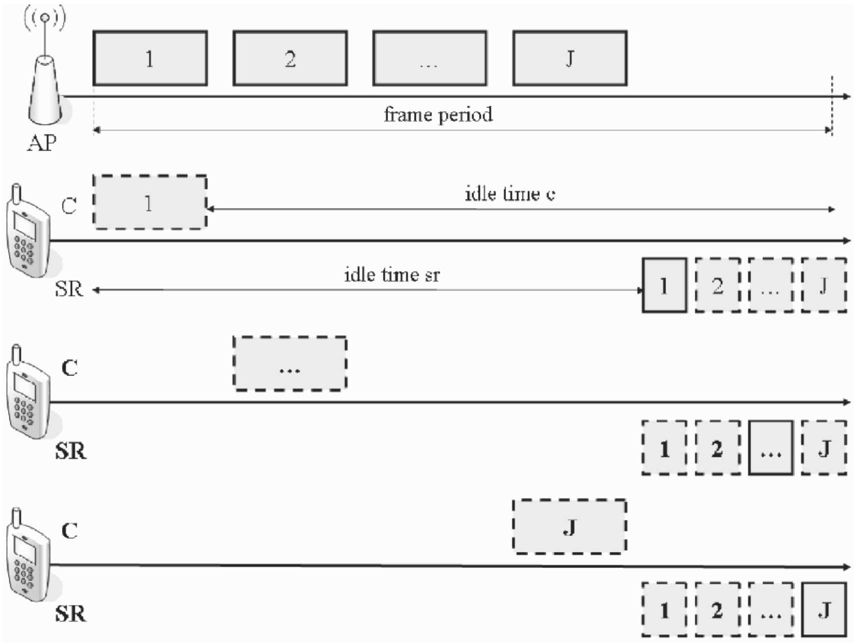

Figure 11.4. Scenario 3: Cooperative reception of the J sub–streams.

Homogeneous Cooperation Capabilities

In this subsection we focus on power consumption for cooperative terminals that have the same cooperative capabilities. We refer to this scenario as *homogeneous cooperation capabilities*. Let us first calculate the power consumption for autonomous (non–cooperating) terminals. The terminal receives always with the same power level P_{NoCoop}:

$$P_{NoCoop} = P_{c,rx} \tag{11.1}$$

To calculate the power consumption in the case of cooperating terminals, we assume that all possible rates among the cooperating terminals are the same. Later we will relax this assumption. The power P_{Coop} can be broken down into its contributions from the central communication (reception of one sub–stream and the related idle time) and the short–range communication (transmission of one sub–stream, reception of $(J-1)$ sub–streams, and a potential idle time). We define:

- $P_{c,rx}$ as the power (energy over unit time) consumed by the terminal for the reception on the centralized radio link, that is from the AP.

- $P_{c,i}$ as the power (energy over unit time) consumed when the radio link to the AP is idle.
- $P_{sr,rx}$ as the power (energy over unit time) consumed by the terminal for the reception on the short–range radio link.
- $P_{sr,tx}$ as the power (energy over unit time) consumed by the terminal for the transmission on the short–range radio link.
- $P_{sr,i}$ as the power (energy over unit time) consumed by the terminal when the short–range radio link is idle.

The total power consumed is

$$\begin{aligned} P_{Coop} = \; & \underbrace{c_{c,rx} \cdot P_{c,rx} + c_{c,i} \cdot P_{c,i}}_{cellular\ contribution} + \\ & \underbrace{c_{sr,tx} \cdot P_{sr,tx} + c_{sr,rx} \cdot P_{sr,rx} + c_{sr,i} \cdot P_{sr,i}}_{short\ range\ contribution} \end{aligned} \tag{11.2}$$

where

- $c_{c,rx}$ is the proportion of time spent on reception on the radio link to the AP.
- $c_{c,i}$ is the proportion of time the link to the AP is idle.
- $c_{sr,rx}$ is the proportion of time spent on reception on the short–range radio link.
- $c_{sr,tx}$ is the proportion of time spent on transmission on the short–range radio link.
- $c_{sr,i}$ is the proportion of time the short–range link is idle.

For Scenario 2, when the short–range link and the link to the access point are simultaneously active, the power consumed by the cooperative terminal is given as:

$$\begin{aligned} P_{Coop}^{Sc2} = \; & \underbrace{\frac{1}{J}}_{c_{c,rx}} P_{c,rx} + \underbrace{(1 - \frac{1}{J})}_{c_{c,i}} P_{c,i} + \\ & \underbrace{\frac{1}{J \cdot Z}}_{c_{sr,rx}} P_{sr,tx} + \underbrace{\frac{J-1}{J \cdot Z}}_{c_{sr,tx}} P_{sr,rx} + \underbrace{(1 - \frac{1}{Z})}_{c_{sr,i}} P_{sr,i} \end{aligned} \tag{11.3}$$

For Scenario 3, when the short–range link and the link to the access point are sequentially active, the power consumed by the cooperative terminal is:

$$
\begin{aligned}
P_{Coop}^{Sc3} = \; & \underbrace{\frac{\frac{1}{J}}{1+\frac{1}{Z}}}_{c_{c,rx}} P_{c,rx} + \underbrace{\frac{1+\frac{1}{Z}-\frac{1}{J}}{1+\frac{1}{Z}}}_{c_{i,rx}} P_{c,i} + \\
& \underbrace{\frac{\frac{1}{J \cdot Z}}{1+\frac{1}{Z}}}_{c_{sr,rx}} P_{sr,tx} + \underbrace{\frac{\frac{J-1}{J \cdot Z}}{1+\frac{1}{Z}}}_{c_{sr,tx}} P_{sr,rx} + \underbrace{\frac{1}{1+\frac{1}{Z}}}_{c_{sr,rx}} P_{sr,i}.
\end{aligned}
\tag{11.4}
$$

We observe that the time required to send the same amount of bits is larger in Scenario 3 than in Scenario 2 by a factor $(1+\frac{1}{Z})$. This has implications with respect to delay, which is beyond the scope of this chapter. However, it might be useful to show the relationship between the total energy requirement for transmission in the various scenarios. For simplicity we normalize the energies E_{Coop}^{Sc2} and E_{Coop}^{Sc3} with respect to the energy consumed in Scenario 1, and define the efficiency ratios η_{Sc2} and η_{Sc3}.

$$
\begin{aligned}
\eta_{Sc2} = \; & \frac{E_{Coop}^{Sc2}}{E_{NoCoop}} = \frac{P_{Coop}^{Sc2} T_{Coop}^{Sc2}}{P_{NoCoop} T_{NoCoop}} = \\
& \frac{\frac{1}{J} P_{c,rx} + (1-\frac{1}{J}) P_{c,i} + \frac{1}{JZ} P_{sr,tx} + \frac{J-1}{JZ} P_{sr,rx} + (1-\frac{1}{Z}) P_{sr,i}}{P_{c,rx}}
\end{aligned}
\tag{11.5}
$$

$$
\begin{aligned}
\eta_{Sc3} = \; & \frac{E_{Coop}^{Sc3}}{E_{NoCoop}} = \frac{P_{Coop}^{Sc3} T_{Coop}^{Sc1}}{P_{NoCoop} T_{NoCoop}} = \frac{P_{Coop}^{Sc3}}{P_{NoCoop}} \left(1+\frac{1}{Z}\right) = \\
& \frac{\frac{1}{J} P_{c,rx} + (1+\frac{1}{Z}-\frac{1}{J}) P_{c,i} + \frac{1}{JZ} P_{sr,tx} + \frac{J-1}{JZ} P_{sr,rx} + P_{sr,i}}{P_{NoCoop}}
\end{aligned}
\tag{11.6}
$$

Now we can apply different current technologies for the central and the short–range communication. In Table 11.1 we show the power levels and data rates motivated by measurements and report of [Atheros Communications, 2003]. Our investigations rely on the data rates provided by the physical layer of the IEEE802.11a or IEEE802.11g standard, as specified in [IEEE Std 802.11a, 1999] and [IEEE Std 802.11g, 2003], respectively. IEEE802.11a and 11g are based on Orthogonal Frequency Division Multiplex (OFDM), where multiple modulation schemes in combination with different coding rates are used. The combination of coding rates and modulation leads to multiple data rates starting at 6 Mbit/s up to 54 Mbit/s. The bit rate on a wireless link depends on the channel quality, which in turn depends heavily on the distance. Once again, let us underline our assumption that the data rate supported by the short–range needs to be larger than the data rate on the link to the AP in order for the proposed cooperative scheme to work.

Table 11.1. Parameters for the Analysis.

Description	Name	Value	Unit
Receiving power from central AP	$P_{c,rx}$	0.90	W
Power while idle	$P_{c,i}$	0.04	W
Receiving power over short–range	$P_{sr,rx}$	0.90	W
Transmitting power over short–range	$P_{sr,tx}$	2.00	W
Power for short–range while idle	$P_{sr,i}$	0.04	W
Rate for the central link	R_c	12.00	Mbit/s*
Rate for the short–range link	R_{sr}	54.00	Mbit/s

* the data rate was chosen to provide multicast transmission of the sub–streams; larger values would not allow the successful decoding of the data by terminals far away from the access point, if these terminals were to operate independently.

As a first result, Figure 11.5 shows the normalized energy consumed versus the number of cooperating entities for three different scenarios. In Scenario 2 each terminal has two WLAN network interface cards, while in Scenario 3 only one network interface card is needed. The energy consumed in the non cooperating case does not change and is normalized to unity, while the two cooperating strategies use less energy as the number of cooperating entities increases. A slightly larger power consumption is observed in Scenario 3 relative to Scenario 2. The power consumed in the cooperating case is approximately 50% of that in the non cooperating scenario for six cooperating terminals. It can also be noted from Figure 11.5 that the benefit from cooperation saturates with the number of cooperating terminals for both cooperating scenarios.

For a more detailed investigation we show how the total power can be broken into its components, *i.e.*, how much corresponds to each activity (transmission, reception or idleness) on each of the given air interfaces. Figure 11.6 illustrates the results for Scenario 2. For a large number of cooperating terminals the power spent on the receiving part from the central AP decreases. The power spent for the transmission in the short–range also decreases with the number of users. The power during the idle time on the central link and during reception of the sub–streams over the short–range communication increases as the number of cooperating users increases. The power for the idle time on the short–range link is constant since it only depends on the ratio of the achievable rates.

Generating Costs of Cooperating Sub–Streams

We note that, the separation of the original data stream into several sub–streams introduces an increase in the amount of data to be sent out. This kind of overhead is caused by the additional IP headers per sub–stream and

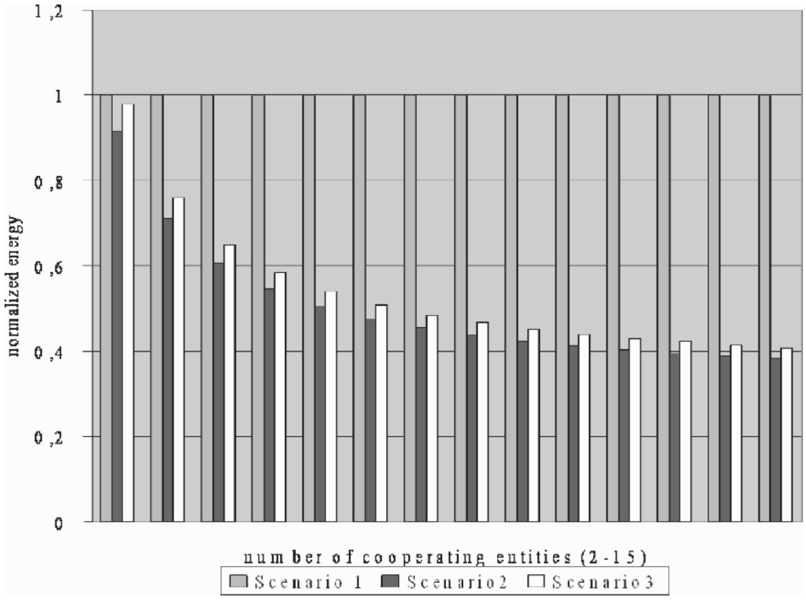

Figure 11.5. Normalized energy versus number of cooperating terminals for all three scenarios with two WLAN cards.

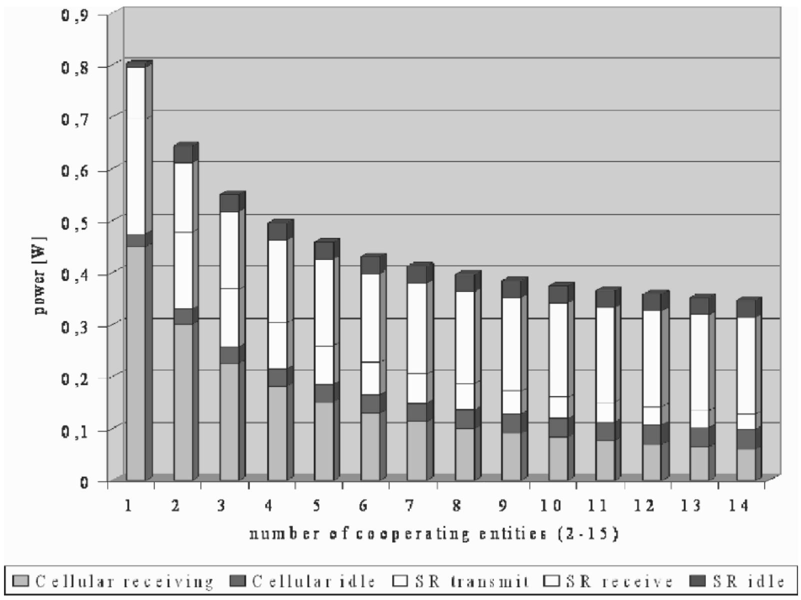

Figure 11.6. Detailed power consumption versus number of cooperating terminals for Scenarios 2.

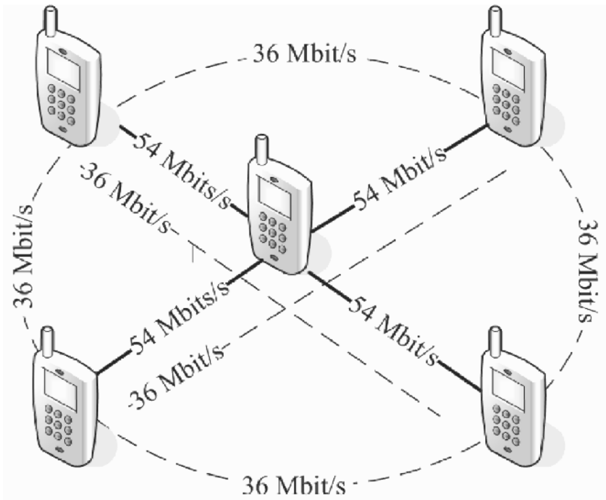

Figure 11.7. Example of an star configuration for the cooperating group with one terminal sending with 54 Mbit/s and others with 36 Mbit/s.

potentially by the encoding overhead. The IP overhead increases linearly with each additional sub–stream. The encoding overhead is more difficult to describe as it depends on the encoder used and the source which has to be encoded. In order to take this overhead into account, we should scale the above results by a function $f(J) \geq 1$, that depends on the number of data streams into which the original data are to be split (in our case this is also the number of cooperating users). Additional techniques such as header compression can help reduce the associated IP overhead (*i.e.*, reduce the value of the function $f(J)$) as given in Chapter 17.

Heterogeneous Cooperation Capabilities

So far we have assumed that the rate on the link between any two terminals within one cooperative group is the same for all of the members of the cooperating group. However, this might not always be the case. In the case of J terminals within one cooperative group, there are $J(J-1)/2$ possible links on the short–range communication with potentially different data rates. Using (11.3) or (11.4), we simply need to find out the minimum of all maximal available rates per link and set R_{sr} to that value. Doing so would still allow all cooperating terminals to successfully communicate, but this would also reduce the power savings dramatically. Therefore better strategies need to be found. To illustrate this, we consider next two possible examples.

Assuming a star configuration for the cooperative group as given in Figure 11.7, the terminal in the middle can communicate with the others at a rate of

54 Mbit/s, while all other communications have an achievable rate of 36 Mbit/s (clearly the achievable rate is the same in either direction of the communication link between any two terminals). In this first example we could derive a cooperation strategy whereby each terminal sends out its data over the short–range communication at a given rate. This rate is given by the minimum (over the links to the other $(J-1)$ terminals) of the maximum achievable rate on any link (dependent on the quality of the link). This may improve the situation compared to the initial scenario. The used power for cooperation differs now from that given in (11.3) as Z is not the same for all terminals and needs to be defined for each terminal individually. Furthermore the power saving gain also differs among the terminals.

If we assume a scenario where the short–range and the central link are allowed to operate simultaneously and the data rates on the link from the AP are all equal, then the power needed for terminal k is given by

$$\begin{aligned} P_{Coop,k} = \; & \tfrac{1}{J} \cdot P_{c,rx} + \left(1 - \tfrac{1}{J}\right) \cdot P_{c,i} + \\ & \tfrac{1}{J \cdot Z_k} \cdot P_{sr,tx} + \tfrac{1}{J} \cdot \textstyle\sum_{i=1, i \neq k}^{J} \tfrac{R_c}{R_{sr,i}} \cdot P_{sr,rx} + c_{sr,i} \cdot P_{sr,i} \end{aligned} \tag{11.7}$$

where

$$Z_k = \frac{R_{sr,k}}{R_c} \tag{11.8}$$

and the new value of c_{sr} (c_c remains the same) for Scenario 2 is

$$c_{sr,i} = 1 - \frac{1}{J} \cdot \sum_{i=1}^{J} \frac{R_c}{R_{sr,i}}. \tag{11.9}$$

The engineering cost of these more advanced schemes lays in the increased synchronization requirements among terminals.

The second example, given in Figure 11.8, is characterized by one outlying terminal. While four terminals could send to each other with a rate of 54 Mbit/s, the link to the exposed terminal has a maximum rate of 36 Mbit/s. In this example we have the aforementioned dilemma. The clustered terminals may agree to not cooperate with the exposed terminal to achieve the largest energy saving gain, which equals 0.608 for the normalized energy regarding Table 11.2 (we assumed a data rate of 12 Mbit/s from the access point and the energy levels given in Table 11.1). The exposed terminal would then be forced to receive the full information from the access point with the normalized energy level of 1.000. If all terminals decide to cooperate, they have to send at the common rate of 36 Mbit/s. In this case the related normalized energy level is 0.680. But in this example there are also intermediate levels of cooperation possible such that the clustered terminals agree to cooperate with the exposed one by sending two (they

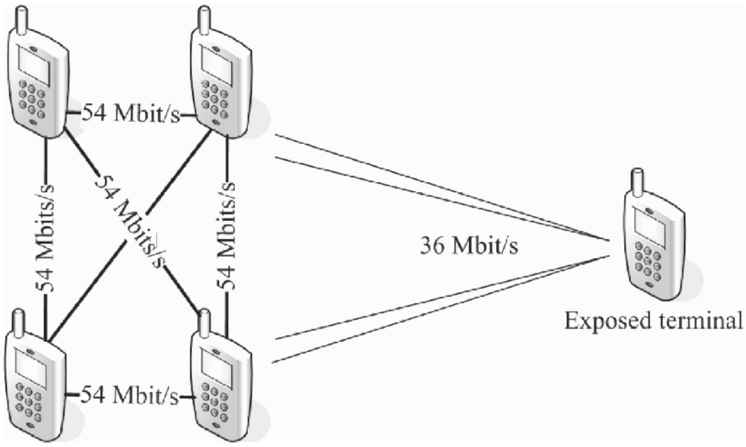

Figure 11.8. Cooperative group with some clustered and one exposed terminal.

want to be nice and generous, but any number may be motivated here instead of two) descriptors at a rate of 36 Mbit/s in exchange of the single descriptor from the exposed terminal. This solution has some charm as the exposed terminal will not get the full video quality and may change its position towards the clustered terminals. This behavior is well known for voice communications where users tend to move to achieve a better receiving position (such as the window in an indoor environment).

In Table 11.2 the scenarios with two and four exposed terminals are also given. In this scenario the exposed terminals communicate with a data rate of 36 Mbit/s with the clustered groups and among each other. For two exposed terminals an overall cooperation (six terminals with data rate of 36 Mbit/s) will require a normalized energy level of 0.634. Still the dilemma exists as the energy consumption level of the cluster group would be smaller (0.608). If the clustered group decide against cooperation with the exposed group, the exposed group would also not cooperate within each other as this cooperation would need more normalized energy than the self-sufficient (autarchic) central reception with 1.088 and 1.000 respectively. In the case of four exposed terminals the dilemma vanishes as the normalized energy level by overall cooperation (eight terminals at 36 Mbit/s) with 0.577 is lower than that of a cooperating group (0.608) with four members, aiming 54 Mbit /s among each other.

So far we have investigated scenarios with omnipresent technologies such as the well known wireless local area networks. Those technologies are not designed specifically to support cooperation, but we show that potential benefits of cooperation exist even with those techniques. Future technology such as ultra–wideband for short–range with high data rate will increase the potential of cooperative communication even more. Providing higher data rates in the

Table 11.2. Example1: Cooperation Matrix for the Clustered and Exposed Terminal.

Scenario		**Normalized Energy**		
		partial cooperation		full cooperation
cluster	exposed	cluster	exposed	
4	1	0.608	1.000	0.680
4	2	0.608	1.088*	0.634
4	4	0.608	0.748	0.577

*as this is larger than the stand alone power, the terminals may dismiss cooperation and receive directly from the access point.

cellular systems between base station and terminal always come along with increased costs in terms of power consumption and complexity. The exploitation of the short–range combined with cooperative techniques seems to be a promising way to support *virtual* high data rate. Instead of having two air interfaces for the short–range and cellular links, we highlight the potential of a unified air interface for short and cellular communication in the next section.

4. Orthogonal Frequency Division Multiple Access Cooperation

In the previous sections we assumed that the communication from the AP to the users and the communication among users happen over two different air interfaces. In this section we assume a common interface and that the two types of links are free to partition the bandwidth that is available to the system, and are allowed to access their respective parts of the spectrum at the same time. The transmission is based on a frequency division scheme, such as Discrete Multi Tone (DMT) or Orthogonal Frequency Division Multiplexing (OFDM). Let us assume that the total system bandwidth BW can be considered as a set of N_{sub} sub-carriers, each with a bandwidth $BW_{sub} = \frac{BW}{N_{sub}}$.

We assume that the access point (AP) allocates equal power on each subcarrier, so that the total transmitted power is P_t. Therefore the power allocated to each subcarrier is $\frac{P_t}{N_{sub}}$.

Let $g^{A \to B}(n)$ be the channel gain for the n-th subcarrier on the link from A to B. Due to channel reciprocity, we expect $g^{A \to B}(n) = g^{B \to A}(n)$. We distinguish the following types of gains:

- $g^{AP \to U_i}(n)$, which correspond to the links from the access point to the i-th user, and
- $g^{U_j \to U_i}(n)$, which correspond to the links between the j-th and the i-th users.

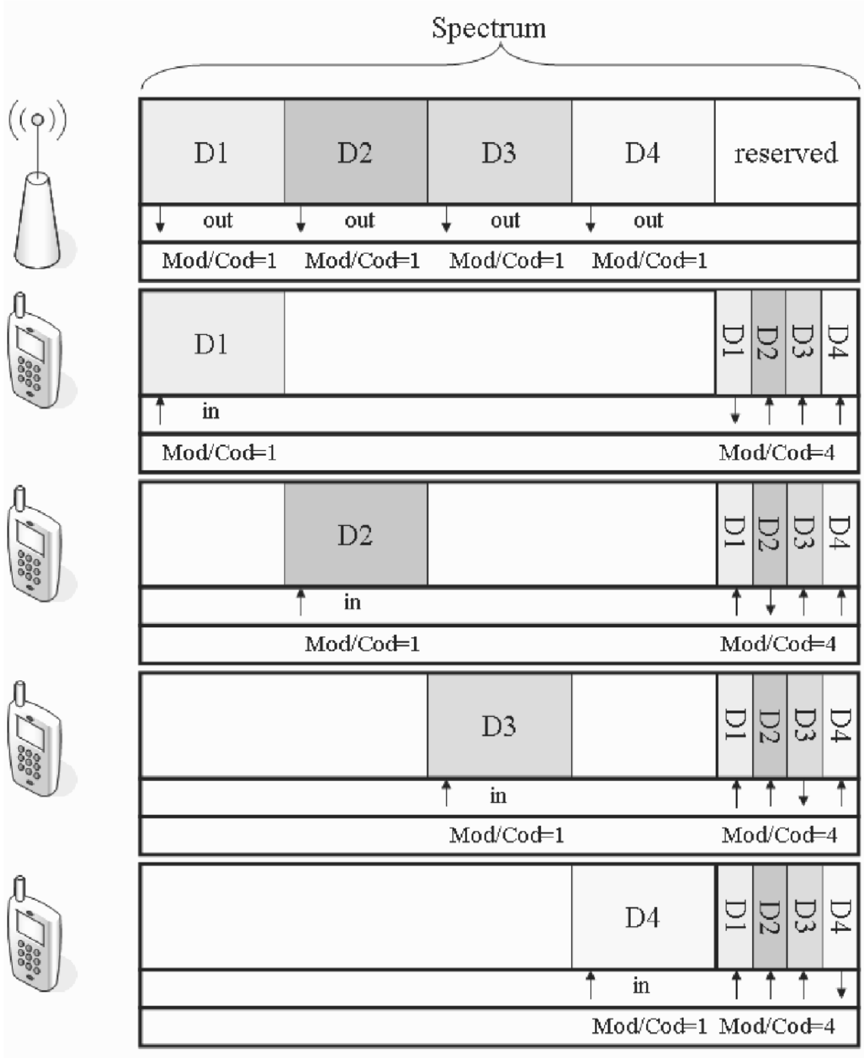

Figure 11.9. Spectrum partitioning: The base station sends out four data streams (D1, D2, D3, D4) on the downlink frequencies on the left. Each one is received by a different terminal, which in turn transmits the data stream to its neighbors over the short–range frequencies on the right, and receives the others on the rest of the short–range frequencies.

We expect that the difference in the length of the links between the access point and the users and the links between users will bias the channel gains such that

$$< g^{U_j \to U_i}(n) > \quad \geq \quad < g^{AP \to U_i}(n) >, \tag{11.10}$$

where $< \cdot >$ denotes the expectation of the argument $(\cdot)$.

Let P be the power transmitted by A on the n-th subcarrier. It is assumed that if A performs adaptive modulation and coding (AMC) with a view to maximizing the achievable rate on the link to B, then the maximum achievable rate on the link from A to B is

$$R^{A \to B} = log_2 \left(1 + \frac{1}{\gamma} \frac{P}{\sigma^2} g^{A \to B}(n)\right) \tag{11.11}$$

σ^2 is the receiver noise at B. The constant γ depends on the coding loss and the target probability of error, and describes the loss relative to the Shannon capacity which would be given by

$$C^{A \to B} = log_2 \left(1 + \frac{P}{\sigma^2} g^{A \to B}\right). \tag{11.12}$$

We assume that the coding loss for the links from the access point to the users is γ_c, and that the coding loss for the links between users is γ_{sr}. We also assume that AMC can be performed individually on each subcarrier, and therefore the total rate is given as the sum of the rates on the individual subcarriers. In a practical system, there is a maximum allowable modulation rate. This constraint would affect our results, but for demonstrating the concept, we assume that our system can decode infinitely high modulation sizes.

Transmission without Spectrum Partitioning

If the entire spectrum is used for the downlink communication from the access point to the users, then the total rate that can be achieved on the link from the access point to the i-th user is:

$$R_{cell\ only}^{AP \to U_i} = \sum_{n=1}^{N_{sub}} log_2 \left(1 + \frac{1}{\gamma} \frac{P_t}{N_{sub}\sigma^2} g^{AP \to U_i}(n)\right) \tag{11.13}$$

The total transmitted power and rates on each subcarrier are selected so that service can be provided to the users in the cell area with a certain outage probability.

In our case we investigate a group of users that can all access the broadcast channel independently, and we assume that the coding and modulation rates are selected so that all the users receive the same quality of service. They are therefore limited by the achievable rates on the link to the weakest user. The achievable rate on the n-th subcarrier is:

$$R^{dl}_{cell\ only}(n) = log_2\left(1 + \frac{1}{\gamma_{cell}}\frac{P_t}{\sigma^2}min_i\left(g^{AP\rightarrow U_i}(n)\right)\right) \qquad (11.14)$$

and the total achievable rate is

$$R^{dl}_{cell\ only,total} = \sum_{n=1}^{N_{sub}} R^{dl}_{cell\ only}(n) \qquad (11.15)$$

Transmission with Spectrum Partitioning

Let us now assume that the spectrum is partitioned into two blocks as given in Figure 11.10:

- The first block contains N_{cell} subcarriers and is used by the access point for cellular downlink transmission. Let $V^{U_i}_{cell}$ be the set of subcarriers allocated to downlink communication to the i-th user, and let $N^{U_i}_{cell} = |V^{U_i}_{cell}|$ be the number of these subcarriers ($N_{sr} = |V_{sr}|$). Then

  $$\sum_{i=1}^{N_U} N^{U_i}_{cell} = N_{cell} \qquad (11.16)$$

  where N_U is the number of users.

- The second block contains N_{sr} subcarriers and is used by the users for the short range communication among them. Let V_{sr} be the set of these subcarriers. This is further partitioned into N_U sets of the form $V^{U_i}_{sr}$, where N_U is the number of users. $V^{U_i}_{sr}$ is the set of subcarriers used by the i-th user for transmission on the short–range link, and let $N^{U_i}_{sr} = |V^{U_i}_{sr}|$ be the number of these subcarriers. The i-th user receives data from all the other $j \neq i$ users in the remaining $N_{sr} - N^{U_i}_{sr}$ subcarriers. Therefore

  $$\sum_{i=1}^{N_U} N^{U_i}_{sr} = N_{sr}. \qquad (11.17)$$

The system bandwidth is the same as before and therefore

$$N_{sub} = N_{cell} + N_{sr}. \qquad (11.18)$$

We first concentrate on the links from the access point to the users. Following this scheme, the AP uses fewer subcarriers, and therefore the question becomes what happens to the transmit power, relative to the case of no spectral partitioning. Let $P_{t,cell}$ denote the transmit power from the AP. One option is that the total transmit power is kept constant ($P_{t,cell} = P_t$), and another is that the total transmit power scales according to the number of subcarriers used for downlink transmission, while keeping the power per subcarrier constant ($\frac{P_{t,cell}}{N_{cell}} = \frac{P_t}{N_{sub}}$).

Moreover, the AP has to decide how to allocate the available frequencies to the users, *i.e.*, how to partition the set of N_{cell} frequency subcarriers into N_U sets of various sizes. If that has been determined, the downlink rate to the i-th user on the n-th subcarrier ($n \in V_{cell}^{U_i}$) is

$$R_{dl}^{U_i}(n) = log_2\left(1 + \frac{1}{\gamma_{cell}} \frac{P_{t,cell}}{N_{cell}\sigma^2} g^{AP \to U_i}(n)\right), \tag{11.19}$$

and the total rate to the n-th user is

$$R_{dl,tot}^{U_i} = \sum_{n \in V_{cell}^{U_i}} R_{dl}^{U_i}(n). \tag{11.20}$$

Clearly the total downlink rate of transmission is

$$R_{coop,tot}^{dl} = \sum_i R_{dl}^{U_i}. \tag{11.21}$$

We observe that

$$R_{dl}^{U_i}(n) \geq R_{cell\ only}^{dl}(n) \tag{11.22}$$

because:

- The transmission is not limited by the minimum user gain:

$$g^{AP \to U_i}(n) \geq g^{AP \to U_i}(n), \tag{11.23}$$

- In the case where the total transmitted power from the AP is kept constant, we have more power available per subcarrier($\frac{P_{t,cell}}{N_{cell}} \geq \frac{P_{t,cell}}{N_{sub}}$).

Let us assume that the i-th user uses total power $P_{t,sr}^{U_i}$ for the cooperative transmission, and that this power is divided equally on all subcarriers in $V_{sr}^{U_i}$. This power might be the same for all users within the cooperating group for reasons of fairness, however we allow for the available transmit powers to vary among users. The AMC on each subcarrier in $V_{sr}^{U_i}$ is determined so that all the users in the cooperative group achieve the same rate. Therefore the maximum total transmission rate on the short–range communication link from the i-th user is:

$$R_{sr}^{U_i} = \sum_{n \in V_{sr}^{U_i}} log_2\left(1 + \frac{1}{\gamma_{sr}} \frac{P_{t,sr}^{U_i}}{N_{sr}^{U_i}\sigma^2} \min_{j \neq i} g^{U_i \to U_j}(n)\right). \tag{11.24}$$

The full problem involves the partitioning of the entire set of subcarriers into two sets (one for the downlink communication between the access point and the users, and one for the communication among the users), and further partitioning of each set into N_U sets, so that the conditions above are satisfied. The criterion for the optimal frequency partitioning can be the maximization of the achievable rate or the minimization of the total power. Clearly the complexity is prohibitive.

In this chapter we make some simplifying assumptions on the spectrum partitioning.

- A fixed percentage α of the total number of subcarriers is allocated to the communication on the short–range links ($N_{sr} = \alpha N_{sub}, N_{cell} = (1 - \alpha)N_{sub}$). Figure 11.10 shows the cases, where α equals 0,0.5, and 0.75.

- The specific subcarriers that are allocated to each type of link are pre-determined. Figure 11.10 shows for example two different ways to allocate 75% of all subcarriers to the short range link.

- The specific subcarriers that are allocated to each user for each type of link are pre-determined (*i.e.*, the sets $V_{sr}^{U_i}$ and $V_{cell}^{U_i}$ are predetermined).

- All users are assigned the same number of subcarriers on both the link to the AP and the short–range link (the algorithm that determines what user is allocated which subcarrier is shown later).

The motivation for the use of cooperation in a scenario like this would be power saving. Clearly, if there is no penalty associated with data reception from the AP or on the short–range link, then the terminals have no motivation to cooperate and expend their power to transmit a data stream to their neighbors. Therefore we define the following costs:

- $P_{cell,Rx}(N)$ is the power consumed per bit received on the link to the AP. It is a function of the number of subcarriers used for the transmission. For example, one would expect the processing cost per bit to be reduced as the size of the Fast Fourier Transform (FFT) as in an OFDM system decreases. For simplicity, we assume it does so linearly.

- $P_{sr,Rx}(N)$ is the power consumed per bit received on the short–range link. It is also a function of the number of subcarriers used for the transmission.

- $P_{t,sr}^{U_i}$ is the power consumed for the transmission on the short–range link. It is determined by the battery level at each user terminal.

The users would be willing to cooperate if the following constraints are satisfied:

- The total achievable rate is the same in the cases with and without spectrum partitioning (otherwise they would just connect to the AP directly):

$$R^{dl}_{coop,tot} \geq R^{dl}_{cell\ only,tot}. \tag{11.25}$$

- The rate of transmission on the short–range link cannot be larger than the rate of reception on the link from the AP (the rates should be supported on both types of links).

$$R^{U_i}_{sr} \geq R^{U_i}_{dl}. \tag{11.26}$$

- There is a power benefit from the cooperation:

$$P_{cell,Rx}(N_{cell}) + (N_U - 1)P_{sr,Rx}(\frac{N_{sr}}{N_U}) + P^{U_i}_{t,sr} \leq P_{cell,Rx}(N_{sub}). \tag{11.27}$$

  Under the assumption that the power consumed for the reception of a data stream scales proportionately to the number of subcarriers used and that a fixed fraction α of the available subcarriers is allocated to the short–range communication (Figure 11.10 shows the cases, where α equals 0,0.5, and 0.75), this equation becomes

$$(1-\alpha) + \alpha\frac{N_U - 1}{N_U} + \frac{P^{U_i}_{t,sr}}{P_{cell,Rx}N_{sub}} \leq 1. \tag{11.28}$$

Given the definitions above, the achievability of all the constraints is a function of the available powers, the coding complexity, the noise level, and the channel gains from the AP to the users and among users.

As mentioned earlier, the optimal solution would allow the adaptive allocation of subcarriers to the various types of link.

Assuming that the number of subcarriers to be allocated to each user is known, then the optimal algorithm for the subcarrier allocation to the users for the downlink transmission is as follows:

Let us assume that we want to allocate N_{sub} subcarriers to N_U users, so that each one of them gets N_{sub}/N_U of them.

- Step 1: Initialization

  Define the set of users $S_U = \{U_1, U_2, \ldots, U_{N_U}\}$ and a set of subcarrier indices $B = \{1, \ldots, N_{sub}\}$, and construct a matrix G of dimensions $N_U \times N_{sub}$ such that $G_{i,j} = g^{AP\rightarrow U_i}(j)$. Also define N_U sets of the form $S_i = \{\}, i = 1, \ldots, N_U$.

  Set n = 1.

- Step 2: Find maximum.

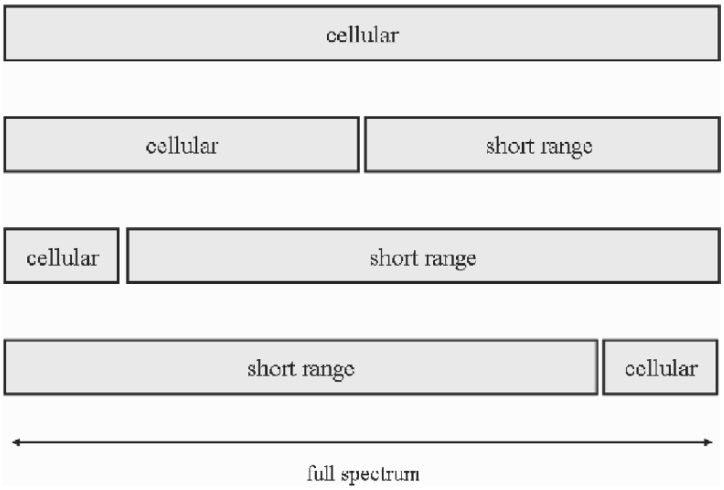

Figure 11.10. Examples where α equals 0,0.5, and 0.75.

Find $i \in S_U, j \in B$ such that $g^{AP \to U_i}(j)$ is maximum.

- Step 3: Allocate to user.
  $S_i \leftarrow S_i \cup \{j\}$
- Step 3: Exclusion
  If $|S_i| = N_{sub}/N_U$, then $S_U \leftarrow S_U - \{U_i\}$. Remove i–th row of the matrix G.
- Step 4: Advance
  $B \leftarrow B - \{j\}$. If $B \neq \{\}$, go to step 2.

A similar algorithm can be applied for the allocation of the subcarriers on the short–range communication link.

5. Conclusion

This chapter explored power consumption paradigms in cooperative networks. The purpose of the present research was twofold, first, to show the potential of power savings using cooperative information reception in two different widely used wireless technologies, and secondly, to introduce a OFDM–based common air interface, as we expect to be used in the 4G wireless communication systems. This kind of common air interface allows us to dynamically set the ratio between cellular and short link capacity. This is an important feature as the capacity on the cellular as well as on the short–range links depends significantly on the number of cooperating terminals. One of the main conclusions of this chapter is the importance of advanced power management schemes. These include hardware capabilities allowing us to power down unsused parts or turn-off not required functionalities. Sleep modes can be implemented on chip as well as in parts using discrete components. Moreover, the clock rate of some processing blocks can be scaled down whenever possible to keep power efficiency high. In addition to hardware, protocols need to be designed to allow dedicated switch off periods for power saving purposes. While power management technologies are relatively advanced, in particular on-chip, more research on power-aware protocols is needed. Indeed, most of the protocols are not considering dedicated switch off periods. Protocol design for cooperative networking is a important and promising area to explore.

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